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Niveo-eolian Sediment Deposits in Coastal South Victoria Land, Antarctica: Indicators of Regional Variability in Weather and Climate

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Abstract

A 35 year chronology from 1965 to 2000 of the deposition of wind-blown sediment is constructed from snowpits for coastal southern Victoria Land, Antarctica. Analysis of local meteorology, contemporary eolian sedimentation, and mineralogy confirm a Victoria Valley provenance, while the presence of volcanic tephra is ascribed to an Erebus volcanic province source. Winter foehn winds associated with anticyclonic circulation are considered responsible for transporting fine-grained sediment from the snow- and ice-free Victoria Valley east toward the coast, while cyclonic storms transport tephra north along the Scott Coast. No trend could be identified in the occurrence of either tephra or wind-blown sediments sourced from the Victoria Valley and retrieved from the snowpits excavated on the Victoria Lower and Wilson Piedmont Glaciers. We infer this to indicate that the region has not undergone a significant change in weather patterns for at least the last 35 years. Our results also confirm the McMurdo Dry Valleys as a regionally significant source of wind-blown sediment.

Introduction

In Antarctica, locally derived wind-transported sediments have remained largely unstudied, due to both the focus on global particulate content of ice cores such as Vostok and Dome-C (Delmonte et al., 2004), and the lack of ice core extraction from areas where significant locally derived signals of eolian sediments are preserved. Predominantly, studies have focused on the deposition of long-traveled fine-grained dust in polar regions for paleoclimate reconstruction spanning thousands to hundreds of thousands of years (Antarctica: Basile et al., 1997; Lunt and Valdes, 2001; Greenland: De Angelis et al., 1997; Zielinski and Mershon, 1997; Maggi and Petit, 1998; Svensson et al., 2000; Penny Ice Cap, Baffin Island, Canada: Zdanowicz et al., 2000). Geochemical analysis of this global dust signal has been used to locate potential source regions, and atmospheric circulation models have been offered to explain the transport histories of this dust from extra-polar sources into the Antarctic or Arctic atmosphere (Shaw, 1979; Grousset et al., 1992; Basile et al., 2001; Delmonte et al., 2004). Polar dust deposition chronologies have subsequently been used as indicators of large-scale global climate variability, including the timing of the Last Glacial Maximum (LGM), the Antarctic Cold Reversal (ACR), and the Younger Dryas (Zdanowicz et al., 2000).

However, locally derived eolian sediments including dust, which is defined as wind-blown mineral grains with a diameter <100 μm (Pye 1987), retrieved from geologic archives such as snow and ice cores, peat, and marine sediment are also important indicators of climate variability and environmental change (Thompson et al., 2000). These records of eolian sedimentation are likely to be influenced by, and reflect, local- to global-scale processes. Kohfeld and Harrison (2001) stated that variability in dust flux may be caused by a combination of factors including changes in, (1) the areal extent of dust sources, (2) wind speed over dust sources and subsequent atmospheric transport of dust, (3) the residence time of dust in the atmosphere, and (4) the relative contributions of wet- to dry-based dust deposition. Therefore, records of the deposition of eolian sediments (coarse- and fine-grained) reflect environmental variability in response to changing weather and climate, and land use. Understanding of this variability in eolian sediment flux is also fundamentally important to resolving the influence of mineral aerosols on climate and their impact in many biogeochemical cycles including deep ocean sedimentation and marine fertilization by iron and silica (Calvo et al., 2004).

In this paper we report on approximately 35 years of deposition of wind-transported sediments at the Victoria Lower Glacier, and 15 years of deposition at the Wilson Piedmont Glacier in South Victoria Land, Antarctica. Results reflect changes in sediment availability and the wind regime of the study area—a region which is considered susceptible to low amplitude climate shifts (Bertler et al., 2004a). They also provide rare data on recent deposition rates of wind-transported sediments in the Antarctic, and polar regions in general, from which few contemporary records exist. These data are required to better constrain, for example, global dust budget and climate models that seek to resolve the influences of atmospheric mineral aerosols on climate systems (Tegen et al., 2002).

Physical Setting

LOCATION

The study area is located along the South Victoria Land coast, bordered by the Trans-Antarctic Mountains to the west and the Ross Sea to the east (Fig. 1). West of the Trans-Antarctic Mountains lies the East Antarctic ice sheet. In some locations outlet glaciers from this polar plateau have carved large east-west–trending valleys in the Trans-Antarctic Mountains, which in most places remain ice filled. However, the Victoria, Wright, and Taylor Valleys are snow and ice free for much of the year, exposing approximately 4000 km^2 of rock and forming what is collectively known as the "McMurdo Dry Valleys" (Selby et al., 1974).

The Victoria Lower Glacier is approximately 20 km long and 8 km wide, occupying the eastern segment of the Victoria Valley system (Fig. 1). It is bounded to the east by the Wilson Piedmont Glacier, a small ice cap fed by coastal snowfall, which extends along the Scott Coast in a north-south direction for approximately 60 km. West of the Victoria Lower Glacier, the Victoria Valley splays into five main branches to the west of Lake Vida. The most northern of these is the upper Victoria Valley, in which lies the Victoria Upper Glacier. The

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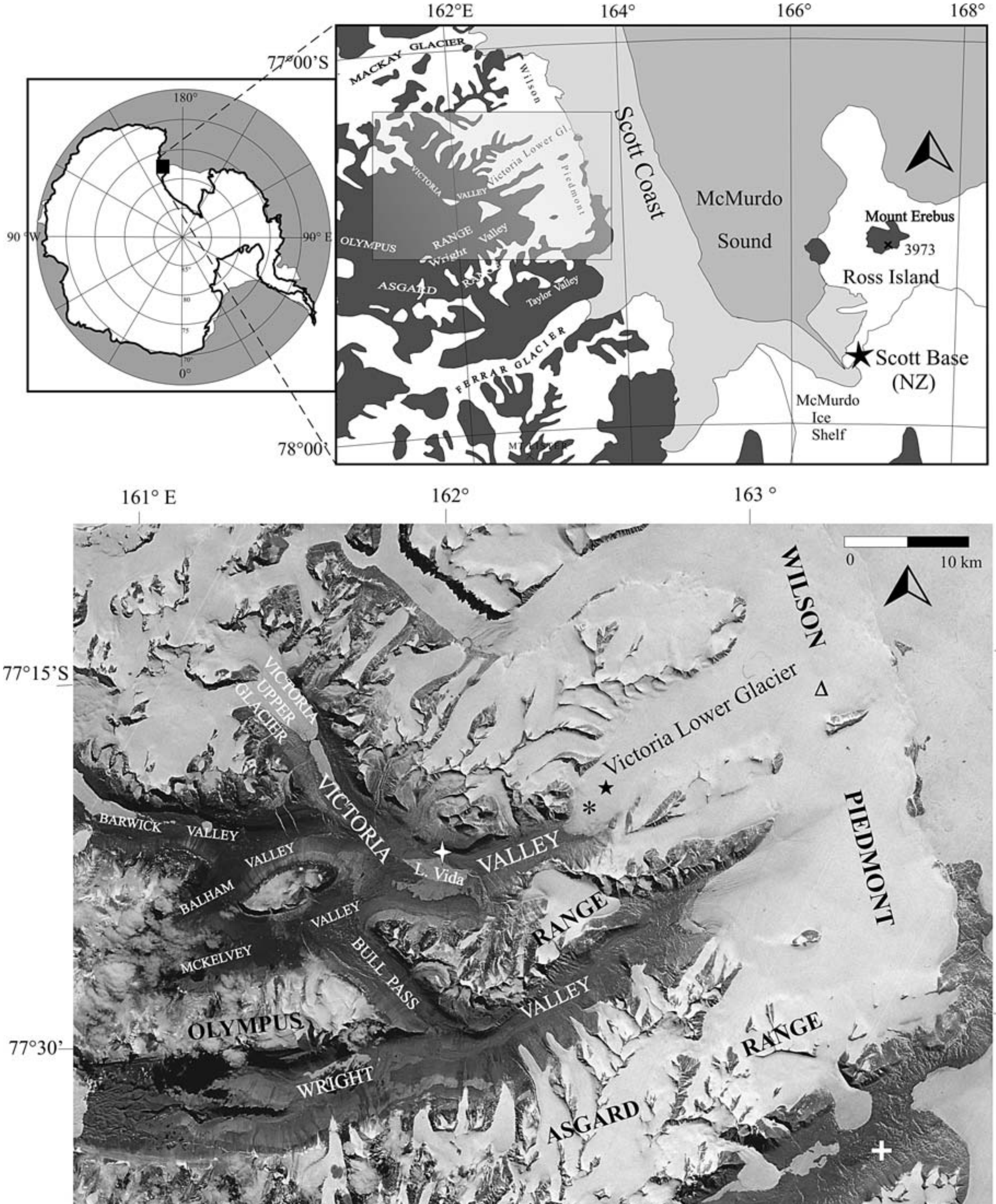

FIGURE 1. Location of study sites, McMurdo Dry Valleys, Antarctica. Satellite image including the Dry Valleys to the west of the field area, and valleys adjacent to the Victoria Valley system. Symbols on the satellite image indicate localities referred to in the text: Δ = Wilson Piedmont snowpit site, ★ = Victoria Lower Glacier snowpit site, * = Shallow snowpit on Victoria Lower Glacier from which tephra was recovered, ✧ = Lake Vida Automatic Weather Station, ✠ = Explorer's Cove Automatic Weather Station.

termini of the Victoria Upper and Lower Glaciers are approximately 26 km apart, with meltwater from both in summer draining into Lake Vida in the center of the Victoria Valley system. The remaining four branches are known as the Barwick, Balham, and McKelvey Valleys and Bull Pass (Fig. 1).

Surface sediments in the snow- and ice-free regions of the Victoria Valley system consist of heavily weathered exposures of bedrock, glacial, and glacio-fluvial sediments that are subject to active periglacial processes. Extensive eolian deposits cover the eastern section of the valley floor including the largest sand dune system on the Antarctic continent, which is located approximately 3 km west of the Victoria Lower Glacier. Large sandurs are also located near the terminus of the Victoria Lower Glacial and east of Lake Vida. Eolian abrasion is believed to be a dominant process in the Dry Valleys leading to the abundance of fine-grain sediments through physical weathering of exposed rock surfaces and intergrain abrasion. Chemical and thermal weatherings are also dominant processes in the formation of first-cycle sands.

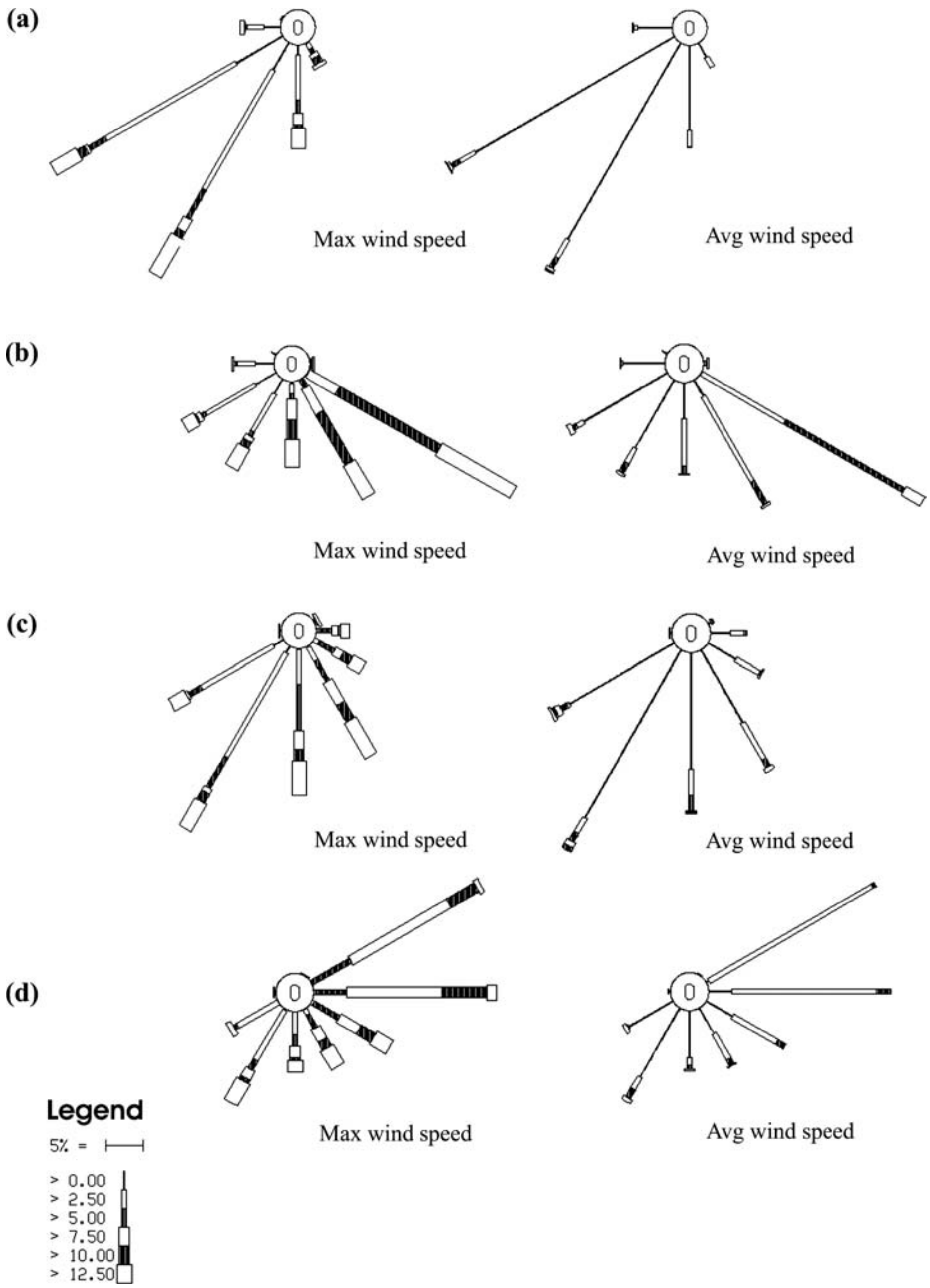

FIGURE 2. Wind roses illustrating the frequency of maximum and average wind speed and direction for: (a) Lake Vida, winter 1996–2000, (b) Lake Vida, summer 1995–2001, (c) Explorer's Cove, winter 1998–2000, (d) Explorer's Cove, summer 1998–2000. Winter is defined as 1 May–31 October and summer as 1 November–30 April. Percentage calms indicated in center of wind roses.

WIND REGIME OF THE VICTORIA VALLEY

The available wind speed and direction records for sites in the study area cover a relatively short period, but we believe they are adequate to provide insight to the region's wind regime. Wind speed and direction data from the Lake Vida automatic weather station (1995–2001) highlight the dominant southwest airflow at this site in the mid-Victoria Valley during winter, with average wind speeds commonly less than 2.5 m s^{-1}, and infrequent maximums of $>$12.5 m s^{-1} (Fig. 2a). This relatively calm wind regime is believed to result as a consequence of a cold air pool that forms in the Victoria Valley (Lake Vida). The associated temperature inversion causes all but the strongest katabatic and foehn winds to decouple from the surface (Nylen et al., 2004). In comparison, the summertime wind regime is dominated by southeasterly winds with wind speeds typically between 2.5 and 7.5 m s^{-1} (Fig. 2b). These winds are the result of a combined valley wind/sea breeze system that develops between the snow and ice-free Dry Valleys and the Ross Sea and Wilson Piedmont Glacier (McKendry and Lewthwaite, 1992). Wind speeds $>$7.5 m s^{-1} are typically associated with topographically channeled easterly to southerly airflow in summer, while during winter they are believed to be caused by upper level deflection of airflow into the valleys resulting in short periods of extreme wind speeds with foehn characteristics. Bromley (1985) observed such winds in the neighboring Wright Valley, where maximum gusts of 40, 41, and 46 m s^{-1} were recorded in the winters of 1969, 1974, and 1979, respectively.

The only other wind speed and direction data available for the study area are from the automatic weather station at Explorer's Cove situated at the coastal end of the Taylor Valley, to the south of Victoria Valley (Fig. 1). On average, summer wind speeds at Explorer's Cove are stronger than during winter, and dominated by airflow from the northeast and east in contrast to southerly quarter airflow during winter, when wind speeds infrequently exceed 10 m s^{-1} (Figs. 2c and 2d). These observations are comparable to the Lake Vida data.

The wind regime of the McMurdo Dry Valleys is therefore dominated in summer by topographically channeled gradient winds from the easterly quarter and sea breezes, which can both produce wind speeds exceeding local threshold entrainment velocities for the dry and loose fine-grained surface sediments on the valley floor of approximately 5.5 m s^{-1}. Reduced insolation and 24-h darkness during the polar winter is associated with lengthy calm periods that are punctuated by violent westerly to southwesterly gales of short duration. These display foehn characteristics and are occasionally also monitored during summer.

EOLIAN TRANSPORT POTENTIAL

Threshold entrainment velocities for dry sand of 150 μm in temperate climates has been found to range from 6 to 7.5 m s^{-1} (e.g., Clements et al., 1963; McCauley et al., 1981; McGowan, 1997). In Antarctica, the colder air temperatures and denser air lower this value to approximately 5.5 m s^{-1} based on field observations made during this study.

Analysis of the Lake Vida wind speed record shows that this threshold entrainment velocity is exceeded 27% and 74% of the time during winter and summer, respectively, while at Explorer's Cove, it is exceeded 60% and 62% of the time during the winter and summer, respectively. Both locations indicate greater eolian transport potential during summer when daily averages of maximum wind speeds are generally <15 m s^{-1} at Lake Vida and Explorer's Cove, with rare occurrences of southwesterly winds reaching 25 m s^{-1} at Lake Vida. These events are most likely foehn caused by the forced channeling of the prevailing gradient wind into the Victoria Valley. In contrast, daily average maximum wind speeds sometimes exceed 30 m s^{-1} in winter at both sites and frequently are greater than 20 m s^{-1}. These wind speeds are likely to overcome the threshold entrainment velocity of exposed fine-grained surface sediments regardless of additional processes acting on them during the extreme cold of winter when, for example, intergrain ice bonds are likely to play a greater role in influencing grain transport.

Methods

FIELD METHODS

Snowpits were excavated on the Victoria Lower Glacier and Wilson Piedmont Glacier in November and December 2000 to depths of 4 m and 3 m, respectively (see Fig. 1). The snowpits were sampled at 5 cm increments using a tape measure and a 500 cm^3 volume aluminum density tube. The samples were then weighed to obtain density values for the snowpack, and emptied into plastic re-sealable bags before being melted in a container of warm water. All samples were then filtered through Whatman quantitative 2.5 μm ashless filter papers, using a hand-held vacuum pump. The filter papers were then sealed in ziplock bags for return to New Zealand for laboratory analysis.

Two Frisbee-type dust deposition traps with diameters of 0.23 m were also deployed on the Victoria Lower Glacier approximately 80 m from the snowpit for 23 days. The traps were positioned approximately 0.1 m above the snow surface and were serviced every two to six days. Samples were retrieved by filtration on Whatman quantitative 2.5 μm ashless filter papers following the washing of sediment from the traps using distilled water.

Age determination of the two snowpits is discussed by Bertler et al. (2004b). Peaks in methylsufonate and sodium snow chemistry were used to identify summer precipitation. In the Victoria Lower Glacier snowpit gross beta radioactivity profiling also confirmed the 1964/1965 nuclear testing fallout peak at 4 ± 0.1 m. In conjunction with the annual layer count from the base of the snowpit to the surface, an age of 35 years was estimated for the Victoria Lower Glacier with an associated error of ±1 year (Bertler et al., 2004b), while the Wilson Piedmont snowpit is believed to represent only 15 years due to its location in a greater snowfall zone closer to the coast.

LABORATORY METHODS

Filter Processing

The filter papers on which the sediment was retrieved were ashed in a Vulcan A-550 Furnace at 500 °C for 24 h with the mineral content determined by loss on ignition of the filter papers. All sediment samples were then expressed in grams of sediment per cubic centimeter of water equivalent following the method outlined by Taylor and Gliozzi (1964), Hamilton and O'Kelley (1971), and Thompson and Mosley-Thompson (1980).

Mineralogy

All sediment samples were mounted on standard microscope slides in glycerol gelatin for examination under an optical microscope. From these mounted samples, 20 samples were selected from the Victoria Lower Glacier, and 15 samples from the Wilson Piedmont for point counting of mineralogy. These samples were chosen from all the major peaks in sediment concentration with snowpack depth (time), and included several intermediate samples between peaks in sediment concentration. Three hundred grains were counted per slide, equivalent to a 95% confidence level as calculated by Van der Plas and Tobi (1965), indicating that in about 95 of 100 cases point counted, the estimate of mineral percentage by volume (P) will be within $P \pm 2$ standard deviations.

Mineralogy was subdivided into seven categories—quartz, feldspar, pyroxene and amphibole, biotite, iron oxide coated grains, opaque, and tephra (volcanic glass). The pyroxenes and amphiboles were grouped together as these were difficult to optically distinguish under the microscope. In addition, the major chemical constituents of selected samples were determined using a JEOL 733 Electron Microprobe. The method was primarily applied to volcanic glass (tephra) as a provenancing tool to identify grains from the different volcanic provenances of the Ross Sea region.

Results

EOLIAN SEDIMENTATION AND SNOWPACK CHARACTERISTICS

The sediment record corrected for snowpack density variability at Victoria Lower Glacier is presented in Figure 3. Three prominent peaks in the deposition of wind-blown sediment are clearly evident and are labeled C, F, and I, along with several smaller peaks labeled A, B, D, E, G, H, J, and K. These were classified as Groups 1 and 2, respectively, and display no obvious patterns or cyclicity in the accumulation of wind-blown sediment in terms of either magnitude of sediment concentration or frequency of occurrence.

Group 1 peaks are believed to reflect the largest episodic eolian events due to greatest wind speed and/or duration, increased sediment supply, and/or proximity to source. The Group 2 peaks represent less accumulation, and therefore are inferred to represent less extreme eolian sediment transport events and/or increased distance from source. With regard to the density of the snowpack, Group 1 deposits are generally associated with low-density snow layers (300–400 kg m^{-3}) (peaks C and I), with part of peak F intersecting a wind-packed snow layer. In contrast, Group 2 peaks are predominantly associated with ice layers and/or medium density snow layers (600–800 kg m^{-3}).

Figure 4 presents the sediment concentrations determined for the Wilson Piedmont Glacier snowpit. Overall the concentrations at

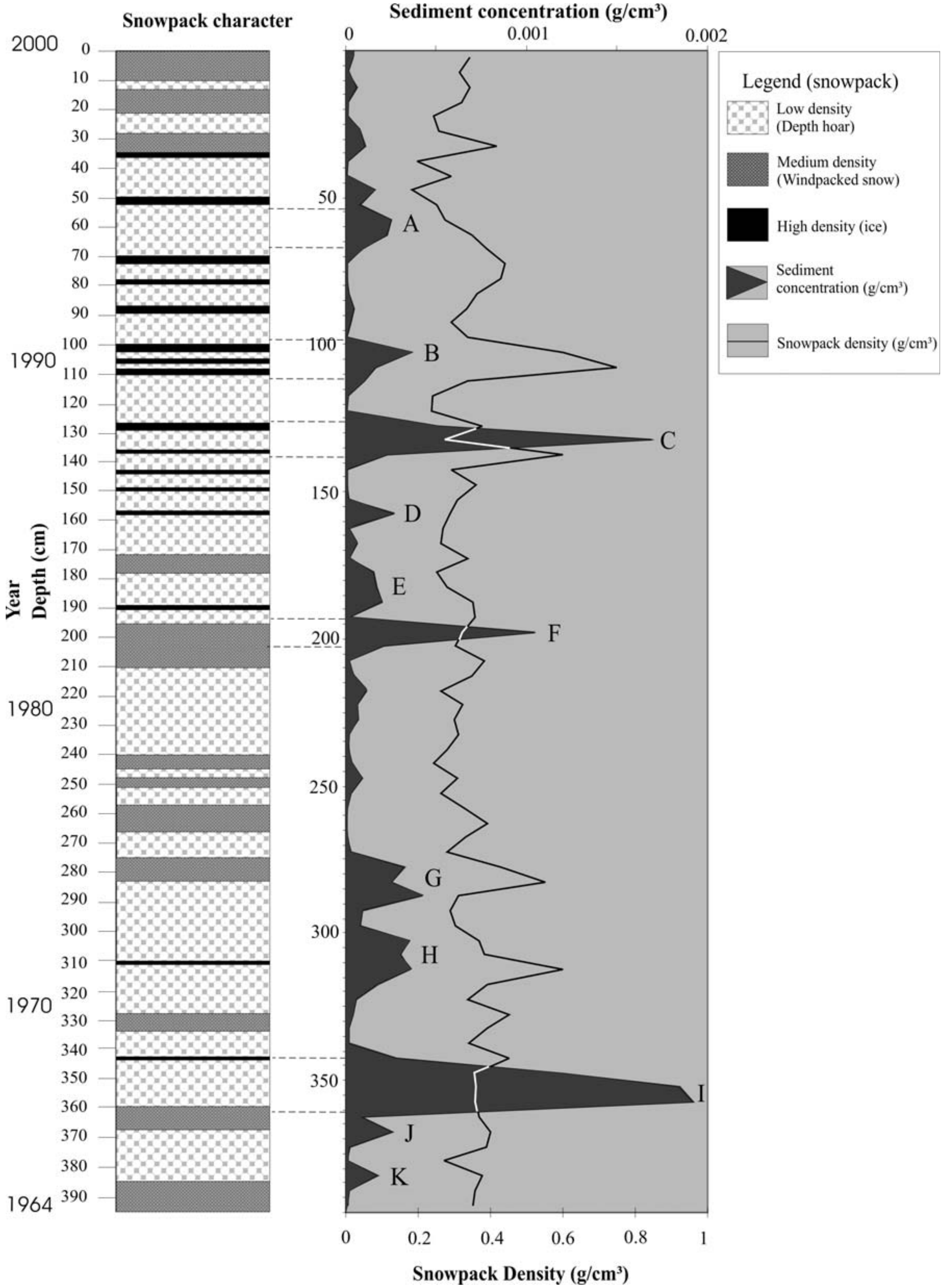

FIGURE 3. Dust concentration and snowpack density as sampled on Victoria Lower Glacier from a 4-m-deep snowpit, November 2000.

this site are less than those for the Victoria Lower Glacier presented in Figure 3, with fewer and more widely spaced peaks in the concentration of wind deposited sediments. These are labeled A to E. It is also apparent that the wind-packed snow units are thicker and more frequent at the Wilson Piedmont than at the Victoria Lower Glacier. This may reflect fewer melt events and higher precipitation rates, which preserve underlying snow surfaces at this coastal locality. Sediment concentration peaks A, C, and D are associated with low-density hoar horizons (Fig. 4). As ice lenses are less common and wind-packed units are thicker and more common than at Victoria Lower Glacier, it is apparent that the conditions experienced at the Wilson Piedmont Glacier are quite different. Fewer ice lenses, we

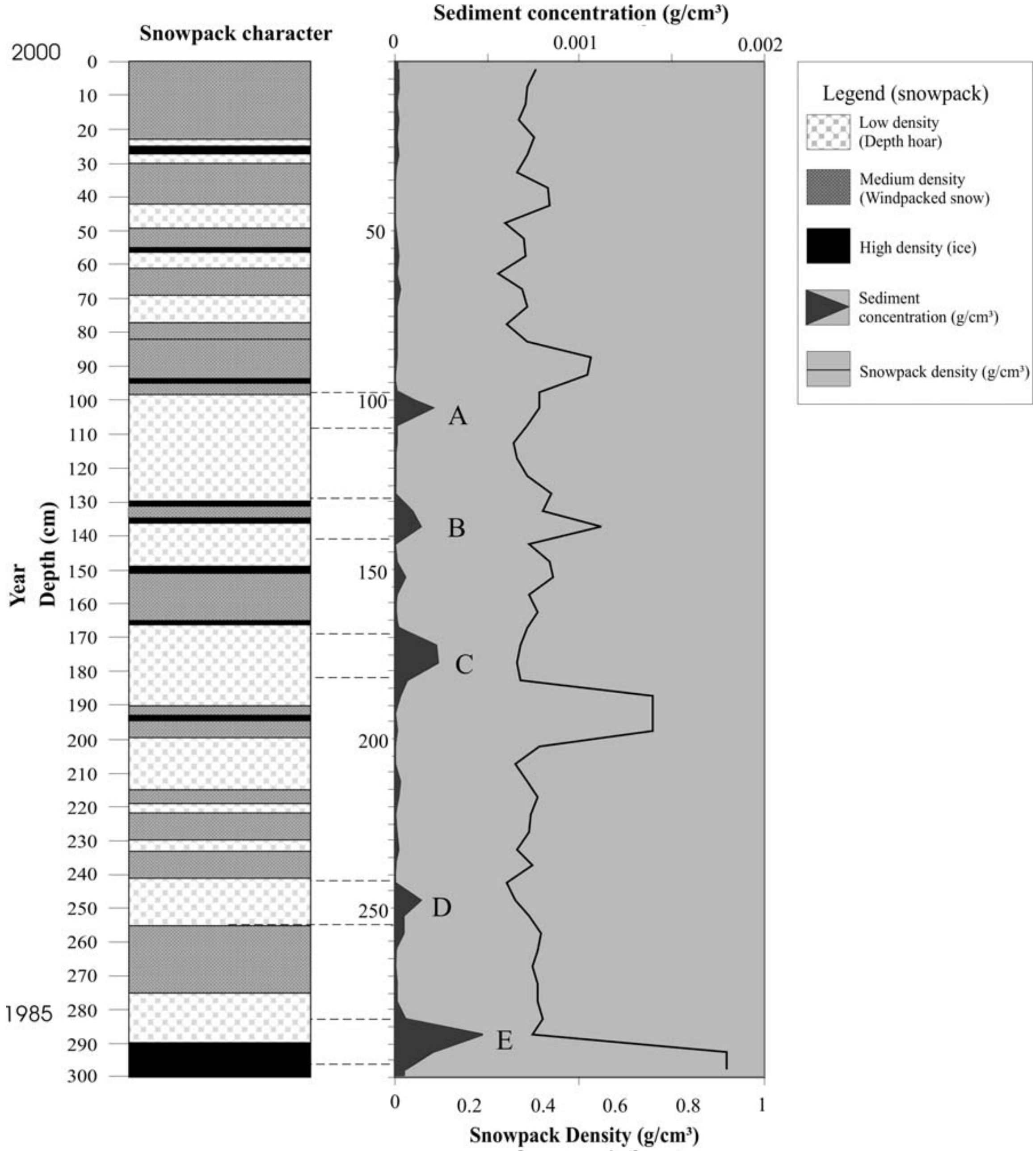

FIGURE 4. Dust concentration and snowpack density as sampled on the Wilson Piedmont from a 3-m-deep snowpit, December 2000.

believe, indicate less direct solar radiation is experienced at this coastal site. This is compatible with field observations of frequent low clouds, while clear conditions were experienced at Victoria Lower Glacier during the field measurement program. Thicker wind-packed units indicate intervals where annual conditions are repeatedly unfavorable for depth hoar formation.

OBSERVATIONS OF CONTEMPORARY DUST DEPOSITION

Results from the dust deposition traps installed on Victoria Lower Glacier from 10 November to 2 December 2000 are presented in Figure 5. All samples were found to contain grains $<$100 µm and are therefore referred to as dust. Also shown are summary wind roses for each sampling period calculated from wind speed and direction data recorded by a portable automatic weather station installed for the study (Fig. 5). Two distinct maximums in dust deposition are clearly evident between 17 and 24 November and 26 and 29 November. As shown in the wind roses, light easterly winds dominated the entire monitoring period with velocities seldom $>$2.5 m s^{-1}, which is well below the local threshold entrainment velocity of 5.5 m s^{-1}. Southeasterly airflow was particularly prevalent during the intervals 24–26 November, and 29 November–2 December. Wind speeds from this direction were typically between 2.5 and 5 m s^{-1} and may have transported very fine dust sourced further south into the study area. Airflow from the west was also recorded, particularly during the first four sampling intervals, but was negligible between 24–26 November and 29 November–2 December. Winds from the southwest and northwest were the strongest experienced during the dust deposition monitoring program, with speeds of 7.5 m s^{-1}, while moderate westerlies between 17–24 November and 26–29 November are believed to have resulted in the higher dust deposition rates (Fig. 5). This dust is believed to have been sourced from the snow and ice-free section of the Victoria Valley to the west of the dust deposition monitoring site.

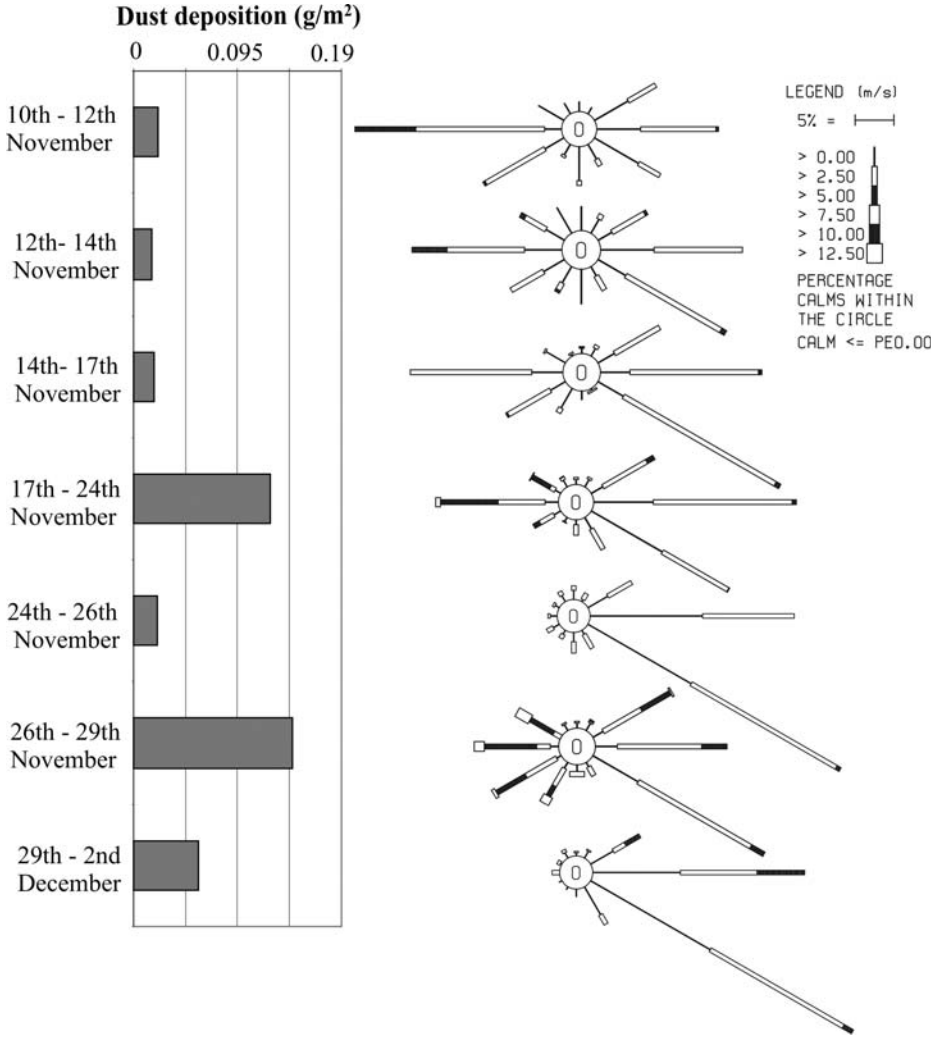

FIGURE 5. Recorded dust deposition on the Victoria Lower Glacier for the period 10 November–2 December 2000. Wind speed and direction monitored by an adjacent portable weather station are presented for each sampling period as wind roses.

MINERALOGY

Analysis of the sediment from the Victoria Lower Glacier snowpit identified feldspars as the most frequently occurring mineral in the samples, which are believed to have been wind transported, usually exceeding 40% and reaching a maximum of 53%. Quartz was the second most frequently occurring mineral, making up on average 21% of all samples. Pyroxenes and amphiboles averaged 15% of samples, while biotite was much less common, occurring only ~9% of the time. Tephra was a minor component of the samples at Victoria Lower Glacier, averaging 1.4%, but was present in all samples point counted.

In the samples from the Wilson Piedmont Glacier, feldspars were again a major component of the mineral assemblage, averaging 54% and reaching a maximum of 66% at 175 cm depth. Quartz contributed much less to the mineral assemblage of the sediment at this coastal site, averaging only 11%, while the pyroxene + amphibole group recorded similar percent frequencies as observed at the Victoria Lower Glacier at 13%. Biotite was the second most frequently occurring mineral at the Wilson Piedmont Glacier, averaging 14%, while tephra accounted for approximately 3% of samples, increasing to a maximum of frequency of 7% at 180 cm depth.

Mineralogical analysis was also conducted on samples of fine-grained sediment believed prone to eolian transport in source areas to the west of the Victoria Lower Glacier and the Wilson Piedmont Glacier. Analysis of dune sands from the Victoria Valley identified that they are dominated by feldspar (53%), followed by pyroxene and amphibole (26%), and quartz (14%). Biotite content was low at ~0.17%. Sand collected from surrounding ridge lines was also dominated by feldspar (53%), followed by pyroxene and amphibole (23%), quartz (8.5%), and biotite (4.5%).

The high feldspar content observed at the Wilson Piedmont and Victoria Lower Glaciers is interpreted to reflect two factors: (1) mineralogy of the source material, which is predominantly metamorphic and plutonic rocks (see Fig. 6); and (2) the slow rates of chemical weathering in Antarctica's polar desert climate, with physical weathering the more dominant process. The majority of material deposited on the Wilson Piedmont and Victoria Lower Glacier is therefore derived from the Victoria Valley region, as there are clear similarities between sediment samples collected in this source area and sediment mineralogy identified in the snowpack deposits (see Fig. 7).

TEPHRA

In addition to the two major snowpit sites on Victoria Lower Glacier and the Wilson Piedmont, a shallow snowpit was excavated approximately 2 km to the west of the main snowpit on Victoria Lower Glacier (Fig. 1). At this site, the snowpack was only 80 cm thick above blue glacial ice. At the contact between these two units, a concentrated eolian deposit was sampled. The greater volume of sediment at this site allowed sufficient tephra grains to be recovered for microprobe analysis—this was not possible for samples extracted from the two main snowpits. We believe that the higher sediment concentrations at this site reflect proximity to the large sand sheets at the terminus of the

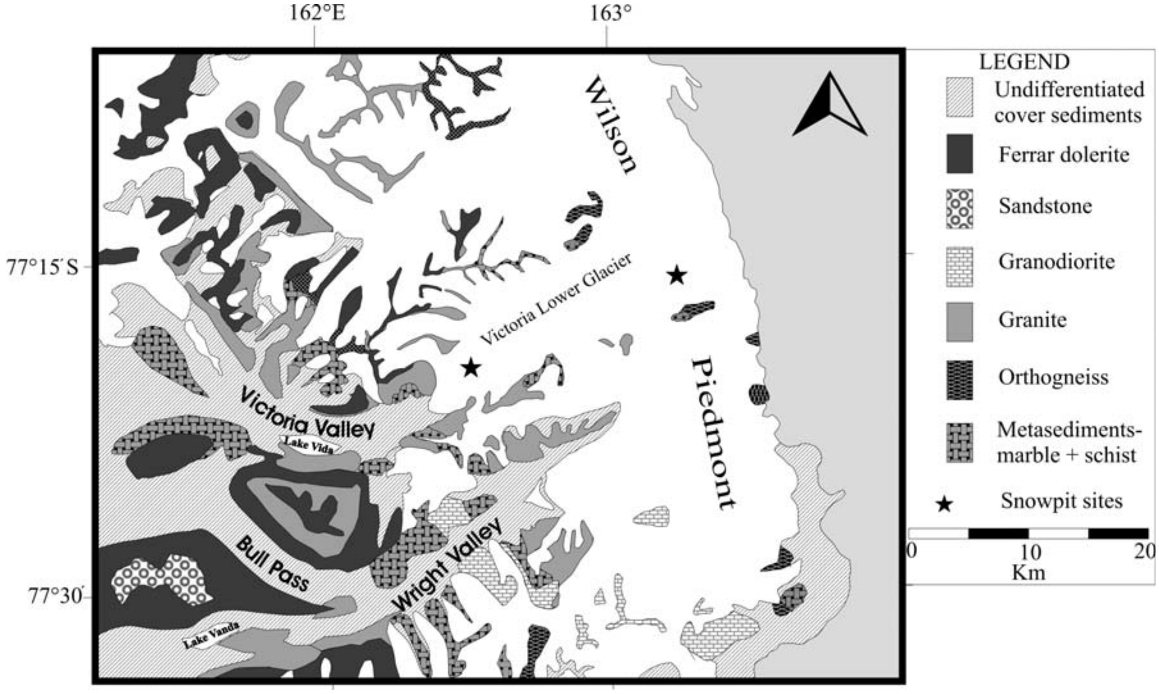

FIGURE 6. Map of regional geology in the vicinity of the Victoria Lower Glacier (modified after Mortimer et al., 2001).

Victoria Lower Glacier, and we acknowledge that some tephra grains retrieved from the snowpit may have been reworked following initial deposition on the snow- and ice-free floor of the Victoria Valley.

Results of the microprobe analysis identified a distinct variation in tephra chemistry. SiO_2 content varied from 65% to less than 43%, and alkali ($Na_2O + K_2O$) components in the tephra ranged between 12% and 4%. Using the International Union of Geological Sciences (IUGS) classification scheme, the tephras identified by this study were dominantly of tephrite—basanite composition, with two shards representing more felsic trachytic compositions. Microscope analysis of samples identified some of the tephra to be relatively "fresh" and unabraded, whereas some exhibited evidence of rounding and such abrasion is interpreted to reflect a reworked origin by eolian processes, i.e., following initial deposition in the Victoria Valley. This is supported by the continuous distribution of tephra throughout both Victoria Lower Glacier and Wilson Piedmont Glacier snowpits, which reflects a constant tephra supply that does not correlate to current volcanic activity in the region.

Figure 8 presents tephra microprobe results and their relationship to whole rock chemistry from the Erebus Province, Mount Erebus, Taylor Valley, and the Pleaides Volcanic Field in the Melbourne Province (~400 km to the north of the Wilson Piedmont Glacier).

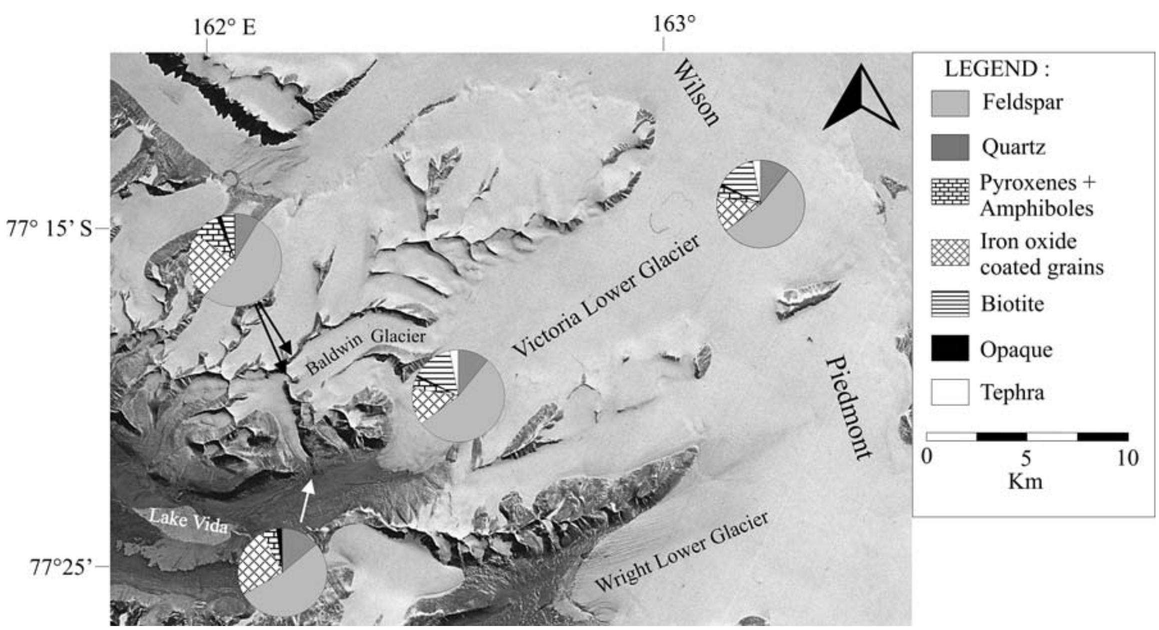

FIGURE 7. Average mineralogical assemblages of dust collected from the Victoria Lower Glacier and Wilson Piedmont, and sediment samples collected from the Victoria Valley dunes and Baldwin Ridge.

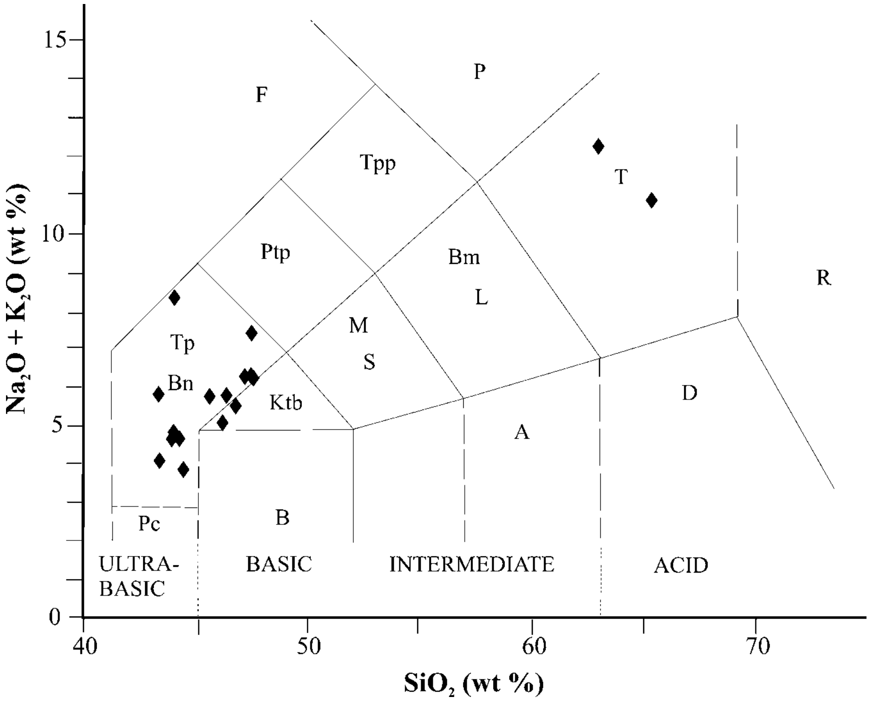

FIGURE 8. The IUGS classification scheme for volcanic rocks, and the composition of the tephras recovered from Victoria Lower Glacier indicated by ♦. Abbreviations are as follows: A: andesite, B: basalt, Ba: basaltic andesite, Bm: benmoreite, Bn: basanite, D: dacite, F: foidite, H: hawaiite, Ktb: potassic trachybasalt, L: latite, M: mugearite, P: phonolite, Pc: picrobasalt, Ptp: phonotephrite, R: rhyolite, S: shoshonite, T: trachyte, Tp: tephrite, and Tpp: tephriphonolite. (modified after LeMasurier, 1990)

Discussion and Climatic Interpretation

INTERPRETATION OF SNOWPACK CHARACTERISTICS

Interpretation of niveo-eolian sedimentation records must account for post-depositional morphological changes in snowpack structure that can modify the record of wind deposited sediments. For example, ablation processes (primarily evaporation or sublimation) may cause mass loss in the snowpack and concentrate the sediment. This may subsequently lead to the incorrect interpretation of a large-scale deposition event. The implication of this is that care must be taken when interpreting niveo-eolian records, to distinguish true eolian sediment deposition events from the apparent peaks in accumulation. In reality this is extremely difficult, as tracing processes such as sublimation is no easy task. Furthermore, deposition of wind transported sediment can potentially initiate these mass loss processes through modification of the surface energy balance by lowering surface albedo. This in turn may increase surface temperatures as the sediment absorbs solar radiation, thereby triggering snow melt and subsequent evaporation. In the snowpit profiles we present, this mechanism could be associated with the formation or enhancement of the Group 2 peaks (except A and E), but not the Group 1 peaks (except F), which suggests that these were formed by a different mechanism (Figs. 3 and 4).

Peaks A, C, E, and I at both sites are present in layers of hoar which are formed by either depositional or diagenetic processes. Depositional formation of hoar generally occurs as the result of surface hoar being buried by a later snowfall. Requirements for surface hoar formation are high humidity levels (greater than 90%), a snow surface temperature more than 5°C lower than the air temperature, and moderate wind speeds (1–2 m s^{-1}) (Hachikubo and Akitaya, 1997). Dominé et al. (2002) noted that such depositional depth hoar forms layers <1cm thick on ice caps, and in the field area for this study would be confined to summer months, while surface hoar could form in all seasons (Alley, 1988).

We believe that diagenetic depth hoar is the dominant process at Victoria Lower Glacier and the Wilson Piedmont, as observed hoar horizon layers are thick (up to 30 cm), which is not characteristic of hoar formed by depositional processes in the Antarctic environment (Alley, 1988). In addition, Alley (1988) noted that the processes responsible for diagenetic depth hoar formation are only strong enough to cause significant mass loss in the top 5–10 cm of firn. Observed hoar horizons at the Victoria Lower Glacier and Wilson Piedmont during this study were sometimes greater than 30 cm in thickness (see Figs. 3 and 4). We suggest that this is caused by a series of annual accumulation cycles, where every summer/autumn conditions are favorable for depth hoar formation. In the winter, accumulated wind-packed snow layers are no thicker than 5–10 cm, which places them in the critical zone to experience subsequent vapor transport processes. Following deposition of a wind-packed layer in the winter, favorable summer/autumn conditions result in mass loss and density reduction of the wind-packed slab, which encouraged depth hoar formation. Providing the above two conditions are met, it is then possible for the wind-packed layers to be incorporated to produce a continuous depth hoar unit, the thickness of which is dependant on the duration of favorable conditions.

Understanding the processes responsible for the density variations in the snowpack may allow seasonality to be assigned to the snowpack, but not to the eolian events as the processes responsible for depth hoar or ice lens formation are not necessarily syn-sedimentary with the deposition of wind transported sediments.

We believe that the deposition of wind transported sediment on the Victoria Lower and Wilson Piedmont Glaciers predominantly occurs during the winter. This is because the strongest winds occur during the winter, i.e., foehn westerly to southwesterly winds, and the distribution of layers of sediment in the snowpack can be explained by their deposition in winter wind-packed layers. Here the sediment remains unless modified by post-depositional processes such as melting (concentrating the sediment in an ice lens) or "cannibalization" of the wind-packed layers and transformation into depth hoar by vapor transport processes (discussed previously). This would explain the observed large peaks in dust concentration in depth hoar units (for example, peaks A, C, and I). Furthermore, it supports the origin of these hoar horizons as diagenetic and not depositional forms. Importantly, favorable conditions for surface hoar formation are not compatible with those required to deposit a large eolian sediment flux on the glacier surface.

As higher sediment concentrations were found at the Victoria Lower Glacier than the Wilson Piedmont (Figs. 3 and 4), we consider the Wilson Piedmont is further from the principal sediment source in this section of coastal South Victoria Land. The observed trend of increasing sediment concentrations moving east to west indicates that the principal source is the snow- and ice-free section of the Victoria Valley system (Fig. 1). This is supported by the mineralogy of the samples collected from the snowpits, which is compatible with sediment samples collected from probable source sediments in the Victoria Valley and surrounding snow-free ridges. Furthermore, during a 48-h period of southwesterly foehn in December 2004, McGowan observed significant deposition of wind transported sediment on the western section of the Victoria Lower Glacier, which displayed a distal thinning toward the east (Wilson Piedmont).

CONTEMPORARY DUST DEPOSITION

Dust deposition measured by the two dust traps installed on Victoria Lower Glacier indicated that the highest levels of dust deposition occurred during westerly quarter foehn winds. Observations from the neighboring Wright Valley documented by Mullan and Sinclair (1990), Keys (1980), and Bromley (1985), and from alpine locations in mid-latitudes, confirm the significant eolian sediment transport potential of foehn winds (McGowan 1997). Dust deposition rates reported by Lancaster (2002) for the Taylor Valley located south of the Wright Valley also show a west to east trend indicating the dominant role of westerly quarter foehn winds in dust transport in this valley system, and the McMurdo Dry Valleys as a whole. Based on the 23-day dust deposition sampling period, we estimate a monthly deposition rate of 5.4 kg ha^{-1} $month^{-1}$ for early summer. By comparison our measured dust deposition rate is only slightly less than the 9.76 kg ha^{-1} $month^{-1}$ measured by Reheis and Kihl (1995) in semiarid desert in Nevada and California. Comparison with Lancaster's (2002) study is difficult because he presents dust deposition rates as annual values. Nevertheless, assuming a constant rate of dust deposition throughout the year for Lancaster's study our results are most similar to the Taylor Glacier dust deposition rate of approximately 3.1 kg ha^{-1} $month^{-1}$.

McKendry and Lewthwaite (1992) noted that episodes of strong surface westerlies penetrating into the Wright Valley were associated with the passage of an upper level trough, which produced prevailing south and southwest airflow above the ridge-line. This flow descends into the Dry Valleys in response to both pressure driven and topographically forced channeling warming adiabatically and taking on foehn characteristics. More recently, observations from the Victoria Valley sand dunes indicate the highest sand transport rates occur during these events when air temperatures rise above 0°C. This promotes the release of frozen sand grains from the surface and their subsequent entrainment by the airstream. Saltating sand grains then eject fine sand and silt (dust size) grains from glacio-fluvial deposits on the valley floor into the airstream through ballistic impact processes which are carried down-valley toward the Lower Victoria and Wilson Piedmont Glaciers where they are deposited.

Sediment concentrations retrieved from snowpits on the Victoria Lower and Wilson Piedmont Glaciers by this study show no cyclic characteristic associated with specific climate forcings such as foehn. Instead, they reflect the frequent irregular emission of fine-grained sediment from the Victoria Valley, which is punctuated by episodic high magnitude events which we believe are associated with winter foehn winds.

Assuming a mean snowpack density of 400 kg m^{-3}, the concentration of wind deposited sediment in the snowpack on the Wilson Piedmont and Victoria Lower Glaciers range from 1.1×10^3 to 7.3×10^3 times greater those reported from the analysis of the EPICA-Dome C ice core (Delmonte et al., 2004) and the Greenland GISP2 ice core (Zdanowicz et al., 2000), which are coincident with the Last Glacial Maximum. This is not unexpected given the proximity of our snowpits to the source of the wind deposited sediments found by our study compared to the more "clean" remote locations of the EPICA and GISP2 sites. However, dust from the Victoria Valley has been observed by the authors to be transported west toward Dome C by topographically channeled south-easterly quarter airflow. If similar conditions occurred during the LGM, then such a process may account for the isotopic similarities between the dust retrieved from the EPICA–Dome C ice core and surface sediments collected from the McMurdo Dry Valleys as presented by Delmonte et al. (2004).

INTERPRETATION OF TEPHRA PROVENANCE: AN INDICATOR OF HISTORICAL WEATHER PATTERNS

It is clear that the tephras recovered from the Victoria Lower Glacier show good correlation with the chemistry of Erebus Volcanic Province rocks, and are not from the less alkali Ferrar Supergroup. This is critical, as a Ferrar Supergroup origin would indicate a local tephra source, which has implications for the interpretation of transport histories and associated atmospheric circulation. The Melbourne Province data clearly show poorer correlation with the tephra than the Erebus Province, which is situated less than 200 km to the south and southeast of the Wilson Piedmont Glacier.

The Erebus Volcanics are predominantly located to the south and southeast of the field area, with small cinder cones present in the Taylor and Wright Valleys to the southwest. However, these cinder cones can be eliminated as primary tephra sources for several reasons. First, the decrease in tephra concentration at our sites when moving from the Wilson Piedmont Glacier into the Victoria Valley indicates that the source of tephra is located outside of the Dry Valleys. Second, any tephra derived from the Taylor and Wright Valleys is likely to be transported east to the coast by foehn westerlies and not north over the 2000-m-high Olympus and Asgard Ranges into the Victoria Valley. Third, the tephra chemistry indicates that some grains are of trachytic chemistry, and this is not compatible with a Taylor or Wright Valley origin, as these cinder cones are of basanitic composition. The two main occurrences of trachyte in the Erebus Province are at Mount Morning and on Mason Spur. Mount Erebus is not believed to be a source of tephra found in the snowpits on the Wilson Piedmont and Victoria Lower Glacier, as this is predominantly phonolitic.

Atmospheric transport of tephra from Mount Morning and Mason Spur into the eastern margins of the Dry Valleys requires southerly airflow which may then be channeled into valleys along the Scott Coast. Keys (1980) stated that cyclonic storms over the Ross Sea and northern margin of the Ross Ice Shelf can produce such conditions, which are most frequent during winter (Mullan and Sinclair, 1990). During these events wind speeds can exceed 100 knots (180 km h^{-1}) (A. Pyne, personal communication, 2001), as the Trans-Antarctic Mountains block the cyclonic systems causing the formation of a strong southerly "barrier jet" which blows parallel to the mountains along the western margin of the Ross Ice Shelf (Mullan and Sinclair, 1990). Under these conditions fine-grained sediment (including tephra) is transported north along the Trans-Antarctic Mountains and into the lower reaches of the Dry Valleys.

As wind-blown sediment deposited on the Victoria Lower Glacier is from two distinct source areas, the relative percentage of tephra in the sediments can be used to indicate the relative importance of southerly airflow (southern sources), as opposed to a westerly airflow (Victoria Valley sources). Using this hypothesis, Table 1 is presented as a theoretical model summarizing these factors and illustrating the possible relationship between the sedimentation record, snowpack character, meteorological conditions, and seasonality. In addition, the

TABLE 1

Reconstructed dust deposition characteristics and suggested synoptic scale weather patterns believed to have been responsible for the peaks in sediment concentrations labeled A–K in Figures 3 and 4.

Dust record	Synoptic circulation systems	Snowpack character	Event seasonality	Victoria Lower Glacier dust peaks	Wilson Piedmont Glacier dust peaks
Relatively large volumes of sediment, low tephra conc., + relatively coarse grain size	Anticyclonic conditions prevailing = westerly gales predominantly experienced	Depth hoar	Winter	C, I	A, D
Relatively large volumes of sediment, + tephra, + coarse–moderate grain size	Westerly gales + cyclonic activity producing strong S winds in McMurdo Sound	Depth hoar	Winter	A	E
Relatively small sediment volumes, + high tephra conc., + moderate grain size	Cyclonic activity over the Ross Sea prevailing = strong S winds	Depth hoar	Winter	E, H	C
Relatively large volumes of sediment, low tephra conc., + relatively coarse grain size	Anticyclonic conditions prevailing = westerly gales predominantly experienced	Windpacked snow	Winter	F, K	
Relatively small sediment volumes, + high tephra conc., + moderate grain size	Cyclonic activity over the Ross Sea prevailing = strong S winds	Windpacked snow	Winter	G	B
Potentially low-high sediment volumes, ± tephra, fine–coarse grain size	Either wind regime	Ice layers	Summer	B, D	

peaks in sediment concentrations labeled in Figures 3 and 4 have been speculatively assigned to each category. We therefore believe that the majority of fine-grained sediments deposited by the wind on the Victoria Lower and Wilson Piedmont Glaciers occurs during the winter when the westerly gales and coastal southerlies are strongest. Under this scenario sediment is initially deposited on a wind-packed slab, after which post-depositional processes such as melting and evaporation or sublimation result in depth hoar formation and alteration of the snowpack. Applying this model to our record and assuming source properties are uniform with time, it appears that there have been no major changes in regional weather patterns for approximately 35 years. In comparison, Bertler et al. (2004a) argued for an increase of southerly airflow along the Scott Coast (including the Wilson Piedmont Glacier) during the past 20 years, which they believe is linked to the El Niño Southern Oscillation phenomenon and is responsible for an observed regional cooling in the southern Ross Sea/McMurdo Dry Valleys region. Based on results from this study, we conclude that if such an increase in frequency of southerly airflow has occurred, then it does not appear to have been associated with an increase in wind speed as we found no increase in the mass flux of tephra from Mount Morning and Mason Spur region as would be expected. As a result, we believe that the cause(s) of the regional cooling monitored in the McMurdo Dry Valleys remain equivocal.

Conclusion

Eolian deposits of fine-grained sediment in firn on Victoria Lower Glacier and Wilson Piedmont Glacier, Antarctica, have been found to be locally sourced from two main areas. These are the Victoria Valley, part of the McMurdo Dry Valleys located west of these two glaciers, and a southern provenance including rocks of the Erebus Volcanic Province 200 km south of the field area. Meteorological conditions responsible for the transport and deposition of sediment from these source areas are, respectively, (a) anticyclonic systems situated over the polar plateau west of the field area that may produce foehn westerly winds, and (b) low pressure systems over the Ross Ice Shelf/Ross Sea which encourage the formation of southerly barrier-jets along the eastern margin of the Trans-Antarctic mountains. The relative importance of each synoptic circulation pattern can be estimated using the record of sediment deposition on these two glaciers by comparing spatial variations in, (a) sediment volume between the sites (observed as a west-east decrease for anticyclonic-generated westerly foehn events), and (b) tephra concentrations (observed as an east-west decrease for southerly/southeasterly winds linked to low pressure systems over the Ross Sea). Using this approach, no apparent change has occurred in the last 35 years in the dominance of either synoptic scale weather pattern and, importantly, winds capable of sediment transport. This result has implications for the proposed mechanism responsible for an observed regional climate cooling in the study area, which has been linked to more frequent southerly airflow along the Scott Coast. While this may have occurred, results from our tephra study suggest that wind speeds associated with this airflow have not increased enough to cause a measurable increase in tephra snow content.

Contemporary dust deposition on the Victoria Lower and Wilson Piedmont Glaciers is similar to that monitored in some semiarid hot desert environments, and exhibits a clear association with foehn events supporting previous studies that have highlighted their significance in eolian processes in mountainous settings, but not polar.

Finally, this study has shown that the McMurdo Dry Valleys are a significant regional source of atmospheric mineral dust under present-day climatic conditions. Understanding of the meteorological controls on sediment transport and dust emissions from the Dry Valleys has application to the interpretation of dust records from Antarctic ice cores such as the EPICA–Dome C ice core, while providing new information on eolian processes in ice marginal environments.

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