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Reconciling persistent sub-zero temperatures in the McMurdo Dry Valleys, Antarctica, with Neogene dynamic marine ice-sheet fluctuations

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ABSTRACT

In the Ross Sea sector of Antarctica, periodic large-scale marine ice-sheet fluctuations since the mid-Miocene are recorded by drill core and seismic data, revealing a dynamic ice-sheet response to past increases in temperature and atmospheric CO_2. In the adjacent, predominantly ice-free McMurdo Dry Valleys (MDVs), preserved terrestrial landscapes reflect persistent cold conditions and have been interpreted as indicators of a stable polar ice sheet, implying that the Antarctic Ice Sheet was largely insensitive during past warm periods. These disparate data-based perspectives highlight a long-standing debate around the past stability of the Antarctic Ice Sheet, with direct implications for the future ice-sheet response to ongoing climate warming. We reconcile marine records of dynamic ice-sheet behavior and episodic open-marine conditions with nearby ancient terrestrial landscapes recording consistent cold-polar conditions. Coupled ice-sheet and regional climate models nested at a high resolution are used to investigate surface temperatures in the MDVs during past warm periods. We find that high-elevation regions of the MDVs remain below freezing even when ice-free conditions prevail in the nearby Ross Sea. We compare observed landscapes with the spatial extent of modeled persistent cold conditions required for preservation of these ancient features, demonstrating that frozen MDVs landscapes could have coexisted with receded or collapsed ice sheets during past warm periods.

INTRODUCTION

Drill-core reconstructions and seismic surveys record dynamic ice-sheet behavior throughout the late Miocene and Plio–Pleistocene. In the Ross Sea, Antarctica, episodic marine ice expansion created large-scale unconformities across the continental shelf (e.g., Anderson and Bartek, 1992; Brancolini et al., 1995; De Santis et al., 1995; Bart et al., 2000), alternating with ice-free periods during warm interglacials. At the ANtarctic DRILLing Project (ANDRILL) core site 1B (A1B in Fig. 1C), multi-proxy sedimentary and micropaleontology investigations have reconstructed periodic open-marine hemipelagic and pelagic sedimentation within a productive ice-free ocean environment (Fig. 1A; Naish et al., 2009; Rosenblume and Powell, 2019). Although glacial sedimentation at the ANDRILL-1B site is primarily sourced from East Antarctic Ice Sheet (EAIS) outlet glaciers, numerical modeling suggests that open-marine conditions at the drill site reflect a receded or even collapsed West Antarctic Ice Sheet (WAIS; Pollard and DeConto, 2009). The combination of drill-core data, seismic records, and ice-sheet modeling demonstrates that the Antarctic ice sheets are sensitive to relatively small CO_2 and temperature fluctuations and receded during past warm periods (Bart and Anderson, 2000; Naish et al., 2009; Pollard and DeConto, 2009; Gasson et al., 2016; Levy et al., 2016).

Less than 100 km away from the ANDRILL-1B site, along the coast of the Transantarctic Mountains, the McMurdo Dry Valleys (MDVs; Fig. 1C) are a primarily ice-free region bounded to the west by the EAIS and to the east by the Ross Sea and the seasonally open waters of McMurdo Sound. The MDVs are characterized by high local relief (elevations range from sea level to ~2800 m) and are dominated by large east-west–trending valleys that once hosted outlet glaciers draining the EAIS into McMurdo Sound. Numerous studies have documented the presence of well-preserved cold-climate landforms and sedimentary deposits in the MDVs (Fig. 1B). These features lack evidence for surface modification from glacial advance or cryoturbation, suggesting that cold-desert conditions have persisted in high-elevation sectors of the MDVs since the Pliocene (Sugden and Denton, 2004; Marchant and Head, 2007) or possibly mid-Miocene (Lewis et al., 2007). These relict terrestrial features have prompted the inference that the EAIS did not recede significantly past its modern configuration during past warm periods (e.g., Sugden et al., 1993) and therefore may be less susceptible to climate perturbations in the future.

We attempt to reconcile these conflicting perspectives on large-scale ice-sheet behavior by revisiting the terrestrial and marine records underpinning these assumptions about the stability of past ice sheets and their imprint on the terrestrial geomorphic record. We employed coupled ice-sheet and climate models, quasi-equilibrated under warm boundary conditions such as those reconstructed at the ANDRILL-1B site, to reproduce surface temperatures in the MDVs. We identify the environmental conditions that could have preserved these ancient terrestrial landscapes while also remaining compatible with the dynamic marine geologic record.

NESTED CLIMATE MODELING

We employed representative model snapshots of ice sheets and climate under warm interglacial boundary conditions. Ice-sheet model evolution is driven by temperature and precipitation from an asynchronously coupled climate model with elevated CO_2 and orbital parameters favorable for Antarctic deglaciation (Halberstadt et al., 2021). Here we imposed a modern MDV ice-free configuration (Fig. 2B;

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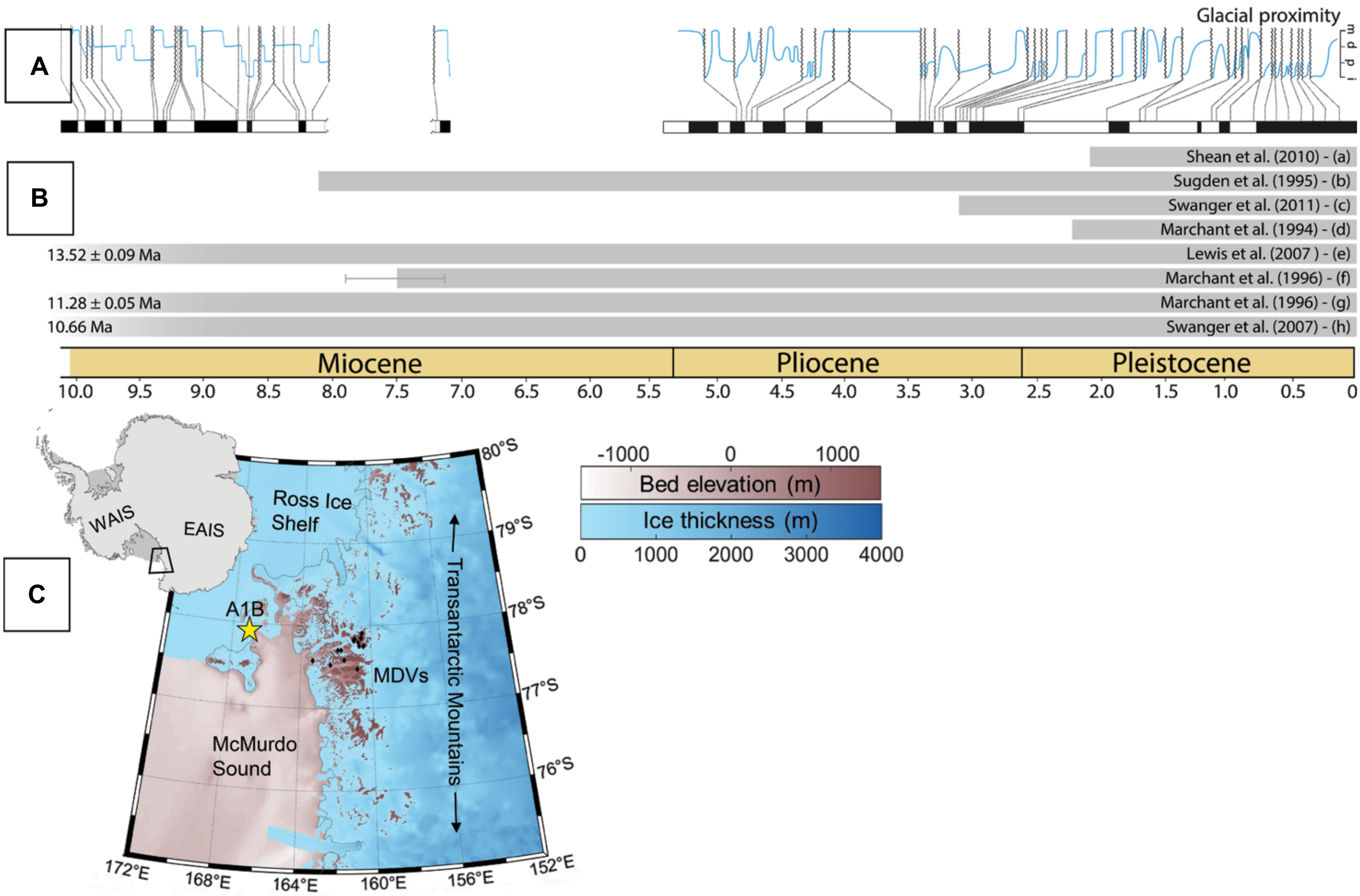

Figure 1. Dynamic glacial variability in McMurdo Sound and landscape preservation in the McMurdo Dry Valleys (MDVs), Antarctica. (A) Facies variability at ANtarctic DRILLing Project (ANDRILL) site 1B (A1B; 77.89°S, 167.09°E) with tie points (wavy lines) to geomagnetic polarity time scale (black and white bars represent global polarity chrons). Gaps reflect discontinuous core recovery. Environmental conditions range from full glaciation to warm ice-free interglacials; glacial proximity varies between ice-contact (i), ice-proximal (p), ice-distal (d), and marine (m) environments, reflecting dynamic Ross Sea ice-sheet behavior (Naish et al., 2009; Rosenblume and Powell, 2019). (B) Ages of relict landscapes across the same time period from various studies. Gray bars therefore indicate the time period of landscape stability. Any reported age errors are represented by the gray whisker plot or labeled accordingly. Locations of features a–h are shown in Figure S5 and described further in Table S1 (see footnote 1). (C) Location of site A1B and MDV landforms and deposits (black diamonds). WAIS—West Antarctic Ice Sheet; EAIS—East Antarctic Ice Sheet.

see the Supplemental Material[1]) and performed nested regional climate model simulations over the MDVs region that downscale coarser climate model output to a 10 km grid resolution. Model CO_2 concentrations (280 and 460 ppm) fall within the range of geologic proxies for the Miocene and Plio–Pleistocene (Rae et al., 2021). The absolute value of CO_2 in our modeling approach is dependent on climate model physics, so CO_2 concentrations should be considered relative and not absolute; we interpret our 280 and 460 ppm simulations as representative of two possible warm interglacials during this time period. We also included an additional 690 ppm simulation as a "high-CO_2" scenario. Comparison with modern meteorological observations provides confidence that our modeling approach can robustly represent the complex climatology of the MDVs (see the Supplemental Material).

RELICT LANDSCAPES AND PALEOCLIMATIC IMPLICATIONS

Ancient landscapes in the MDVs can serve as paleoclimate indicators, reflecting environmental conditions at the time of formation as well as subsequent temperature and precipitation patterns.

Across the highest elevations in the MDVs, in the upland frozen zone (UFZ), mean daily maximum summer air temperatures and soil temperatures have remained well below freezing (Marchant and Head, 2007). Unique features that form and remain intact under UFZ conditions include cold-based drift deposits and sublimation tills associated with cold-based glaciation, as well as stable rectilinear ice-cemented slopes.

Cold-based glaciers and their resultant cold-based drift lack the glacial abrasions, striations, and polishing that are commonly associated with wet-based basal conditions. Post-depositional wet-based or supraglacial conditions with significant melt production would result in stratified outwash deposits and reworking of cold-based drift deposits, which is not observed in the UFZ. Sublimation of cold-based glaciers in the UFZ produces sublimation till commonly superimposed by sublimation polygons formed from the thermal contraction of underlying massive ice. Long-term preservation of sublimation polygons requires climatic conditions that prohibit the formation of a true active layer in the soil, characterized by percolation of liquid water into the thermal contraction crack (Sugden et al., 1993; Marchant et al., 2002; Marchant and Head, 2007). Mean summer atmospheric temperatures below −3 °C are required to

[1]Supplemental Material. Additional details on the numerical climate and ice-sheet modeling methods, the impact of prevailing wind patterns on MDVs climate, temperature dependence on regional ice sheet geometry, the compilation of MDVs landforms and sedimentary deposits, and modeled snow accumulation. Please visit https://doi.org/10.1130/GEOL.S.18822092 to access the supplemental material, and contact editing@geosociety.org with any questions.

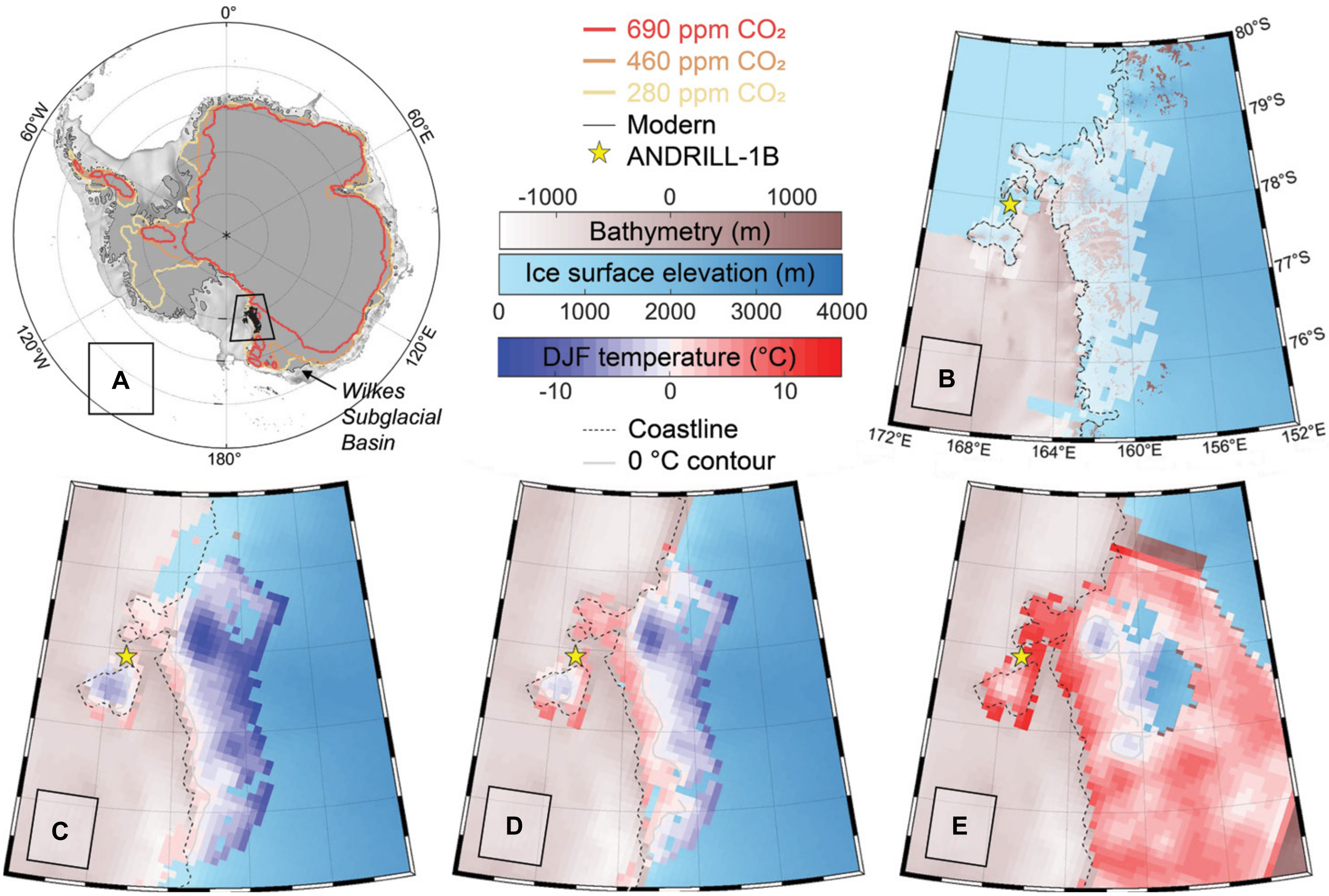

Figure 2. Nested high-resolution climate modeling of the McMurdo Dry Valleys (MDVs), Antarctica. Star denotes location of the ANDRILL-1B core site, which was ice free during past warm periods. (A) Continent-wide ice-sheet configurations during past warm interglacials (Halberstadt et al., 2021) used as boundary conditions for our nested climate models (see the Supplemental Material [see footnote 1]). (B) Ice-free MDVs mask (white) imposed on our 10-km-resolution paleoclimate model simulations, shown relative to modern ice sheet configuration (Morlighem et al., 2019). (C–E) Modeled mean summer temperatures (DJF—December-January-February) across the MDVs under 280 ppm, 460 ppm, and 690 ppm CO_2, respectively.

prevent modification of these landscapes via supraglacial melt (Lewis et al., 2008).

Stable rectilinear ice-cemented slopes have also been identified throughout the MDVs. The top 10–50 cm of unconsolidated deposits typically overlies an ice-cemented layer. Sufficient thawing of this layer or surface meltwater production upslope would likely induce sliding and is estimated to occur if modern mean summer soil surface temperatures increase to a range between −5 °C to −1 °C (Swanger and Marchant, 2007).

The pristine preservation and ancient ages of these UFZ landscapes rule out the past occurrence of active cryoturbation, supraglacial melt, and slope destabilization, which are associated with mean summer surface temperatures above approximately −3 °C. The presence of these preserved features also excludes past glacial advance across these landscapes. UFZ landscapes have thus been used to support arguments for Antarctic ice-sheet stability since the mid-Miocene (e.g., Sugden et al., 1993; although other terrestrial evidence from the Transantarctic Mountains has been interpreted to indicate marine flooding of EAIS basins; Webb and Harwood, 1987).

LANDSCAPE PRESERVATION DURING PAST WARM PERIODS

Under warm boundary conditions, our model simulates frozen high-elevation regions of the MDVs at CO_2 levels consistent with proxy reconstructions, despite open marine conditions in the nearby McMurdo Sound (Figs. 2C and 2D).

The modeled relationship between summer temperature and elevation under past warm conditions resembles that of a present-day climatology translated to a warmer mean state, regardless of

(1) Large-scale prevailing wind patterns. Despite the intermixing of onshore and offshore winds across the MDVs, a generally linear relationship is observed between summer temperature and elevation (Fig. 3; see the Supplemental Material).

(2) Microclimate variability. Complex topography and intermixing winds in the MDVs create microclimate zones observed today. Although modern microclimate variability generally occurs below the resolution of our 10 km simulations (cf. Doran et al., 2002), nested climate modeling under modern boundary conditions is able to adequately replicate modern meteorological measurements (Fig. S2). We therefore conclude that our modeled elevation-dependent summer temperature pattern is robust.

(3) Ice configuration surrounding the MDVs. Sensitivity experiments with and without a surrounding ice mass over the Transantarctic Mountains (see the Supplemental Material; Fig. S4) show that glacial proximity does not exert a primary control on maintaining persistently cold upland regions.

We leverage the observed elevation-dependent summer temperature pattern to extrapolate model results onto the modern topography at an even higher resolution. For each modeled climate, we identified a representative elevation characterizing the −3 °C isotherm (Fig. 3). Isotherm elevations were used to identify the

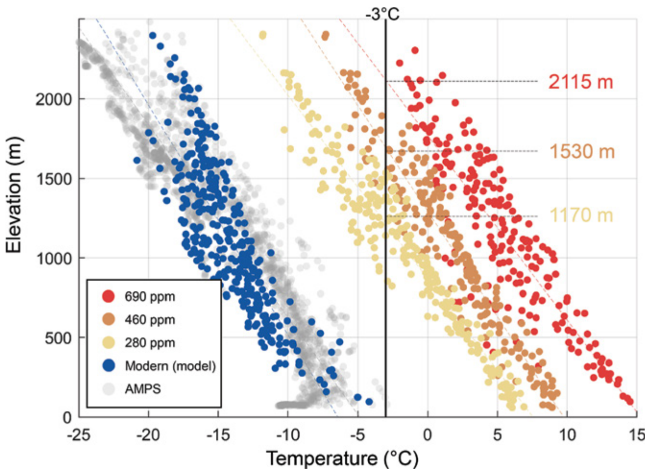

Figure 3. Mean summer temperature versus elevation under past warm boundary conditions in the McMurdo Dry Valleys, Antarctica. To compare similar regions across different CO_2 levels (280 ppm, 460 ppm, and 690 ppm), we plot only grid cells contained by a modern ice-free mask. Modern climate model results are similar to high-resolution weather prediction model output over the McMurdo Dry Valleys (gray; Antarctic Mesoscale Prediction System [AMPS] model at 0.89 km resolution; Powers, 2012) that is averaged across three different days (15 December 2017, 15 January 2018, and 15 February 2018) to approximate December-January-February (DJF) average temperature. Isotherm elevations are identified (horizontal dashed lines) where least-squares fit lines intersect –3 °C degrees.

spatial extent of modeled cold zones (Fig. 3) where air temperatures remained below −3 °C throughout the summer during past warm interglacials, precluding landscape modification.

Relict landscapes in the MDVs are generally observed only at high elevations (Fig. 4), indicating that climatic conditions supporting landscape preservation were restricted to MDV uplands during the warmest interglacials (Marchant and Head, 2007). Model results are consistent with an elevation-based stability transition across the MDVs, separating regions of landscape modification from those of landscape preservation; persistently cold temperatures existed at high elevations while valley floors experienced summer thaw (Fig. 4). A spatial comparison between modeled cold zones and a compilation of mapped MDV landforms and deposits (see the Supplemental Material) underscores the climatic sensitivity of these features to warm conditions (Fountain et al., 2014). We find that the oldest preserved landscapes are broadly situated along the fringes of modeled cold zones and are not present at elevations significantly below the modeled −3 °C isotherm under 280 and 460 ppm CO_2 boundary conditions. Under the "high-CO_2" scenario (690 ppm CO_2), the −3 °C isotherm occurs significantly higher than all relict landscapes (Fig. 4), suggesting that those conditions have not been experienced since the mid-Miocene. The "high-CO_2" scenario is further incompatible with the MDVs geologic record because it produces significant snow accumulation, which could have supported glacial advance and landscape modification, while the 280 and 460 ppm simulations maintain generally ice-free conditions across MDV uplands (see the Supplemental Material).

RECONCILING HIGH-ELEVATION LANDSCAPE PRESERVATION WITH DYNAMIC ICE-SHEET BEHAVIOR

We find that persistent cold conditions in high-elevation regions of the MDVs can coexist with receded sections of the EAIS, a reduced or collapsed WAIS, and an open marine Ross Sea. If we extrapolate this finding to other ice-free regions around Antarctica, we can similarly reconcile large-scale ice-mass loss during past warm periods with persistent polar desert conditions at other high-elevation ice-free locations since the mid-Miocene across Antarctica (Bibby et al., 2016; Spector and Balco, 2020). We note that landscape preservation does not require a present-day EAIS configuration during past warm periods; our 460 ppm model member shows substantial ice loss in the Wilkes Subglacial Basin (Fig. 2A).

Because temperature patterns are primarily controlled by elevation, climate across the MDVs warms uniformly with elevated atmospheric CO_2 and coastal warmth, and the zone of persistently cold temperatures migrates upland (Figs. 3 and 4). We can therefore use the distribution of relict frozen landscapes in the MDVs to establish an upper limit of climate warming during past warm periods. For example, the extreme "high-CO_2" scenario (690 ppm CO_2; Fig. 2E) restricts persistent cold conditions to the very tops of mountain peaks and would have exposed relict landscapes to potential thaw (as well as glacial advance; see the Supplemental Material).

We have demonstrated that dynamic Antarctic ice sheets during past warm periods are compatible with persistent cold conditions in the MDV uplands; this finding reconciles previously contradictory data sets but does not conclusively rule out a large and stable EAIS during past warm climates. To better understand past (and future) ice-sheet stability, potentially divergent responses of the WAIS and EAIS to environmental forcings should be considered. For example, increased precipitation during past warm periods may have contributed to positive surface-mass balance over the EAIS (Hall et al., 2015) while warming ocean temperatures, global sea-level rise, and surface melt on ice shelves may have destabilized the WAIS and marine-based sectors of the EAIS (e.g., DeConto and Pollard, 2016; Gomez et al., 2020). Although terrestrial and marine ice sheets can be susceptible to divergent feedbacks under warm climates, increasing geologic evidence suggests that large portions of the EAIS likely deglaciated during past warm periods (e.g., Cook et al., 2013; Grant et al., 2019) while still preserving ancient landscapes in high-elevation regions of the MDVs.

SUMMARY

High-elevation landscape preservation in the MDVs indicates sustained cold-desert conditions; these landscapes have been used to infer EAIS stability since the mid-Miocene. By demonstrating that frozen MDV landscapes could have coexisted with open marine conditions in the nearby McMurdo Sound during past warm periods, we reconcile the possible preservation of ancient MDVs landscapes with dynamic marine and terrestrial ice-sheet fluctuations.

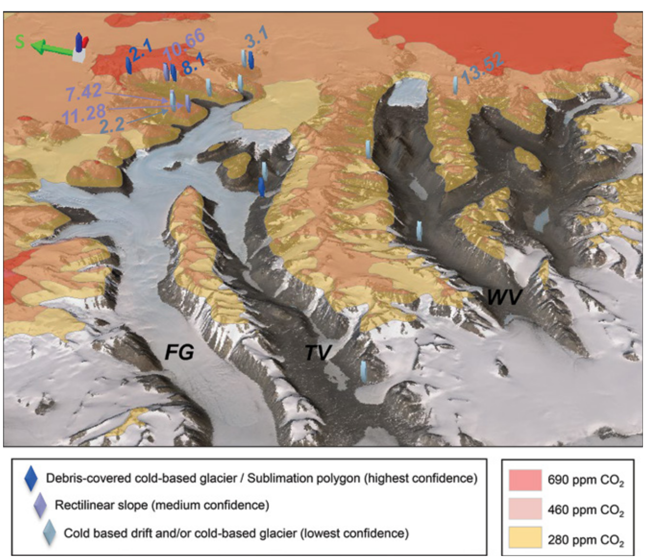

Figure 4. Spatial comparison between modeled cold zones and mapped relict landscapes in the McMurdo Dry Valleys, Antarctica, with ages labeled in Ma (see the Supplemental Material [see footnote 1] for landscape compilation and an explanation of confidence rankings). Topography is from Morlighem et al. (2019). FG—Ferrar Glacier; TV—Taylor Valley; WV—Wright Valley. Additional location context is shown in Figure S5 in the Supplemental Material.

Nested high-resolution climate modeling of the MDVs under past warm interglacial conditions reveals elevation-based cold zones characterized by persistent sub-zero temperatures. These modeled cold zones protect high-elevation MDV landscapes, but only below a CO_2 threshold. Thus, relict landscapes in the MDVs provide a valuable constraint on Antarctic warming in the geologic past.

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