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Dry Valleys Late Holocene Climate Variability

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Final Report for Period: 07/2007 - 06/2008 **Submitted on:** 10/29/2008
Principal Investigator: Kreutz, Karl J. **Award ID:** 0228052
Organization: University of Maine
Submitted By:
Kreutz, Karl - Principal Investigator
Title:
Dry Valleys Late Holocene Climate Variability

Project Participants

Senior Personnel

Name: Kreutz, Karl
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Mayewski, Paul
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Arcone, Steven
Worked for more than 160 Hours: Yes
Contribution to Project:
GPR work during 2003/04 field season

Name: Kenna, Timothy
Worked for more than 160 Hours: No
Contribution to Project:
Tim is running Cs and Pu/Np isotope analysis on ice core samples collected for this project.

Name: Morgenstern, Uwe
Worked for more than 160 Hours: No
Contribution to Project:
Uwe is running tritium analysis on ice core samples collected for this project.

Name: Bostick, Benjamin
Worked for more than 160 Hours: No
Contribution to Project:
We have started a new collaboration with Ben Bostick (Dartmounth Department of Earth Sciences) to use synchrotron analysis of dust particles in Dry Valleys snow, firn and ice as a method to provide addtional quantitative information on individual particle geometry, mineralogy, and geochemistry.

Post-doc

Graduate Student

Name: Williamson, Bruce
Worked for more than 160 Hours: Yes
Contribution to Project:
RA supported on project for field, laboratory, and interpretation of data

Name: Osterberg, Erich
Worked for more than 160 Hours: Yes
Contribution to Project:

Field assistant

Name: Vogan, Nathan

Worked for more than 160 Hours: Yes

Contribution to Project:

Nathan is a Earth Science graduate (MS) student, who was supported briefly last summer (2006) to help process and analyze Dry Valleys samples.

Name: Gross, Benjamin

Worked for more than 160 Hours: Yes

Contribution to Project:

Ben is a CCI graduate student (MS), who worked on Dry Valleys snowpit samples last fall (2006) as part of his UMaine Provost Fellowship requirement.

Undergraduate Student

Name: Von Hasseln, Zachary

Worked for more than 160 Hours: No

Contribution to Project:

Laboratory aide

Name: Burdet, Tobias

Worked for more than 160 Hours: Yes

Contribution to Project:

Toby served as a field assistant during the 2005/06 Antarctic field season.

Name: Wilson, Lee

Worked for more than 160 Hours: Yes

Contribution to Project:

Lee is supported by the grant through hourly wages. He is involved in snowpit and ice core sample processing, and is an undergraduate Earth Sciences major.

Name: Kelley, Sam

Worked for more than 160 Hours: No

Contribution to Project:

Sam was an undergraduate at Dalhousie University, and worked a short time last summer (2006) processing and analyzing Dry Valleys samples. Sam is entering the CCI graduate program this fall.

Name: Butcher, Kaitlyn

Worked for more than 160 Hours: No

Contribution to Project:

Lab assistant, helping with ice core processing and sample preparation

Name: Gilman, Brittany

Worked for more than 160 Hours: No

Contribution to Project:

Lab assistant, helping with ice core processing and sample preparation

Technician, Programmer

Name: Introne, Douglas

Worked for more than 160 Hours: Yes

Contribution to Project:

Stable isotope analyses

Name: Handley, Michael

Worked for more than 160 Hours: Yes

Contribution to Project:

ICP-MS analyses

Name: Sneed, Sharon

Worked for more than 160 Hours: Yes

Contribution to Project:

Major ion analyses

Name: Waskiewicz, Michael

Worked for more than 160 Hours: Yes

Contribution to Project:

Mike was one of the ICDS drillers on this project during the 2005/06 field season.

Name: Gacke, Terrence

Worked for more than 160 Hours: Yes

Contribution to Project:

Terry was one of the ICDS drillers on this project during the 2005/06 field season.

Other Participant

Research Experience for Undergraduates

Name: Scofield, Marcienne

Worked for more than 160 Hours: Yes

Contribution to Project:

Marci was supported last summer (2006) with an REU award. She is a junior Earth Science major, and worked on GIS data analysis and sample analysis of Dry Valleys snowpit samples. She is planning to use the data in her senior thesis.

Years of schooling completed: Junior

Home Institution: Same as Research Site

Home Institution if Other:

Home Institution Highest Degree Granted(in fields supported by NSF): Doctoral Degree

Fiscal year(s) REU Participant supported: 2006

REU Funding: REU supplement

Organizational Partners

US Army Cold Regions Research and Engine

Columbia University Lamont Doherty Earth Observatory

Institute of Geological and Nuclear Scie

Dartmouth College

The Ohio State University

Other Collaborators or Contacts

Nancy Bertler and Peter Barrett, Victoria University , New Zealand
Uwe Morgenstern, Institute of Geological and Nuclear Science, New Zealand

Berry Lyons and Rebecca Witherow, Ohio State University
Brenda Hall, University of Maine
Benjamin Bostick, Dartmouth College
Steve Arcone, U.S. Army CRREL

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

Findings: (See PDF version submitted by PI at the end of the report)

Training and Development:

The training and development associated with this project over the past four years are summarized as follows:

ò Bruce Williamson has been involved in all aspects of the project, and as such has gained a large amount of hands-on research experience. This includes field and laboratory experience, communications skills (presentations ranging from K-12 to graduate level courses), writing skills (he has completed his MS thesis, published one paper in a peer reviewed journal (J. Glaciology), and is in the process of publishing two papers related to this project), and advising skills (Bruce has helped to guide and direct the undergraduate students involved in this project). Starting in fall, 2008, a new graduate student, Bess Koffman, will be working on the aspects of the Dry Valleys project.
ò Several undergraduate and graduate students have had the opportunity to work on this project over the past year in the laboratory. Marcy Scofield (REU support) participated in sample analysis and comparison of climate reconstructions from Antarctica and Maine. Sam Kelley (Dalhousie University) and Lee Wilson, Brittany Gilman, Kaitlyn Butcher, and Zach Von Hasslen (UMaine) have also participated in sample processing and analysis. In part because of his participation in this project, Sam Kelley decideded to pursue a MS degree at UMaine starting in fall 2007. Other UMaine graduate students (Erich Osterberg, Nate Vogan and Ben Gross), whose thesis research involves snow and ice chemistry in the St. Elias Mountains, have participated in sample processing and analysis.
ò The PI has used data from this project in several classes, most notably ERS200 (Earth Systems), ERS527 (Isotope Geology), and ERS602 (Climate Analysis). This has provided an important improvement in teaching effectiveness in all three courses, leading to a much more active style of learning for the undergraduate students involved in the class.

Outreach Activities:

The following are the outreach activities associated with this project over the past four years:

ò Asa Adams Elementary School, Orono, Maine: PI Kreutz visited fourth grade classes in each of the last four years and spoke about life and research in Antarctica. Bruce Williamson also visited the fourth grade classes in Sept. 2005 and 2006 and spoke about the scientific method, and how it relates to our work in Antarctica. The PI has also developed an ongoing environmental geochemistry program at Asa Adams school, where students participate in
hands-on sample collection in local rivers, sample analysis at UMaine, and basic

interpretation techniques. The relevance of Antarctic research in the context of understanding local, regional, and global-scale environmental problems is always featured, and stories from the Dry Valleys are a highlight.
ò Our research (and field camp life) is featured in a story by Antarctic Artist and WriterÆs participant Sarah Andrews titled ôPie on Iceö published in TravelerÆs Tales. Our work is also a central feature in SarahÆs new forensic geology mystery novel In Cold Pursuit, published in 2007.
ò The PI and project graduate RA (Bruce Williamson) have given several general public lectures over the past four years (e.g., Old Town Rotary club, Page Home and Farm Museum),
and always include data and idea from the Dry Valleys project.

Journal Publications

Osterberg, E., Handley, M., Sneed, S., Mayewski, P.A., and Kreutz, K.J., "A continuous ice core melter system with discrete sampling for major ion, trace element, and
stable isotope analyses", Environmental Science and Technology, p. , vol. , ( ). Accepted,

Bertler, N., Naish, T., Oerter, H., Kipfstuhl, S., Barrett, P., Mayewski, P., and Kreutz, K., "The effects of joint ENSO-Antarctic Oscillation forcing on the McMurdo Dry Valleys, Antarctica", Antarctic Science, p. 507, vol. 18, (2006). Published,

Williamson, B., Kreutz, K., Mayewski, P., Bertler, N., Sneed, S., Handley, M., and Introne, D., "A coastal transect of McMurdo Dry Valleys snow and firn: marine and terrestrial influences on", Journal of Glaciology, p. , vol. 53 (183, (2007). Published,

Bertler, N.A.N. and 30 others
, "Snow chemistry across Antarctica", Annals of Glaciology, p. 167, vol. 41, (2005). Published,

Bertler, N.A.N., Barrett, P., Mayewski, P.A., Fogt, R., Kreutz, K.J., and Shulmeister, J., "Reply to comment by
Doran et al. on El Nino suppresses Antarctic warming", Geophysical Research Letters, p. L07707, vol. 32, (2005). Published,

Bertler, N.A.N., Barrett, P., Mayewski, P.A., Fogt, R., Kreutz, K.J., and Shulmeister, J.,, "El Nino suppresses
Antarctic warming", Geophysical Research Letters, p. L15207, vol. 31, (2004). Published,

Bertler, N.A.N., Mayewski, P.A., Barrett, P.J., Sneed, S.B., Handley, M.J., and Kreutz, K.J., "Monsoonal
circulation of the McMurdo Dry Valleys, Ross Sea region, Antarctica: signal from the snow
chemistry", Annals of Glaciology, p. 135, vol. 39, (2004). Published,

Arcone, S. and Kreutz, K., "Ground penetrating radar profiles of Clark and Commonwealth Glaciers in the Dry Valleys, Antarctica", Annals of Glaciology, p. , vol. , (2008). Accepted,

Books or Other One-time Publications

Williamson, B., "Sources and deposition processes linking
atmospheric chemistry and firn records
from four glacier accumulation zones in
the McMurdo Dry Valleys, Antarctica", (2006). Thesis, Published
Bibliography: University of Maine Department of Earth
Sciences M.S. thesis, 131 pp.

Kreutz, K.J., "Glaciochemistry", (2006). Encyclopedia chapter, Published
Editor(s): Elias, S.
Collection: Encyclopedia of Quaterary Science
Bibliography: Elsevier Publishers

Andrews, S., "Pie on Ice", (2006). Book, Published
Editor(s): Jordan, M., and Brady, S.
Collection: The World is a Kitchen
Bibliography: Traveler's Tales, Palo Alto, California; distributed by Publishers Group West, Berkeley, California

Andrews, S., "In Cold Pursuit", (2007). Book, Published
Bibliography: St. Martin's Press, New York, New York

Stone, E., "Getting to the Core", (2005). Periodical, Published
Collection: Antarctic Sun, December 4, 2005
Bibliography: United States Antarctic Program

Web/Internet Site

URL(s):

http://gcmd.nasa.gov/getdif.htm?kreutz_0228052

Description:

This is the Global Change Master Directory (GCMD) website developed for the project, and will archive all meteorological, glaciological, and glaciochemical data produced as part of the project.

Other Specific Products

Contributions

Contributions within Discipline:

Contributions within discipline: Several aspects of our work over the past four years have made
specific contributions within the discipline:

ò Ice core processing: The development of a new continuous ice core melting system at UMaine provides a valuable new approach for ice core processing, namely collecting discrete samples for a number of different measurements that have different contamination requirements. Our new system, developed in part because of this project, has certain advantages over direct injection melter systems, and likely will be of greater use in some ice core situations. However, we have determined that this system is not optimal for sites where there is high particulate load. The unique character of the Dry Valleys, given the high rate of dust input from local regions, is an ideal test case. We have therefore refined processing techniques that involve manual removal of the outer portion of the core, and these refined techniques are applicable for several sites in Asia and South America.
ò Air/snow transfer: Our ongoing work using AWS data and high-resolution snowpit data is providing new insights into glaciological and atmospheric dynamics in the Dry Valleys region. These techniques, along with the results, are of value to several groups working in the area.
ò Filtering/acid digestion techniques: Refining methods for quantifying soluble vs. insoluble chemical concentrations remains a challenge at ice core sites with high

particulate loads. Our work with filtering and acidification techniques has already made specific contributions to our understanding of which elements are affected and to what degree. In addition, our work points out potentially new techniques that would be valuable in the context of producing high-resolution trace element records from ice cores, where large numbers of samples need to be analyzed quickly and precisely. Results from our Dry Valleys work has directly transfered into our WAIS Divide research, in particular the behavior of various particulate material under different acid strengths and leaching times.

Contributions to Other Disciplines:

Contributions to other disciplines: Several aspects of our work over the past four years have
made specific contributions to other disciplines:

ò Spatial glaciochemical variability in the Dry Valleys: Our understanding of aerosol deposition in the Dry Valleys has already contributed to the LTER groupÆs investigation of biogeochemical processes in the region. In particular, the Ohio State group has worked with us to develop a mercury record for the Commonwealth Glacier, which relies in part on understanding the aerosol transport history in the area. Our results published in J. Glaciology and Annals of Glaciology highlight the regional spatial variability, and emphasixze the importance of
both inter-valley and intra-valley trends in geochemistry that may be important for ecosystem function.
ò Our ongoing attempts to reconstruct interannual to decadal scale atmospheric variability makes a contribution to understanding ecosystem function and response in the Dry Valleys, and is also critical to the ITASE and other international programs that seek to understand spatial climate variability in Antarctica.
ò Dry Valleys meteorology: The AWS data collected on the Clark and Commonwealth Glacier, particularly our snow depth, wind speed, temperature, and energy balance data will make a significant contribution to the LTER groupÆs meteorological work in the Dry Valleys.

Contributions to Human Resource Development:

The project continues to support the UMaine ICP-MS facility for sample analysis, and the technician, Michael Handley, has gained a wide range of training as part of this. In particular, the Dry Valleys samples represent something of an analytical challenge, in that a typical depth profile contains both very high and very low concentration samples. Analysis techniques to deal with such contrasts have required Mike to investigate and implement new methodology that otherwise would not have occurred.

Contributions to Resources for Research and Education:

Our collaboration with a specialty machine shop in California has resulted in the use of a new ultra-pure nickel alloy for use in ice core melt heads. These heads are now being used by several collaborators, including New Zealand, China, Brazil, and Canada.

Contributions Beyond Science and Engineering:

We hosted visits in our field camp from two participants in the Antarctic Artists and Writers Program, Sara Andrews and Gabrielle Walker. Each has now published books in part related to their time in Antarctica, and by extension in part to their time with us.

Categories for which nothing is reported:

Any Product

Annual Report, 2004-2005

Dry Valleys Late Holocene Climate Variability

NSF OPP 0228052, Kreutz PI, Mayewski co-PI; Arcone subcontract

Activities and Findings

The primary goal of the second year of the project was to drill intermediate length (~100-200 meter) ice cores from the Clark and Commonwealth Glaciers (Fig. 1). These sites were identified as suitable coring locations during the previous 2003/04 field season. The field participants during 2004/05 (K. Kreutz, B. Williamson [UMaine graduate student], T. Gacke and M. Waskiewicz [ICDS]) were in Antarctica for roughly two months (mid-Oct. to mid.-Dec).

We first visited the Clark Glacier (Oct. 27 – Nov. 15) with a small camp and the Eclipse drill system. Based on radar results from the previous field season, ice depth at the chosen drillsite was ~300 meters. Drill performance and core quality in the upper firn was good for both a shallow 16.4 meter core (radionuclide measurements) and a second deep core, however we ran into several problems as we approached the firn/ice transition and then into ice. Figure 2 shows density data collected on each drill run, and the increased variability below ~50 meters reflects decreasing core quality (loss of core from cracking, chips, core dog scars, etc.). Density data from very poor quality core runs has been removed. After 10 days of

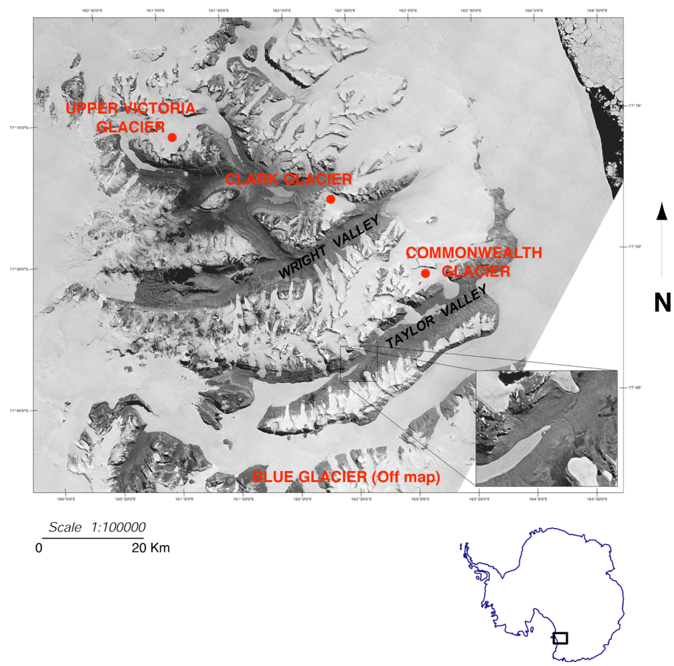

Figure 1. Location map for sites visited in the Dry Valleys during the 2004/05 season.

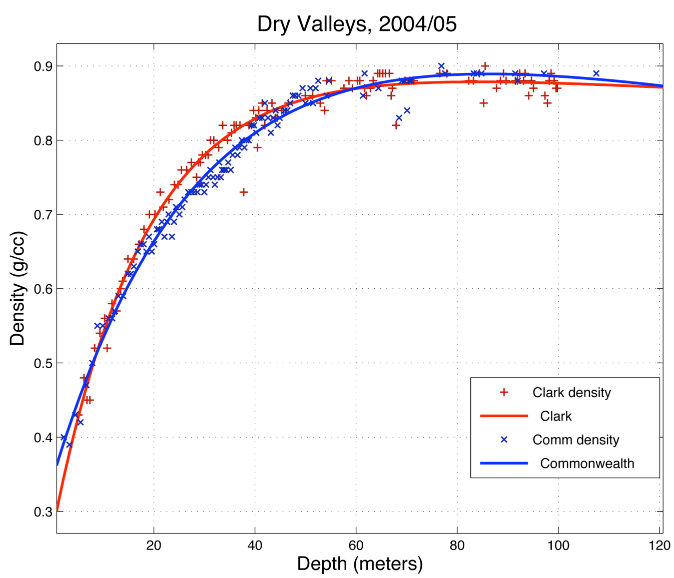

Figure 2. Depth vs. density data for the long cores drilled on the Clark and Commonwealth Glaciers during 2004/05/

drilling we reached 100.4 meters depth, and decided to end drilling on the Clark due to poor drill penetration and nearly unusable core quality. We then visited the Commonwealth Glacier (Nov. 15-Nov. 29), and again drilled two cores with the Eclipse system (18.2 and 119.2 meters; total ice depth ~300 meters). Drill performance was slightly better on the Commonwealth, however the same issues existed and can be seen in the density data (Fig. 2). We again decided to stop drilling due to low core recovery and poor core quality.

The ice cores recovered during the 2004/05 will be sufficient for isotope, major ion, and some trace element analysis, and therefore a useful part of the project. However, given the overall scientific goals of the project, we had hoped to drill deeper (at least 150 meters) at each site, and with significantly better core quality for use in the UMaine melter system. Observations and conversations with ICDS personnel in the field lead to the following conclusions regarding the Eclipse system performance:

1) Pre-season: There appeared to be inadequate preparation of the drill in Madison during summer 2004. This includes the drill being shipped south late, little to no information on what repairs/medications were done to the system at Icefield instruments to address problems identified during 2003/04, very inadequate selection of spare and replacement parts with the system, and the drill having a flattened end on one inner barrel which presumably occurred in Madison as the shipping container was not damaged.
2) The anti-tourque section of the drill did not perform correctly. Adjustments were not obvious in field, which led to very poor performance – either the drill spins in hole (anti-tourque too loose), or the drill hangs in hole (anti-tourque too tight). Correct adjustment was very hard to find, and the design and specifications should be checked.
3) Drill penetration was very poor below the firn/ice transition. This is likely due in part to problems with cutter core dog design, core dog spring tensions, and potentially the inner barrels being elliptical. Chip transport was also very poor, adding to the core penetration problems.

Most of these problems had been identified during the use of this Eclipse drill system in Antarctica during 2003/04 by a different group. Therefore, after our similar experiences in 2004/05, a robust set of ideas and data now exist with which to form potential solutions. After speaking to ICDS personnel after the Eclipse drill testing in Greenland during summer 2005, it seems likely that many of these problems have been fixed. In summary, based on drilling performance during the 2004/05 season and modifications done during summer 2005, we plan to return to the Clark Glacier in 2005/06 and attempt to drill a deeper ice core (hopefully decent core quality to 200 meters). We also plan to drill on the Upper Victoria Glacier, thereby providing spatial ice core coverage in the Dry Valleys.

Additional activities during the 2004/05 field season included installation of automatic weather stations on the Clark and Commonwealth Glaciers. Each of the stations is equipped with temperature, pressure, humidity, radiation, snow temperature, and snow depth sensors. We plan to collect the data and stations during the 2005/06 field season, as well as dig snowpits at the stations to calibrate snow chemistry/atmospheric relationships. With the help of UNAVCO (B. Bartel), we GPS-surveyed mass balance/velocity poles on the Clark and Commonwealth glaciers (arrays of 20 poles each). We will re-survey and remove the poles during the 2005/06 season. We also visited the Blue Glacier to re-survey mass balance poles installed during 2003/04, and sampled a 2 meter snowpit. Finally, we sampled a spatial array of snowpits on the Commonwealth and Clark Glaciers (five 2 meter pits on a grid at each site), as well as a 2 meter snowpit on the Upper Victoria Glacier.

All cores and snowpit samples were returned frozen via ship/surface truck to UMaine in spring 2005. Stable isotope, major ion, and trace element analyses have been completed on all snowpit samples collected during 2003/04 and 2004/05. As previously reported, annual chemical signals appear to be present in the major ion species, possibly related to patterns in wind strength, pressure, and dust entrainment/deposition in the Dry Valleys. To test this idea, we have used principle component analysis (PCA) to identify common variance in the combined suite of major ion and trace element snowpit data from each site (Fig. 3). At each site, but particularly at the Blue and Clark Glaciers, the major ion (soluble) and trace element (largely insoluble) concentrations partition differently on the first and second PCA. We interpret these patterns as being due the relative importance of wind transport of eroded crustal material vs. precipitation from coastal storm systems. On the Clark, the first PCA is positively loaded for all species, suggesting a wind-dominated regime that is consistent with field observations at the site. On the Blue, the first PCA splits the major ion and trace element data, suggesting that a strong coastal precipitation signal is responsible for major ion

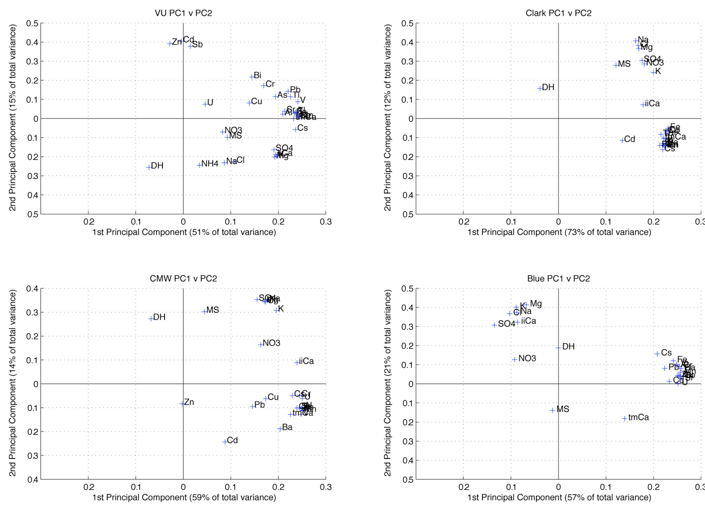

Figure 3. Principal component analysis (PCA) of major ion and trace element data from 2004/05 snowpit samples. Abbreviations are: VU (Upper Victoria) and CMW (Commonwealth).

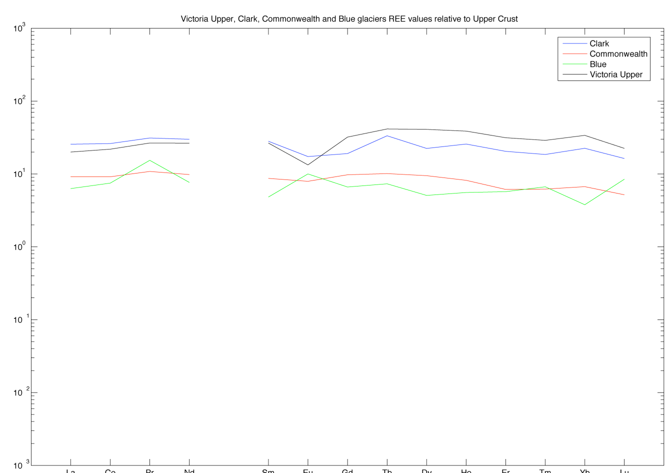

Figure 4. Rare earth element (REE) data from 2004/05 snowpits.

deposition. Rare earth element (REE) data from each site support these interpretations (Fig. 4), where the REE patterns and concentrations are slightly lower on the Commonwealth and Blue vs. the Upper Victoria and Clark Glaciers. These results have important implications for our interpretation of the ice core chemical data, and are the subject of a publication in preparation (Williamson et al., "Deposition mechanics for chemical species in McMurdo Dry Valleys firn based on IC, ICP-OES, ICP-MS and gas-source stable isotope mass spectrometry", to be submitted to *J. Glaciology*). In addition, the sample preparation techniques used in the snowpit analysis have required method development due to the large range in concentration, and the methods are the subject of a second paper in preparation (Williamson et al., "Determination of trace metal concentrations in firn using ICP-MS and a combination of control, filtered and acidified samples", to be submitted to *Analytical Chemistry*).

Processing and analysis of the ice cores collected during 2004/05 is ongoing. The shallow cores collected for radionuclide analysis on the Clark and Commonwealth Glaciers are being processed for ^{137}Cs analysis at Columbia University and tritium analysis at the University of Wellington (New Zealand). We are currently modifying our continuous melter system to deal with the high particulate concentrations present in the Dry Valleys cores.

Publications related to this project over the past year include:

Bertler, N.A.N., Barrett, P., Mayewski, P.A., Fogt, R., Kreutz, K.J., and Shulmeister, J., 2005, Reply to comment by Doran et al. on "El Nino suppresses Antarctic warming", *Geophysical Research Letters*, 32, doi:10.1029/2005GL022595.

Bertler, N.A.N., Barrett, P., Mayewski, P.A., Fogt, R., Kreutz, K.J., and Shulmeister, J., 2004, El Nino suppresses Antarctic warming, *Geophysical Research Letters*, 31, L15207, doi:10.1029/2004GL020749.

Education, Training and Development

To date, two UMaine graduate students (B. Williamson and E. Osterberg) and one Ohio State graduate student (B. Witherow) have participated in the field program. B. Williamson is using the samples and data collected during the 2003/04 and 2004/05 as the basis of his MS thesis under the direction of the PI. He plans to defend and complete his MS thesis in Fall 2005 (prior to Antarctic deployment), and continue on at UMaine for a PhD using data from the Dry Valleys project. In addition, one UMaine undergraduate student (Z. Von Hasseln) is being employed during summer 2005 to participate in the laboratory portion of the project, and another (T. Burdet) will be deploying to Antarctica as part of this project during 2005. Several UMaine technical staff members (D. Introne, S. Sneed, M. Handley) are involved in sample analysis. Lastly, the PIs have used the data and ideas generated thus far in the project in several UMaine undergraduate and graduate classes (Earth Systems, Isotope Geology, and Climate Analysis).

Outreach Activities

A local K-12 teacher (S. Eaton) is spending summer 2005 in the UMaine ice core labs as part of an NSF-sponsored GK-12 program, and is expected to participate in the project sample analysis and interpretation. Several presentations have been made in local schools that have included results of this project, including the Indian Island Elementary School (Old Town, ME), and the Asa Adams Elementary School (Orono, ME). The UMaine Climate Change Institute maintains a project website, and interactive expedition logbook for the time we are in the field (http://climatechange.umaine.edu/).

We also hosted a 3-day field visit from G. Walker, a science writer in Antarctica as part of the Artists and Writers program, during the 2004/05 season. We hope that the opportunity she had to observe our field work and discuss the project scientific issues will help the book she is currently working on, and may perhaps be a featured piece.

<u>Final Report – Summary of Findings</u>

Dry Valleys Late Holocene Climate Variability

NSF OPP 0228052, Kreutz PI, Mayewski co-PI

Findings associated with the Dry Valleys grant over the past four years are interdisciplinary in nature, and span several related fields in the earth sciences. We summarize these findings here in the following categories:

Geochemistry of Dry Valleys snow and ice: Snowpit major ion data have been added to the growing database of Antarctic glaciochemical data, thereby improving our understanding of the major controls on snow and ice geochemistry. In particular, Bertler et al. (2005) clearly show that glaciochemical concentrations from our and other Dry Valleys work have some of the highest values anywhere in the continent. For most species, this is attributable to local controls on glaciochemistry, namely the proximity to a marine source. However, in the case of the Dry Valleys, there obviously are additional local controls that elevate values much beyond what is observed in other coastal regions. We attribute this to the extensive wind-blown deposits in the Dry Valleys that are sporadically entrained by high velocity katabatic winds and deposited on glacier accumulation zones. High chemical values (in the ppm range) on Dry Valleys glaciers, coupled with observation of distinct stratigraphic layers of silt and even sand sized particle, attests to this mechanism. Another result from the Bertler et al. (2005) paper is that gridding techniques commonly used for spatial analysis are often not capable of resolving small-scale regional variations, and this is certainly the case in the Dry Valleys – a much finer-scale (local) analysis is necessary to discern the relevant controls.

In light of the Bertler et al. (2005) spatial results, Bruce Williamson used his thesis research to focus on the local glaciochemical controls in the Dry Valleys (Williamson, 2007). In addition to the standard suite of major ions, Williamson investigated the spatial patterns of trace elements as well, the first such detailed study of its kind in Antarctica. The relatively straightforward spatial pattern that relates distance inland to decreasing chemical concentration, a pattern that has been observed and published many times in the Antarctic, is true in individual valleys in the Dry Valleys system (Williamson et al., 2007). This confirmed our previous conclusion that there is a seasonal monsoon-type circulation in the Dry Valleys, with onshore flow in the summer and offshore flow in the winter, with related effects on seasonal glaciochemistry (Bertler et al., 2004; confirmed by AWS data from the Clark Glacier accumulation zone; Arcone and Kreutz, 2008). These seasonal patterns of chemical deposition are quite robust, and comparison of accumulation rates derived from glaciochemistry, mass balance poles, and tritium (^{3}H) measurements are in good agreement (Williamson et al., 2007). However, when looking at major ion and trace element concentrations among the three primary valley systems (Taylor, Wright, Victoria) in a north-south orientation, trends in elevation and distance inland do not hold true. Rather, we conclude that variations in related to different soil sources and exposures to the Ross Sea dominate coastal mean chemistry gradients at these sites (Williamson et al., 2007). In addition, spatial variability at local scales (i.e., within an individual accumulation zone) becomes important, where both marine and soil inputs and the local wind regime determined from AWS stations (both ours and LTER) are necessary to explain gradients in chemical concentration.

Glaciology/Meteorology: Our initial effort to locate suitable ice core drill sites resulted in several glaciological findings, particularly when coupled with the unique glaciochemistry in the Dry Valleys outlined above (Arcone and Kreutz, 2008). First, we were able to profile the complete ice column on the Clark and Commonwealth Glaciers, and provide accurate ice depths (~270 m a the deep point, sloping up towards glacial margins) for the first time to our knowledge. Second, englacial horizons are not present in either glacier below ~100 m, the first time this has been observed in GPR profiles from the Dry Valleys, but a ubiquitous yet unexplained phenomena in valley glaciers. Given the normal density profiles in the Clark and Commonwealth Glaciers, with firn/ice transition at ~35 m depth, density contrasts alone are not an explanation. We suggest that, based on chemical concentrations in firn and ice cores processes thus far, and the high degree of spatial variability in snowpit chemical concentrations, the lack of englacial reflections is likely due primarily to dilution of the radar signal because of uneven signal response off conductivity layers. The high spatial noise factor in the chemistry is likely related to local wind patterns, and noted in the Clark and Commonwealth AWS data (Arcone and Kreutz, 2008), and the spatial variability in accumulation rate determined from glaciochemistry, mass balance poles, and AWS snow depth sounding (Williamson et al., 2007). These findings have implications for the tradeoffs between various antenna frequencies and signal/noise ratios necessary to achieve layer detection on the one hand and full depth profiling on the other. An additional important finding, both from a site selection and glaciological perspective, is the ice velocity on the Clark and Commonwealth Glaciers. In collaboration with UNAVCO, we performed repeat kinematic surveys on mass balance pole strain grids in 2004 and 2005. Results indicate divide flow on the Clark Glacier, with velocities off divide ranging from 4-22 cm yr^{-1}. Flow direction on the Commonwealth Glacier is to the southwest, consistent with surface slope observations, with velocities ranging from 56-194 cm yr^{-1}. We have further investigated the relationship between seasonal snow accumulation and glaciochemical deposition using data from the AWS snow depth sounder and high resolution (0.5 cm) snowpit samples collected from the profiled snow. Initial results suggest that there is striking correspondence between snow accumulation timing on the Clark and Commonwealth Glacier during 2004-2005, suggesting that storm system are preserved nearly identically at both sites. Chemical concentrations, particularly MSA, also snow large changes during this period that are highly correlated between the two sites, suggesting that local marine conditions do indeed play a major role in shaping glaciochemical profiles in he Dry Valleys. We are currently working on publication of these findings. Finally, taken together the various glaciological data have allowed us to pursue 2 dimensional ice flow modeling in an effort to produce a robust time scale below the core depth where we resolve annual chemical signals.

Ice core continuous melting: The high glaciochemical concentrations observed in Dry Valleys snow, firn, and ice turn out to not only have important implications for glaciology, but also for ice core processing. Over the past decade, the focus in ice core processing has turned from hand scraping to continuous melting. We have had a part in this trend, developing a continuous flow discrete melting system (Osterberg et al., 2006). The Dry Valleys project was part of the impetus for developing the system, and in fact contributed to the initial design criteria. However, detailed work on the high particulate-load samples common to the Dry Valleys presented large challenges for a melter system (Williamson, 2007; chapter 1). Particle reactivities were found to vary considerably across the large concentration range in a typical Dry Valley snowpit or ice core record, and the sporadic nature of the particle load in depth-series caused a severe “memory” effect in all types of tubing tried. Inline filtration was explored, but ultimately abandoned due to filters clogging after one high-particle layer. We eventually resorted to hand scraping of the Dry Valleys cores with modified techniques to accommodate trace element, major ion, and stable isotope measurements (Williamson et al., 2007; Arcone and Kreutz, 2008). Resulting ice core processing is a slower process than with ultra-clean plateau core processed via continuous melting, however we feel hand scraping of the Dry Valleys cores is necessary to preserve data integrity.

Dry Valleys climatology/paleoclimatology: Our main focus to date has been the near and longer term effect of the El Nino Southern Oscillation teleconnection and associated ocean/atmosphere processes in the Dry Valleys region. A host of previous meteorological and ice core work in West Antarctica pointed us in this direction, and indeed our major findings to date have confirmed the influence of ENSO on both the meteorology and glaciochemistry in the Dry Valleys. Isotope data from snowpits and shallow cores throughout the Dry Valleys region indicate that recent cooling observed in Dry Valleys meteorological data was likely driven by ENSO-induced changes in regional atmospheric circulation, and thus may not be indicative of any longer-term pattern (Bertler et al., 2004a; 2005). Likewise, snow accumulation data also shows a link to both ENSO and the Antarctic Oscillation (AAO), such that warming and increased moisture delivery to the Dry Valleys tend to correlate with high values of the Southern Oscillation and AAO. In addition, our results suggest that over the past two decades summer temperatures are influenced by opposing ENSO and AAO forcings, and support previous studies that identified a change in the tropical-Antarctic teleconnection between the 1980s and 1990s (Bertler et al, 2005). Our focus now is on extending these interpretations with the annual resolved portion of our ice core records (~150 years; Arcone and Kreutz, 2008), and then interpreting persistence of ENSO-AAO associations back ~2000 years with the full, albeit lower resolution, core records that will be available from the Clark, Commonwealth, and Upper Victoria Glaciers.

Data archive and access: We have begun working with Rob Bauer at NSIDC to archive datasets associated with the Dry Valleys project. As of this writing, a Global Change Master Directory website (http://gcmd.nasa.gov/getdif.htm?kreutz_0228052) has been established, and we are in the process of placing all meteorological (AWS), mass balance, ice velocity, ice temperature, ground penetrating radar, snowpit chemistry, and published ice core data on this site. As additional ice core chemistry and isotope data become available, we will update the appropriate files on the web servers.

Final Report – Summary of Research and Education Activities

Dry Valleys Late Holocene Climate Variability

NSF OPP 0228052, Kreutz PI, Mayewski co-PI

The research and education activities associated with the Dry Valleys grant over the past five years have encompassed field, laboratory, and teaching-related activities. We summarize these activities here in the following categories:

Field research activities: A total of three Antarctic field seasons (2003/04, 2004/05, and 2005/06) were completed as part of this project. The first season served mainly as a reconnaissance to located suitable sites or ice core recovery, and involved using a combination of geophysical (ground penetrating radar; in collaboration with Dr. Steve Arcone, CRREL) and geochemical analysis. The primary field activities included shallow firn core drilling (with M. Waskiewicz), installation of mass balance poles, sampling of snowpits, and GPR/GPS surveys. Based on analysis of four separate accumulation basins in the Dry Valleys, we selected three site sites for ice coring: the Clark, Commonwealth, and Upper Victoria Glaciers. During the 2004/05 season, we drilled multiple intermediate-length ice cores on the Clark and Commonwealth Glaciers, installed automatic weather stations (including meteorological and snow depth sensors) on the Clark and Commonwealth Glaciers, and installed mass balance/velocity poles on the same two glaciers with assistance from UNAVCO. Due to relatively poor drill performance and core quality in 2004, we decided to return to the Clark Glacier in the 2005/06 season as well as the Upper Victoria Glacier. During the 2005/06 season, we drilled additional intermediate length cores at those two sites, and also recovered the two AWS stations installed in 2004/05 and re-surveyed and removed the mass balance/velocity poles installed in 2004. For study of spatial chemistry variability in the Dry Valleys, we sampled snowpits on several additional glacier accumulation zones (Blue, Rhone, Newall, and Meserve Glaciers). In total, we recovered one firn core from the Blue Glacier (16 meters), three firn/ice cores from the Commonwealth Glacier (13, 19, 120 meters), five firn/ice cores from the Clark Glacier (13, 20, 100, 117, 160 meters), and two firn/ice cores from the Upper Victoria Glacier (20, 136 meters). Ice core drilling in both the 2004/05 and 2005/06 seasons was carried out with two ICDS drillers (M. Waskiewicz and T. Gacke).

Field education activities: Several graduate and undergraduate students were involved in the three Dry Valleys field seasons. During the 2003/04 season, Erich Osterberg (UMaine PhD student) and Bruce Williamson (UMaine MS student) were involved in all field preparations, Antarctic field seasons, and follow-up activities. During 2004/05, Bruce Williamson was primarily responsible for field preparations, and was the initial team member in McMurdo to gain valuable logistical experience. During 2005/06, Bruce again led the field preparation activities, and had the opportunity to train a UMaine undergraduate student, Tobias Burdet, in field logistics. Bruce and Toby again were the initial field team members in McMurdo to conduct field preparation activities. In addition, in 2003 we supported the snowpit sample collection of a PhD student from Ohio State University (Rebecca Witherow), as part of the Dry Valleys LTER program.

Laboratory research activities: All samples collected in the Dry Valleys, either from snowpits or ice cores, were analyzed for a broad suite of trace elements, major ions, and stable water isotopes. A significant amount of effort went into the development of a continuous melter system to process the collected Dry Valleys cores, including fabrication of new melter heads from various pure metals that could accommodate a complete Eclipse core. Ultimately, the wide range of chemical and particle concentrations in the Dry Valleys core precluded the use of continuous melter systems, given the problem of system clogging. We continue to utilize the older, yet proven, method of hand scraping the outer portion of the core to remove contamination. Extensive additional experimentation went into designing a protocol for aliquoting samples after scraping, given the disparate demands of the different measurements to be performed (e.g., trace element, sulfate, nitrate, and water isotopes). We have determined what we feel is the optimal combination of measurement integrity, but this procedure in total is time consuming. We continue to process the lower portions of all the deep cores, and are working on glaciological flow modeling to constrain depth/age scales. Three different laboratory technicians/managers continue to coordinate student lab assistance and measurement: Michael Handley (ICP-MS), Sharon Sneed (IC), and Doug Introne (stable isotopes). Additional laboratory work at the Lamont Doherty Earth Observatory (in collaboration with T. Kenna) and at the New Zealand

Laboratory education activities: Bruce Williamson was involved in all laboratory activities associated with the project, including ice core processing and analysis for major ions, trace elements, and stable isotopes. Several additional graduate students (Erich Osterberg, Nathan Vogan, and Benjamin Gross) have been involved in the project, mainly through construction and testing of the various ice core processing equipment and techniques. Erich Osterberg (UMaine PhD, 2007) used the melter development work as part of his dissertation. A diverse array of undergraduate students from the Earth Science and Education departments have been involved in laboratory activities, primarily related to sample preparation and assistance with vial cleaning (Lee Wilson, Brittany Gilman, Kaitlyn Butcher, Zachary Von Hasseln, Sam Kelley). Each of these undergraduate students has had exposure to all aspects of the project, and at least one (Sam Kelley; MS with G. Denton in progress) has gone on to graduate school in climate science.

Teaching and advising activities: Bruce Williamson was supported on the project research assistantship, and completed his MS thesis ("Sources and deposition processes linking atmospheric chemistry and firn records from four glacier accumulation zones in the McMurdo Dry Valleys, Antarctica") in August, 2006. Bruce has since moved to Seattle, Washington, and is considering further PhD graduate training in ice core sciences at the University of Washington (were he obtained his BS in Earth Sciences). We anticipate bringing in another graduate student to work on the project starting in summer 2009, supported either through a Earth Sciences teaching assistantship or Climate Change Institute research assistantship. Marcy Scofield completed a Research Experience or Undergraduates project associated with the project during the summer of 2006, focusing primarily on the relationship between Antarctic ice core records and the history of ice margin retreat through Downeast Maine. Data and ideas from this project are routinely used in several UMaine courses, including ERS200:Earth Systems (taught each fall semester by Kreutz), ERS527:Isotope Geology (taught every other fall semester by Kreutz), and ERS542:Climate and the Earth System (taught every other fall by Mayewski).