The Onyx River, McMurdo Dry Valleys: Exploring Antarctica as a Mars Analogue

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Abstract

The climate in the McMurdo Dry Valleys (MDV) of Antarctica on Earth is hyper-arid and hypothermal, with mean annual temperatures far below the melting point of water and most water trapped as ice in glaciers. Despite the freezing climatic conditions, significant seasonal fluvial activity persists – the Onyx River is active for typically 2-3 months in Antarctica in the austral summer, is ~30 km in length, and is fed predominantly by glacial meltwater. Researchers have proposed that the early martian climate may have been similar to the MDV climate in many ways, with mean annual temperatures far below the melting point of water, all water trapped as ice in the southern highlands, and all fluvial activity related to melting of glaciers and surface runoff. However, the martian fluvial valley networks have commonly been cited as evidence for a much warmer and wetter climate, characterized by mean annual temperatures >0° C and rainfall as the dominant erosive mechanism. Here, we hypothesize that the Onyx River may be a good process analogue for glacial meltwater-fed fluvial activity in a "cold and icy" early martian climate. We characterize the morphology and climate controls of the Onyx River and then compare the results of our morphological analysis to the morphological characteristics of the martian valley networks to test the hypothesis that the martian valley networks could have formed in a similar "cold and icy" climatic regime as the Onyx River in the MDV. We find that the majority of the valley networks are equal to or less developed than the Onyx River, implying that these widespread martian fluvial features may not preclude a long-lived, continuous "cold and icy" climate in the Late Noachian-Early Hesperian on Mars.

I. Introduction

The current martian climate is hyper-arid and hypothermal, similar in many ways to the climate of the Antarctic McMurdo Dry Valleys (MDV) on Earth (Marchant et al., 2007). This climate has persisted throughout the Amazonian era (past ~3 Gy) on Mars. Geologic evidence, including the widespread fluvial martian valley networks (MVN) (Hynek et al., 2010) and open- and closed-basin lakes, suggest that the martian climate at the Late Noachian and Early Hesperian boundary (~3.7 Ga) may have been much different than the current martian climate (Cabrol and Grin, 1999). This climate scenario is commonly referred to as "warm and wet" and is characterized by abundant stable liquid water at the surface and persistent rainfall to form these fluvial and lacustrine features (Fassett and Head, 2008; Goudge et al., 2015; Craddock and Howard, 2002). In contrast with the geologic evidence for a "warm and wet" climate, recent climate modeling studies have suggested that the early martian climate may have been "cold and icy". This climate scenario is characterized by global mean annual temperatures far below the melting point of water (~225 K), an adiabatic cooling effect (Wordsworth et al., 2011), and ice distributed across the southern highlands (Head and Marchant, 2014). In this "cold and icy" climate scenario, transient or punctuated heating events would be responsible for ice melting, liquid runoff, ponding at the surface, and formation of the MVN and lakes (Wordsworth et al., 2011; 2015; 2016). One possible transient heating process that can produce significant volumes of meltwater is seasonal temperature variations and summertime melting (Palumbo et al., 2018). Thus, it is possible that the climate of early Mars and processes responsible for driving fluvial activity were similar to what is observed in the MDV: mean annual temperatures are far below freezing; however, the warmest part of the summer season experiences temperatures >0° C, permitting transient ice melting and runoff (Head and Marchant, 2014).

In this work, we consider the MDV as an analogue for early Mars processes in an effort to better understand the role of ice melting and liquid water runoff in a "cold and icy" environment. We explore the geomorphology of the Onyx River (Shaw and Healy, 1980), the longest river in the MDV which flows for ~30 km, measured as the river winds, and then compare our results tothe geomorphology of the MVN in order to determine whether these features could have formed under the conditions of the proposed "cold and icy" climate (Gooseff et al., 2007). The geomorphologic characteristics of rivers provides information about the characteristics of the climate in which they formed. Thus, if the MVN appear inconsistent with the characteristics of the Onyx River, we consider that a "warm and wet" climate, characterized by abundant rainfall and runoff instead of snowmelt and runoff, may have been necessary to explain the formation of the MVN.

II. Background

II.A Wright Valley Geology

The MDV cut through the Devonian to Triassic-age Beacon Supergroup of conglomerate, sandstone, and orthoquartzite members as well as older Ross Orogeny granites and gneisses (Bradshaw, 2011). Thin and patchy glacial tills from previous cold-based glacial advance are scattered about the bedrock landscape, which differ from the mud-rich tills of the northern hemisphere resulting from wet-based glaciation. Wright Valley is one of three main valleys out of the fifteen valleys that are located within the MDV, along with Victoria Valley and Taylor Valley. Wright Valley is located between the Olympus Range to the north and the Asgard Range to the south (Figure 2). The Onyx River is the largest of seven Antarctic rivers and the only river within Wright Valley. Lakes within Wright Valley include Lake Brownworth, Lake Vanda, and Don Juan Pond, comprising three of the twelve lakes that are located within the MDV. River-smoothed and angular granitic blocks along with finer sediments dominate the sedimentary record within the Onyx River (Figure 2).

II.B Wright Valley Hydrology

The MDV hydrological cycle at the Onyx River is distinct from the hydrological cycle at many northern hemisphere rivers because the MDV exist within the Antarctic tundra environment, characterized by the presence of frozen subsoil permafrost for most of the year. Despite the majority of the MDV being ice-free, most of Antarctica cannot support vegetation because it is too cold and dry (Shaw and Healy, 1980); vegetation is a major control on river development in typical northern hemisphere rivers. The desert-like MDV conditions inhibit rainfall, evapotranspiration, and soil percolation within the Antarctic tundra, which is a marked difference from northern hemisphere environments. We must then consider the dominant MDV hydrological cycle processes to be top-down glacial melting of cold-based glaciers, meltwater runoff, river and ocean evaporation, condensation, and precipitation mostly as snowfall.

III. Methods

We combine a variety of meteorological and morphological datasets collected at the Onyx River, Antarctica with morphological measurements of the MVN to determine whether the MVN could have formed in a "cold and icy" climate through seasonal ice melting and surface runoff.

III.A Methods: Antarctic Dry Valleys

The Antarctic Dry Valleys are terrestrial systems that have been studied through geochemical, geophysical, and biological investigations. NASA has equipped the underside of aircrafts with Continuous Airborne Mapping by Optical Translator (CAMBOT) and Landsat imaging systems, which traverse over the Antarctic Dry Valleys in efforts to understand Antarctic geomorphology. One such successful mission operated during the Antarctic summer field season from 18-29 December 2001 and provided high-resolution imagery of the region. CAMBOT took down-looking images and recorded associated latitude/longitude position during flights by using a Prosilica GT 4905 harsh environment GIGE Ethernet camera with a global shutter capable of 7.5 fps at 16 Megapixel as part of NASA Airborne Topographic Mapper. CAMBOT collected hundreds of images over the 12-day mission and many images overlapped along the same flight path because they were taken in rapid succession.

During its traverse, the aircraft passed over Wright Valley, where the Onyx River is located. We analyzed the images taken along the aircraft's flight path during the 18-29 December 2001 mission that were spatially consistent with the Onyx River. Individual image resolutions differ as a function of distance between the aircraft and surface but are on average ~0.5 m/pixel. We then used Adobe Illustrator to produce seamless blended mosaic .tiff files of the CAMBOT images of

Wright Valley, the region of the Antarctic MDV in which the Onyx River flows. We then used the locations recorded for each photo and georeferenced these mosaics in ArcGIS to Wright Valley 1 m/pixel Landsat data using at least 4 control points per image to preserve scale (2014-2015 LIDAR survey of the McMurdo Dry Valleys, Antarctica).

Armed with a georeferenced and scale-preserved seamless mosaic of Wright Valley, Antarctica, we were capable of performing a geomorphological analysis of the Onyx River while it was active because CAMBOT images were taken during austral summer. First, we analyzed the branching complexity of the Onyx River. Branching complexity is commonly used to characterize dendritic fluvial systems in hydrological analyses of terrestrial rivers. One mathematical representation of stream complexity is based on a hierarchy of tributaries and is referred to as the Strahler stream order method, an ordering system first developed in hydrology by Robert Horton and Arthur Newell Strahler (Figure 1) (Strahler, 1957). To visualize the Strahler stream order method, consider a tree as a directed graph oriented from the root towards the leaves. We assign each node of the tree a Strahler number in bottom-up order. This is such that nodes that are leaves of the tree have a Strahler number of one (Figure 1). Only nodes with two or more children with Strahler number i, and no children with greater Strahler number, will have a Strahler number of $i + 1$ (see Figure 1) (Strahler, 1957). In hydrology, we consider each river segment as a node of a tree, with the next segment downstream of its parent. When two first order streams join, they form a second order stream. When two second order streams join, they form a third order stream, and so on. However, the joining of a first and second order stream does not form a third order stream (Briney, 2017). On Earth, Strahler stream indices range from 1 (streams without tributaries) to 12 (the Amazon River). Higher numbers represent more complex stream networks and higher numbers can be used as a proxy to describe the size and strength of the channels within stream networks (Briney, 2017). Channel width relates to Strahler number because high-order streams must accommodate more water inputs (Strahler, 1957). Thus, there are potential implications that water volume scales cumulatively with river development as described by Strahler number.

The Onyx River qualifies as a stream because it contains recurring hydrological features with water in channels for at least part of the year. Thus, we performed a Strahler number analysis on the Onyx River using the high-resolution CAMBOT images super-imposed over the Wright Valley hillshade data. We produced a shapefile feature in ArcGIS to trace every visible stream node in CAMBOT imagery, following the stream identification methodology of similar work of in analyses of MVN (Hynek et al., 2010). Using the same methodology is critical for the comparison between our results for the Onyx River and the results of the analysis of the MVN by Hynek et al. (2010). We attributed Strahler numbers to observed segments and considered multiple channels from the same glacier to be only one stream. This step is useful for (1) distinguishing individual sources to the main river channel and (2) comparison to Mars because erosion within MVN channels reduces channel resolution today so that the main channel is likely the only remaining channel. The purpose of this stream order analysis is to qualify the hydrological system within the Onyx River watershed, including identification of water sources and sinks within the system and an estimate of the Strahler stream order, which can be used as a proxy for river development.

Another important factor for understanding the nature and evolution of the Onyx River is the regional climatic controls. To do this, we analyze Long Term Ecological Research (LTER) climate records of the MDV that have been previously collected and are publically available. The National Science Foundation (NSF) funded the LTER program in 1977-78 in order to initiate and maintain close consultation with the ecological sciences community and record data over long time and broad spatial scales at many locations worldwide. In 1993, researchers installed LTER stations within the MDV. Twenty meteorological stations were set up across the MDV and recorded continuous data at fifteen-minute increments. These stations are still active today. Environmental Data Initiative (EDI) publishes and maintains this data for public use. LTER datasets used in this study include (1) the Lower Wright meteorological station and (2) the Lake Brownworth discharge gauge. These LTER stations are useful because they record climate and hydrological variables at the headwaters of the Onyx River within Lake Brownworth, which is located at the base of Lower Wright Glacier; Lower Wright Glacier meltwater overflow feeds discharge within Lake Brownworth. These climate and hydrological variables can then be correlated to Onyx River formation in time to determine processes operating on annual river formation and re-activation. The Lower Wright meteorological station collects a variety of meteorological data at the Onyx River and the Lake Brownworth discharge gauge collects discharge data from the overflow of Lake Brownworth into the Onyx River. The specific variables that we consider in this study are air temperature, discharge rate, solar radiation, and relative humidity.

We used LTER data to compare Onyx River discharge rate with the meteorological variables because we are interested in understanding both the physical and climatological aspects of the Onyx River system and our hydrological maps of Onyx River stream order do not explain the process of cold-based glacial meltwater formation perennially. The climate datasets exist from 1995 to present and the discharge rate dataset exists from 1977 to present. For this reason, we can only compare the meteorological data with the discharge rate data from the year 1995 until present. We characterized changes in discharge rate and meteorological variables in order to characterize controls on river activity in the Onyx River for the data spanning 1995 to present. In our analysis, we plotted (1) every data point available in each year, collected at 15-minute intervals, in order to consider trends within seasons (Figure 3), as well as (2) yearly averages in order to consider trends across the record of available data (Figure 4 a). We searched for correlations between the variables to determine the most important meteorological influences for the process of ice melting and runoff.

III.B Methods: Mars

The Mars Orbiter Laser Altimeter (MOLA) collected high-resolution topographic data of the surface of Mars (Zuber et al., 1992; Smith et al., 2001). Hynek et al. (2010) used MOLA topography and THEMIS visible and infrared data (Christensen et al., 2004) to map all observable MVN and recorded the Strahler number of river segments globally (Hynek et al., 2010). This assessment improves upon MVN distributions determined in previous studies that used Viking data (Carr, 1995; Carr and Chuang, 1997). The MVN database of polylines and associated Strahler number (Hynek et al., 2010) has been utilized for interpretations of the martian climate in the Late Noachian-Early Hesperian. However, these polylines lacked spatial connectivity in ArcGIS – each polyline was considered independent of any other polyline that mapped a valley within the same valley network system. The distribution of networks by Strahler number was then unquantifiable because polylines within a single network system were not connected and each network system lacked an overall Strahler number for identification. This result prevented any meaningful comparison of MVN to the MDV as a potential analog. In this work, we unified every polyline within each network system into a singular network polyline and identified each by the max Strahler number (MSN) identified within the network (Figure 7). This update to the MVN database provides an understanding of the distribution of MVN by MSN globally. This analysis of degree of MVN complexity could provide useful information for relating meteorological variables to water availability on Mars.

Further, the distribution of MVN with respect to greatest Strahler number (MSN) has not previously been explored in detail. In this analysis, we consider this spatial distribution to better understand regional variations in MVN development, which we also compare with the terrestrial MDV Onyx River. The specific results of this part of our analysis include: (1) a simplified distribution of MVN with a single polyline representing all of the polylines within a network and the network's MSN (Figure 7), and (2) the frequency of network MSN (Figure 8 a) in order to understand MVN development and compare these results with the terrestrial MDV Onyx River network MSN.

IV. Analysis and Results

IV. A Onyx River Morphology and Water Sources and Sinks

The morphology of the Onyx River is complex because of its multiple sources as well as the transition in river morphology from meandering to braided channels along its traverse from the headwaters to the mid-catchment. Typically, glacial meltwater streams coalesce within singular channels and enter the Onyx River. However, Clarke Glacier meltwater channels entering the

Onyx River are characteristically more dendritic than meltwater channels from other glaciers, which may result from greater wall slopes or a younger incision history into bedrock. In addition, terrain slope, flow velocity, and river sediment load influence the Onyx River transition from a meandering river at the headwaters near Lake Brownworth into a braided river along the mid-catchment near Bull Pass into the lowland plains near Lake Vanda (Figure 2) (Fryirs and Brierley, 2011). The headwaters illustrate connected tributaries to the trunk system, the mid-catchment illustrates irregular hillslope and channel connectivity and floodplain activity, and the lowland plain illustrates sediment accumulation zones and decoupled channels (Fryirs and Brierley, 2011). The Onyx is an atypical river because of its endorheic drainage flowing from Lake Brownworth ~300 meters above sea level (masl) to Lake Vanda ~160 masl in the opposite direction of the Ross Sea (Figure 2).

Maritime glacier net mass balance is most strongly controlled by water precipitation (Hodge et al.,1998; Bitz and Battisti, 1991), although water currents can also affect maritime glacier formation and inhibition (Moore et al., 2009). Winter precipitation can influence summer ablation because high albedo snow can cover lower elevation glacial ice and fern, and thus inhibits summertime melting (Moore and Demuth, 2001; Young et al., 1981). As a result, flow augmentation should be most notable in years with low-snow accumulation where the area of exposed low-albedo ice is greatest. Summer temperature is a proxy index for the available energy for melting of surface ice (Moore et al., 2009); relatively hot and dry conditions that generate low flows in un-glacierized catchments favor high rates of glacier melt that can increase stream flow, especially during late summer (Meier et al., 1969).

The primary source of water to the Onyx River is seasonal meltwater from multiple cold-based glaciers that are adjacent to Wright Valley; the Onyx River is active perennially during the austral summer season, December through February (Shaw and Healy, 1980). The largest meltwater source to the Onyx River is overflow from the glacial meltwater-fed Lake Brownworth, located at the base of Lower Wright Glacier; meltwater accumulated within the open-basin Lake Brownworth reservoir behind a terminal moraine overflows into the Onyx River. Lake Brownworth average discharge rates range from 0 to ~3.5 m^3/s (Figure 6c). In addition, our fluvial hydrology map finds meltwater-fed inlet channels to the Onyx River at Clarke Glacier, Denton Glacier, Goodspeed Glacier, Hart Glacier, Meserve Glacier, and Bartley Glacier in "warmer than average" years. Specifically, these additional inlet channels are observed in the 2001-2002 year when the CAMBOT data was collected (Figure 2), which previous studies have suggested was an anomalously warm year (Gooseff et al., 2017). It is also likely that meltwater from Heimdall Glacier and Conrow Glacier contribute to the river in warmer-than-average years due to their proximity to the Onyx River, but this was not observed during the 2001-2002 season (Figure 2). In addition, gulley meltwater and precipitation are candidate water sources for the Onyx River. Gulley meltwater pools along the shallow ice table can source water to the Onyx River from alluvial fans at the base of valley walls south of Bull Pass, and precipitation as snowfall either accumulates atop glaciers in the MDV or sublimates away after deposition onto the valley floor.

Water sinks of the Onyx River are primarily evaporation and discharge from the river into Lake Vanda at the mouth of the river. Evaporation rates are not well constrained and should be further studied beyond this theoretical understanding. Evaporation occurs everywhere in the MDV including at the Onyx River, the Ross Sea, and as sublimation within the ablation zone at lower elevation than the equilibrium line altitude (ELA) for ice stability. The Onyx River outflows into Lake Vanda at the Onyx River terminus ~32 km from the Onyx River mouth at Lake Brownworth. Percolation into the ground is another possible water sink, but the shallow ice table in the MDV limits percolation into the ground via runoff as the water flows downstream (Figure 2).

IV.B Onyx River Meteorological Controls

Multiple variables measured by the LTER instruments at Lake Brownworth have recorded meteorological data at various stations in Wright Valley for decades. In this work, we use this data to interpret controls on top-down glacial meltwater production and possible precipitation sources of water to the Onyx River. We use LTER data from the Lake Brownworth station because these two locations represent the beginning and the end of the traverse of the Onyx River, respectively. We have produced time series showing the annual and inter-annual variation in surface air temperature, incident solar radiation, and relative humidity, all with respect to discharge rate. Solar insolation is a measure of electromagnetic radiation in the visible, near infrared, and ultraviolet light spectrum that is incident at the surface. Some of this energy can be absorbed as heat energy within chemical bonds and thus can indirectly record warming, which is a proxy for the ability to melt ice. Surface air temperature directly records the temperature at the LTER station and is measured 3 m above the surface. Relative humidity directly records the available water vapor in the near-surface atmosphere as the percent of water vapor needed in order to reach saturation at the current air temperature; 100% relative humidity implies that the air is saturated, the water vapor will condense, and precipitation will occur. In performing our analysis, we have analyzed only a subset of the twenty-year meteorological record in order to decrease the size of our dataset and computational expense. Specially, we have identified “normal” years and “warmer than normal” years, which we use to constrain MDV climate. We can provide insights into the influence of warm pulses on fluvial hydrology in a “cold and icy” climate by comparing case studies of “typical” (Figure 6 a, b, d, e, g, h; e.g. in a “normal” year) and “atypical” (Figure 6 b, c, e, f, h, i; e.g. in a “warmer than normal” year) austral summer discharge rates. We identify the 2001-2002 austral summer as a “warmer than normal” year and 2002-2003 as a “normal” year and we present many of the results of our study by showing data from these two austral summers.

IV.B.a Onyx River Meteorological Controls: Incident Solar Radiation

Incident solar radiation changes as a function of the Sun’s orientation in the sky with respect to the MDV because the proximity of the MDV to the Earth’s pole leads to an annual, instead of diurnal, day-night cycle. The MDV are illuminated in austral summer and are in darkness in austral winter. Specifically, solar insolation is nonexistent (0 W/m^2) during the austral winter (June – August) when the southern hemisphere is positioned away from the Sun, increases during the austral spring, peaks (800-1000 W/m^2) during the austral summer, and decreases during the austral fall (Figure 5 a, b, c). Records of annual average solar insolation vary between 200 and 330 W/m^2 and annual average solar insolation appears to increase from the mid-1990’s to the mid-2000’s and then decrease until present day (Figure 6 b).

However, there are multiple factors that influence the measured solar insolation that are unrelated to the day-night cycle which we must consider when completing our analysis to determine whether solar insolation is a key factor in summertime melting in the MDV. First, while the sun is more directly over the LTER station during the austral summer, the MDV elevation gradient between the Olympus and Asgard Ranges and Wright Valley impose daily shadows over the LTER station (Figure 2). This artifact appears similar to the effect of diurnal cycling in the solar insolation data. Second, we must consider the influence of cloud cover in this solar insolation analysis; clouds can either warm or cool the surface. Low, thick clouds tend to reflect incoming solar radiation and cool the surface. Alternatively, high, thin clouds tend to transmit as well as trap and re-radiate incoming solar radiation back to the Earth, warming the surface.

Armed with an understanding of major factors that influence recorded solar insolation values, we next compare trends in incident solar radiation between the "normal" year, 2002-2003, and the "warmer than normal" year, 2001-2002. Specifically, our goal is to determine whether increased solar insolation in the "warmer than normal" year is a critical factor for increased discharge rate. Measured values of incident solar radiation at Lake Brownworth and Lake Vanda reached averages of 700 W/m^2 from December 2001 to January 2002, the austral summer of the "warmer than normal" year. Discharge began in late November 2001 and peaked at ~11 m^3/s in January 2002. The onset of river discharge followed a week of consistent relatively high incident solar radiation with approximately a 2 to 3-week delay (Figure 5 a, b). Onyx River discharge began approximately a month earlier during the "warmer than normal" 2001-2002 season than in more typical seasons, such as the "normal" 2002-2003 season (Figure 5 b, c). During the "normal" 2002-2003 season, there are more instances of solar insolation exceeding 800 W/m^2 than in the 2001-2002 season. However, these high solar radiation values appear less consistent with respect to the 2001-2002 season and these high values do not appear to persist for long durations, perhaps corresponding to increased cloud cover in the 2002-2003 austral summer (Figure 5 b, c). In general, the 2002-2003 austral summer has lower incoming solar radiation values than does the 2001-2002 season. The greatest average solar insolation values occurred during the 2005-2006 austral summer season at Lake Brownworth (Figure 6 b). This austral summer was also “warmer than normal” with average summer temperatures about -3°C rather than -6°C during “normal” summers (Figure 6 a). We interpret highest average solar insolation values to induce warmer austral summers because more solar energy enters Antarctica than in other years.

IV.B.b Onyx River Meteorological Controls: Surface Air Temperature

Surface air temperature measurements can be used as a proxy to determine when cold-based glaciers within the MDV will melt; temperatures exceeding 0° C suggest the possibility of meltwater production. Temperatures are at a general minimum during the austral winter (-5 to -50° C), increase during the austral spring, peak during the austral summer (10° C), and decrease during the austral fall (Figure 5 d, e, f). Temperatures favorable to melting tend to occur during the warmest hours of the summer season, which occur continuously just barely exceeding 0° C in austral summer because there are no diurnal austral cycles (Figure 5 d). Austral summer temperature averages appear to have been steadily increasing from the mid-1990’s (-6.5° C) until present day (-5° C) (Figure 6 a). The only year that does not appear to fit this trend is 2012, and this may be because there is not complete data collection throughout this year.

Air temperatures during the “warmer than normal” 2001-2002 austral summer are consistently and significantly above 0°C for a few weeks in the summer season. The 2001-2002 season also appears to have abnormally high discharge rates. Temperatures were >0°C for a longer duration than other austral summers within this dataset, which is consistent with relatively higher discharge rates at the Onyx River (Figure 5 d, e). In December 2001, temperatures were >0°C for the whole month and correspond with the peak annual discharge rates. For comparison, surface air temperatures rarely exceed 0°C in December of the following austral summer season (2002), which we characterize to be a “normal” year with respect to discharge rates and temperature (Figure 5 e, f). Our observations of the link between surface air temperature >0°C and increased discharge rate suggest that surface air temperature has a direct influence on river discharge. Specifically, surface air temperature >0°C appears more directly correlated with increased river discharge than increased solar insolation. This result reflects a glacial response to temperatures >0°C and indicates that summer air temperature is indeed an index for the available energy in the system (Moore, et al., 2009); when temperatures go above 0°C, the ice sheets begin to melt and the meltwater enters the Onyx River. Air temperatures during the “normal” 2002-2003 season exceed 0° C rarely and the number of degrees above freezing is less than during the 2001-2002 season. We find that there is a link between discharge and long periods of temperature >0°C, not just occurrences of temperatures >0°C. This finding is also in agreement with the delayed onset of Onyx River discharge occurring in late December of 2002 versus late November/early December of 2001 (Figure 5 d, e).

IV.B.c Onyx River Meteorological Controls: Relative Humidity

Relative humidity measurements indirectly record precipitation events within the MDV annually; relative humidity values reaching 100% indicate atmospheric saturation with respect to water vapor, which results in precipitation. In the MDV, precipitation is mostly snowfall because rainfall is temperature-inhibited. In other words, temperatures are generally below freezing at times of precipitation. Throughout the years studied here, relative humidity values are never lower than 10% (Figure 5 g, h, i). Precipitation events appear randomly distributed throughout the year and do not relate to solar insolation or temperature (Figure 5 a, g). Relative humidity reaches saturation (precipitation occurs) less frequently in the “warmer than normal” 2001-2002 austral summer than during the “normal” 2002-2003 austral summer (Figure 5 g, h, i). These events do not appear associated with increases in discharge rate (Figure 5 g, h, i) because these precipitation events occur frequently in the “normal” discharge year (2002-2003) (Figure 5 h, i) and are infrequent in the “warmer than normal” and anonymously high discharge year (2001-2002) (Figure 5 g, h). This observation implies that precipitation is dominantly snow and, because of this, precipitation and MDV fluvial activity are not directly related; rainfall is not a dominant water source to the Onyx River. Snowfall in the MDV either sublimates once deposited in the MDV or contributes to the growth of local glaciers. This observation is consistent with previous work because it implies previous observations that snow accumulation sublimates prior to making a hydrologic contribution (Fountain et al., 2009).

Although fluvial activity is not a direct water source to the Onyx River, our analysis suggests that relative humidity is indirectly connected to fluvial activity by the surface-atmosphere water balance. Snowfall events occurred frequently during the 2001 austral winter and may have initially reduced overall discharge during this “warmer than normal” year. Fresh snowfall during the 2001 austral winter was deposited throughout the MDV glaciers and valley floors and increased the MDV albedo relative to pre-existing glacial ice and bedrock. This is because there is a relationship between older snow and lower albedo measurements (Qu & Hall, 2007). This increased albedo leads to the reflection of relatively more incident solar radiation by the surface, which results in less absorbed solar radiation and colder temperatures in comparison to a year following a snow-free austral winter (Moore et al., 2009). However, the 2001-2002 austral summer is anonymously warm. How can a snowy austral winter result in an anonymously warm austral summer? Possible explanations include (1) the intensity and continuity of relatively high austral summer incident solar radiation in 2002-2003 forced enough of a heating pulse to produce increased top-down melting in the following austral summer despite the preceding snowy winter; (2) the snow was deposited on already snowy surfaces, leading to little-to-no change in albedo; or (3) this effect is negligible due to the small amount of cumulative austral winter snowfall.

IV.B.d Onyx River Meteorological Controls: Summary

The Onyx River is only active in the austral summer, when conditions are suitable for top-down melting of ice from the cold-based Lower Wright Glacier, allowing for the fill and overflow of the open-basin Lake Brownworth, which is the main water source of the Onyx River. Temperatures >0° C have a stronger correlation with discharge rate than does relative humidity or solar insolation. This is consistent with previous observations of the Onyx River: the river is dominantly fed by glacial meltwater (not by precipitation as either rain or snow) (Shaw and Healy, 1980). Further, our analysis confirms that temperature is the major control on ice stability and top-down melting. In many years, the onset of discharge into the Onyx is closely associated in time with continuous, long-lived temperatures >0° C. It is important to note, however, that if only a few hours are spent >0° C, there is no significant increase in meltwater flux (Figure 5 e, f); temperature >0°C itself is not related to increased discharge rates, but long durations of temperature >0°C is related to increased discharge rates. Additionally, solar insolation does not appear directly correlated with periods of increased discharge rates and we attribute this lack of correlation to the role of clouds. Precipitation is not linked to the onset of discharge or increased discharge rates in the Onyx River (Figure 5 g, h, i). This finding agrees with previous assessments that precipitation is not an important source of water to the Onyx River, but instead that sustained >0°C produce glacial meltwater floods and commonly last for several days (Shaw and Healy, 1980), feeding into the Onyx River and leading to increased discharge rates.

We observe that discharge rates vary annually, directly reflecting peak summertime conditions. Specifically, the Onyx River is characterized by the highest discharge rates during the years with the warmest summertime temperatures that are continuous in time throughout much of the austral summer. This observation is consistent with observations at other locations in the Antarctic Dry Valleys, which experienced peak stream flow values during the anomalously warm 2001-2002 austral summer (Gooseff et al., 2017). Thus, the Onyx River, like much of the other MDV environment, can have dramatic responses to small climatic changes, leading to more intense flooding of the river in relatively warmer years. Additionally, following an unusually warm year, discharge rates can be relatively high for up to ten subsequent years, implying that the climate takes time to re-equilibrate back to its original state (Gooseff et al., 2017).

IV.C Onyx River Strahler Stream Order Analysis

High-resolution CAMBOT images of the MDV allows for the identification of smaller tributaries than can be seen in lower resolution MOLA imagery of the MVN (which was used in the work by Hynek et al., 2010) (Carr and Malin, 2000). For this reason, we have down-sampled

CAMBOT data using the centerline Strahler method to match that of the global MVN database to provide the most accurate comparison (Cabrol and Grin, 1999). Specifically, every meltwater stream from a glacier is averaged into a single first-order headwater stream. By this process, we find that the Onyx River is a second-order river (Figure 4 b).

IV.D The Onyx River in Comparison to Northern Hemisphere Rivers

First- through third-order streams comprise the majority (~80%) of terrestrial river systems. Higher-order systems tend to be larger rivers with more available water. In general, rivers scale in length and cavity volume with order. Examples of this observation include three of the largest rivers on Earth, which also have some of the highest observed stream orders including the Ohio River (eighth order), the Mississippi River (tenth order), and the Amazon River (twelfth order).

IV.D.a Temperature Dependence on Glacial versus Rainfall-fed Rivers

Latitude-dependent meteorology is a major control on terrestrial river formation processes. Higher-latitude glacially-fed rivers have been relatively unstudied in comparison to mid- to low-latitude snowmelt/rainfall-fed rivers (Milner and Petts, 1994). Typical glacial rivers have summer temperatures below 10°C with a peak in discharge during the summer season; this contrasts with the behavior of snowmelt/rainfall streams, especially in the summer season. We observe this glacial river behavior in discharge at the Onyx River system (Figure 5 e). Generally, downstream, glacially-fed river temperatures increase, channels stabilize, and valley floors increase in age (Milner and Petts, 1994). Lower-latitude rainfall-fed river discharge tends to reflect the stability of precipitation within the catchment zone. For example, India subcontinental river catchments are largely stable and may reflect monsoon recurrence (Mirza et al., 1998). Orographically driven variations in precipitation influence greater erosion in mountainous regions than in river valleys, which limits relief in unglaciated mountain ranges and thus flattens river profiles (Roe et al., 2002). As a result, glaciated mountain ranges have well-preserved relief despite extensive river dissection (Figure 2).

IV.D.b Effects of Vegetation on River Morphology

Vegetation-related processes fundamentally alter fluvial geomorphology but are typically ignored because they are not easily quantifiable. However, the influence of vegetation is critical when comparing northern hemisphere rivers with the Onyx River, which has no regional vegetation due to the cold and dry climatic environment. Vegetation controls river behavior by influencing flow resistance, bank strength, bar sedimentation, altered flow path, and channel isolation (Hickin, 1984). Erosional processes are largely limited by developed riparian root systems along braided river banks. Channel mobility decreases with increasing vegetation density. Vegetated channels favor decreased channel width and increased channel depth with time (Jang and Shimizu, 2007). In the "cold and icy" vegetation-free Antarctic environment, there is mobility in the non-vegetated Onyx River braided channels on seasonal timescales (Dickson, et al., 2014). This high mobility is perhaps amplified by ephemeral channel formation seasonally in response to temperature pulses, which repeatedly optimizes channel orientation (Figure 3, 5 e). The major influence of vegetation on the formation and development of northern hemisphere streams implies that the Onyx River, located in a non-vegetated region, may be the best process-based analogue for the MVN.

V. Application to Mars

We have produced a map of MVN describing Strahler number by using the MVN database (Hynek et al., 2010) in order to compare the MVN to our analysis of the MDV Onyx River (Figure 7). To do this, we have computed the MSN of every MVN system for a simplistic understanding of network complexity and comparison to terrestrial system complexity. Approximately 89% of the MVN have a Strahler number of either 1 or 2 (blue and dark green lines in Figure 8 b), which is similar to or lower than the Onyx River Strahler number at a similar image resolution. This result suggests that the majority of MVN are equally as complex as or less complex than the Onyx River. Additionally, some of the second order MVN are similar in length to the Onyx River (Figure 9 a).

We are not aware of the precise processes that formed the 11% of MVN with MSN exceeding second-order. Perhaps the MVN of third-order and greater formed by wet-based glaciation, meteorite impact-related melting, rainfall and runoff, or climate change leading to a long-lived and continuous warm and wet climate. It is likely that a transient warmer and wetter climate scenario existed on the Noachian-Hesperian boundary, perhaps favoring persistent rainfall instead of intermittent ice melting (Craddock and Howard, 2002). This climate scenario would be consistent with interpretations of climate change at this period of time, where glaciers were no longer stable. This scenario would suggest that liquid water existed at the surface in greater quantities and for longer durations than the climate in which the majority of lower-level systems formed, which may have been a “cold and icy” Antarctic-like climate. Greater water availability from precipitation is a more likely process for formation of the higher-order MVN because higher-order terrestrial systems exist in rainfall-dominated climates with great relief from headwaters to river terminus. This precipitation-related formation is likely. However, wet-based glaciation is less likely. We do not suggest that wet-based glaciation or greater connectivity of MVN systems were likely to have occurred in this 11% of the MVN systems because there is no geomorphic evidence for either process, such as eskers, which flow topographically up-hill.

The climatic implications for higher-order systems rely on the relationship between river development and Strahler number. If lower order systems reflect underdeveloped catchments, then increased water availability and catchment connectivity by topography were perhaps integral to the formation of higher–order systems, regardless of the climate scenario. Some MVN with MSN >2 integrate cratered walls, the predicted 1 km ELA for a “cold and icy” climate, and continuous valleys within catchment zones. Further, some of the MVN within the identified 11% are equatorially bound systems; these equatorially bound systems are at low elevations, which receives increased solar radiation at low obliquity. More melting of glacial ice can occur in low obliquity equatorial regions, leading to the formation of more complex and integrated rivers than in higher latitude regions (Figure 9 b). Thus, a short-lived river-dominated climate may not be required, and the difference may be related to the proximity of the fluvial systems to the equator, the proposed southern hemisphere ice sheet, and subsequent melt. On Earth, we see that the higher-order systems are equatorially bound in areas of high relief and available solar energy to produce warmer temperatures. The lower-order polar Onyx River received lower rates of incident solar radiation in comparison to equatorial regions. This terrestrial observation is consistent with observed higher-order streams forming in the equatorial region on Mars.

In addition to the climatic regime, glacial moraines appear critical to the history of Onyx River activity at the overflow point of Lake Brownworth. Past glacial advance and melt back of the Wright Lower Glacier have left the bedrock-dominated landscape marred with terminal and lateral moraines that appear to control the formation and re-activation of fluvial features within the Onyx River. In the case of Lake Brownworth, a terminal moraine has bounded outpouring glacial meltwaters and formed a moraine-dammed lake (Shaw and Healy, 1980). Similarly, structured moraine-dammed lakes are also found within northern hemisphere fluvial systems and provide a process for the outbreak of flood events into river systems (Moore et al., 2009). Meltwater forms ephemerally from Lower Wright Glacier and then funnels through the terminal moraine, controlling activity in the river channel as headwaters aggregate. The Lake Brownworth moraine is the eroded record of glaciation by fluvial processes. The presence of this moraine is critical to the Onyx River's meandering headwater morphology. In contrast, meltwater that forms at Clarke Glacier, which does not have a terminal moraine, do not merge into a single channel until reaching a topographic low (Figure 3). The presence or absence of open-basin lakes may be important to determining the fluvial geomorphology of MVN. MVN with open-basin lakes, perhaps formed by terminal moraines, may preferentially form meandering channels in low-relief topographies. MVN lacking open-basin lakes may instead form braided channels in high-relief topographies.

Topography appears to influence MVN connectivity. Lower-order rivers tend to be linearly oriented (Figure 9 a, b). The presence of topographic lows between near-equatorial craters establish catchments where lower-order rivers merge into higher-order rivers. This influence imposed by the martian cratered surface influences river tendencies to become more radially oriented towards the topographic low as lower-order rivers merge within catchments. Thus, we expect regional topographic profiles and perhaps the distance between crater rims to influence the stream order of MVN. Lower-order rivers tend to linearly incise either topographically flat surfaces (Figure 9 a, b) or. Higher-order rivers tend to incise topographically complex surfaces, such as heavily cratered regions, and better reflect catchment-scale topography with rounded perimeters (Figure 9 c). The watersheds of higher-order MVN have frequently recurring smaller craters ($<10^4$ m diameter), sourcing many low-order systems that aggregate into higher-order systems at topographic lows between nearby crater walls. In some cases, such as in the only seventh-order system on Mars, the higher-order systems can also result from merging two complex river systems from adjacent watersheds (Figure 7).

We propose the following model for top-down glacial meltwater river formation in the MDV as adapted by a previous study of MDV moraine formation after glacial melt back (Atkins and Dickinson, 2007) (Figure 10): (1) the relic moraine dams meltwater from the same glacier that produced the moraine, (2) once filled, this open-basin reservoir can overflow seasonally in the MDV into a centralized channel and flow downslope. Future analog studies can apply this model to MVN formation.

In summary, we find that the majority of MVN are similar in complexity to the Onyx River in Antarctica, suggesting that similar climates may have existed during the formation of these fluvial features. Thus, "cold and icy" climate conditions could have produced many of the river features found on Mars today. The small exception to these systems likely formed from significant climate change occurring on the Noachian-Hesperian boundary or are related to regions of enhanced melting and runoff due to proximity of the higher-order streams to the equator. Higher-order systems are more geomorphologically complex and reflect watershed boundaries, whereas lower-order systems are generally more linear features strictly following local topography. If topography is indeed the main control on both terrestrial and martian fluvial morphology, then precipitation and proximity to the equator are not critical to river formation. Given that obliquity and precipitation likely varied greatly over the Noachian-Hesperian boundary, the consistency of topographic relief explains MVN river development well.

VI. Conclusions

We have explored the climatic controls and morphological characteristics of the Onyx River in order to improve our understanding of river formation in a "cold and icy" climate. We compared the results of our analysis with the characteristics of the MVN to determine whether the MVN could have formed in a "cold and icy" climate, similar to the climate of the Antarctic MDV, where the Onyx River is seasonally active. We found that the major control on discharge rate is the duration of temperatures >0°C; "normal" years of typical river discharge (e.g. 2002-2003) reveal fewer days with temperatures exceeding 0°C than "warmer than normal" years (e.g. 2001-2002), where relatively higher discharge rates reflect pulses of temperatures >0°C, favoring top-down melt. Annually, there are <20 degree days above freezing at Lake Brownworth since the late 1980s (Doran et al., 2002).

The anomalously high discharge rates that are observed in the 2001-2002 austral summer does not directly correlate to anomalously high average incident solar radiation or relative humidity. Instead, the frequency and intensity of warm days during the austral summer appears to result in increased discharge rates weeks after sustained durations of temperatures >0°C. Because a generally higher value for incident solar radiation leads to a temperature increase, we observe that incident solar radiation is indirectly linked to discharge rates; clouds are a major controlling factor on measured incident solar radiation and the effects of clouds preclude a direct relationship between incident solar radiation and discharge rate. In conclusion, our analysis of the "warmer than normal" 2001-2002 austral summer provided critical information regarding our understanding of climate controls on discharge rate at the Onyx River: there is a correlation between the magnitude and duration of surface air temperature >0°C and increased discharge rate at the meltwater source to the Onyx River. If incident solar radiation was the driving factor, the 2005-2006 season would have been characterized by higher discharge rates than the 2001-2002 season because incident solar radiation values are higher in the 2005-2006 austral summer than in the 2001-2002 austral summer, which is not observed. Additionally, we find that there is no correlation between relative humidity and discharge rate; precipitation is not a major water source for the Onyx River. These observations are consistent with our conclusion that relatively long durations of temperature >0°C is the driving factor for increased discharge rate at the Onyx River.

The "warmer than normal" 2001-2002 austral summer season resulted in the activation of inlet channels to the Onyx River that do not regularly (annually) supply water to the Onyx River. Specifically, we observed ~30 active inlet channels entering the Onyx River during the 2001-2002 austral summer season as the result of meltwater contributions from Hart, Meserve, and Bartley

Glacier. Perhaps even more meltwater-carved inlet channels from Heimdall and Conrow Glaciers will contribute to the Onyx River as temperatures are expected to continue warming in future summers. We can confirm this hypothesis with CAMBOT imagery of the MDV in warm austral summer seasons in the near future.

Below, we describe the main conclusions from our morphologic and climatologic analysis of the Onyx River and applications of our analysis to Mars.

Overview and broad characterization of the Onyx River. The Onyx River is a ~30 km long river in the hyper-arid and hypothermal MDV climate zone. The river is seasonally active and flows from Lake Brownworth to Lake Vanda. Lake Brownworth fills seasonally with glacial meltwater from the Lower Wright Glacier. When the lake overflows, the meltwater pours into the Onyx River, where it travels downslope until reaching Lake Vanda. This river in not unique in the MDV but provides proof that significant fluvial activity can occur in a “cold and icy” climate, characterized by mean annual temperatures <0°C and precipitation that is dominated by snowfall. Using a combination of high resolution CAMBOT and Landsat imagery, and LTER climate data, we have constrained the geomorphology and climate at the Onyx River in order to provide unprecedented insight into the formation and evolution of rivers in a “cold and icy” climate. This analysis is important for our understanding of the climatic implications of the MVN: is it possible that the martian fluvial systems formed in a “cold and icy” climate, similar in many ways to that of the Antarctic MDV?

Sources of water to the Onyx River. The primary input to the Onyx River is overflow of glacial meltwater from Lake Brownworth. Wetting events and active gullies also contribute to the river, but the contribution is relatively small. Meltwaters are observed to form from other nearby glaciers during years with relatively warmer austral summer seasons (e.g. 2001-2002).

Interpretation of LTER climate data at the Onyx River: climatic controls on river activity. Our analysis of the LTER climate data at the Lake Vanda and Lake Brownworth stations suggests that the main control on river activity and increased discharge rates is long-lived surface air temperature >0°C. During periods of sustained temperatures >0°C, significant water flow occurs through the Onyx River because more water than usual is melting off of nearby glaciers, including the Lower Wright Glacier, and entering the Onyx River system. We also searched for a possible relationship between river activity and solar insolation or relative humidity, finding that neither exhibit a clear correlation. Regarding solar insolation, we find that the lack of correlation is because of complicated processes that distort solar insolation measurements. These processes may include the presence of clouds, which decrease incident solar radiation without necessarily decreasing surface temperature; high altitude clouds increase surface temperatures while low altitude clouds decrease surface temperatures. Regarding relative humidity, we find that when relative humidity reaches 100%, precipitation as snowfall is expected, not rainfall. Snowfall is the dominant form of precipitation in the MDV; the lack of correlation between discharge and precipitation events suggest that precipitation is not a major source for the Onyx River which is to be expected since little-to-no rainfall occurs.

Analysis of Cambot and hillshade imagery to estimate Strahler stream order. We applied the Strahler stream order to the Onyx River. We find that the Onyx River is a second-order network when considering a lower-resolution center-lined network (Strahler, 1957). We have used a centerline approach to down-sample the higher resolution CAMBOT imagery of the MDV to that of the MVN. This allows us to avoid a resolution bias in our subsequent comparative analysis because using higher resolution data in the MDV may lead to the identification of streams that are below the image resolution used to map the MVN.

Comparison of the Onyx River to temperate and Northern Hemisphere river systems. The intensity and frequency of flow and runoff scales differently between tropical, temperate, and arid climates. Vegetation, rainfall, and soil cohesion are essential to channel variability and mobility in all but arid climates. Strahler number also increases with greater incision history, topography, and the persistence of warmer and wetter climates. The Onyx River is atypical from other terrestrial river systems because it lacks vegetation and rainfall as a dominant water source. Specifically, in typical terrestrial rivers, vegetation root systems control channel direction, and rainfall provides annual sources of runoff and groundwater recharge. In contrast to these typical terrestrial rivers, the Onyx River receives water input via glacial meltwater in the austral summer season and dries up for the remainder of the year. Channel migration is frequent because vegetation and annual flow regimes are not present, especially within the braided river component of the system. The lack of vegetation in the MDV Onyx River system makes it a good analogue for the formation and structure of the MVN. Additionally, the lack of rainfall and presence of a cold and arid climate makes the MDV Onyx River a good candidate for testing the hypothesis that the MVN could have formed through similar processes on a "cold and icy" early Mars.

Comparison to Mars: "cold and icy" climate and fluvial activity. The Onyx River is proof that fluvial activity can occur in a "cold and icy" climate. The main source for fluvial activity at the Onyx River is the production of glacial meltwater and runoff through summertime melting. It is possible that Late Noachian Early Hesperian Mars was similar in many ways to the MDV, with mean annual temperatures far below 0°C, precipitation dominated by snowfall, and all surface water stored as ice in the southern highlands (Head and Marchant, 2014). Transient or punctuated melting events may permit melting of the surface ice, allowing for glacial meltwater-fed fluvial activity on the surface of Mars, possibly similar in many ways to the seasonal fluvial activity formed through summertime melting that is observed at the Onyx River in the MDV. We hypothesize that the arid fluvial activity at the Onyx River may be a good process analogue for arid fluvial activity on early Mars.

Comparison to Mars: stream order comparison to global MVN database, geomorphic comparison to individual systems. Stream order measurements are used as a proxy to estimate river connectivity and river volume. Thus, an analysis of stream order may explain the climate system in which rivers develop and persist. The MVN database includes measurements of the stream order of each MVN system, also measured by Strahler order, which we update in Figure 7 to illustrate the MSN of each system (Hynek et al., 2010). We find that 89% of the MVN have maximum stream number of 1 or 2, implying that the majority of the MVN are equal to or less developed than the Onyx River. Our result suggests that the majority of the MVN could have formed in a "cold and icy" climate similar to the current climate in the MDV, Antarctica, where the Onyx River flows.

Using the Onyx River as a MVN analogue: what are the critical factors controlling the evolution of the Onyx River system? There are multiple factors that control the annual onset of fluvial activity at the Onyx River: (1) sustained warm temperatures, (2) water trapped as ice in glaciers within the Onyx River watershed, (3) an open-basin lake at the head of the river which has a terminal moraine that allows for pooling of large volumes of water and then rapid overflow of meltwater into the Onyx River. The Onyx River is a low-order river because the system flows through a relatively topographically uniform polar landscape relying on meltwaters for river connectivity. On Mars, the MVN are distributed near the edges of the predicted Late Noachian Early Hesperian ice sheet, implying that they, too, could be fed by glacial meltwater during the warm summer season or transient/punctuated heating events in an ambient "cold and icy" climate (Head & Marchant, 2014). However, the martian southern highlands are not topographically uniform and large topographic variation is caused by the dense population of impact craters. At the Onyx River, the presence of an open-basin lake near the headwaters appears to be important for high discharge rates at the beginning of the season. Topography plays a role in river development because slope influences the type of river and connectivity of streams at topographic lows. Meandering rivers flow slowly in flat areas and valleys, whereas braided rivers flow over a steep gradient while carrying high sediment loads. Since topography influences the distinction between these river types, and can integrate multiple rivers into larger networks, topography could be the main control on higher-order network formation. MVN formation at open-basin lakes likely also centralized flow into meandering headwater channels. MVN formation without moraine-dammed lakes could imply braided networks in high-relief topographies; however, the abundance of martian craters reduces the effective area of low-relief topography, thus making centralized channels more likely on the surface than braided networks. There are no observable MVN channels as a result of billions of years of erosion into the channels. However, because meandering channels more deeply incise topography than do braided channels, observable MVN likely reflect deeply incised channels that have since been partially filled.

Comparison to Mars: understanding MVN that are more developed than the Onyx River. Although the majority of MVN are equal to or less developed than the Onyx River, 11% of the MVN are more developed based on our Strahler stream order analysis. We used high-resolution imagery to analyze some of the most developed MVN. These complex features exist within the heavily cratered southern highlands, which may influence the more complex fluvial morphologies observed in this analysis. This is important because proximity to the predicted ELA, elevation differences, and available incoming solar radiation appear to coalesce into more hydrologically integrated and connected systems. Further research into the age of high order MVN may also find climate links related to the formation of more complex systems.

Moving forward: does the MDV provide a good martian process analogue? Many MVN are similar in maturity to the MDV Onyx River system. Thus, we hypothesize that the Onyx River is an appropriate process analogue for formation of VNs in a "cold and icy" early martian climate. Based on our analysis, the presence of MVN does not preclude a continuous, long-lived "cold and icy" climate in the Late Noachian Early Hesperian on Mars. Our analysis does not explain whether there was punctuated or seasonal fluvial activity on Mars as the result of volcanism, cratering, or a transient reducing atmosphere; other works consider these theories. Some believe that these events may have been of a hydrothermal origin by magmatic intrusions and volcanic outgassing, others suggest large impacts released the heat required to melt glacial ice and form the MVN (Gulick, 1998; Phillips et al., 2001; Segura et al., 2008).. Our analysis shows that seasonal fluvial activity occurrs in a terrestrial system possibly similar to Late Noachian Early Hesperian Mars.

Life on Mars? There are multiple types of extremophiles that live in the cold and barren Antarctic climate, implying that a “cold and icy” early martian climate does not preclude the possibility for the onset of life.

Figures.

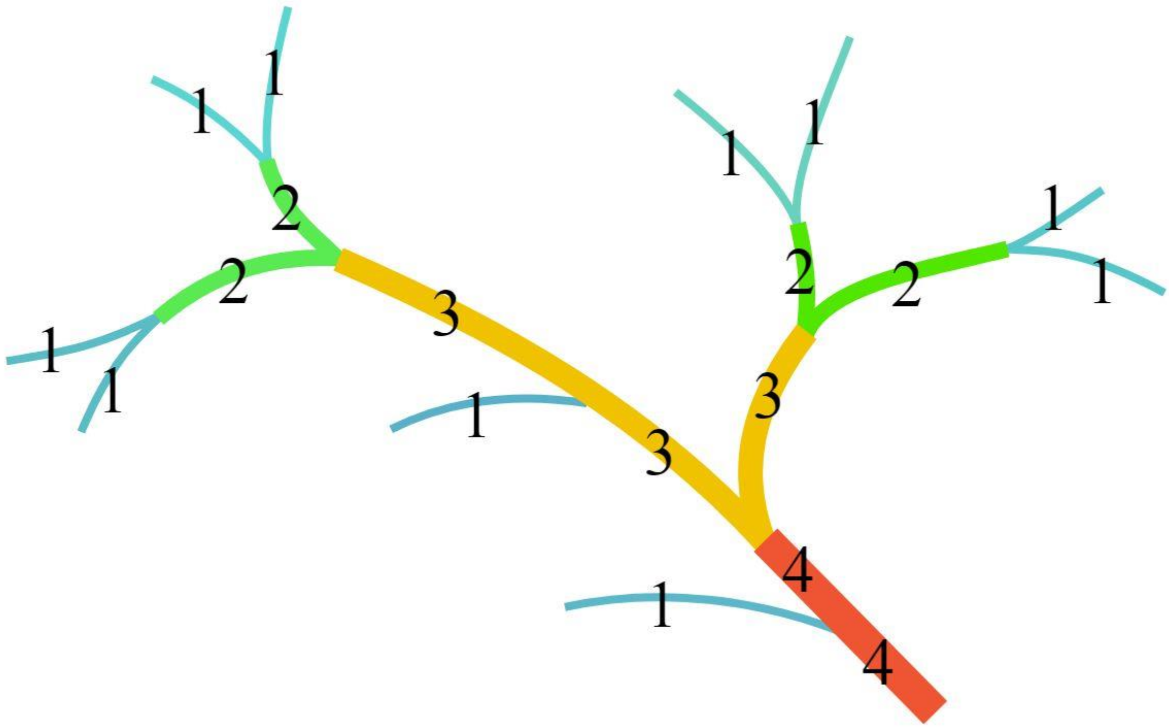


Figure 1: Strahler stream order method illustrating the scale and connectivity of each river channel of different stream order. Again, we see that two first-order streams result in a second-order stream, and that two second-order streams result in a third-order stream, but a first and a third-order stream still result in a third-order stream. In addition, the scale of each channel theoretically increases as stream order increases.

Figure 2: Overview map of the MDV and labelled hydrogeological features on Landsat imagery. Water accumulates at Lake Brownworth from top-down melting of Lower Wright Glacier. This water overtops the terminal moraine seasonally and flows southwest in a meander channel until transitioning into braided channels and entering Lake Vanda. Meltwater also contributes to the Onyx River from top-down melting of other glaciers along Wright Valley in "warmer than normal" austral summers, such as the 2001-2002 year.

Figure 3: Completed map of georeferenced CAMBOT imagery on MDV Landsat data in December 2001. High-resolution fluvial features illustrate ephemeral flow within the Onyx.

Figure 4a: CAMBOT and Landsat imagery with overlain polylines in order to describe Strahler order within the Onyx River.

Figure 4b: Map shown in Figure 2 with centerline polylines describing Strahler number within Onyx, a down-sampled geomorphological analysis that simplifies multiple meltwater channels from a glacier into a singular meltwater channel.

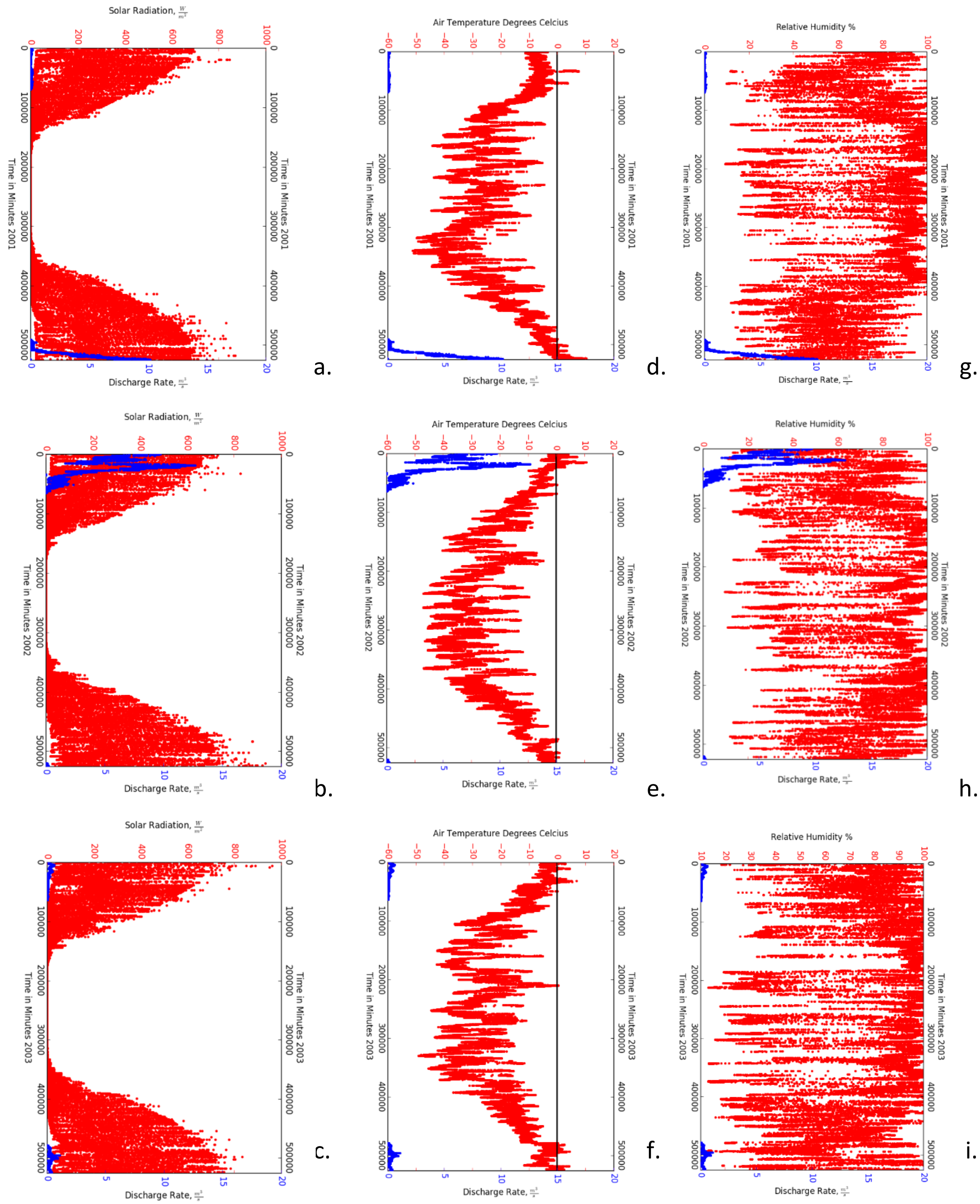
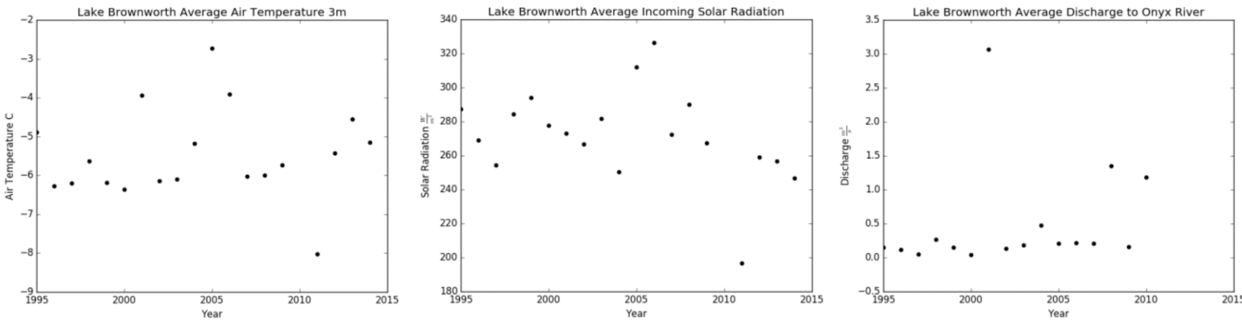


Figure 5: Discharge rates plotted with LTER meteorological data over three years. Solar radiation is recorded in (a) 2001, (b.) 2002, (c.) 2003; air temperature in (d.) 2001, (e.) 2002, (f.) 2003; and relative humidity in (g.) 2001, (h.) 2002, (i.) 2003. We consider temperatures "warmer than normal" during the 2001-2002 austral summer and "normal" in the 2002-2003 austral summer.



a. b. c.

Figure 6: Average air temperature, incoming solar radiation, and discharge annually within the Onyx River.

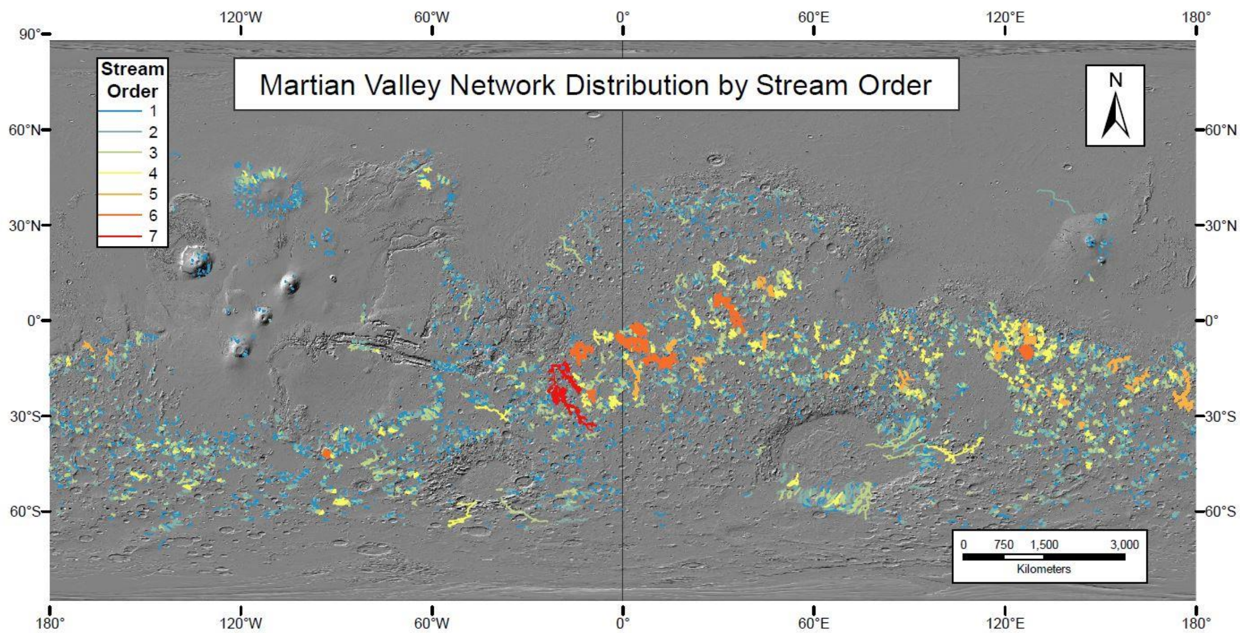


Figure 7: Global MVN map illustrating spatial relationships of MVN by network complexity using Strahler order. Here we have updated the Hynek et al. 2010 dataset of MVN to illustrate the MSN of each system. Warmer colors indicate networks that are more complex whereas cooler colors indicates less complex networks.

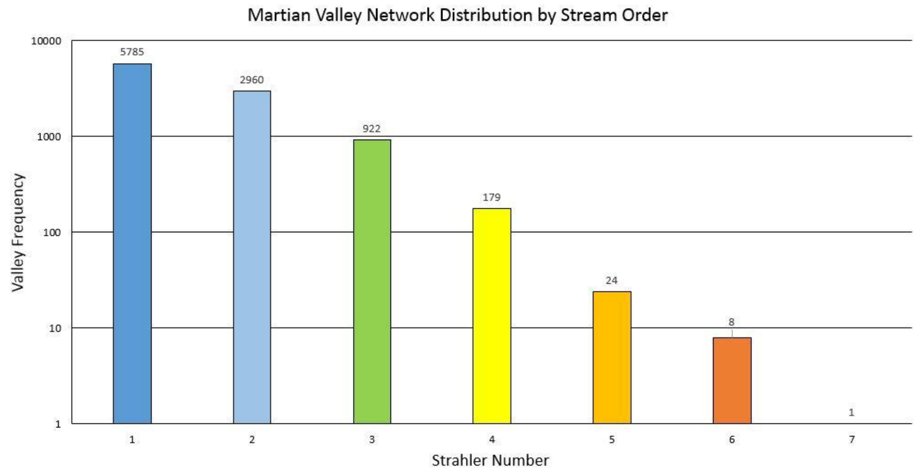


Figure 8a: Log relationship between valley frequency and Strahler number from Figure 6.

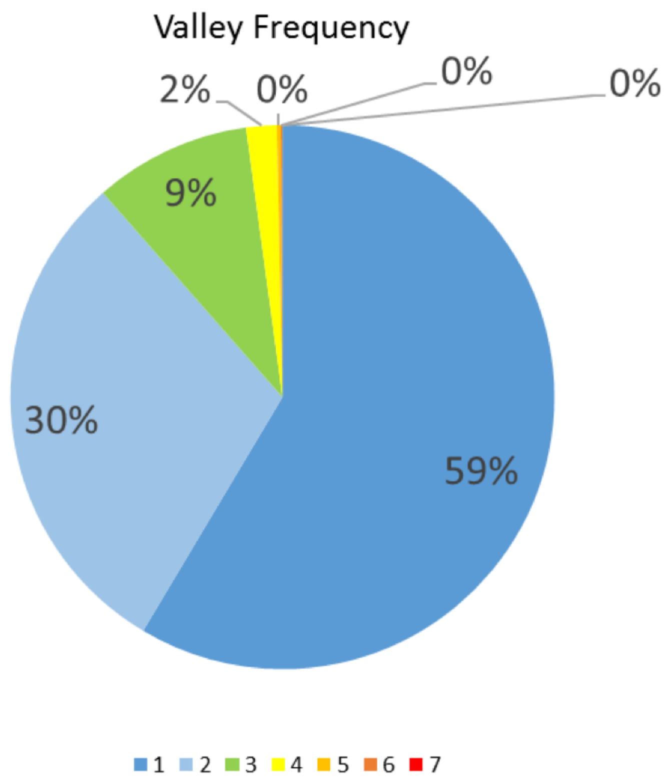


Figure 8b: First through seventh-order systems on Mars as a percent based on Strahler number.

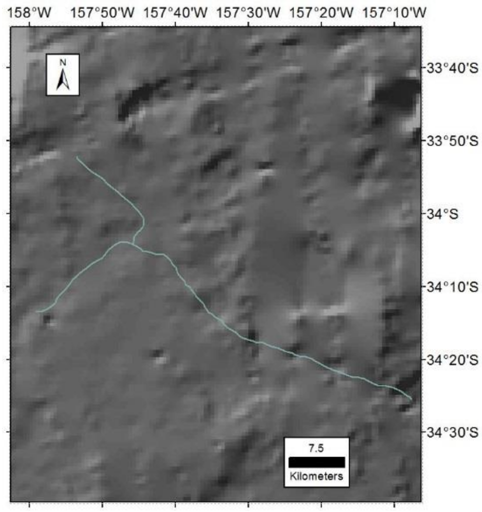
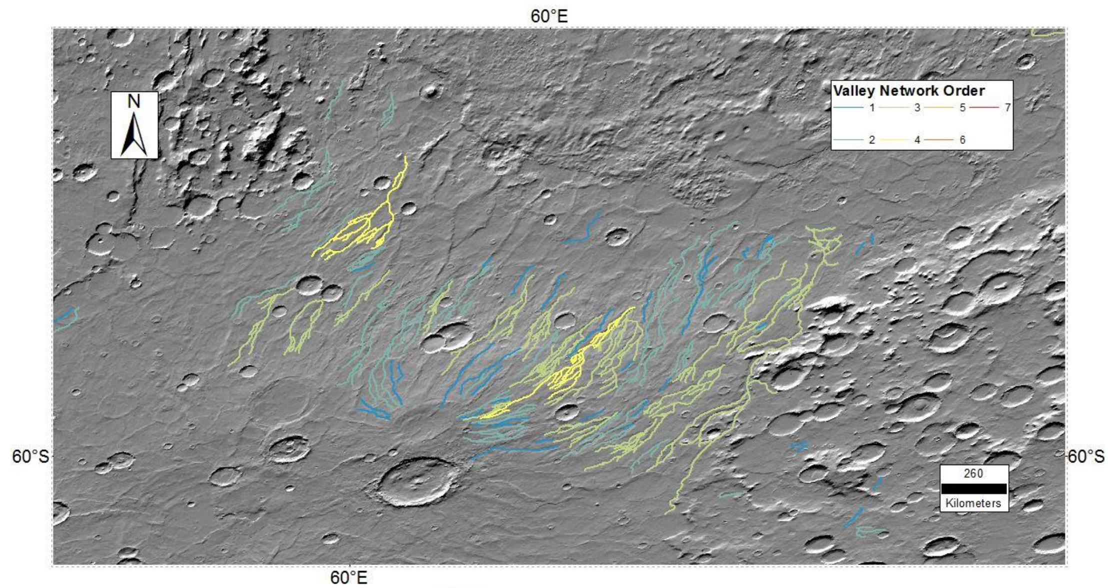
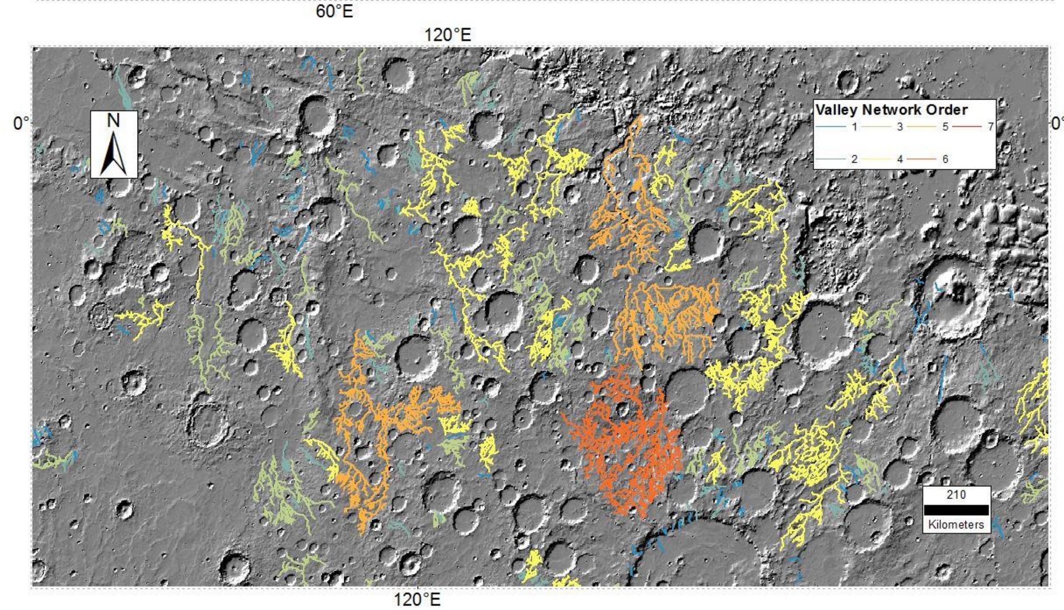


Figure 9 a: A MVN similar in linear morphology and length to the Onyx River system in the MDV. Both this system and the Onyx River are second-order systems. Figure 9 b: Lower-order systems (first through third-order systems) tend to have relatively linear profiles along low relief topography. Figure 9 c: Higher-order systems (fourth-order and greater) tend to have more rounded profiles reflecting watershed-scale river systems.

a.



b.



c.

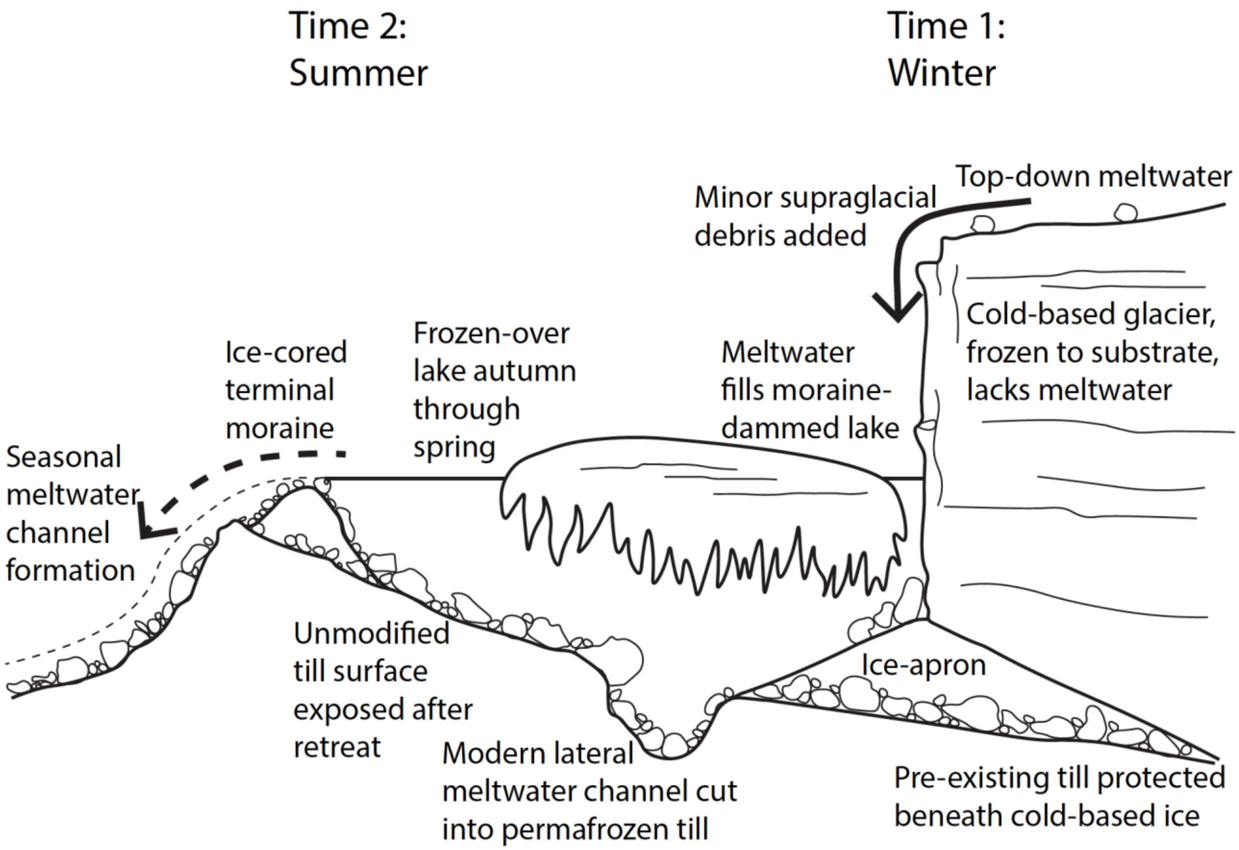


Figure 10: Proposed MDV formation model at the Onyx River based on the model proposed for moraine formation in the MDV after glacial melt back in interglacial periods (Atkins and Dickinson, 2007). After melt back, till gets deposited at the base of the glacier's furthest extent and is exposed in interglacial periods. In the winter, snow collects on the glacier and in the catchment between the glacier and the terminal moraine. In the summer, supraglacial debris and top-down melting of the glacier pools meltwater within this catchment. This reservoir eventually overflows and forms the major channel of the river system after sufficient top-down melting had occurred. The remaining water in this open-basin lake will then freeze over at the onset of the winter season.

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