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The McMurdo Dry Valleys: A landscape on the threshold of change

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ABSTRACT

Field observations of coastal and lowland regions in the McMurdo Dry Valleys suggest they are on the threshold of rapid topographic change, in contrast to the high elevation upland landscape that represents some of the lowest rates of surface change on Earth. A number of landscapes have undergone dramatic and unprecedented landscape changes over the past decade including, the Wright Lower Glacier (Wright Valley) — ablated several tens of meters, the Garwood River (Garwood Valley) has incised >3 m into massive ice permafrost, smaller streams in Taylor Valley (Crescent, Lawson, and Lost Seal Streams) have experienced extensive down-cutting and/or bank undercutting, and Canada Glacier (Taylor Valley) has formed sheer, >4 meter deep canyons. The commonality between all these landscape changes appears to be sediment on ice acting as a catalyst for melting, including ice-cement permafrost thaw. We attribute these changes to increasing solar radiation over the past decade despite no significant trend in summer air temperature. To infer possible future landscape changes in the McMurdo Dry Valleys, due to anticipated climate warming, we map 'at risk' landscapes defined as those with buried massive ice in relative warm regions of the valleys. Results show that large regions of the valley bottoms are 'at risk'. Changes in surface topography will trigger important responses in hydrology, geochemistry, and biological community structure and function.

1. Introduction

The geomorphology of the McMurdo Dry Valleys (MDV) reveals a landscape strongly controlled by climate processes. The MDV are composed of a mosaic of ice-covered lakes, ephemeral streams, valley glaciers and large expanses of a sandy–gravelly soil (Fig. 1). Mean annual air temperature in the valleys is −17 °C, and precipitation (all snow) spans 3–50 mm water-equivalent (Doran et al., 2002; Fountain et al., 2010), making the MDV a cold, polar desert (Monaghan et al., 2005). Despite these harsh climate conditions, a microbially-dominated biological community inhabits the valleys and consists of cyanobacteria, heterotrophic bacteria, diatoms and mosses in the streams, phytoplankton in the lakes, and heterotrophic bacteria, nematodes, tardigrades, and rotifers in the soils (Fountain et al., 1999).

Continuous permafrost, by definition a regional land surface with temperatures below 0°C on interannual timescales where 90–100% of the area is characterized by permafrost, underlies the MDV. The permafrost is predominantly ice-cemented (ranging from ice-saturated to weakly cemented), although "dry-frozen" (ice-free) permafrost is common in the upper ~1 m along valley walls above ice-cemented permafrost (Bockheim et al., 2007). Massive buried ice (ground ice) is common in the MDV and has been mapped in alpine sections of the MDV, in the Quartermain Range, in the Victoria Valley, and in extensive ice-cored Ross Sea drift deposits emplaced during the last glacial maximum (Péwé, 1960; Stuiver et al., 1981a; Hall et al., 2000; Bockheim et al., 2007; Swanger et al., 2010). All three types of permafrost (dry, ice-cemented, and massive ice) are susceptible to warming-related degradation—either directly through slumping of melt-lubricated sediments and surface ablation by sublimation-driven ice removal (Kowalewski et al., 2006; Hagedorn et al., 2007; Swanger and Marchant, 2007), or indirectly, as ice-free permafrost sediments are preferentially removed by warming-induced fluvial erosion (Levy et al., 2010). Climate warming in this region is anticipated in the coming decades (Shindell and Schmidt, 2004; Arblaster and Meehl, 2006; Chapman and Walsh, 2007) and we expect geomorphic changes to follow.

The cold temperatures and lack of a strong hydrological cycle suggest the MDV are a relatively stable landscape (Denton et al., 1993) that becomes increasingly stable at higher elevations (colder temperatures) and with increased distance inland from the Ross Sea (less precipitation). At high elevations surrounding the valleys, ~2000 m, bedrock erosion rates are <0.3 m Ma^{-1} (Marchant and Head, 2007). Even the glacial component of the landscape is extremely stable: the largest known advance of the local alpine glaciers was only a few hundred meters at most and occurred 70–130 thousand years ago

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(Higgins et al., 2000). This landscape stability inland contrasts with recently observed changes in near-coastal valley landscapes (Fig. 2).

The MDV have been divided into geomorphic zones based on prevailing climate conditions and the equilibrium landforms that result from interactions between climate conditions and the ground surface (Marchant and Denton, 1996; Marchant and Head, 2007). The coastal thaw zone is characterized by wet active layer (seasonally-thawed surface of permafrost) conditions during the summer months, that produce ice-wedge polygons, solifluction lobes, thermokarst landforms (e.g., ponds), and mature gullies (Marchant and Head, 2007). The inland mixed zone is dominated by dry active layer conditions during summer, and supports characteristic landforms including gelifluction lobes, sand- and composite-wedge polygons, desert pavements, and immature gullies (Marchant and Head, 2007). Finally, the stable upland zone remains frozen throughout the year (little or no active layer) and is characterized by sublimation polygons and salt-cemented duricrust (Marchant and Head, 2007). This model provides a useful framework for predicting regions of the MDV that are particularly susceptible to rapid change due to enhanced seasonal or secular warming. Where landforms are present under microclimate conditions different from those that caused their formation, climate change can be inferred from overprinting. For example, gelifluction lobes cross-cut by mature gully networks result from an inland mixed zone landform (gelifluction lobe) modified by a coastal thaw zone landform (mature gullies) (Marchant and Head, 2007). These types of geomorphic relationships led Marchant and Head (2007) to conclude that in aggregate, the MDV are a relatively stable landscape, but that stability is most pronounced in the upland stable zone (no major changes to microclimate conditions over the last ~13 Ma), while the landscape is beginning to respond to microclimate changes in the inland mixed zone and the coastal thaw zone.

In this paper we refine the geomorphic model of Marchant and Head (2007) using a spatially-resolved temperature model to identify regions in the MDV at risk for rapid geomorphic change, including potential hydrological and biological changes in response to anticipated climate warming. We propose a conceptual model for the presence of massive buried ice in the MDV and broadly map the anticipated extents based on surface geomorphic features. These results will provide a template for future investigations of landscape change in this region. Geomorphic and hydrological changes in the landscape impart significant geochemical and biological repercussions in the water-limited ecosystem of the MDV that will be investigated.

2. Recent observations of rapid landscape change

Over the last decade we have witnessed notable changes to the MDV landscape. The Garwood River in Garwood Valley has rapidly incised through ice-cemented permafrost and buried massive ice. The lower ablation zone of the Wright Lower Glacier has disintegrated (Fig. 2). The ablation zones of some other glaciers in the region seem to be disintegrating in a similar fashion. The glacier surfaces in Taylor Valley are becoming increasingly rough, as noted by field teams that visit the glaciers repeatedly to make mass balance measurements. The topography in the coastal margins of several valleys is changing due to melting of subsurface deposits of massive ice. In Taylor Valley, during the 2011–12 austral summer we observed undercutting of the banks of Crescent Stream, and down-cutting of the banks of Lawson Stream due to thermal erosion of the streambed and banks. In the 2012–13 austral summer, similar thermal erosion was observed in Lost Seal Stream (also in Taylor Valley). Over the 50+ years of observations of these streams this change is the first of its kind. Common to all changes is the occurrence of a veneer of sediment over massive ice. In the case of the valley floor the sediment veneer is ~10^{-1} to 10^{0} m in thickness whereas on the glaciers it is patchy with thicknesses of ~10^{-3} to 10^{-2} m.

Here, we describe each of these landscape changes in detail. Clean glacial surfaces in the MDV tend to be uniformly smooth with whitish-blue bubbly ice and pockmarked by ice-lidded cryoconite holes (Fountain et al., 2004). The cryoconite holes represent locations where thin (<10 mm) patches of eolian sediment have melted into the ice. Where more massive sediment sheets occur, including rock debris from moraines or rock avalanches, the ice topography changes to large basins (~10 m diameter, ~4 m deep) or canyon-like channels

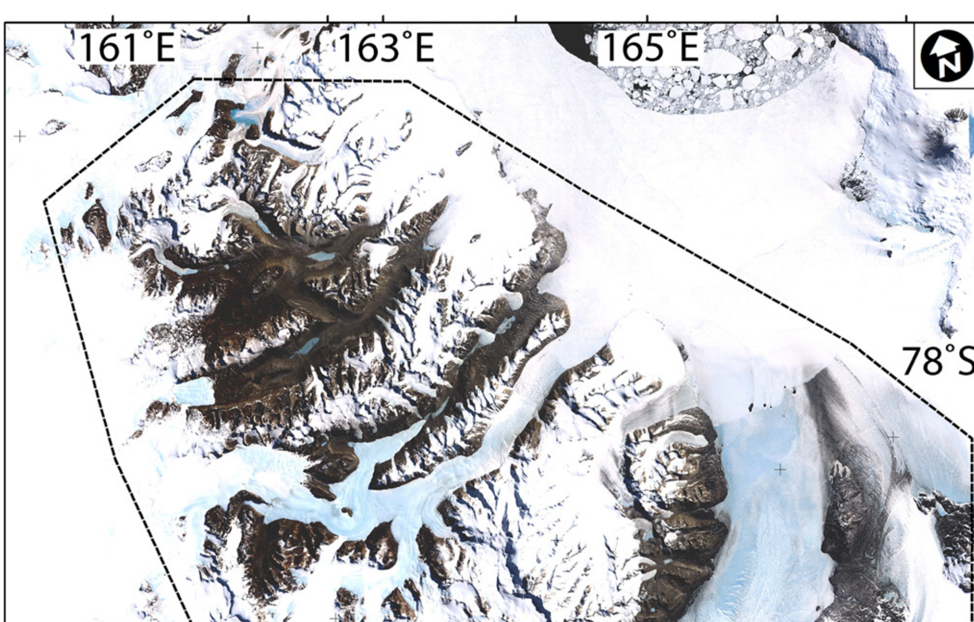

Fig. 1. The McMurdo Dry Valleys (MDV), Antarctica. A LandSat mosaic of the region of interest.

(Johnston et al., 2005). In all cases, the lower albedo of the sediment, compared to the surrounding ice, absorbs more solar radiation and melts the ice beneath. If the sediment is sparse, it collects in small patches, melts into the ice, and becomes a cryoconite hole. If the sediment is pervasive then large areas of the ice melts. On the Wright Lower Glacier sediment has been pervasive and the lower ablation zone has been melting rapidly in recent decades (MacDonell et al., 2013). Similarly, on Canada Glacier, large sheets of sediment have become exposed creating deep basins. In both cases the meltwater runoff is insufficient to transport significant volumes of sediment and the sediment has persisted on the ice for at least a decade.

Fluvial and lacustrine thermokarst features are common in Garwood Valley (Stuiver et al., 1981a; Pollard et al., 2002; Levy et al., 2012). A buried remnant of the Ross Sea Ice Sheet (the Ross I drift) fills the mouth of Garwood Valley, and extends up-valley to an elevation of >100 m (Stuiver et al., 1981a; Levy et al., 2013), creating a unit of massive buried ice at the valley floor. Melt ponds are abundant in this debris-covered ice and form linked depressions characteristic of thermokarst ponds and alases (Pollard et al., 2002). The Garwood River flows down-valley across the buried ice (Fig. 2), and has cut a steep-sided, v-shaped channel through the drift unit, that has incised to >4 m depth. Buried ice deposits are exposed in the channel walls at many locations. In several locations, the Garwood River undercuts surface sedimentary deposits or tunnels under surface sediments by eroding underlying ice. Removal of buried ice by Garwood River erosion results in slumping and subsidence of overlying sedimentary units (Fig. 2d) and greater incision of the Garwood River channel where it flows over ice-cored sediments than where it flows over ice-free or ice-cemented sediments (Fig. 2e).

Small streams (compared to the Garwood River) in Taylor Valley have median flows that are typically below 100 L/s (Conovitz et al., 1998), and experienced some of the highest flows on record during the very high flow austral summer of 2001–02 (Doran et al., 2008). During these high flows, the wide, incised channels were stable with no significant thermal degradation of permafrost in bed or banks noted. However, in the past two austral summers, we have noted significant downcutting of the streambed in Crescent and Lawson Streams, and undercutting of banks in Crescent and Lost Seal Streams (Fig. 3). Along Crescent Stream, degradation was observed for ~2.5 km along the stream. The cause of the thermal degradation along Crescent Stream is likely a short-lived high flow event that occurred due to daming of streamflow behind a snowbank that formed in the channel. Lost Seal and Lawson Streams were not subject to such bursts of discharge, so it is expected that the degradation is due to 'priming' the permafrost with increased energy input to the ground (banks and bed) making it more susceptible to degradation from moderate discharges.

3. Climate control of landscape change

We hypothesize that these observed changes are climatically caused. Long term meteorological data show that the decadal trend of cooling summer air temperatures (Doran et al., 2002) is continuing, although slowing (Fig. 4). In contrast, summer solar radiation is increasing at a rate of $+2$ W m^{-2} yr^{-1} and soil temperatures have generally been warming. Ice temperatures (measured on MDV glaciers), in clean ice, have not been warming (although it can be difficult to deconvolve ice warming from solar heating of the thermistor in translucent ice). The specific cause of soil warming is unclear, but we hypothesize it is associated with a trend of increasing solar radiation (Guglielmin and Cannone, 2012). Although the average summer wind speed has been slowing, the trend is small and not significant. Over two decades the increase in summer solar radiation is ~20 W m^{-2}, or about 10% of the summer average radiation and 5% of radiation on days when the glaciers

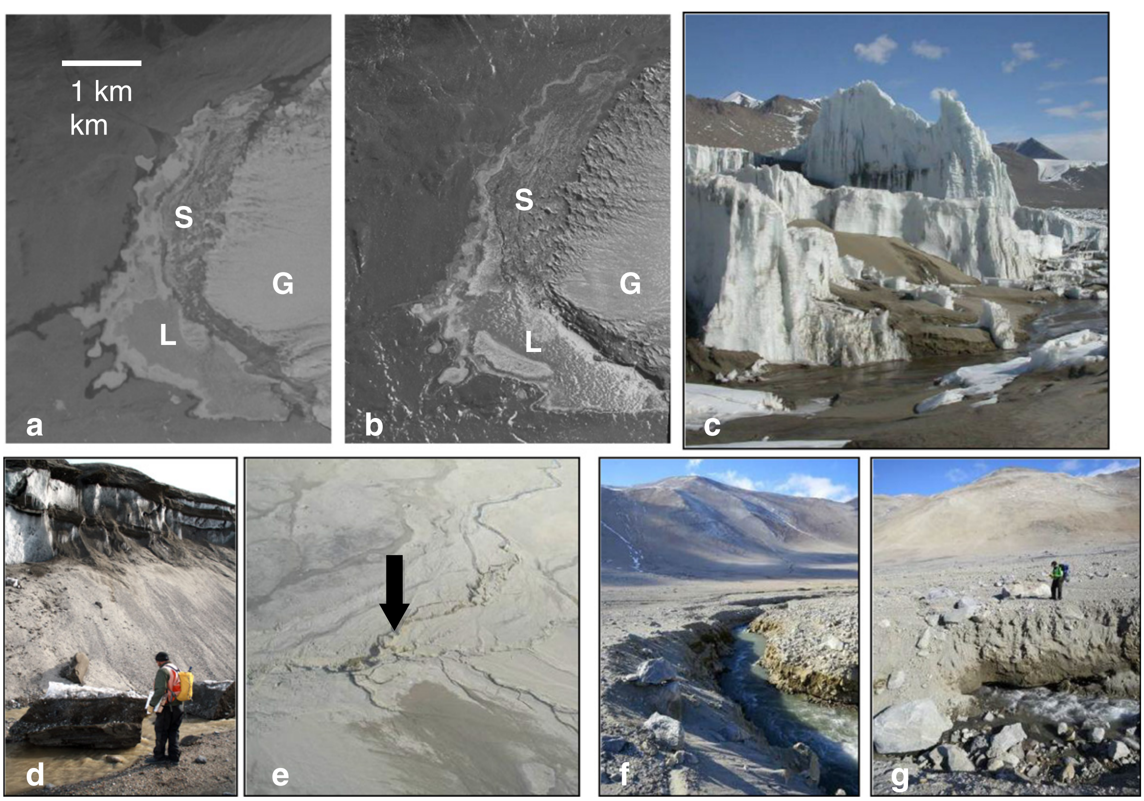

Fig. 2. Disintegration of the lower ablation zone of the Wright Lower Glacier, Wright Valley, a) 1980; b) 2008. S — sediment-covered part of the glacier, G — relatively clean part of the glacier, I — Lake Brownworth. The dots just below the S in the 2008 photo are ice spires several meters tall with sediment-covered ablated ice surrounding it, depicted in (c, photo: M. Sharp); d) ice cliff exposed by the eroding Garwood River; e) aerial view of Garwood River incision and bank collapse. River flows right to left. Arrow points to the where photos f and g are taken; f) recent incision, note color differences; g) the river has carved a thermokarst tunnel.

Fig. 3. Lateral and vertical incision of Crescent Stream banks and bed, respectively, as first observed in January 2012.

melt (Hoffman, 2010). Given the albedo of clean ice (0.6) and sediment cover (0.3) the energy increase to clean ice is, 8 W m^{-2}, and for sediment cover, 14 W m^{-2}. This difference would cause the sediment-covered ice to exceed the melting threshold much more often than for clean ice. Clean ice is often significantly below the melting temperature during the summer (Hoffman et al., 2008; MacDonell et al., 2013) whereas sediment-covered ice is much closer to the melting point more often. To explain the appearance of the sediment sheets on Canada and Wright Lower glaciers we conjecture that both glaciers, due to their landscape position, are exposed intermittently to large fluxes of eolian sediment. The sediment formed an extensive population of cryoconite holes. In the summer of 2001/02, a two-week period of warm air temperatures (+4 °C) caused extensive surface melt revealing the sediment which collected in sheets by fluvial transport on the ice surface.

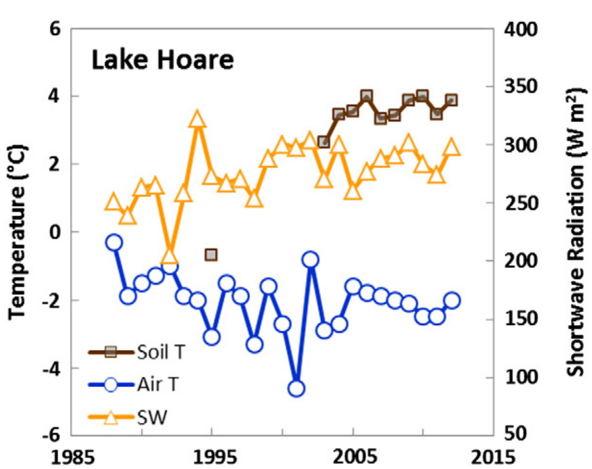

Fig. 4. Summer (Dec–Jan) air temperature, soil temperature, and solar radiation for the Lake Hoare, MDV.

We hypothesize that enhanced solar radiation is warming low albedo sediment, despite atmospheric cooling, and melting the subsurface ice including dirty glacial ice. Stream water flowing over the dark soils increases subsurface heat content leading to rapid thermal erosion of ice-cemented permafrost and massive subsurface ice. We argue that the landscape response to this solar warming of sediment mimics the expected soil warming due to regional climate warming in the coming decades (Shindell and Schmidt, 2004; Arblaster and Meehl, 2006; Chapman and Walsh, 2007).

4. Geomorphic models

To anticipate geomorphic change in the MDV due to climate warming, we first use the geomorphic model of Marchant and Head (2007) to frame our understanding of landscape processes. We apply a model of spatially distributed air temperatures to quantitatively define landscapes vulnerable to thaw. We then propose a conceptual model for the occurrence of buried massive ice in the MDV and map the probable location of buried ice. Finally, we highlight the intersections between locations of buried ice in the MDV and locations in which the spatial temperature model predicts warming that would destabilize buried ice present in the warming locations.

The geomorphic model of Marchant and Head (2007) is a conceptual model that groups major geomorphic processes and landforms in the MDV by regional estimates of climatic variables including air temperature, relative humidity, wind direction, soil temperature and anecdotal observations of precipitation. The model serves to link regional climate variables to the equilibrium landforms that develop under particular microclimate conditions. The mapping of the geomorphic zones based on these climate variables is generalized and method of interpolation/extrapolation relies on mapping the occurrence of equilibrium landforms, rather than on calculation of the spatial distribution of mean meteorological parameters. Using this concept as a starting point, we map variations in summer air temperature because it is the dominant meteorological variable controlling sensible heat in the atmosphere, which greatly affects soil temperature. We apply a simple landscape-based model of air temperature (Doran et al., 2002; revised by Ebnet et al., 2005) in which summer (December and January) air temperature everywhere in the MDV depends on location in the MDV,

$$T = 0.09(X - X_o) + 0.24(Y - Y_o) \ -9.8\ (Z - Z_o) + T_o \quad (1)$$

where X is the distance (km) from the coast along the thalweg of the valley, Y is the distance (km) perpendicular from the thalweg up the valley walls, Z is elevation (m), and T_o is the reference temperature measured at a meteorological station in the valley at location X_o, Y_o, Z_o. The constant of −9.8 °C km^{-1} is the dry adiabatic lapse rate. We applied (1) to multiple valleys rather than just Taylor Valley for which it was developed. In so doing, the X and Y were relative to each valley's thalweg. A discontinuity in temperature occurs at the along the watershed divides at the mountain peaks but it is ignored because we are only interested in temperature regions defined by thresholds and these occur well below the elevation of the divides. The temperature threshold between coastal thaw and transition zones was set at −5 °C and between transition and inland stable zones at −10 °C.

Eq. (1) was applied using different reference stations to the MDV and the results compared over the period 1996–2010 when the greatest numbers of stations (15) were operational. The temperature differences due to using different reference stations were small (<0.5 °C), therefore the station at Lake Hoare was used because its record is the longest

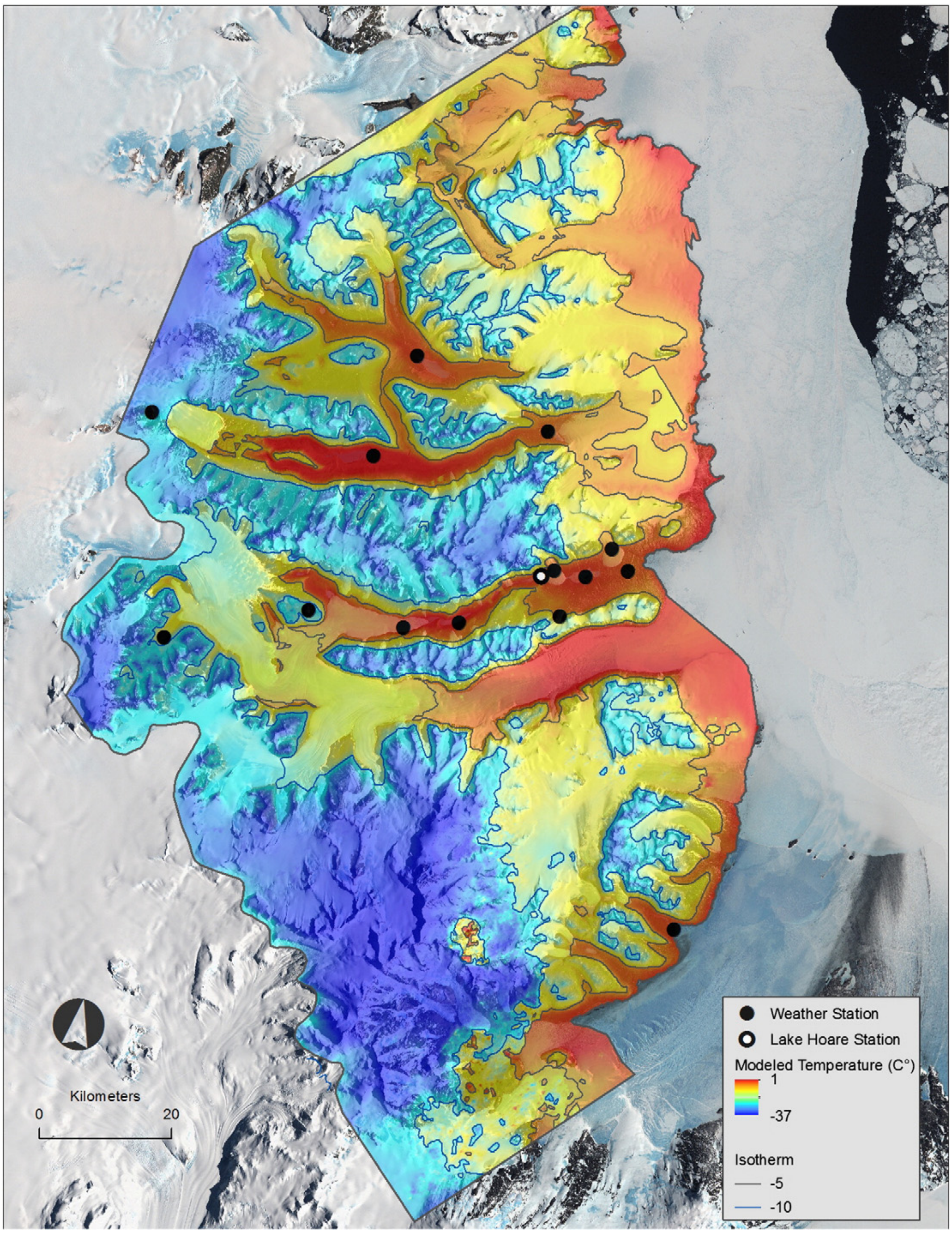

Fig. 5. Map of modeled mean summer (December and January) air temperatures for the MDV for the period 1996–2010. Isotherms of −5 °C and −10 °C denote the geomorphic transitions, coastal thaw zone to the transition zone, −5 °C, and from transition zone to upland stable zone, −10 °C, (Marchant and Head, 2007). The locations of the meteorological stations are included with the Lake Hoare station, from which the model is calculated.

(1988-current) and most continuous of all stations. Predicted temperatures were tested against all 15 stations, over the 15 year period, including the Lake Hoare station. The stations ranged in location from the coast in to 50 km inland and elevations from 20 m above sea level to 1868 m. Comparing all stations for all summers (n = 169, a few stations had data gaps), showed a mean difference of −0.2 °C (predicted colder than measured) and an RMSE of 0.53 °C, demonstrating an excellent fit between the modeled and observed data. Surprisingly, the model also successfully reproduces temperatures (<1.2 °C difference) on two mountain peaks, Mt. Friis and Mt. Fleming, at elevations of 1590 m and 1868 m, respectively. These two stations were not included in the original model formulation (Ebnet et al., 2005). The resulting distribution of mean summer temperatures (1996–2010) shows, as expected, warm valley floors and cold mountain peaks (Fig. 5). The geomorphic zones are denoted by temperature, following Marchant and Head (2007) with the coastal thaw zone located where temperatures are >−5 °C, stable upland zones located where temperatures <−10 °C, and the transition zone at temperatures >−10 °C and <−5 °C. Although called the 'coastal thaw zone' these regions are found as far as ~30 km inland in low elevation valleys.

Our conceptual model of buried massive ice (BMI) in the MDV is based on our field observations and previous studies (e.g. Healy, 1975; Pollard et al., 2002; Levy et al., 2013). We contend that BMI results from debris covering glacier ice, either from alpine glaciers or lobes of the Ross Ice Shelf (past incursions into the valleys), or from buried stream icings. For relict ice to survive for long periods (~10^4 years) a mantle of debris is required for insulation against warm summer temperatures and solar radiation in order to severely limit ablation. With mean annual temperatures of around −17 °C (Doran et al., 2002), ice protected from summer heat and sun should survive for millennia (Pollard et al., 2002). Indeed, ice under 2 m of rock debris may be as much as 8 Myr old (Sugden et al., 1995; Marchant et al., 2002). Glacier ice may obtain a protective cover of rock debris either by rock avalanching on to the glacier from the valley walls or by ice ablation revealing incorporated rock material. Moraines and debris ramparts (rock avalanches deposited material) along the glacier margin can cover the edge of the glacier forming a protective surface (Fig. 6a-c). An entire ice surface can be covered with material ablating out of the ice leaving much of the ice intact (Fig. 6d). Pools or water-filled channels of streams can be preserved if the stream course differs the next year and the icing that winter is covered by sediment (Fig. 6e). This ice may fail to survive if a lake forms in the valley bottom over the buried ice. Some benthic lake waters warm due the absorption of solar radiation and density gradients dampening buoyancy (Wilson and Wellman, 1962). This source of heat will melt BMI beneath the lake bed. This simple conceptual model predicts ice-cored moraines, thermokarst, and random icings in gently sloping landscapes with streams. No BMI will predate formation lakes with warm benthic waters.

Anecdotal observations of BMI are common but published data are relatively few therefore definitive associations between geomorphic features and BMI are limited. We know from experience that a thin veneer of sediment over glacier ice is easily observed but a thick mantle of debris over BMI typically precludes direct observation. BMI has been detected in the MDV using ground penetrating radar (Arcone et al., 2002; Fitzsimons et al., 2008). One example is from our GPR survey (frequencies of 25 MHz–800 MHz) in Garwood Valley that reveals massive ice under a relic delta (Fig. 7) but within the intrusion of Ross Drift. Unfortunately, we do not have enough data at this time to define the frequency of association between BMI and geomorphic features, using the association at this time as a working hypothesis (Fig. 8).

5. Predicting 'at risk' landscapes

The potential geomorphological effects of peak warming events have long been recognized in the MDV (Chinn, 1979; Swanger and Marchant, 2007; Doran et al., 2008). Melting of ice-rich permafrost by seasonal or secular warming is a process that affects the active layer of MDV permafrost (the active layer is the upper portion of the permafrost that is seasonally warmed above 0 °C). We anticipate that the low elevation and relatively warm coastal thaw zone will be the most susceptible to change due to their presumably ice-rich character and thermal condition relatively near thaw during the summer. Therefore, our preliminary estimate of 'at risk landscapes' is defined by geomorphic features associated with BMI located in the coastal thaw zone (Fig. 9).

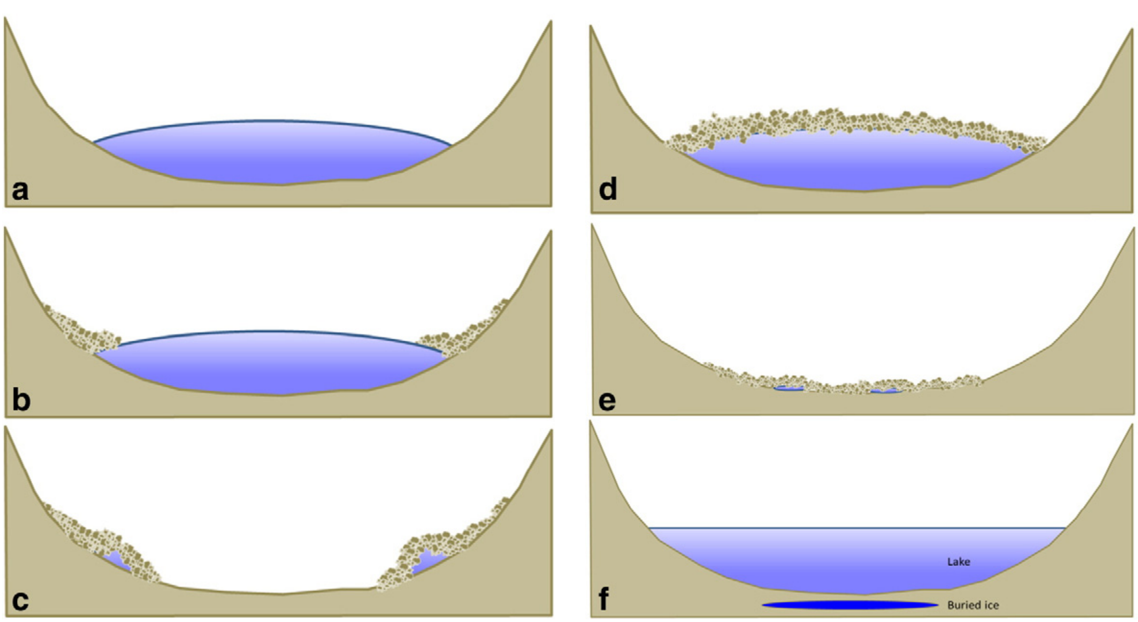

Fig. 6. Stages of the formation of buried massive ice. Moraines and rock avalanches cover glacier ice along the ice edge. The debris-free ice ablates leaving ice-cored deposits of rock debris (a–c). A glacier with sufficient rock material incorporated in the ice will form a mantle of debris by ice ablation. The accumulation of debris will slow ablation preserving the ice (d). Stream icings covered with sediment will also be preserved as thin random ice deposits on the valley floor (e). If a lake forms over a deposit of buried ice, the solar warmed lake waters will eventually melt the ice (f).

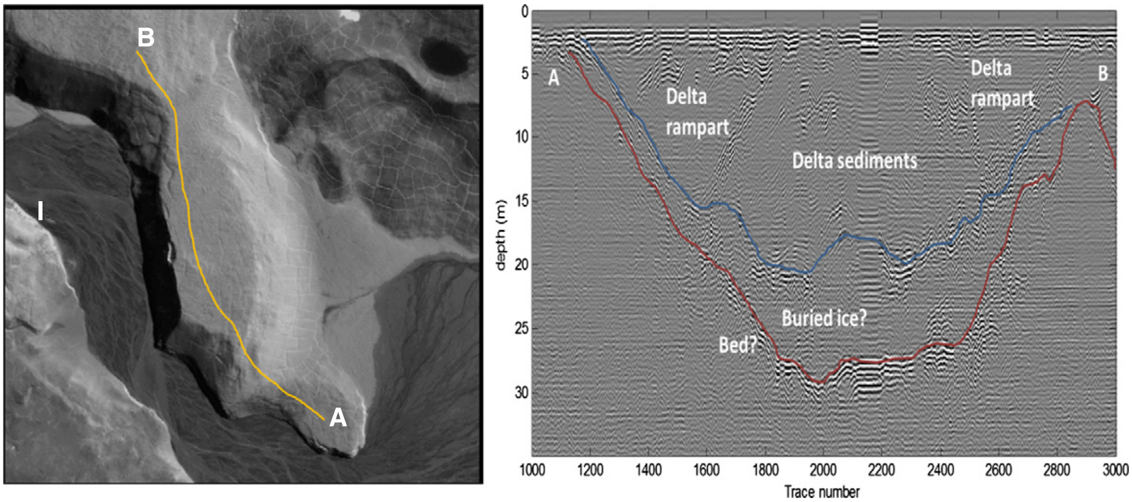

Fig. 7. Radar profile across a paleo-delta in the Garwood Valley that overlies massive buried ice. The satellite image on the left shows the profile path. The ice cliff shown in Fig. 2 is on the left at 'I'. The radar profile is shown on the right, not corrected for surface elevation, with preliminary interpretation.

6. Anticipated hydrological and biological responses to landscape change

The primary landscape change due to melting of BMI will be surface deflation initiating changes in stream course, slope, and cross-section geometry. These changes will result in new patterns of erosion and deposition and beginning a cycle of geomorphic change that may take years (decades?) for the stream to become fully adjusted to new conditions. Microbial ecosystem communities in and adjacent to the streams will respond as well due to the obvious mechanical effects of erosion and deposition and the less obvious changes in nutrient supply caused by waters interacting with previously dry or isolated landscapes adjacent to the channels, in addition to the nutrients released by the melting ice.

Streams are an important feature of the changing landscape. Streams convey water from the glaciers to the enclosed lakes, and in some cases, to the ocean. Their current morphology (e.g. sinuosity, slope) and composition (e.g. bed grain size distribution) are functions of past flow regimes and landscape legacies. The relatively stable condition of these channels over the past two decades is threatened by the potential for thaw and mechanical erosion at the margins of the current stream channels. In January 2012, we observed significant undercutting of banks of Crescent Stream (Fig. 10). Bed sediments had been significantly reworked and banks were found to be undercut in several locations and eroded and slumped in others. The consequences of this thaw and mechanical erosion are significant in moving sediments into streams and receiving lakes, and also in providing more intimate contact between stream waters and soils/sediments that have otherwise been dry likely for decades or more.

Stream and lake-marginal hyporheic zones have a strong influence on the ground thermal regime around these bodies of water: wet soils have a higher thermal diffusivity than adjacent dry soils (Ikard et al., 2009). The high apparent thermal diffusivity of wet soils in lake margin hyporheic zones may be leading to melting of lake-marginal permafrost and the formation of fracture and slump features around Taylor Valley lakes. Wet soils are also commonly observed in the MDV away from streams and lakes and they are known as 'wet patches' (Levy et al., 2012) and 'water tracks' (Levy et al., 2011). While many of these patches and tracks are thought to source in snow patches, isolated wet patches and water tracks are commonly observed in ice-cored drift units in Taylor and Wright valleys during particularly during warm summers (Harris et al., 2007) suggest the potential of melting subsurface ice.

The landscape changes discussed will significantly impact MDV biological communities through increased water availability, a primary constraint on life in the MDV (Kennedy, 1993; McKnight et al., 1999), and altered hydrologic connections and the spatial pattern of moist and dry mineral soils. As increased downslope flow interacts with previously dry soils it will solubilize sequestered nutrients. If the flow drains to a stream entrained solutes and particulates will modify in-stream supplies of limiting resources and increase scour. Transported materials will be collected and concentrated in downstream lakes altering the lentic physical and chemical characteristics. The limited diversity found in the MDV biological communities increases their susceptibility to changing conditions (Wall, 2007) as biological diversity is positively related to resistance and resilience in a wide variety of ecosystems (Tilman, 1999; Ptacnik et al., 2008; Boyer et al., 2009).

The wetting of previously dry soils through the lateral expansion of lake and stream margins and an increase in 'wet patches' and 'water tracks' is likely to impact numerous biologic parameters. Soil bacteria represent the most diverse group of organisms in the MDV (Freckman and Virginia, 1997; Connell et al., 2006; Fell et al., 2006; Cary et al., 2010), are responsible for processing nutrients and organic matter (Gregorich et al., 2006; Hopkins et al., 2006), are a food source for higher organisms (Treonis et al., 1999), and are highly responsive to changing conditions (Hopkins et al., 2006; Tiao et al., 2012). In a recent experiment (unpublished data) increasing the soil moisture of in-situ mesocosms in the MDV for 30 days significantly increased soil respiration and altered extracellular enzyme activities and the structure of the bacterial communities. Additionally, previous surveys have found wetted margin soils have bacterial communities distinct from those found in adjacent dry soils which are comprised of endemic, dry adapted organisms (Zeglin et al., 2011). The nematode communities found in the MDV are also responsive to changing soil moisture conditions with the dominant dry soil microbivore *Scottnema lindsayae* declining and the micro-algal feeder *Eudorylaimus* spp. increasing in abundance after a flooding event (Simmons et al., 2009). Thus, given the current distribution of microbial communities and their documented response to increased moisture, the structure and function of the soil biological communities is expected to change rapidly in newly wetted areas.

Landscape changes will affect MDV stream cyanobacterial mat and diatom communities through altered solute, discharge, and scouring regimes. Increased stream flow contacts newly thawed soils laterally expanding stream margins, and bank slumps, entraining nutrients, solutes, and particulates each of which will likely effect biological communities. Nutrient diffusing substrates recently deployed in MDV streams

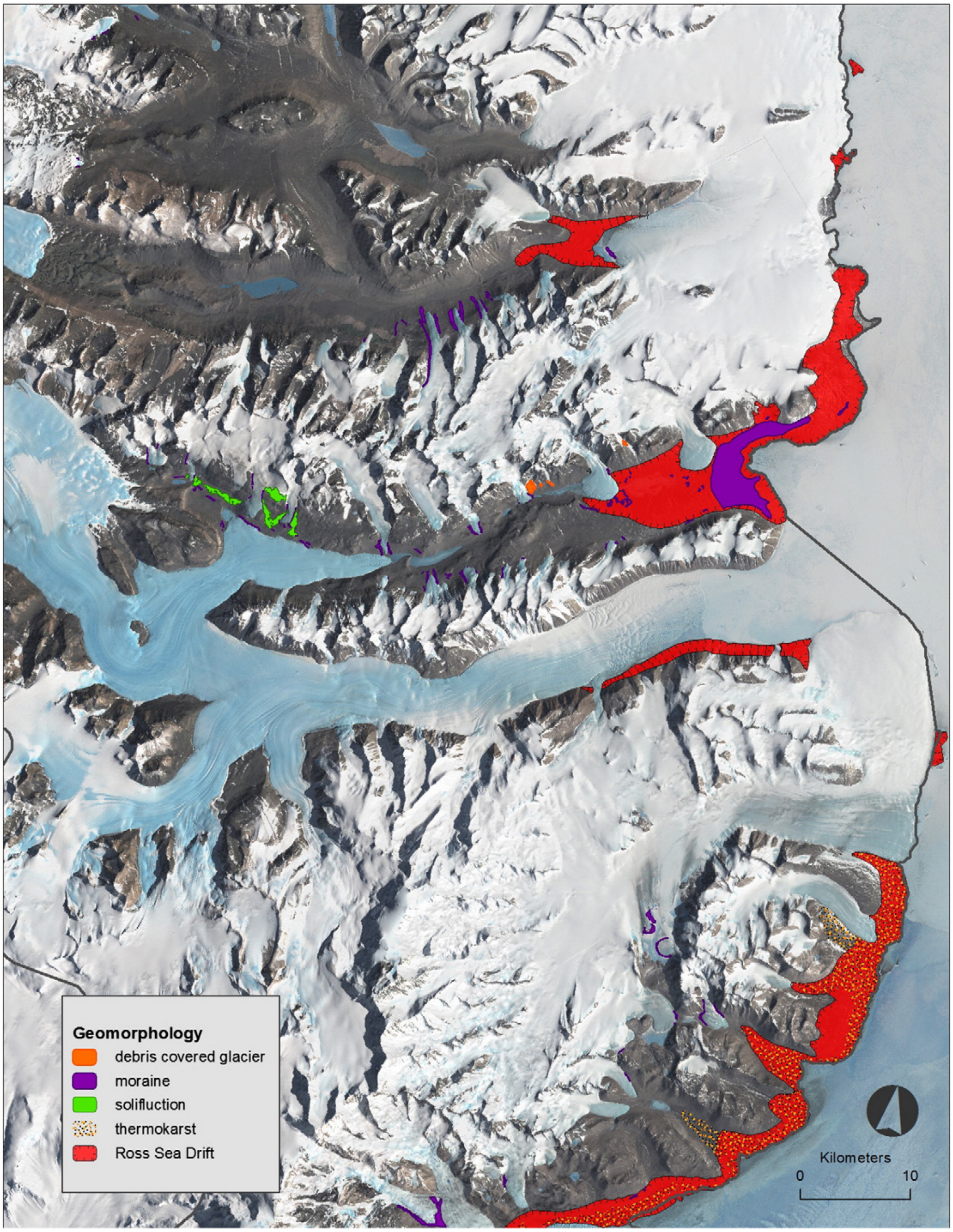

Fig. 8. Mapped geomorphic features based on field reports (Hall and Denton, 2000, 2005; Hall et al., 2000), previous maps (Stuiver et al., 1981b; LINZNTO, 2012), and satellite imagery.

(unpublished data) significantly increased algal chlorophyll-a, suggesting landscape change related resource additions are likely to result in increased in-stream primary production. Altered flow regimes will also affect the stream biological communities as flow is the best predictor of MDV stream diatom community structure, is negatively correlated with algal biomass, and is linked to the distribution of heterotrophic bacteria (Stanish et al., 2011, 2012a). High flow events also result in persistent shifts in diatom communities in some MDV streams toward smaller generalist species (Stanish et al., 2011) and flow intermittency favors endemic species adapted to frequent drying events (Stanish et al., 2012b). Thus increased flow in established channels and reduced intermittency are expected to reduce the distribution of highly endemic organisms and favor generalist taxa. High flow events and the increase in particulates will also accelerate the scouring of stream substrates which has been previously observed in the MDV (Stanish et al., 2011, 2012b) and was recently observed downstream of thermokarst features (personal observation). Thus competing processes are likely to affect biomass accrual: nutrient addition will stimulate biomass while scouring events will decrease it. The net effect of landscape scale change on algal mat biomass in MDV streams is an important parameter as high biomass has been shown to decrease the export of nutrients to downstream lake ecosystems (McKnight et al., 2004).

The downstream transport of materials mediated by landscape change is also expected to impact the biological communities in the MDV lakes. These lakes are perennially ice covered with seasonal moats and a majority are have closed basins with no outflow, concentrating inputs and limiting the export of materials once they have entered the lake system. Primary production in these lakes has been

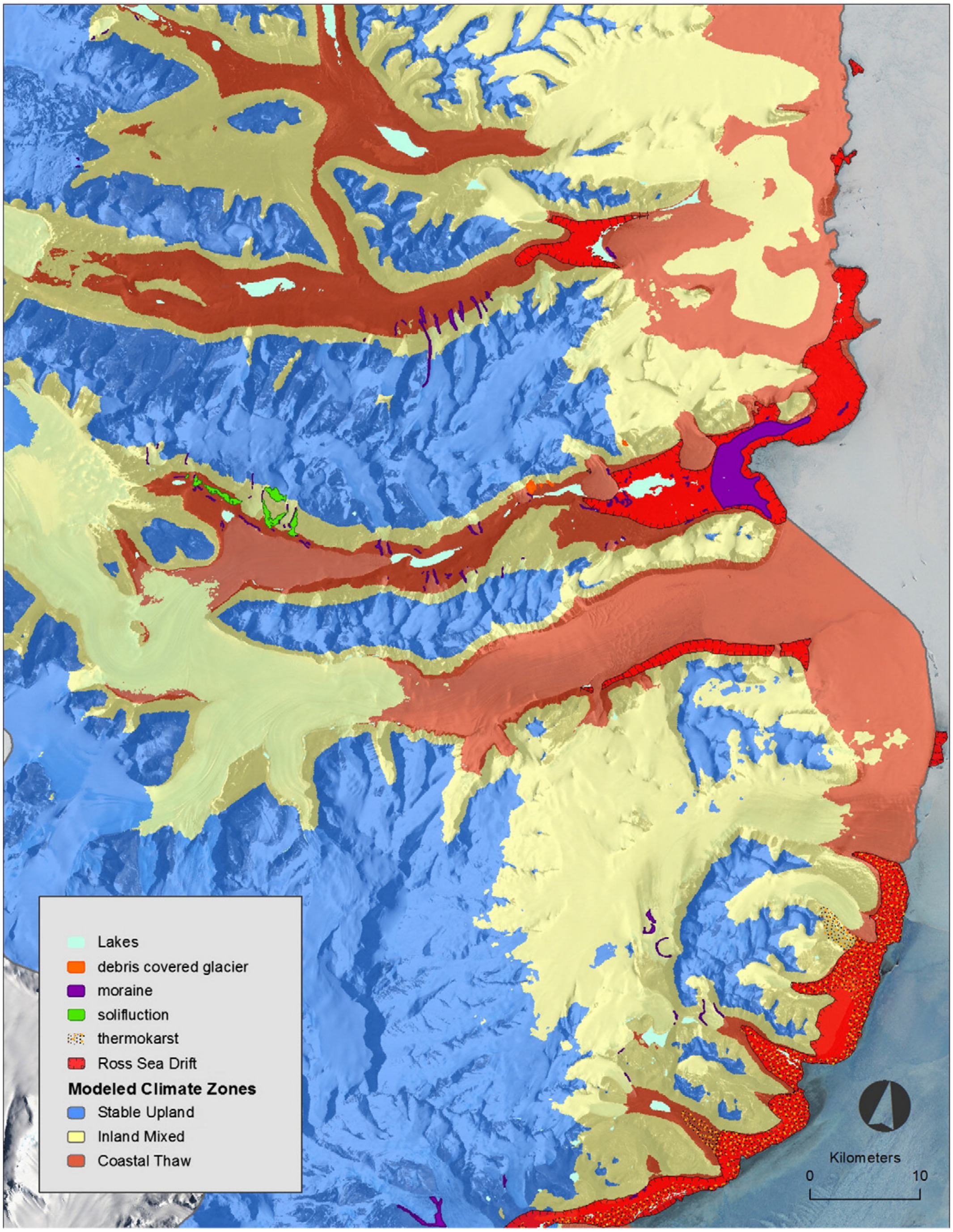

Fig. 9. Geomorphic zones overlay on geomorphic features. The features in the coastal thaw zone are considered to be the most 'at risk' landscapes for change in response to climate warming.

shown to be nutrient limited with P limiting in Lake Bonney and N + P limiting in lakes Hoare and Fryxell (Priscu, 1995; Dore and Priscu, 2001). Data following a high stream flow year suggest that increased turbidity initially limits primary production, however, once turbidity decreased, a significant increase in water column nutrients and primary production was observed (Foreman et al., 2004).

We expect landscape changes to alter a variety of MDV habitats including isolated mineral soils and hydrologically connected soils, streams, and lakes. Increased water availability will relieve a primary constraint on life in the MDV and result in new patterns of nutrient enrichment, erosion and deposition causing a cascade of ecological effects in streams and lakes. The increase in water and nutrient availability will stimulate primary production and associated heterotrophic activities, however, endemic dry adapted oligotrophic organisms may be outcompeted in their current habitats by generalist organisms causing shifts in community structure and function.

7. Summary and conclusions

The McMurdo Dry Valleys have experienced isolated but sizeable landscape changes due to the melting of buried massive ice. The deflation has caused a major response in stream slope and erosion. We estimate that the biologic response is or will be similarly sizable in these streams. And we see more melting from the sediment-covered glaciers that we suggest increases stream flow in this recent climatic period of variable but trend-absent summer air temperatures. Measured

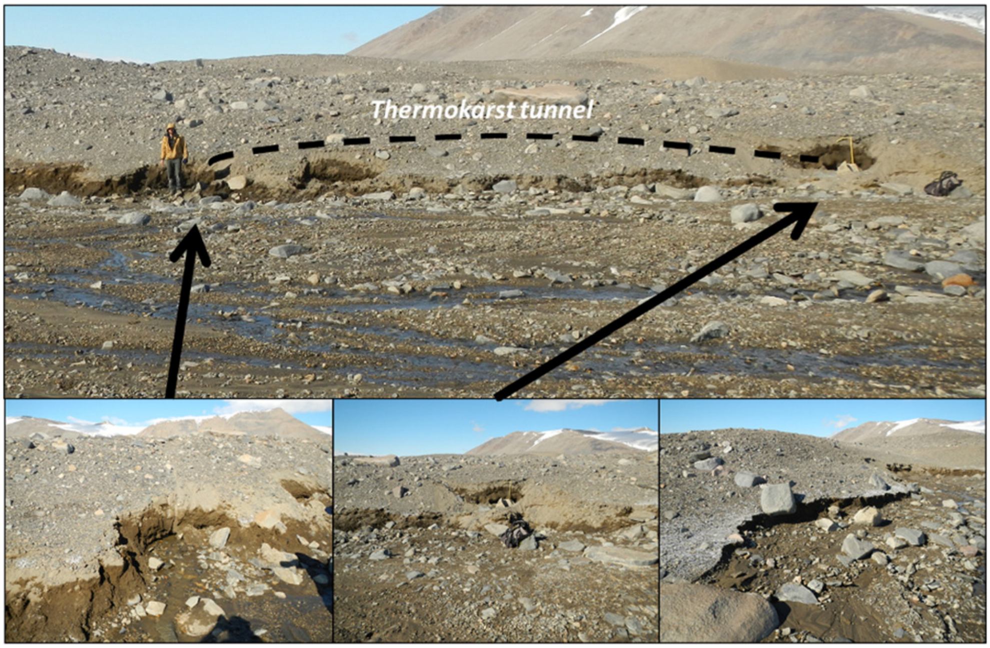

Fig. 10. Bank and bed erosion discovered on Crescent Stream, Taylor Valley, in January 2012. A thermokarst tunnel of approximately 20 m in length was found, but significant bank erosion occurred along 3 km of the stream.

increases of solar radiation are thought to be the proximal cause for increased ice melt when sediment is present.

Our conceptual model of 'at risk' landscapes show the potential for massive changes in the valley bottoms because most of them are within the coastal thaw zone. Often air temperatures can be warmer up valley (Doran et al., 2002; Nylen et al., 2004) rather than closer to the coast due to the warming of the sea breeze as it flows up valley. Therefore, it may be that melting of buried massive ice may occur inland prior to coastal locations. However, many other variables control this outcome including debris thickness, local aspect of the deposit and whether it is on the north-facing or south-facing valley wall, and local patterns of snow patches which will keep the subsurface cool.

Once these changes occur, we expect extensive reorganization of stream courses and substantial erosion and deposition of sediment that will eventually find its way to the enclosed lakes, further enhancing lake level rise. And this sediment flux will increase the nutrient flow to the lakes creating algal blooms much like that experienced the year after the big melt event in the summer of 2000/01 (Foreman et al., 2004; Barrett et al., 2008).

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