Antarctic Contributions to Future Sea-Level Rise: Possible Tipping Points

Testimony of

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Glacial and Ice Sheet Melt in a Changing Climate

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*Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author and do not necessarily reflect those of the Pennsylvania State University, the Intergovernmental Panel on Climate Change, the National Academy of Sciences, or other organizations.

Personal introduction and background. My name is Richard Alley. I am an Evan Pugh University Professor of Geosciences and Associate of the Earth and Environmental Systems Institute at the Pennsylvania State University. I have authored or coauthored more than 300 refereed scientific papers, and I have made more than 1000 public presentations concerning my areas of expertise. I have been recognized with awards for research, teaching and service, including election to the US National Academy of Sciences and foreign membership in the Royal Society; as noted above, my comments are my own and do not represent these bodies or any other bodies, but the recognition by these bodies may help establish my credentials as a witness.

My research is especially focused on the great ice sheets of Antarctica and Greenland, their potential for causing major changes in sea level, the climate records they contain, and their other interactions with the environment; I also study mountain glaciers, and ice sheets of the past. I have served with distinguished national and international teams on major scientific assessment bodies, including chairing the U.S. National Research Council's Panel on Abrupt Climate Change (report published in 2002), and serving the U.S. Climate Change Science Program, and the Nobel-Peace-Prize-Winning Intergovernmental Panel on Climate Change (IPCC) in various ways on their Second (1995), Third (2001) and especially Fourth (2007) Assessment Reports. I have had the honor on several occasions of providing requested testimony and briefings to high government officials at the federal as well as state levels, including to legislative committees chaired by members of both major political parties, and to executive officials in administrations of both major political parties, drawing on my expertise to provide scientific information to those working for the public good. Additional information is given in the short biography at the end of this document.

My testimony here is updated from my testimony of November 17, 2010 to the Subcommittee on Energy and Environment of the House Committee on Science and Technology of the United States House of Representatives; the consistency of this testimony reflects the consistency of the scientific understanding, which continues to strengthen without fundamentally changing.

Background on climate change, global warming and sea-level rise. Scientific assessments such as those of the National Academy of Sciences of the United States (e.g., National Research Council, 1975; 1979; 2001; 2006; 2008; 2010a; 2010b), the U.S. Climate Change Science Program (CCSP), and the Intergovernmental Panel on Climate Change (IPCC) have for decades consistently found with increasingly high scientific confidence that human activities are raising the concentration of carbon dioxide and other greenhouse gases in the atmosphere, that this has a warming effect on the climate, that the climate is warming as expected, and that the changes so far are small compared to those projected if humans burn much of the fossil fuel on the planet.

The basis for expecting and understanding warming from carbon dioxide is the fundamental physics of how energy interacts with gases in the atmosphere. This knowledge has been available for over a century, was greatly refined by military research after World War II, and is directly confirmed by satellite measurements and other data (e.g., American Institute of Physics, 2008; Harries et al., 2001; Griggs and Harries, 2007).

With very high scientific confidence, this warming is causing sea level to rise. Since 1993, when high-quality satellite altimetry data have been available, sea-level rise has averaged approximately 3.1 mm/yr, or about 1 inch per 8 years. (Of many sources for this general information on sea-level change, Church et al., 2013 and Lemke et al., 2007 are good starting points, and important information is available at http://sealevel.colorado.edu/ and in Nerem et al., 2018.) The rate of sea-level rise has accelerated. The rise comes from several sources. Much of the energy added to the Earth system because of the rise in atmospheric greenhouse gases has heated the ocean, causing the water to expand and raise sea level. Warming is causing melting of glaciers, shifting water from land to the ocean, with local impacts on water availability and hazards as well as global implications through sea level. Melting has increased mass loss from the surface of the Greenland ice sheet. Faster flow of non-floating ice into the ocean to float and melt has caused mass loss from some parts of the Greenland and Antarctic ice sheets. In addition, groundwater "mining"—removing well-water from the ground more rapidly than replenished—may be contributing a little to sea-level rise. (Note that the IPCC found with high confidence that warming is causing loss of other temperature-sensitive snow and ice, including springtime snow cover and Arctic sea ice, but that these do not contribute in any significant way to sea-level rise; e.g., Lemke et al., 2007.)

Many strands of mutually supporting evidence are woven into the confident knowledge that loss of land ice and warming of the ocean are driving sea-level rise. A large and consistent scientific literature exists on this topic (e.g., The IMBIE Team, 2018), and the synopsis of techniques in Lemke et al. (2007; section 4.6.2.1) provides a broad overview. As explained there, for large ice sheets the gain or loss of mass contributing to sea-level change is measured in three ways: by repeatedly "weighing" the ice sheet using satellites that measure Earth's gravity field, supplemented by data from aircraft and surface measurements; by repeatedly measuring the surface elevation of the ice sheet using altimeters on satellites or aircraft supplemented by surface measurements; and, by measuring and modeling the addition of snowfall to the ice sheet, and the loss by runoff of meltwater or by flow of nonfloating ice into the ocean to float and then melt. Measurements of ocean temperature provide data to estimate the expansion of ocean water, and measurements of changes in mountain glaciers similar to those for ice sheets but involving more on-the-glacier work and more analysis of size changes from satellite imagery provide additional constraints. Sea-level measurements from satellites and tide gauges monitor the rise of the ocean. Scientists then assess the consistency among the various lines of evidence, and find agreement. Additional tests are also applied. Melting of ice from near the poles and motion of the water into the ocean actually slows Earth's rotation very slightly, something like a spinning ice skater sticking out her arms. And, while Greenland is far north, it is not all the way to the North Pole, so melting of Greenland's ice causes Earth to wobble a bit, something like the skater moving one arm but not the other. These changes in Earth's rotation are tiny, they are not important to most people most of the time, but they test and confirm the other measurements.

Insights from climate history. The hills around Los Angeles have always burned, so we worry about people shooting illegal fireworks during dry summers. People have always died, so we worry about murder. An arson investigator must understand natural fires, and a homicide investigator must understand how people live and die naturally.

The science of climate and sea level includes a "CSI" component (see, for example, CCSP, 2009; Masson-Delmotte et al., 2013). Summarizing those summaries and many other studies, climate has always changed, which shows that climate is changeable. Climate has changed for many reasons—dust from single large volcanic eruptions blocking the sun and causing occasional cold years, features of Earth's orbit slowly shifting sunshine around over tens of thousands of years, small changes in the brightness of the sun, shifts in ocean circulation, the very slow drifting of continents—but naturally caused changes in greenhouse gases and especially carbon dioxide have been very important over Earth's climate history. When warming has occurred, ice has melted and sea level has risen. Careful study of these natural changes and their causes contributes to the strong knowledge that the changes now occurring are not primarily the continuation of some natural cycle, but are instead caused primarily by the human-driven rise in greenhouse gases, mostly carbon dioxide.

Past warming and cooling in response to changing greenhouse-gas concentrations and other forcings including features of Earth's orbit have caused much larger past changes in ice and sea level than have occurred in the last century or that are projected for the next century. But, human burning of fossil fuels could cause a climate change that rivals or exceeds those of the past in combined size and speed (White et al., 2010), raising questions about the future that are discussed next.

Looking to the future. Some additional sea-level rise is already committed, under the future emissions pathways considered by the IPCC. Just as an ice cube placed in a glass of tea takes a while to melt, the warming of the ocean and mass loss from land ice have not yet "caught up" with the warming that has already been caused, and would continue to contribute to some additional sea-level rise even if temperature were stabilized today. Looking toward the time when today's students are old, toward the end of this century and beyond, future human decisions become increasingly important and then dominant in controlling projected sea-level rise (e.g., Church et al., 2013, Fig. 13.27). Under strong warming (RCP8.5), projected sea-level rise in 2100 compared to preindustrial is slightly more than 3 feet, with an uncertainty that the IPCC considered likely to be no more than about 1 foot (details and more-precise numbers available in the source).

One occasionally hears the unsubstantiated claim that the IPCC projections are overly alarmist. In fact, several studies have suggested that, if the IPCC is open to criticism on this subject, it is overly conservative. Rahmstorf et al. (2007), for example, compared observed sea-level rise at the time to projections from earlier IPCC work, and found that the sea was rising faster than the most-likely projection and near the projected likely upper limit. The Third Assessment Report of the IPCC projected a most-likely future in which climate change would cause growth of the Antarctic ice sheet over this century (Church et al., 2001), but Antarctic ice is shrinking (The IMBIE Team, 2018); more-recent central projections from the IPCC indicate less ice loss from Antarctica than observed (Slater and Shepherd, 2018). Garner et al. (2018) compared the history of IPCC projections to other science-based projections, many of which were available to the IPCC assessment teams; Figure 2a in Garner et al. (2018) shows no tendency for the IPCC projections to be higher than in the underlying literature, and some tendency for the IPCC projections to be lower. The new expert elicitation from Bamber et al. (2019) includes information obtained since the IPCC Fifth Assessment Report (Church et al., 2013), and yields potential for higher sea-level rise than generally projected. Quoting from the Abstract, with English units added:

> "For a +2 °C (+3.6 °F) temperature scenario consistent with the Paris Agreement, we obtain a median estimate of a 26 cm (0.85 ft) SLR contribution by 2100, with a 95th percentile value of 81 cm (2.7 ft). For a +5 °C (+9 °F) temperature scenario more consistent with unchecked emissions growth, the corresponding values are 51 and 178 cm (1.7 and 5.8 ft), respectively. Inclusion of thermal expansion and glacier contributions results in a global total SLR estimate that exceeds 2 m (6.6 ft) at the 95th percentile. Our findings support the use of scenarios of 21st century global total SLR exceeding 2 m (6.6 ft) for planning purposes. Beyond 2100, uncertainty and projected SLR increase rapidly. The 95th percentile ice sheet contribution by 2200, for the +5 °C (+9 °F) scenario, is 7.5 m (24.6 ft) as a result of instabilities coming into play in both West and East Antarctica. Introducing process correlations and tail dependences increases estimates by roughly 15%."

Focus on ice-sheet changes. The large ice sheets of Greenland and Antarctica are of special interest, because they are so big and thus could affect sea level so much. Expansion of the ocean as it warms gives just under 1 foot of rise per degree F of warming (0.4 m/1°C) (Levermann et al., 2013), but the ~1000-year time for heat to mix into the ocean makes the resulting sea-level rise relatively slow. Melting of all of the world's mountain glaciers and small ice caps might raise sea level by about 1 foot (0.3 m), but melting of the great ice sheets would raise sea level by just over 200 feet (more than 60 m), with ~23 feet from Greenland (7.3 m) and the rest from Antarctica (Lemke et al., 2007). We do not expect to see melting of most of that ice over the next century or centuries, but even a relatively small change in the ice sheets could matter to the world's coasts; roughly 10% of the world's population lives within 33 feet (10 m) of sea level (McGranahan et al., 2007). I thus next consider the possibility of rapid changes (National Research Council, 2002; 2013; CCSP, 2008; 2009).

Ice-sheet behavior. An ice-sheet is a two-mile-thick, continent-wide pile of snow that has been squeezed to ice under the weight of more snowfall. (For a more-detailed background, see

Cuffey and Paterson, 2010.) Growth or shrinkage of an ice sheet depends on the balance between snowfall and melting on top, and on flow taking accumulated ice to lower elevation, often to the ocean to make icebergs.

The balance between snowfall and melting is of great importance. I will not treat this aspect in detail, however; additional information is available from the IPCC reports cited herein. Generally, warming of subfreezing conditions is expected to increase snowfall because warmer air can carry more water, although additional processes are important. For Greenland and mountain glaciers, the increase in melting from warming is expected to exceed the increase in snowfall. For Antarctica, fairly large warming would be required for mass loss by surface melting to become important, so the surface is expected to gain mass with moderate warming; however, flow increases have recently exceeded changing snowfall leading to mass loss, and this is expected to continue. I thus focus next on the flow characteristics. A review of much of this information is available in Alley et al. (2015) and Scambos et al. (2017) as well as in the IPCC reports and in Cuffey and Paterson (2010). The literature is large and increasing rapidly.

All piles, including glaciers and ice sheets, tend to spread under their own weight, restrained by their own strength (which is why spilled coffee spreads on a table top but the stronger table beneath does not spread), by friction beneath (so pancake batter spreads faster on a greased griddle than on a dry waffle iron), or by “buttressing” from the sides (so an appropriately placed spatula will slow the spreading of the pancake batter).

Some early gothic cathedrals suffered from the “spreading-pile” problem, in which the sides tended to bulge out while the roof sagged down, with potentially unpleasant consequences. The beautiful solution was the flying buttress, which transfers some of the spreading tendency to the strong earth beyond the cathedral. Ice sheets also have “flying buttresses”, called ice shelves. In the coldest regions, the ice reaching the ocean usually does not immediately break off to form icebergs, but remains attached to the ice sheet while spreading over the ocean. The friction of these ice shelves with local high spots in the sea floor, or with the sides of embayments, helps restrain the spreading of the ice sheet much as a flying buttress supports a cathedral. The ice shelves are at the melting point where they contact water below, and are relatively low in elevation hence warm above. Ice shelves thus are much more easily affected by climatic warming than are the thick, cold central regions of ice sheets. Rapid melting or collapse of several ice shelves has occurred recently, in response to both atmospheric warming and to intrusion of warmer ocean water, allowing the “gothic cathedrals” behind to spread faster, contributing to sea-level rise. Many additional ice shelves remain that have not changed notably, and these contribute to buttressing of much more ice than was supported by those ice shelves that experienced the large recent changes, so the potential for similar changes contributing to sea-level rise in the future is large.

There are no large ice shelves fed by glaciers in warmer areas, including Alaska, southern Greenland, and elsewhere. Warming of air or water beyond some threshold leads to ice-shelf loss, leaving a calving cliff of the sort that tourists visit on Alaskan cruises or that produce Greenland icebergs that have been filmed and viewed tens of millions of times on video-sharing sites.

Many tourists on Alaskan cruises visit Glacier Bay National Park and Preserve, Alaska. When George Vancouver visited the area in 1794, the bay, which is now about 65 miles long, was completely filled with ice. Less than a century later, when John Muir studied there, most of the bay had lost its ice, as icebergs broke off the front of the glacier at a rate of up to 7 miles per year (Meier and Post, 1987; Post, 1975), and the ice thinned by as much as 1 mile (Larsen et al., 2005). As described by Meier and Post (1987) and many other researchers, ice that ends in the ocean often stabilizes on a local high point or a narrowing of a fjord. It then may remain there for some time despite small climate changes. Under sufficiently large forcing, though, it may retreat rapidly through the deeper or wider part of its valley to the next point of stability, losing ice at a rate that tends to increase with water depth and valley width, but that also depends on other controls. Such behavior has been observed from other Alaskan glaciers, in Greenland, and along the Antarctic Peninsula and elsewhere, and geological evidence indicates that such processes contributed to loss of older ice masses during past, natural warmings.

For Glacier Bay, and many others, the glacier flowed in a relatively narrow fjord. When the ice retreated rapidly from one point of stability to the next, the local changes were spectacular, but the global significance was relatively small. Even in Greenland, the beds of the deep fjords rise inland to near or above sea level, and rapid iceberg calving in deep water cannot discharge most of the ice sheet. Some parts of the Antarctic ice sheet, however, have glaciers that drain large basins rather than narrow fjords, but with ice that is much too thick to float and thus that can raise sea level. Attention is especially, but not uniquely, focused on Thwaites Glacier in West Antarctica, where sufficient retreat could trigger loss of the marine ice of West Antarctica that would add about 11 feet to the total sea-level rise (Scambos et al., 2017). One attempt to put this process into a model and simulate the future found that, once rapid retreat was initiated, most of West Antarctica's marine ice would be lost over the next century or so (DeConto and Pollard, 2016). That model, though, did not allow icebergs to calve faster than a rate that was based on previous observations in Greenland; Thwaites could retreat to regions where the water is much deeper and the valley much wider than in Greenland, and the tendency for deeper water and wider valleys to have faster calving then allows the possibility of even faster sea-level rise.

The uncertainties about this topic are very large. Thwaites Glacier, and other Antarctic outlets, may resist retreat, or they may retreat with intact ice shelves that limit iceberg calving and thus slow the resulting sea-level rise, and additional stabilizing influences may resist collapse. But, Thwaites may retreat rapidly, and East Antarctic ice may join, with even greater potential to cause rise than has been modeled by, e.g., DeConto and Pollard (2016). The basic physical processes involved have been known for a long time, but properly modeling them is at a very early stage, subject to deep uncertainty.

Uncertainty and commuting. I am fortunate to ride my bicycle or jog to work; my wife and I share one car, which she mostly drives. But, I have on occasion driven to Washington, DC, and observed automobile commuting. In my experience, a typical commuter on the Beltway heading downtown at rush hour expects notable delays—say, half an hour. The best commute has no delays. Some commuters may waste an hour in traffic. But, occasionally, a commuter is run over by a drunk driver, and ends up in the hospital or worse. When a commuter sets off on a trip, the most-likely future (half an hour in traffic) is close to the “good” end of the possible futures (no traffic, versus run over by drunk driver).

The uncertainties about sea-level rise have a vaguely similar distribution. With warming, ocean water expands, mountain glaciers and the edges of Greenland’s ice sheet melt more, and the ocean rises in response. The relevant science, as assessed by the IPCC or other authoritative bodies, gives very high confidence that some additional sea-level rise is already committed as the ice and ocean “catch up” with the warming already caused. Furthermore, additional warming will cause more sea-level rise. The uncertainties include a little less or a little more sea-level rise. But, those projections do not include major instability of Antarctic ice. If “collapse” is triggered in West or East Antarctica, a natural “drunk driver”, then the sea-level rise could be much larger and faster than in the most-likely projections, with no real agreement on what might be the worst-case scenario.

Dedicated police officers, watchful bartenders, and other community members help reduce drunk driving, while automotive engineers, highway designers, and additional experts help improve safety in the event of an accident. Society thus has considerable knowledge of ways to reduce risks to commuters. But, we still cannot predict the where and when of every drunk driver. Please note that my next statement is potentially self-serving, because colleagues, students, and I personally enjoy conducting research and may receive funding to do research; but, further research can greatly reduce uncertainties on ice sheets and sea-level rise, providing guidance to policy-makers. Nonetheless, even with well-supported, vigorous research, including ongoing efforts by exceptional colleagues, there may remain some irreducible uncertainty.

Synopsis. With high scientific confidence, human actions are raising the greenhouse-gas concentration of the atmosphere especially by releasing carbon dioxide from fossil-fuel burning, this is having a warming influence on the climate, and the resulting rise in temperature is contributing to sea-level rise by expanding ocean water, melting ice, and changing ice flow. Some additional sea-level rise is already committed, but human decisions will become increasingly important in determining how much the sea rises over the coming decades and centuries. If Antarctic ice avoids rapid collapse, then uncertainties in projections of sea-level rise are important but not huge, are being addressed by ongoing research, and can be reduced further by planned research. Rapid iceberg calving under too much warming is a well-known but poorly modeled process; if this becomes active in large, deep Antarctic basins, then sea-level rise could be much larger than generally projected, with much greater uncertainties.

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Short Biography. Dr. Richard Alley (PhD 1987 University of Wisconsin; MSc 1983 and 1980 The Ohio State University, all in Geology) is Evan Pugh University Professor of Geosciences and Associate of the Earth and Environmental Systems Institute at the Pennsylvania State University. He has spent more than 40 years studying the great ice sheets to help predict future changes in climate and sea level, and has made four trips to Antarctica, nine to Greenland, and additional expeditions to Alaska and elsewhere. He has been honored for research (including election to the US National Academy of Sciences and Foreign Membership in the Royal Society), teaching (including Penn State's highest teaching award), and service. Dr. Alley participated in the UN Intergovernmental Panel on Climate Change (co-recipient of the 2007 Nobel Peace Prize), and has provided requested advice to numerous government officials in multiple administrations including a US Vice President, Presidental Science Advisors, and committees and individual members of the US Senate and House of Representatives. He has authored or coauthored more than 300 refereed scientific papers. He was presenter for the PBS TV miniseries on climate and energy *Earth: The Operators' Manual*, and author of the book. His popular account of climate change and ice cores, *The Two-Mile Time Machine*, was Phi Beta Kappa's science book of the year. Dr. Alley is happily married with two grown daughters, two stay-at-home cats, a bicycle, and a pair of soccer cleats.

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Curriculum Vitae

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Selected indicators:

Awards for Teaching, for Research, and for Service.
U.S. National Academy of Sciences member
Royal Society foreign member
Heinz Award in the Environment
Tyler Prize for Environmental Achievement
American Geophysical Union (AGU) Revelle Medal, Fellow, Horton Award (Hydrology), Emiliani Lecturer (Paleo.), Nye Lecturer (Cryospheric Sci.), Bjerknes Lecturer (Atmospheric Sci.) and Public Lecturer
Geological Society of America (GSA) Public Service Award, and Fellow, and Easterbrook Award (Quaternary)
International Glaciological Society (IGS) Seligman Crystal
American Association for the Advancement of Science (AAAS) Public Engagement with Science Award, and Fellow
American Academy of Arts and Sciences Fellowship
European Geosciences Union (EGU) Louis Agassiz Medal (Cryospheric Section)
Schneider Award for Science Communication
American Geological Institute (AGI) Award For Outstanding Contribution To Public Understanding of Geosciences;
Pennsylvania Geographical Society (PGS) Distinguished Geographer Award
Renewable Natural Resources Foundation (RNRF) Sustained Achievement Award
US News and World Reports STEM Hall of Fame.

D.&L. Packard Fellowship, Presidential Young Investigator Award, and G. Comer Mentorship
Honorary Doctorates from University of Chicago, University of Wisconsin and Albion College

Pennsylvania State Evan Pugh Professorship and Faculty Scholar Medal, Eisenhower Award (highest University-wide teaching award, and College of Earth and Mineral Sciences Wilson Teaching Award, Mitchell Innovative Teaching Award and Faculty Mentoring Award.

Wrote book (Norton, 2010) and presented three-hour PBS miniseries based on it, *Earth: The Operators' Manual*. 3.6 million viewers (Nielsen) for first two hours, more from rebroadcasts.
Phi Beta Kappa Science Book Award and Choice Award for *The Two-Mile Time Machine: Ice Cores, Abrupt Climate Change, and Our Future* (Princeton, 2000)
Phi Beta Kappa Science Book Award and American Publishers Awards for Professional and Scholarly Excellence (PROSE Award) in Earth Science for *The Fate of Greenland* (P. Conkling, R. Alley, G. Denton and W. Broecker; MIT Press, 2010)

Independent Publisher Book Awards ‘‘Most Likely to Save the Planet’’ Award, 2010, and the Atmospheric Librarians International Choice Award for *Planet Ice: A Climate for Change*, photography by James Martin, text by Chouinard, Y., Cassasa, G., Alley, R., Stirling, I., Jans, N., Coburn, B. and Ehrlich, G., Braided River, 2009).

Invited presentations/testimony to US government officials in multiple administrations including US Vice President, President’s Science Advisor, two Senate and five House Committees, various senators and representatives, travel to Greenland as a speaker and expert with 10% of U.S. Senate, informal briefing of a larger group of senators, and briefings of additional cabinet-level officials.

Answering inquiries from the press averaging daily; appeared frequently on television (BBC, Nova, etc.), radio (NPR, etc.), print (NYTimes, etc.).

Answering inquiries from citizens, students, etc. more than once/day.

Formal reviews (papers, promotions, etc.) averaging 2/week.

Over 300 refereed publications (and over 60 additional publications including books and popularizations).

Main research contributions:

Provided key data and interpretations helping demonstrate that regional to global climate changes larger than any experienced by agricultural or industrial humans have occurred repeatedly, in decades to as little as a single year; helped reveal mechanisms and possibility of recurrence;

Through data analysis and modeling of ice sheets and glaciers, helped understand ice-bed interactions with implications for flow changes affecting sea level, and for interpretation of geological records, climatic changes and mountain-belt evolution;

Contributed extensively to the toolbox for measurement of ice-core properties, and accurate and confident conversion to well-dated histories of temperature, accumulation rate, and other paleoclimatic variables.

Experience:

Born August 18, 1957, Columbus, Ohio; US Citizen, married, two children
BSc 1980 (With Honors, With Distinction, *Summa cum Laude*) and MSc 1983, The Ohio State University (Geology and Mineralogy).
PhD 1987, The University of Wisconsin (Geology, Minor in Materials Science and Metallurgical Engineering)
Assistant Scientist 1987-88, The University of Wisconsin
Assistant Professor (1988-1992), Associate Professor (1992-1994), Professor (1994-2000) and Evan Pugh Professor (2000-), Department of Geosciences, The Pennsylvania State University

Field Experience:

Three field seasons in Antarctica (geology 1978, glaciology 1984, 1985); eight in Greenland (glaciology 1985, 1989-1992; glacial geology 2003 and twice in 2005), three in Alaska (glaciology 1995, 2000, 2002), two in Utah (geology

1979, 1981); one in Wyoming (glacial geology, 2008); much work (many months in total) in National Ice Core Laboratory, Denver.

Service:

Extensive ongoing or past service at numerous levels, including international (participant in Nobel-Peace-Prize-winning IPCC process on climate change including lead author of the cryospheric chapter and writing team of the Summary for Policymakers and Technical Summary for Working Group I of the Fourth Assessment, as well as participating in Second and Third Assessments; wrote statement based on IPCC used in final document from UN COP16 Climate Change Conference report from Cancun, Mexico), US Government (advice to officials in NOAA, NSF, EPA, CCSP, State Department, etc.; wrote blurb on Antarctic research used by US President in a speech; advice to US Vice President, President's Science Advisor, and to Senators, etc.), National Research Council (chaired Committee on Abrupt Climate Change, served on Polar Research Board, Committee on Environment and National Security, Revelle Lecturer of Ocean Studies Board, chaired committee on redesign of climate-change museum exhibit, etc.), served or serving various research organizations (national and international, including past service to Board of Arctic Consortium of the US, chair of Ice Core Working Group, steering committee of West Antarctic Ice Sheet project, vice president of International Glaciological Society), and university (member or chair of many committees at departmental, college, and university levels). Presenting ~50 public lectures per year (and 69 in 2012).

Teaching and Advising:

Average >3 courses/year while at Penn State.

Typically 6 out of 7 on Student Rating of Teaching Effectiveness; University-wide Eisenhower Teaching Award, and both Wilson and Mitchell Teaching Awards of my college, co-lead professor for CAUSE class trip to US southwestern national parks; efforts highlighted in University President's State of the University message in 2006 and used in many other ways including for new-student and new-faculty orientations; film on the trip won a regional Emmy Award.

Advised numerous senior theses, including winners of a Fulbright Fellowship, the Dean Steidle Scholar Award, and at the National Undergraduate Research Conference, multiple published.

Former advisees at various levels now on faculties at University of California Berkeley, University of Washington, Woods Hole Oceanographic Institution, University of Maryland, University of New Mexico, Lake Superior State University, Northern Illinois University, New Mexico Tech, University of Utah, Miami University (Ohio), and Pennsylvania State University (at both University Park and Dubois campuses); others working for industry and government.

Wrote targeted textbooks for introductory courses, and named a Penn State Undergraduate Student Government "Textbook Hero" for providing comprehensive teaching materials at no additional cost to students.

Bibliography (a few selected papers from more than 300)

1. Alley, R.B., D.D. Blankenship, C.R. Bentley and S.T. Rooney. 1986. Deformation of till beneath ice stream B, West Antarctica. *Nature* **322**, 57-59.

2. Alley, R.B. 1988. Fabrics in polar ice sheets: development and prediction. *Science* **240**, 493-495.

3. Alley, R.B., D.A. Meese, C.A. Shuman, A.J. Gow, K.C. Taylor, P.M. Grootes, J.W.C. White, M. Ram, E.D. Waddington, P.A. Mayewski and G.A. Zielinski. 1993. Abrupt increase in snow accumulation at the end of the Younger Dryas event. *Nature* **362**, 527-529.

4. Cuffey, K.M., G.D. Clow, R.B. Alley, M. Stuiver, E.D. Waddington and R.W. Saltus. 1995. Large Arctic temperature change at the glacial-Holocene transition. *Science* **270**, 455-458.

5. Alley, R.B., P.A. Mayewski, T. Sowers, M. Stuiver, K.C. Taylor and P.U. Clark. 1997. Holocene climatic instability: A prominent, widespread event 8200 years ago. *Geology* **25**, 483-486.

6. Alley, R.B., J. Marotzke, W.D. Nordhaus, J.T. Overpeck, D.M. Peteet, R.A. Pielke, Jr., R.T. Pierrehumbert, P.B. Rhines, T.F. Stocker, L.D. Talley and J.M. Wallace. 2003. Abrupt climate change. *Science* **299**, 2005-2010.

7. Alley, R.B., D.E. Lawson, E.B. Evenson, G.J. Larson and G.S. Baker. 2003. Stabilizing feedbacks in glacier bed erosion. *Nature* **424**, 758-760.

8. Denton, G.H., R.B. Alley, G.C. Comer and W.S. Broecker. 2005. The role of seasonality in abrupt climate change. *Quaternary Science Reviews* **24**, 1159-1182.

9. Alley, R.B., S. Anandakrishnan, T.K. Dupont, B.R. Parizek and D. Pollard. 2007. Effect of sedimentation on ice-sheet grounding-line stability. *Science* **315**, 1838-1841.

10. Alley, R.B., H.J. Horgan, I. Joughin, K.M. Cuffey, T.K. Dupont, B.R. Parizek, S. Anandakrishnan and J. Bassis. 2008. A simple law for ice-shelf calving. *Science* **322**, 1344-1344.

11. Walker, R.T., B.R. Parizek, R.B. Alley, S. Anandakrishnan, K.L. Riverman and K. Christianson. 2013. Ice-shelf tidal flexure and subglacial pressure variations. *Earth and Planetary Science Letters* **361**, 422-428.

12. Zoet, L.K., R.B. Alley, S. Anandakrishnan and K. Christianson. 2013. Accelerated subglacial erosion in response to stick-slip motion. *Geology* **41**, 159-162.