Learning Resources

Details

Completion Time: Less than a week

Permission: Download and Share

Coming or Going: Where does Antarctica's Ice Fit In?

Materials

- Graph paper
- Colored pencils
- Ruler
- Calculator
- Topographic maps: Ford Ranges, Marie Byrd Land, Antarctica and Reedy Glacier, Antarctica; Antarctic Continent
- Computers with Microsoft Excel (optional)
- Powerpoint Presentation (attached)
- Handouts, worksheets, and maps (attached)

Overview

The long-term objective of PolarTREC teacher Lesley Urasky's expedition research in Antarctica (Glacial History in Antarctica) is to determine the rate at which glaciers have receded since the Last Glacial Maximum. This lesson is designed to give students an understanding of the Last Glacial Maximum, the climatic conditions that lead to glacial periods, and how the rate of glacial retreat can be determined. Students will have an opportunity to use real data collected by researcher John Stone (University of Washington) and his teams from earlier expeditions to glaciers along the Transantarctic Mountains in Antarctica.

Objectives

- To be able to describe the climatic and geographic (sea level and ice sheet coverage) conditions that existed during the Last Glacial Maximum
- To be able to compare the climatic and geographic conditions of the Last Glacial Maximum to the Present
- To be able to describe how past climates can be reconstructed using a glacier's equilibrium line altitude (ELA) and glacial ice cores
- To be able to accurately plot exposure age data and use this data to determine the rate of glacial retreat.
- To be able to plot sample locations accurately on a topographic map and link these geographic locations and glacial retreat rates to climate changes across geologic time.

Lesson Preparation

The basics of glacial morphology, formation, and movement may need to be addressed prior to conducting these activities. Students will need to understand the basics of glacial growth and retreat in order to fully comprehend how knowledge of a glacier's ELA helps scientists understand past climate. The links to several internet-based interactive tutorials and activities on glaciers have been given at the end of this document.

To prepare for Part I: What is the Last Glacial Maximum (LGM)?, teachers need access to a computer and LCD projector to show the PowerPoint presentation. Colored pencils and rulers need to be available to students for completion of the Dome C (EPICA) ice core diagram. It may also be helpful to either show students or have them work through the following websites:

- Rocky Mountain National Park: Glaciers and Glacier Change - Timeline of Recent Ice Ages interactive (http://www.nps.gov/features/romo/feat0001/BasicsIceAges.html)
- Rocky Mountain National Park: Glaciers and Glacier Change – Glaciers and Climate interactive (http://www.nps.gov/features/romo/feat0001/BasicsGlcClim.html)

To prepare for Part II: Climate Change and Glacial Size, teachers need to decide if students will be graphing the data by hand or will use Microsoft Excel. There are two different files included: a hard copy Global ELA data table as well as an Excel file containing Global ELA data. The one used will depend upon the selected method of data analysis. There is also a separate document that gives brief descriptions of how to graph the data using Excel in case this is an unfamiliar method.

To prepare for Part III: Antarctic Glacial Retreat Analysis, teachers need to decide if students will be graphing the data by hand or will use Microsoft Excel. There are two different files included: a hard copy set of data for the following locations: Ford Ranges, Marie Byrd Land; Reedy Glacier; and Mt. Rigby, Scott Glacier as well as an Excel file containing data for these sampling sites.

The topographic maps for the Ford Ranges and Reedy Glacier will need to be copied for each student or group of students. Each of these maps is in two parts, a right and a left side, which will need to be assembled after copying (unless the copier supports extra-large pieces of paper). There is a red line on each of the map halves indicating where the maps join together. Depending upon the age of the students and/or their experience with topographic maps, the teacher may want to enlarge the maps when copying them. (If they are enlarged, make sure each one is enlarged by the same percentage.) If this exercise is planned for several classes, laminating the assembled maps is highly suggested.

Procedure

Part I: What is the Last Glacial Maximum (LGM)?

The PowerPoint presentation "The Last Glacial Maximum" is shown to students. While viewing the presentation, students will complete the accompanying worksheet. After completing the presentation portion of the lesson, students will read the background information given about the glacial and interglacial periods of the Quaternary. Using the given explanation of how scientists use glacial ice cores to determine the climate at the time a glacier formed, students will complete the diagram of Dome C from the European Project for Ice Coring in Antarctica (EPICA) and answer the following questions.

Part II: Climate Change and Glacial Size
After reading the background information about glacial equilibrium line altitudes, students will plot the climate data for the 70 glaciers. They may plot them either by hand or use the Excel file to create a scatter graph. Using the background information along with the student-generated graph, students will answer the analysis questions.

Part III: Antarctic Glacial Retreat Analysis
Students will create three graphs from the retreat data for each of the sample sites: Ford Ranges, Marie Byrd Land; Reedy Glacier; and Mt. Rigby on Scott Glacier. Using these graphs, they will draw trend lines for each of the data sets and calculate the rate of retreat of the glacier at each of the sample sites. The Ford Ranges and Reedy Glacier sample sites will be plotted on their respective topographic maps, while the three general sample locations will be plotted on a map of the Antarctic continent. Using all of these resources (graphs with trend lines, completed data tables showing rate of retreat, and the background information), students will answer the analysis questions.

Extension
n/a

Resources
- Rocky Mountain National Park: Glaciers and Glacier Change - Timeline of Recent Ice Ages interactive http://www.nps.gov/features/romo/feat0001/BasicsIceAges.html
- Rocky Mountain National Park: Glaciers and Glacier Change - Glaciers and Landscapes interactive http://www.nps.gov/features/romo/feat0001/BasicsGlcLandscape.html
- Rocky Mountain National Park: Glaciers and Glacier Change – Glaciers and Climate interactive http://www.nps.gov/features/romo/feat0001/BasicsGlcClim.html
- NOVA: Mountain of Ice – Life Cycle of a Glacier http://www.pbs.org/wgbh/nova/vinson/glacier.html
- Using ice cores to understand past climates: http://www.antarctica.ac.uk/bas_research/science/climate/icecore/page1.php
- NOAA Paleoclimatology: Exploring Weather and Climate Change Through the Powers of 10 http://www.ncdc.noaa.gov/paleo/ctl/
- Interactive computer simulation of glaciers and their movement: http://phet.colorado.edu/en/simulation/glaciers
- Interactive flashcards on glacial vocabulary: http://quizlet.com/16231986/noaa-glaciers-flash-cards/

Assessment
Summative assessment: Parts I, II, and III of the lesson. Teacher answer key is provided. All three parts may be completed together, or each one can stand alone.

PolarTREC Learning Resources

Credits

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Parts I and II of this lesson were adapted from the following source:

- Anderson, D. (n.d.). Glacial landscapes: Past climate and glaciation of the Drakensberg Mountains, southern Africa. Retrieved January 4, 2013, from Royal Geographical Society with Institute of British Geographers: http://www.rgs.org/OurWork/Schools/Teaching+resources/Key+Stage+5+resources/Key+Stage+5+-+From+the+field+resources/Glacial+landscapes/Glacial+landscapes.htm

Data for Part III is a result of research conducted in Antarctica by Dr. John Stone and colleagues of the University of Washington:

- Complete data sets can be found at the following sites:

Stone J.O., Balco G., Sugden D.E., Caffee M.W., Sass L.C. III, Cowdery S.G. and Siddoway C. (2003) Late Holocene deglaciation of Marie Byrd Land, West Antarctica Science 299, 99-102.
Input data for cosmogenic Be-10 calculations, Mt Rigby, Scott Glacier retrieved from: http://depts.washington.edu/cosmolab/data/Scott_Glacier_exp_ages.html
Exposure ages: Reedy Glacier, Antarctica retrieved from: http://depts.washington.edu/cosmolab/data/Reedy_Glacier_exp_ages.html

POLAR TREC Learning Resources

National Science Education Standards (NSES)

Content Standards, Grades 9-12

Content Standard A: Science as Inquiry
a. Abilities necessary to do scientific inquiry
b. Understandings about scientific inquiry

Content Standard D: Earth and Space Science
a. Energy in the earth system
b. Origin and evolution of the earth system

Content Standard E: Science and Technology
a. Understandings about science and technology

Content Standard G: History and Nature of Science
a. Science as a human endeavor
b. Nature of scientific knowledge
c. Historical perspectives

Other Standards
Next Generation Science Standards (from January 2013 draft: subject to final adoption)

HS.ESS-SS: Space Systems
ESS1.B: Earth and the Solar System

HS.ESS-HE: History of Earth
ESS2.E: Biogeology

HS.ESS-ES: Earth's Systems
ESS2.A: Earth Materials and Systems
ESS2.C: The Roles of Water in Earth's Surface Processes

HS.ESS-CC: Climate Change
ESS2.D: Weather and Climate

Coming or Going: Where Does Antarctica's Ice Fit In?

Part I: What is the the Last Glacial Maximum (LGM)?

Answer the following questions while viewing the associated PowerPoint presentation: "The Last Glacial Maximum".

1. When was the Last Glacial Maximum (LGM)?

2. How can the temperatures during the LGM be described?

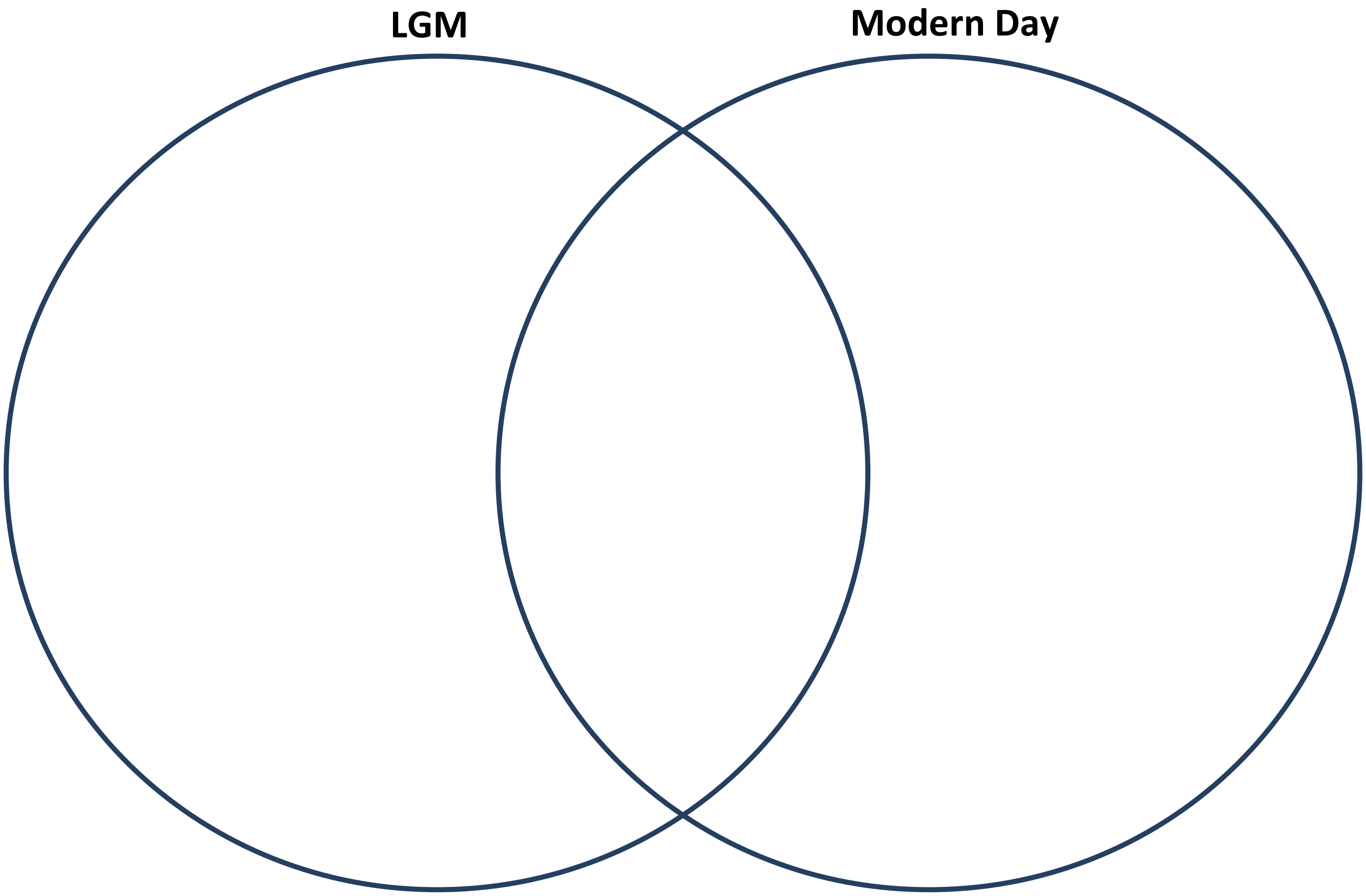
3. How much of the Earth's surface was covered by ice (compared to today's coverage)?

4. Would your state have been covered by the Laurentide Ice Sheet? Explain.

5. Looking at the Ice Age Temperature Changes graph, how many high temperature periods similar to our current period, the Holocene, has the Earth experienced in the past 450,000 years, and when did they occur?

6. Is there a correlation between the Antarctic ice core data and the red ice volume curve on the Ice Age Temperature Changes graph? If so, describe it.

7. Compare and contrast the extent of sea ice and continental ice coverage in the Northern Hemisphere between the LGM and modern day.



8. Comparing global glacial coverage: By what percentage did the following continental coverage increase (+) or decrease (-) from the LGM to Modern Day?

   Antarctica: 30% to 85%

   Greenland: 5% to 11%

   Remainder of the World: 65% to 4%

9. Why do you think that the percentages of ice grew in Antarctica and Greenland if we are in an interglacial period?

Read the following information about the Quaternary Period of Earth's geologic time and, using the associated graph containing ice core data from Antarctica's EPICA Dome C, complete the following steps. When you are finished annotating the graph, answer the questions that follow.

The Quaternary Period can be divided into two epochs, the Pleistocene and the Holocene. The Pleistocene Epoch began about 2.6 million years ago. It is famous for the megafauna that were alive at that time like the woolly mammoth and saber tooth tigers. We are living in the Holocene Epoch, which began 11,700 years ago (approximately 500 human generations)! The Holocene is broken into its own epoch because of its uniqueness: a warm time frame when early agriculture and the first civilizations developed.

Throughout geologic time, the Earth has experienced changes in the environment and climate. We know the most about recent changes because over time, geologic processes "erase" evidence of earlier events through the rock cycle and plate tectonics. The recent changes that we have data for are from the Quaternary Period. It is unique because it is characterized by a relatively cold climate with major ice sheets covering large portions of the Earth. The Pleistocene is the time of the Last Glacial Maximum (LGM).

Another characteristic of the Quaternary is that the Earth's climate has been highly variable. There have been repeated periods of warmer and colder climates. The diagram below (not to scale) [Figure 1], summarizes this period's climate change. Throughout the Quaternary, there have been a series of interglacial and glacial cycles. The Holocene is the most recent interglacial period and is similar to those that occurred episodically throughout the Pleistocene.

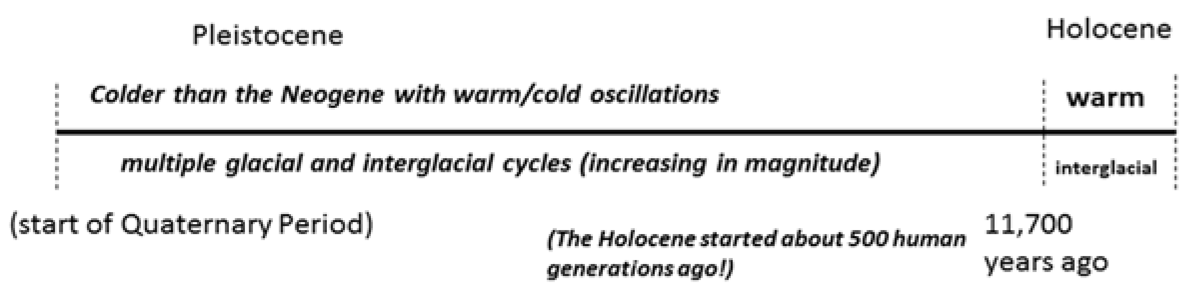


Figure 1: Glacial and interglacial cycles of the Quaternary (Anderson, 2012)

The element Hydrogen, exists in Earth's atmosphere as water vapor (H_2O). The amount of water vapor in the atmosphere is affected by the ambient air temperature; the warmer the air, the more water it can hold, while the colder the air, the less water it can hold. Water vapor is preserved within air bubbles in layers of ice. Paleoclimatologists can reconstruct the composition of the atmosphere that existed at the time a particular sample of ice formed. One of the ways they can do this is through looking at the ratio of hydrogen isotopes (they also look at many other elements for a complete picture). (Isotopes of an element have varying numbers of neutrons. This means they have different atomic masses. The atomic mass that you see on the periodic table is an average of the masses of all the element's isotopes. All elements exist as a variety of isotopes in nature.) The isotopes of interest in paleoclimatology are deuterium (^2H – also known as 'heavy Hydrogen') and hydrogen (^1H). In warmer times, there are more deuterium atoms than hydrogen atoms. In colder periods, the opposite is true; there are more hydrogen atoms than those of deuterium. For example, a less negative ratio would indicate a much warmer climate than a more negative (less deuterium-hydrogen) ratio.

The graph on the following page (Figure 2) shows the glacial and interglacial cycles reconstructed from an ice core extracted by the European Project for Ice Coring in Antarctica (EPICA) at Dome C. This core was drilled on the East Antarctic Ice Sheet. The surface where the drilling rig was located is at 3,233 m above sea level. They reached bedrock at a depth of 3,270 m; this means that the ice is 3,270 m (almost 2 miles) thick!

Complete the EPICA Dome C diagram on the next page by following the directions below:

1. Draw a vertical line from today's Deuterium/Hydrogen ratio (-400) to the bottom of the diagram using a ruler.
2. Draw a horizontal line across the diagram to indicate the end of the Pleistocene and the beginning of the Holocene (see the background information for the date).
3. Look at your vertical line and identify other intervals in the Quaternary where the temperatures were similar to those today. Bracket each of these intervals with a horizontal line and shade them in with a red colored pencil. At what times did the temperatures within these interglacial periods peak? Write the time (years ago) within the right margin of the diagram.
4. How many of these interglacial periods reached temperatures warmer than today? ____ Indicate these with a star next to the time.
5. Do you notice a pattern in the glacial/interglacial cycles from about 450,000 years ago towards the present? _______ Describe this pattern.

6. The most recent glacial phase began about 115,000 years ago. It ended around 18,000 years ago. Draw a horizontal line across the diagram at each of these times. Shade the area in between the lines with a blue colored pencil and label it as the Last Glacial Maximum (LGM)
7. How much of Earth's history did the LGM span? Record your answer in thousands of years.

8. What percentage of Earth's history is comprised of Quaternary glacial periods? The Earth is roughly 4.6 billion years old (4.6 x 10^9 years). A thousand years is 1 x 10^3 years. For **<u>full credit</u>**, show your work below! Report you answer to three decimal places.

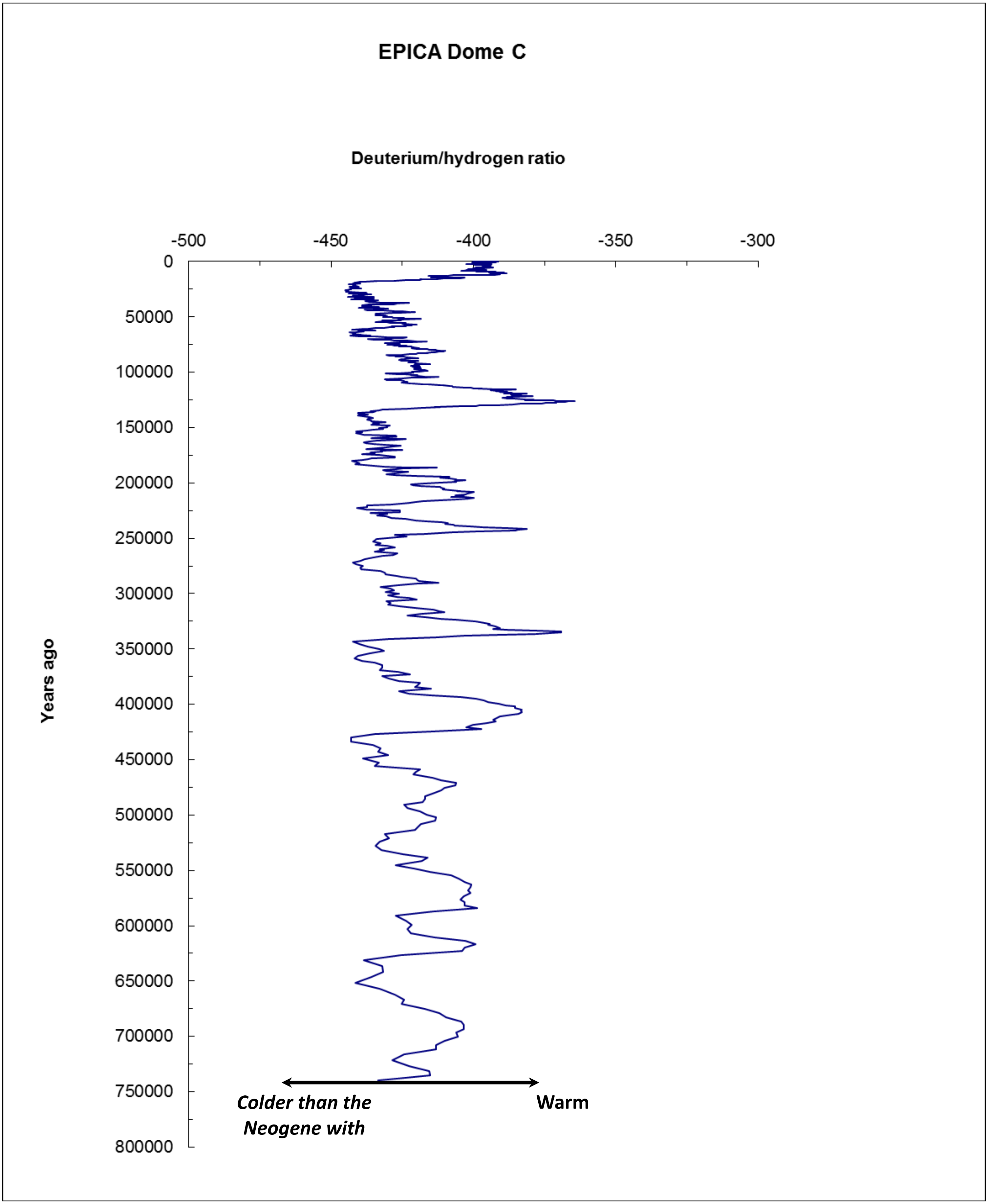


Figure 2: the European Project for Ice Coring in Antarctica (EPICA) at Dome C

Part II: Climate Change and Glacial Size

The equilibrium line altitude (ELA) of a glacier is the point where the snowfall adding to the glacier's mass is equal to the amount of glacier's mass lost through melting. The glacier's accumulation zone (above the ELA) is where snow or ice is added to the glacier through snowfall, freezing rain, avalanches, or wind-blown snow. The ablation zone (below the ELA) is where the processes of melting, sublimation, and evaporation remove ice from the glacier's mass (Figure 3).

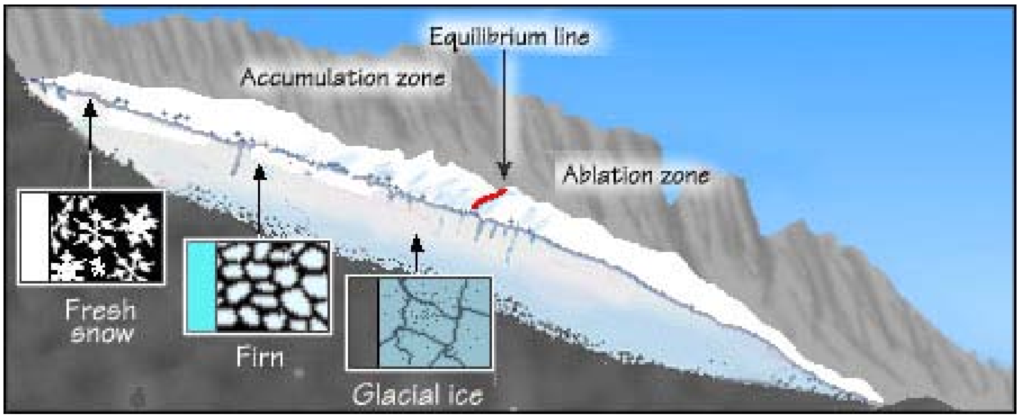


Figure 3: Equilibrium Line of a Glacier (Source: Glacier Change in the Upper Skagit River Basin, http://www.glaciers.pdx.edu/Projects/LearnAboutGlaciers/Skagit/Basics00.html)

The climate of an area where a glacier is found affects the mass balance of a glacier. The net balance (measured over the course of a year) is the difference between accumulation and ablation for the entire glacier. If the mass balance of a glacier is stable, the accumulation of snow and ice equals the amount of ice lost by the glacier. For most glaciers located in temperate ecosystems, the winter balance is positive, and the summer balance is negative (Figure 4).

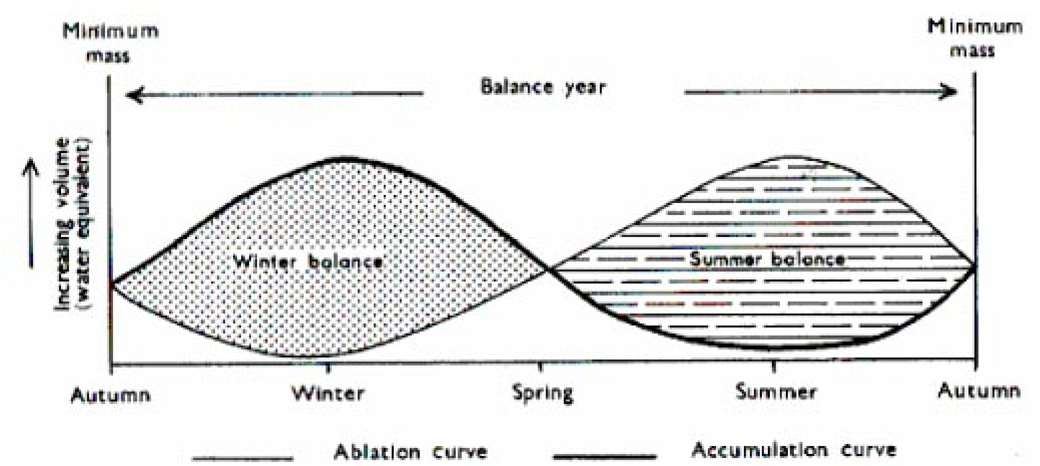


Figure 4: Annual Net Balance of a Glacier (Source: Revision World: http://revisionworld.co.uk/a2-level-level-revision/geography/glacial-environments/introduction-modules/cross-profile)

If more mass is gained overall than lost, the glacier has a positive mass balance and is growing (either in length or thickness). Climatic conditions that can cause a positive mass balance are colder temperatures and/or periods of increased precipitation. If more mass is lost than gained, the glacier has a negative mass balance and is shrinking (retreating – becoming shorter in length or becoming thinner – decreasing volume of ice). Negative mass balance occurs when the climate is warmer and/or drier (Figure 5).

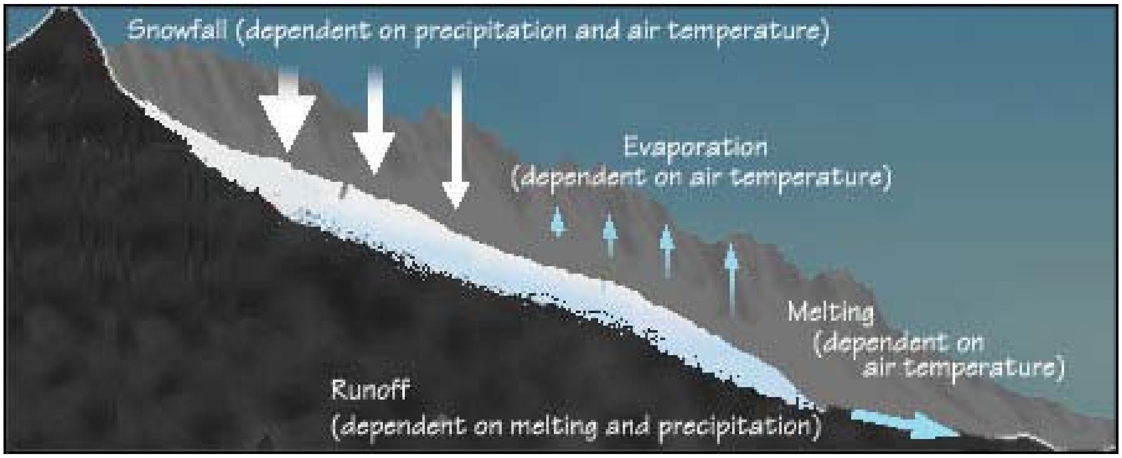


Figure 5: Simplified diagram of glacier mass budget, showing major mass input and outputs
(Source: Glacier Change in the Upper Skagit River Basin,
http://www.glaciers.pdx.edu/Projects/LearnAboutGlaciers/Skagit/Basics00.html)

Glaciers respond to environmental conditions that last a few decades. Because of this their trends are useful in climate studies. Several studies exist that have considered the relationship between the ELAs of glaciers and their present climate relationships. Scientists can take what they know about ELAs and climate and extrapolate this knowledge to reconstruct past glacial conditions. In order to be able to reconstruct past ELAs, scientists must be able to determine the extent (size) of the glacier in the past. To do this, they need to be able to identify moraine locations that indicate the length (terminal moraine) and width of the glacier (lateral moraine).

As a glacier loses mass, some of the first landforms to be exposed are along the terminus (toe) of the glacier as well as regions along its sides. If the glacier or ice sheet is overlying a landscape with large variations in topography, the tops of hills or mountains having greater elevations than the surrounding area will also be exposed early on. In Antarctica and the Arctic, these features are called nunataks. A nunatak is a small mountain or rocky outcrop projecting from and surrounded by a glacier or ice sheet.

Procedure:

1. Using the data given on the attached handout: "Climate Data for 70 Glaciers at Their Equilibrium Line Altitudes" (Anderson, 2012), create a scatter graph of the "Average Summer Temperature (°C)" vs. "Winter Accumulation + Summer Precipitation (mm)".

2. Draw a Best Fit Line through your data points. A 'line of best fit' summarizes the relationship between data. If the points lie close to the line, a strong correlation exists. If there appears to be a trend, but the points don't lie close to the line, the correlation is weak.
3. Answer the following analysis questions.

Analysis

1. Describe the relationship between the temperature and accumulation. Is it a 'positive' or 'negative' correlation? (Hint: look at the slope of your Best Fit Line.) Explain.

2. Is there a strong or weak correlation in your data? Explain.

3. Your scatter graph should suggest that when the summer temperature is higher at the ELA of a glacier, the accumulation must also increase. Why do you think this is the case?

4. If precipitation (winter and summer) is low, then the summer temperature is usually low. Based on what you've learned about glaciers, why does this relationship have to exist in order for a glacier to form?

5. From the graph you created, it is apparent that when temperatures increase, precipitation also increases. If this is true globally, why do you think the majority of Earth's glaciers have a negative mass balance (why are they shrinking)?

6. It is not difficult to determine where the ELA is located on a glacier. What do you think the appearance of the glacier's surface will be like above the equilibrium line? Below the equilibrium line?

7. What assumptions must scientists make if they are to use current glacial and climate data and apply it to glaciers in the past?

8. Discovering the ELA of former glaciers provides useful information about the climate at the time the glacier existed. Knowing that temperature decreases, on average, 2-3°C for every 1,000 meters of elevation gained, how might determining the location of the ELA of a glacier help reconstruct past climates? (Hint: If the equilibrium line were to occur at a lower altitude than present ELAs, what might that say about temperatures of the paleoclimate?)

Part III: Antarctic Glacial Retreat Analysis

Scientists have been collecting data for several years that give them the date glacially transported rocks were exposed to the atmosphere. The samples were found in moraines from the Last Glacial Maximum. As glaciers shrink, rocks that were buried deep within the ice gradually become exposed on the surface of landforms surrounding the glacier (lateral moraines). This is known as losing glacial mass.

Once these rocks are exposed to the atmosphere, they begin to be bombarded by cosmic rays from outer space. These rays can penetrate the Earth's surface up to 10 meters deep. As these rays enter the rocks, they interact with the atoms making up the rock. These interactions involve striking the nucleus of the atom and knocking off a neutron or proton. Stray neutrons are captured by another element. As neutrons are captured, the atom becomes an isotope of that element; they are known as cosmogenic nuclides. Researchers, such as John Stone of the University of Washington, take these rocks and break them down to isolate individual atoms.

The isotopes scientists focus on are Beryllium-10 (^{10}Be), Chlorine-36 (^{36}Cl), and Aluminum-26 (^{26}Al). You are probably most familiar with Beryllium-9 (^{9}Be), Chlorine-35 (^{35}Cl), and Aluminum-27 (^{27}Al) on the periodic table. Once the rock samples are processed to isolate individual atoms, they are run through an accelerated mass spectrometer (AMS) (Figure 6) to look at the ratios of the desired isotopes: ^{9}Be:^{10}Be, ^{36}Cl:^{35}Cl, and ^{26}Al:^{27}Al. "Accelerator mass spectrometry (AMS) is a technique for measuring long-lived radionuclides that occur naturally in our environment. AMS uses a particle accelerator in conjunction with ion sources, large magnets, and detectors to separate out interferences and count single atoms in the presence of $1x10^{15}$ (a thousand million million) stable atoms." (Department of Physics, Purdue University, 2013). Cosmogenic nuclide measurements can be used for various dating application in geology, archaeology, and biomedicine.

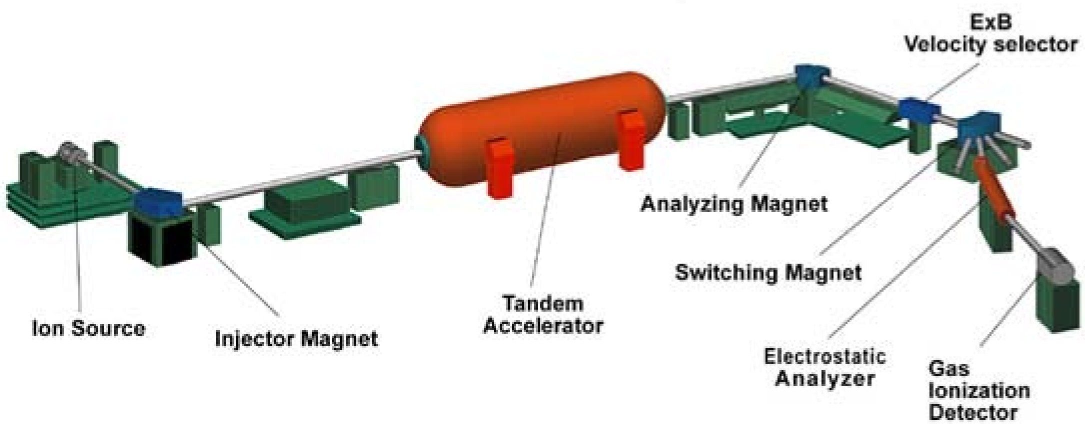


Figure 6: Generalized Accelerated Mass Spectrometer (Department of Physics, Purdue University, 2013)

When compared to a known baseline, these ratios tell scientists how long these samples have been exposed to the atmosphere. There are several assumptions that scientists must make. Unfortunately, science conducted in the natural world has several variables that make it very difficult to isolate just one. (In class, you are taught that only one variable can be tested at a time; when conducting science outside of a controlled laboratory environment, to compensate for multiple variables, assumptions must be made.) Some of these assumptions are: there is a steady production of the measured isotope, the sample has been continually exposed since its initial contact with the atmosphere, and no erosion has occurred at the sampling site. Some factors that affect the production of cosmogenic nuclides are: the concentration of target nuclides (atoms that lose a neutron), elevation (samples are closer to space), geomagnetic latitude (higher latitudes have less protection from the Earth's magnetosphere), and surface orientation (are samples sheltered by other landscape features). Other factors affect the accumulation of cosmogenic nuclides: the production rate as well as the rate of erosion (either of the sample itself or of the overlying materials).

Once all of these assumptions and production/accumulation factors have been considered, the researchers can determine an age since initial exposure. The longer a sample has been exposed, the greater the concentration of cosmogenic nuclides. The most accurate dates are from those samples that have been exposed for long periods of time at high elevations. Young samples, those that only have ages of a few hundred years, tend to have large errors (± 5-10%) and are not considered as reliable. Older samples or those that have been collected from high elevations are much more reliable, with a low percentage of error (± 1-2%). This means that if a sample is dated to be 16,000 years old, in reality, it could be anywhere from 15,680-16,320 years old.

For this exercise, you will be using actual data collected by Dr. John Stone (University of Washington) and his team. They have sampled moraines created during the Last Glacial Maximum that have been exposed as glaciers across Antarctica have begun to retreat. The majority of these moraines are lateral, lying alongside the outside margins of the glacier. Some samples exposed by the shrinking glacier were also collected from nunataks within the confines of the glaciers. Due to the manner in which glaciers shrink, from the top down, it stands to reason that higher elevations are exposed first. Therefore, one would expect that samples collected at higher elevations would have older exposure ages than those samples collected at lower elevations (Figure 7).

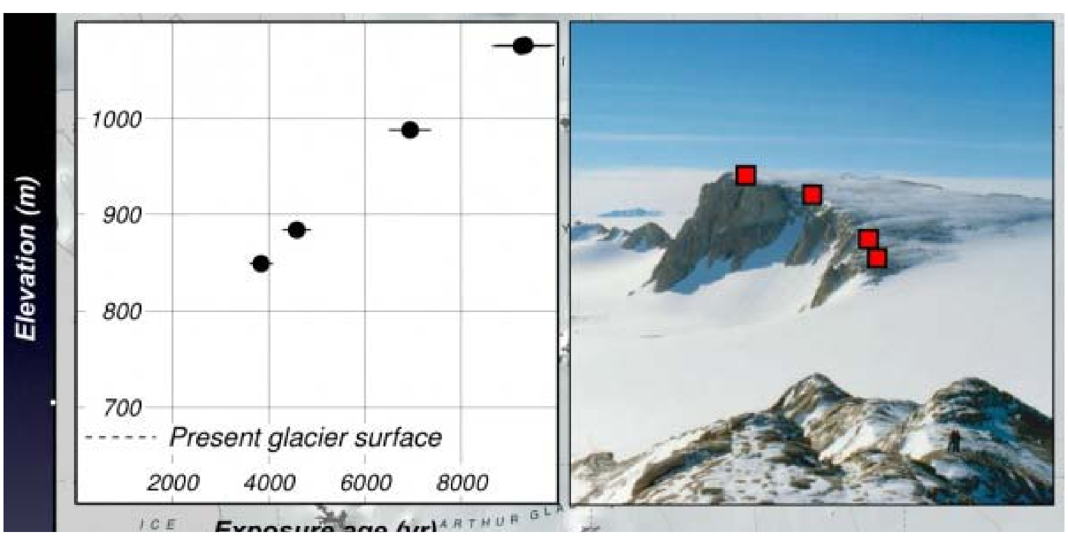


Figure 7: Elevational Influences of Surface Exposure Ages. (Image Source: Greg Balco, University of Washington)

Because conducting research in Antarctica is very expensive and the window of time field research can be conducted is very narrow, the data you will be working with was collected and processed over a period of years (2003-2007).

Procedure:

1. Using the data given on the accompanying handout of Antarctic data, create a scatter graph for the ^{10}Be Exposure Ages of Glacial Erratics, Ford Ranges, Marie Byrd Land, Antarctica data set.
    a. You will be plotting Exposure Age (1×10^3 years) vs. Elevation (m).
2. Don't forget to include all the important components of a graph such as:
    a. Title
    b. Correctly scaled axes
    c. Labels that include units on the axes
    d. Key.
3. On the graph, draw a Best Fit Line through each set of data points. A 'line of best fit' summarizes the relationship between data. In this case, the line indicates the rate of glacial retreat/shrinking (positive slope) or glacial growth (negative slope).
4. Determine the rate of retreat for each set of data by calculating the slope of each data set's line of best fit. Enter these values into the data table.
5. Determine the average age of each sample site. Enter this information in the data table.
6. On the Ford Ranges map, plot each of the sample locations.
7. Using the data given on the accompanying handout of Antarctic data, create a scatter graph for the ^{10}Be Exposure Ages of Glacial Erratics, Reedy Glacier, Antarctica data set.
    a. Repeat steps 2 through 5 for this data set.
8. On the Reedy Glacier map, plot each of the sample locations.
9. On the map of the Antarctic continent, plot the location of each of the three data sets.
10. Answer the following analysis questions.

Analysis:

Ford Ranges, Marie Byrd Land, Antarctica

1. What is the average age of samples at Mt. Rea? ____
2. What is "statistical error?

3. What is the average error for this location (Mt. Rea)? _________________ This means that the rocks sampled here could represent a range of years during which the glacier retreated enough to expose the rocks. This could have happened anytime between _________________________ and ____________________________________.

4. Consider the data plotted on your graph for the Ford Ranges in Marie Byrd Land, Antarctica. Of these seven locations, the Boyd and Balchen glaciers are retreating at varying rates. List the locations in order from the slowest retreat to the most rapid retreat.

   a. Slowest____
   b. ____
   c. ____
   d. ____
   e. ____
   f. ____
   g. Most rapid____

5. One would expect a glacier to begin retreating at its terminus as well as along its margins. The terminus for each of these glaciers (Boyd and Balchen) is to the west. Looking at your map, list the sample locations from the farthest east to the most westerly.

   a. Farthest east____
   b. ____
   c. ____
   d. ____
   e. ____
   f. ____
   g. Most westerly____

6. Do you see any pattern in the rates of retreat and the sample location relative to the glacier's terminus? ______ Hint: look for increasing or decreasing rates of retreat as you move inland from the glacier's terminus as well as patterns related to the elevations of sample locations. If so, explain the pattern(s) you see.

7. Why do you think Mt. Darling/Mt. Spencer may have one of the oldest ages of exposure?

8. Mt. Van Valkenberg is the furthest east and therefore, the furthest from the glacier's terminus. It also has the highest elevation of all the sample sites. Why do you think is has a younger exposure age than the Mt. Darling/Mt. Spencer sample site? In other words, why do you think it is younger than you would expect?

Reedy Glacier, Antarctica

9. Looking at the data, are there any samples at lower elevations that have greater ages than samples collected at higher elevations? _______ At which location(s)?

10. Explain why these ages might be greater than expected. Please give at least two reasons.

11. What is a shear force?

12. A glacier's shear margin is usually found at the edges where the glacier is moving past the surrounding rock. What is most likely happening along these edges that would cause the samples here to exhibit the youngest exposure ages?

13. Quartz Hills has the oldest exposure age of the four sampling sites (12,600 years – 10,200 years). Why do you think this is even though it is much further from the glacier's terminus than the other sites?

Rate of Retreat in Antarctica:

14. Which of the three locations would have most affected by geomagnetic latitude?

15. In general, does the data from all of the sample sites (Ford Ranges, Reedy Glacier, and Mt. Rigby on Scott Glacier) reflect the idea that as a glacier begins to retreat, higher elevations are exposed first? Hint: Look at the data tables and your graphs to analyze the elevation vs. exposure age data.

16. Order the three sample sites from their oldest average exposure age to the youngest. Include their average age.
    a. Oldest: ____
    b. ____
    c. Youngest: ____

17. Scientists have found that the ice in Western Antarctica is melting much more rapidly than in Eastern Antarctica. How might this research and associated data help with climate change predictions?

Teacher Answer Key

Coming or Going: Where Does Antarctica's Ice Fit In?

Part I: What is the the Last Glacial Maximum (LGM)?

Answer the following questions while viewing the associated PowerPoint presentation: "The Last Glacial Maximum".

1. When was the Last Glacial Maximum (LGM)?

26,000-18,000 years ago

2. How can the temperatures during the LGM be described?

The average temperatures reached a minimum.

3. How much of the Earth's surface was covered by ice (compared to today's coverage)?

3 times.

4. Would your state have been covered by the Laurentide Ice Sheet? Explain.

Answers will vary; based upon the map shown in slide 4 and student location. If European students are using this, change the question to ask about the Scandinavian Ice Sheet.

5. Looking at the Ice Age Temperature Changes graph, how many high temperature periods similar to our current period, the Holocene, has the Earth experienced in the past 450,000 years, and when did they occur?

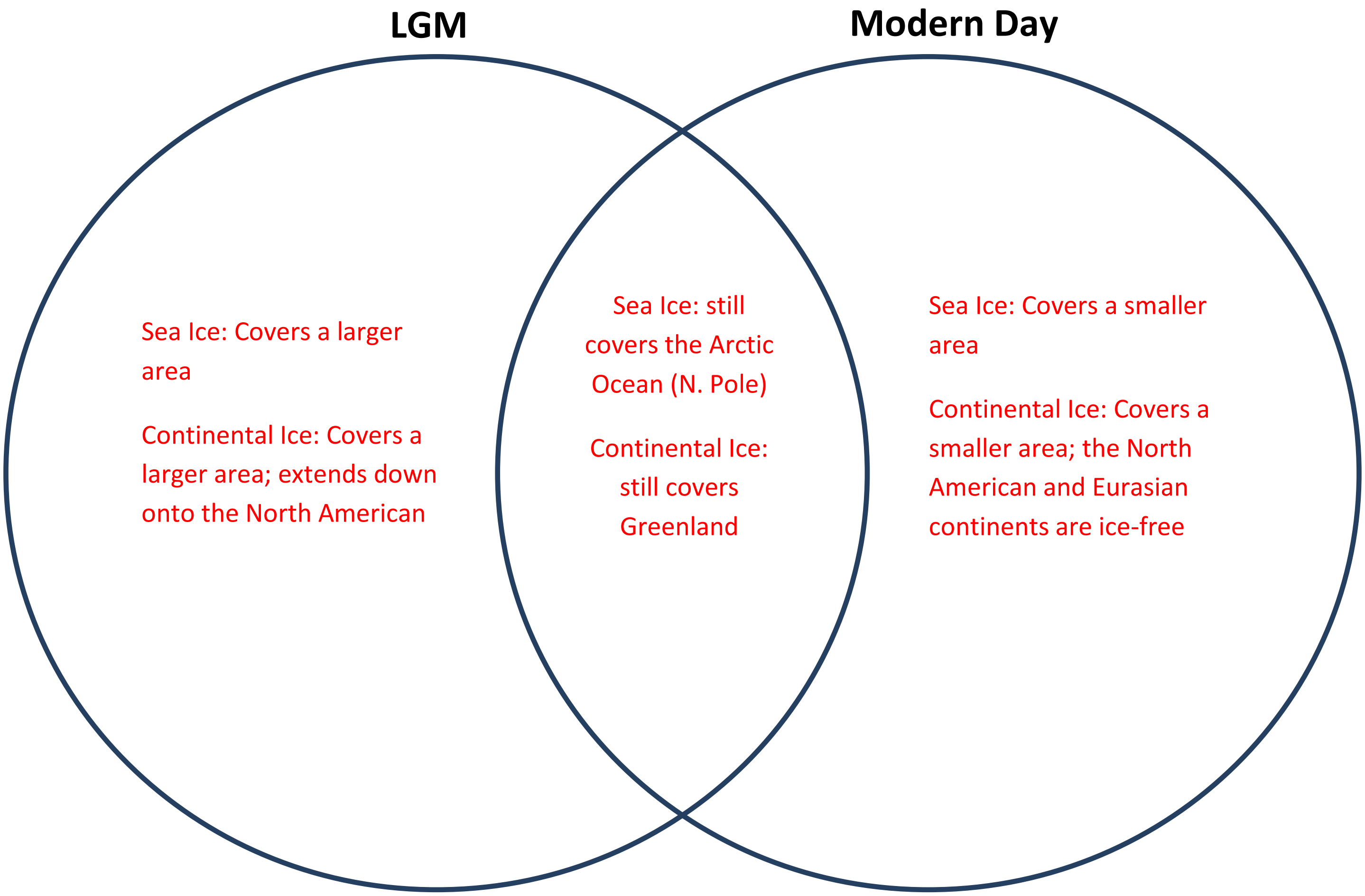
3 periods, approximately 125,000, 325,000, and 415,000 years ago.

6. Is there a correlation between the Antarctic ice core data and the red ice volume curve on the Ice Age Temperature Changes graph? If so, describe it.

Yes. The lowest temperatures (deviating from current temperatures) correspond to the greatest volume of ice.

Teacher Answer Key

7. Compare and contrast the extent of sea ice and continental ice coverage in the Northern Hemisphere between the LGM and modern day.



8. Comparing global glacial coverage: By what percentage did the following continental coverage increase (+) or decrease (-) from the LGM to Modern Day?

Antarctica: 30% to 85% +55%

Greenland: 5% to 11% +6%

Remainder of the World: 65% to 4% -61%

9. Why do you think that the percentages of ice grew in Antarctica and Greenland if we are in an interglacial period?

Percentages of ice in Antarctica and Greenland grew because around the globe, ice sheets were shrinking, thus boosting Antarctica's and Greenland's content. (Globally, the overall amounts of ice diminished greatly. What ice is left is now primarily located in Antarctica and Greenland.)

Read the following information about the Quaternary Period of Earth's geologic time and, using the associated graph containing ice core data from Antarctica's EPICA Dome C, complete the following steps. When you are finished annotating the graph, answer the questions that follow.

The Quaternary Period can be divided into two epochs, the Pleistocene and the Holocene. The Pleistocene Epoch began about 2.6 million years ago. It is famous for the megafauna that were alive at that time like the woolly mammoth and saber tooth tigers. We are living in the Holocene Epoch, which began 11,700 years ago (approximately 500 human generations)! The Holocene is broken into its own epoch because of its uniqueness: a warm time frame when early agriculture and the first civilizations developed.

Throughout geologic time, the Earth has experienced changes in the environment and climate. We know the most about recent changes because over time, geologic processes "erase" evidence of earlier events through the rock cycle and plate tectonics. The recent changes that we have data for are from the Quaternary Period. It is unique because it is characterized by a relatively cold climate with major ice sheets covering large portions of the Earth. The Pleistocene is the time of the Last Glacial Maximum (LGM).

Another characteristic of the Quaternary is that the Earth's climate has been highly variable. There have been repeated periods of warmer and colder climates. The diagram below (not to scale) [Figure 1], summarizes this period's climate change. Throughout the Quaternary, there have been a series of interglacial and glacial cycles. The Holocene is the most recent interglacial period and is similar to those that occurred episodically throughout the Pleistocene.

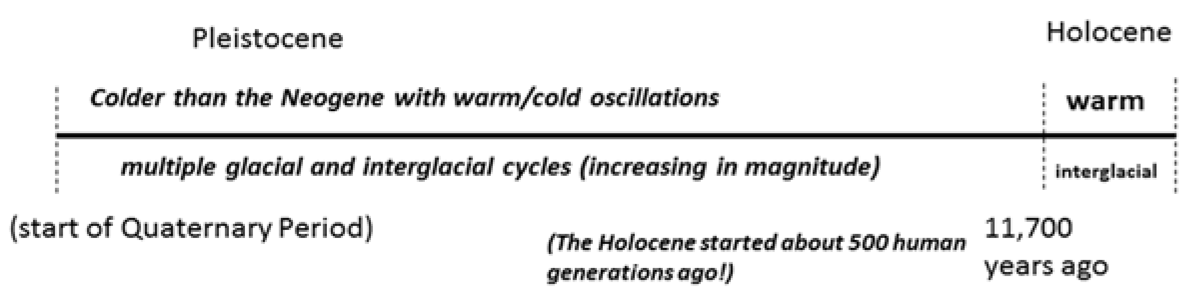


Figure 1: Glacial and interglacial cycles of the Quaternary (Anderson, 2012)

The element, Hydrogen, exists in Earth's atmosphere as water vapor (H_2O). The amount of water vapor in the atmosphere is affected by the ambient air temperature; the warmer the air, the more water it can hold, while the colder the air, the less water it can hold. Water vapor is preserved within air bubbles in layers of ice. Paleoclimatologists can reconstruct the composition of the atmosphere that existed at the time a particular sample of ice formed. One of the ways they can do this is through looking at the ratio of hydrogen isotopes (they also look at many other elements for a complete picture). (Isotopes of an element have varying numbers of neutrons. This means they have different atomic masses. The atomic mass that you see on the periodic table is an average of the masses of all the element's isotopes. All elements exist as a variety of isotopes in nature.) The isotopes of interest in paleoclimatology are deuterium (^2H – also known as 'heavy Hydrogen') and hydrogen (^1H). In warmer times, there are more deuterium atoms than hydrogen atoms. In colder periods, the opposite is true; there are more hydrogen atoms than those of deuterium. For example, a less negative ratio would indicate a much warmer climate than a more negative (less deuterium-hydrogen) ratio.

The graph on the following page (Figure 2) shows the glacial and interglacial cycles reconstructed from an ice core extracted by the European Project for Ice Coring in Antarctica (EPICA) at Dome C. This core was drilled on the East Antarctic Ice Sheet. The surface where the drilling rig was located is at 3,233 m above sea level. They reached bedrock at a depth of 3,270 m; this means that the ice is 3,270 m (almost 2 miles) thick!

Complete the EPICA Dome C diagram on the next page by following the directions below:

1. Draw a vertical line from today's Deuterium/Hydrogen ratio (-400) to the bottom of the diagram using a ruler.
2. Draw a horizontal line across the diagram to indicate the end of the Pleistocene and the beginning of the Holocene (see the background information for the date).
3. Look at your vertical line and identify other intervals in the Quaternary where the temperatures were similar to those today. Bracket each of these intervals with a horizontal line and shade them in with a red colored pencil. At what times did the temperatures within these interglacial periods peak? Write the time (years ago) within the right margin of the diagram.
4. How many of these interglacial periods reached temperatures warmer than today? __4__ Indicate these with a star next to the time.
5. Do you notice a pattern in the glacial/interglacial cycles from about 450,000 years ago towards the present? ___Yes____ Describe this pattern.

   The first two are 75,000 years apart after that, the intervals increase slightly to about 100,000 years apart

6. The most recent glacial phase began about 115,000 years ago. It ended around 18,000 years ago. Draw a horizontal line across the diagram at each of these times. Shade the area in between the lines with a blue colored pencil and label it as the Last Glacial Maximum (LGM)
7. How much of Earth's history did the LGM span? Record your answer in thousands of years.

   About 97,000 years

8. What percentage of Earth's history is comprised of Quaternary glacial periods? The Earth is roughly 4.6 billion years old (4.6×10^9 years). A thousand years is 1×10^3 years. For **full credit**, show your work below! Report you answer to three decimal places.

$$\frac{6.65\ x\ 10^4}{4.6\ x\ 10^9} x100 = 0.001\%$$

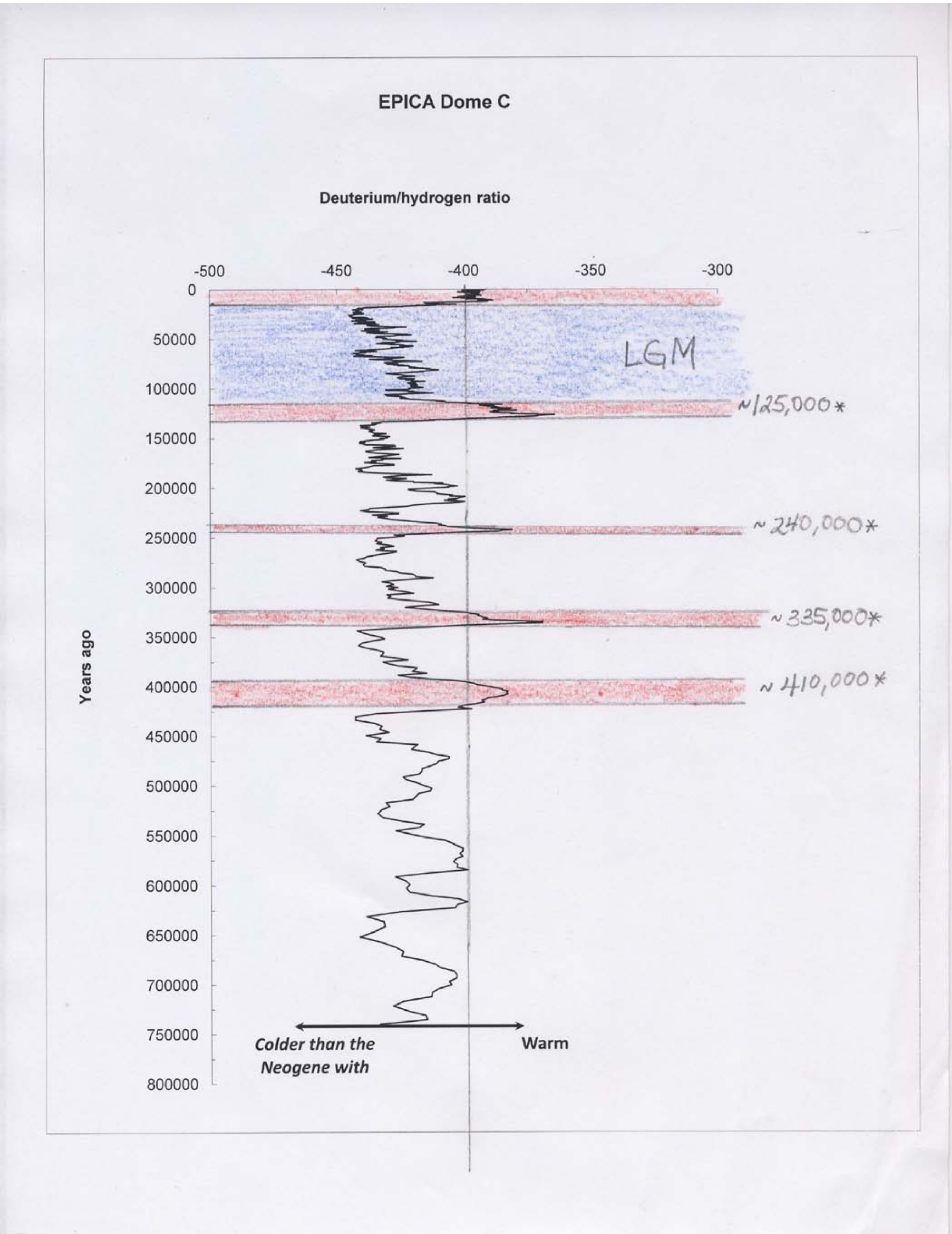


Figure 2: the European Project for Ice Coring in Antarctica (EPICA) at Dome C

Part II: Climate Change and Glacial Size

The equilibrium line altitude (ELA) of a glacier is the point where the snowfall adding to the glacier's mass is equal to the amount of glacier's mass lost through melting. The glacier's accumulation zone (above the ELA) is where snow or ice is added to the glacier through snowfall, freezing rain, avalanches, or wind-blown snow. The ablation zone (below the ELA) is where the processes of melting, sublimation, and evaporation remove ice from the glacier's mass (Figure 3).

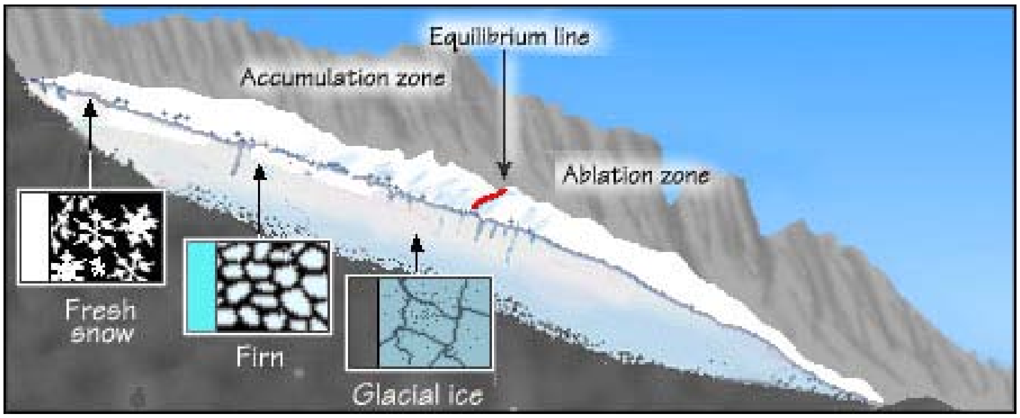


Figure 3: Equilibrium Line of a Glacier (Source: Glacier Change in the Upper Skagit River Basin, http://www.glaciers.pdx.edu/Projects/LearnAboutGlaciers/Skagit/Basics00.html)

The climate of an area where a glacier is found affects the mass balance of a glacier. The net balance (measured over the course of a year) is the difference between accumulation and ablation for the entire glacier. If the mass balance of a glacier is stable, the accumulation of snow and ice equals the amount of ice lost by the glacier. For most glaciers located in temperate ecosystems, the winter balance is positive, and the summer balance is negative (Figure 4).

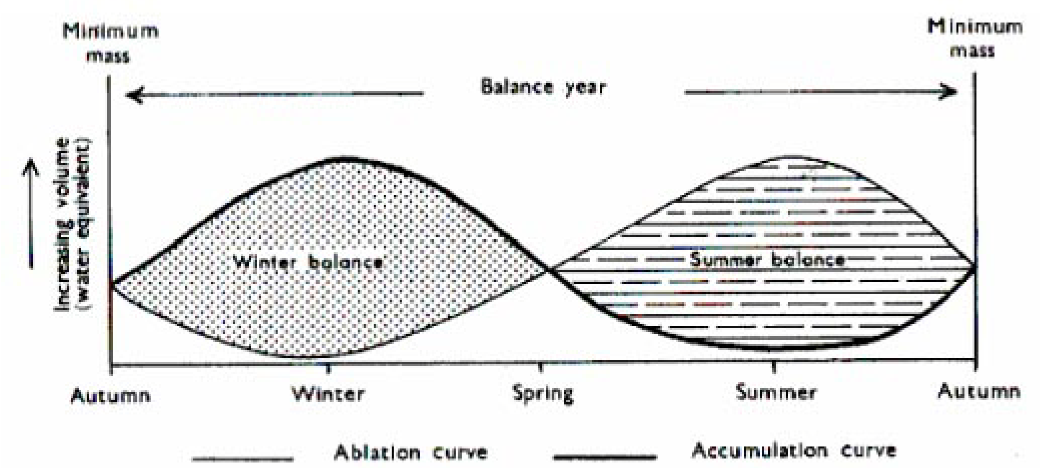


Figure 4: Annual Net Balance of a Glacier (Source: Revision World: http://revisionworld.co.uk/a2-level-level-revision/geography/glacial-environments/introduction-modules/cross-profile)

If more mass is gained overall than lost, the glacier has a positive mass balance and is growing (either in length or thickness). Climatic conditions that can cause a positive mass balance are colder temperatures and/or periods of increased precipitation. If more mass is lost than gained, the glacier has a negative mass balance and is shrinking (retreating – becoming shorter in length or becoming thinner – decreasing volume of ice). Negative mass balance occurs when the climate is warmer and/or drier (Figure 5).

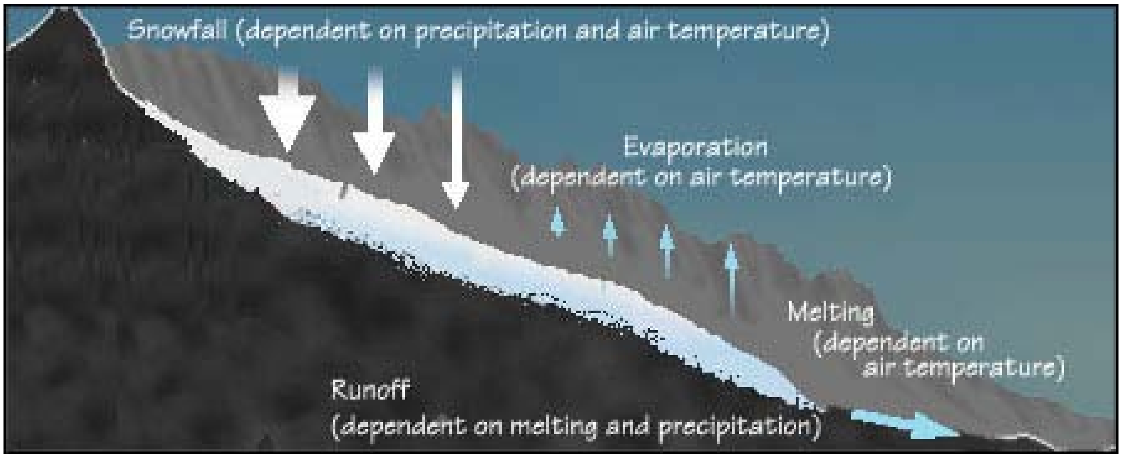


Figure 5: Simplified diagram of glacier mass budget, showing major mass input and outputs
(Source: Glacier Change in the Upper Skagit River Basin,
http://www.glaciers.pdx.edu/Projects/LearnAboutGlaciers/Skagit/Basics00.html)

Glaciers respond to environmental conditions that last a few decades. Because of this their trends are useful in climate studies. Several studies exist that have considered the relationship between the ELAs of glaciers and their present climate relationships. Scientists can take what they know about ELAs and climate and extrapolate this knowledge to reconstruct past glacial conditions. In order to be able to reconstruct past ELAs, scientists must be able to determine the extent (size) of the glacier in the past. To do this, they need to be able to identify moraine locations that indicate the length (terminal moraine) and width of the glacier (lateral moraine).

As a glacier loses mass, some of the first landforms to be exposed are along the terminus (toe) of the glacier as well as regions along its sides. If the glacier or ice sheet is overlying a landscape with large variations in topography, the tops of hills or mountains having greater elevations than the surrounding area will also be exposed early on. In Antarctica and the Arctic, these features are called nunataks. A nunatak is a small mountain or rocky outcrop projecting from and surrounded by a glacier or ice sheet.

Procedure:

1. Using the data given on the attached handout: "Climate Data for 70 Glaciers at Their Equilibrium Line Altitudes" (Anderson, 2012), create a scatter graph of the "Average Summer Temperature (°C)" vs. "Winter Accumulation + Summer Precipitation (mm)".
2. Draw a Best Fit Line through your data points. A 'line of best fit' summarizes the relationship between data. If the points lie close to the line, a strong correlation exists. If there appears to be a trend, but the points don't lie close to the line, the correlation is weak.

3. Answer the following analysis questions.

Analysis

1. Describe the relationship between the temperature and accumulation. Is it a 'positive' or 'negative' correlation? (Hint: look at the slope of your Best Fit Line.) Explain.

   There is a positive correlation. It shows that as summer temperatures increase, the accumulation also increases.

2. Is there a strong or weak correlation in your data? Explain.

   The correlation is stronger when the temperatures are lower, and while still strong at higher temperatures, it is not as strong as with the lower temps.

3. Your scatter graph should suggest that when the summer temperature is higher at the ELA of a glacier, the accumulation must also increase. Why do you think this is the case?

   The atmosphere is able to hold more moisture at warmer temperatures than at lower temperatures.

4. If precipitation (winter and summer) is low, then the summer temperature is usually low. Based on what you've learned about glaciers, why does this relationship have to exist in order for a glacier to form?

   If more mass is gained than lost, the glacier will grow. Low summer temperatures mean less melting and therefore, less mass lost. If the precipitation is greater than the temperature, the glacier will possibly grow, or at least stay the same and not retreat. The positive winter balance must be greater than the negative summer balance.

5. From the graph you created, it is apparent that when temperatures increase, precipitation also increases. If this is true globally, why do you think the majority of Earth's glaciers have a negative mass balance (why are they shrinking)?

   Temperatures are increasing, but because global weather patterns are changing due the oceans warming due to this increase, precipitation patterns have changed. Glaciers are not receiving the same amounts of precipitation as before and this is causing the mass to decrease.

6. It is not difficult to determine where the ELA is located on a glacier. What do you think the appearance of the glacier's surface will be like above the equilibrium line? Below the equilibrium line?

   Above: surface with snow or firn. Blue ice and crevasses.
   Below: possibly down to blue ice; melt water channels, etc.

7. What assumptions must scientists make if they are to use current glacial and climate data and apply it to glaciers in the past?

Answers may vary. They assume that weather patterns (precipitation, prevailing winds, etc.) were the same in the past; ocean currents were the same; other climate patterns were similar.

8. Discovering the ELA of former glaciers provides useful information about the climate at the time the glacier existed. Knowing that temperature decreases, on average, 2-3°C for every 1,000 meters of elevation gained, how might determining the location of the ELA of a glacier help reconstruct past climates? (Hint: If the equilibrium line were to occur at a lower altitude than present ELAs, what might that say about temperatures of the paleoclimate?)

   If the calculated paleo-ELA of a glacier was lower in elevation, then scientists could interpret that the climate was either cooler, precipitation was greater, or a combination of these factors existed. Maybe summers were cooler over all or winters were colder than at present.

Part III: Antarctic Glacial Retreat Analysis

Scientists have been collecting data for several years that give them the date glacially transported rocks were exposed to the atmosphere. The samples were found in moraines from the Last Glacial Maximum. As glaciers shrink, rocks that were buried deep within the ice gradually become exposed on the surface of landforms surrounding the glacier (lateral moraines). This is known as losing glacial mass.

Once these rocks are exposed to the atmosphere, they begin to be bombarded by cosmic rays from outer space. These rays can penetrate the Earth's surface up to 10 meters deep. As these rays enter the rocks, they interact with the atoms making up the rock. These interactions involve striking the nucleus of the atom and knocking off a neutron or proton. Stray neutrons are captured by another element. As neutrons are captured, the atom becomes an isotope of that element; they are known as cosmogenic nuclides. Researchers, such as John Stone of the University of Washington, take these rocks and break them down to isolate individual atoms.

The isotopes scientists focus on are Beryllium-10 (^{10}Be), Chlorine-36 (^{36}Cl), and Aluminum-26 (^{26}Al). You are probably most familiar with Beryllium-9 (^{9}Be), Chlorine-35 (^{35}Cl), and Aluminum-27 (^{27}Al) on the periodic table. Once the rock samples are processed to isolate individual atoms, they are run through an accelerated mass spectrometer (AMS) (Figure 6) to look at the ratios of the desired isotopes: ^{9}Be:^{10}Be, ^{36}Cl:^{35}Cl, and ^{26}Al:^{27}Al. "Accelerator mass spectrometry (AMS) is a technique for measuring long-lived radionuclides that occur naturally in our environment. AMS uses a particle accelerator in conjunction with ion sources, large magnets, and detectors to separate out interferences and count single atoms in the presence of $1x10^{15}$ (a thousand million million) stable atoms." (Department of Physics, Purdue University, 2013). Cosmogenic nuclide measurements can be used for various dating application in geology, archaeology, and biomedicine.

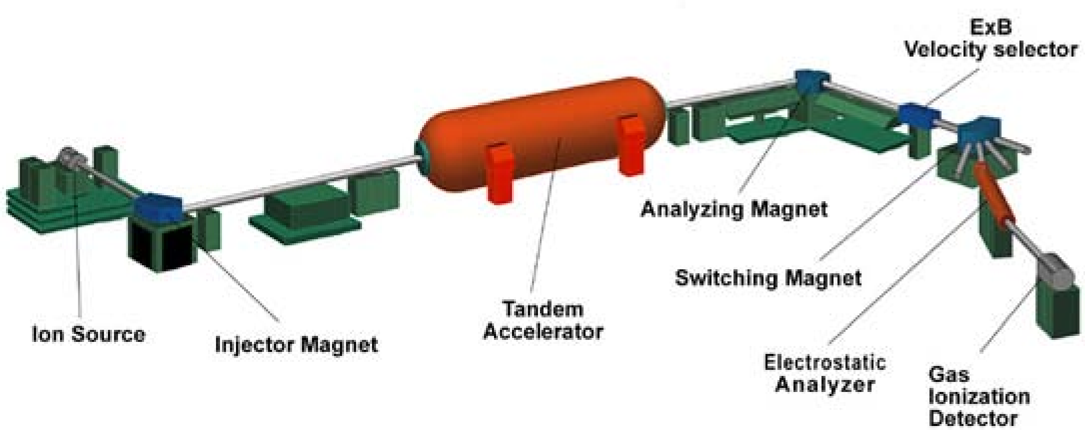


Figure 6: Generalized Accelerated Mass Spectrometer (Department of Physics, Purdue University, 2013)

When compared to a known baseline, these ratios tell scientists how long these samples have been exposed to the atmosphere. There are several assumptions that scientists must make. Unfortunately, science conducted in the natural world has several variables that make it very difficult to isolate just one. (In class, you are taught that only one variable can be tested at a time; when conducting science outside of a controlled laboratory environment, to compensate for multiple variables, assumptions must be made.) Some of these assumptions are: there is a steady production of the measured isotope, the sample has been continually exposed since its initial contact with the atmosphere, and no erosion has occurred at the sampling site. Some factors that affect the production of cosmogenic nuclides are: the concentration of target nuclides (atoms that lose a neutron), elevation (samples are closer to space), geomagnetic latitude (higher latitudes have less protection from the Earth's magnetosphere), and surface orientation (are samples sheltered by other landscape features). Other factors affect the accumulation of cosmogenic nuclides: the production rate as well as the rate of erosion (either of the sample itself or of the overlying materials).

Once all of these assumptions and production/accumulation factors have been considered, the researchers can determine an age since initial exposure. The longer a sample has been exposed, the greater the concentration of cosmogenic nuclides. The most accurate dates are from those samples that have been exposed for long periods of time at high elevations. Young samples, those that only have ages of a few hundred years, tend to have large errors (± 5-10%) and are not considered as reliable. Older samples or those that have been collected from high elevations are much more reliable, with a low percentage of error (± 1-2%). This means that if a sample is dated to be 16,000 years old, in reality, it could be anywhere from 15,680-16,320 years old.

For this exercise, you will be using actual data collected by Dr. John Stone (University of Washington) and his team. They have sampled moraines created during the Last Glacial Maximum that have been exposed as glaciers across Antarctica have begun to retreat. The majority of these moraines are lateral, lying alongside the outside margins of the glacier. Some samples exposed by the shrinking glacier were also collected from nunataks within the confines of the glaciers. Due to the manner in which glaciers shrink, from the top down, it stands to reason that higher elevations are exposed first. Therefore, one would expect that samples collected at higher elevations would have older exposure ages than those samples collected at lower elevations (Figure 7).

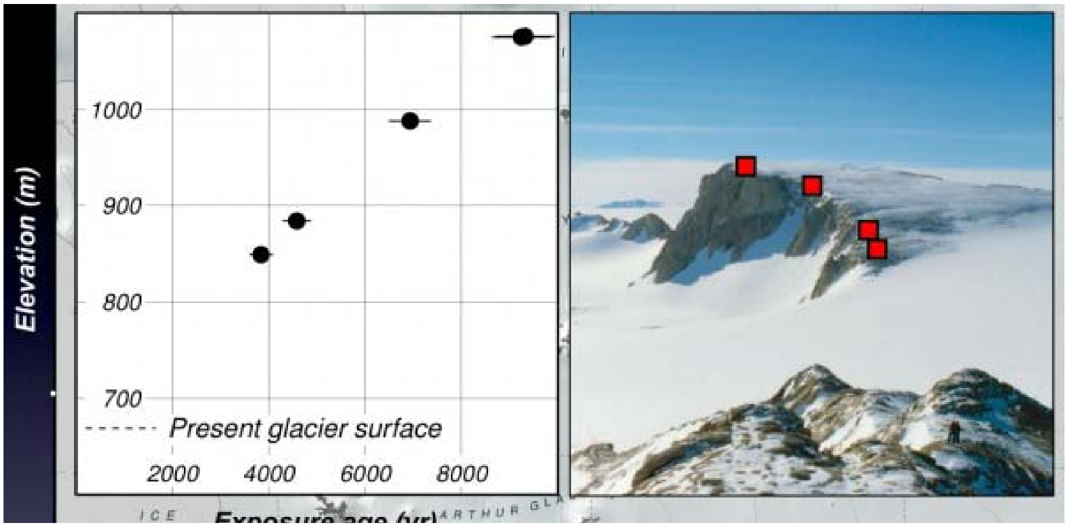


Figure 7: Elevational Influences of Surface Exposure Ages. (Image Source: Greg Balco, University of Washington)

Teacher Answer Key

Because conducting research in Antarctica is very expensive and the window of time field research can be conducted is very narrow, the data you will be working with was collected and processed over a period of years (2003-2007).

Procedure:

1. Using the data given on the accompanying handout of Antarctic data, create a scatter graph for the ^{10}Be Exposure Ages of Glacial Erratics, Ford Ranges, Marie Byrd Land, Antarctica data set.
   a. You will be plotting Exposure Age (1 x 10^3 years) vs. Elevation (m).
2. Don't forget to include all the important components of a graph such as:
   a. Title
   b. Correctly scaled axes
   c. Labels that include units on the axes
   d. Key.
3. On the graph, draw a Best Fit Line through each set of data points. A 'line of best fit' summarizes the relationship between data. In this case, the line indicates the rate of glacial retreat/shrinking (positive slope) or glacial growth (negative slope).
4. Determine the rate of retreat for each set of data by calculating the slope of each data set's line of best fit. Enter these values into the data table.
5. Determine the average age of each sample site. Enter this information in the data table.
6. On the Ford Ranges map, plot each of the sample locations.
7. Using the data given on the accompanying handout of Antarctic data, create a scatter graph for the ^{10}Be Exposure Ages of Glacial Erratics, Reedy Glacier, Antarctica data set.
   a. Repeat steps 2 through 5 for this data set.
8. On the Reedy Glacier map, plot each of the sample locations.
9. On the map of the Antarctic continent, plot the location of each of the three data sets.
10. Answer the following analysis questions.

Analysis:

Ford Ranges, Marie Byrd Land, Antarctica

1. What is the average age of samples at Mt. Rea? _____2.2 x 10^3 years (2,200 yrs.)____________

2. What is "statistical error"? It is the amount by which an observation differs from its expected value. (Potential clarification for student may be needed; may want to cover this in class prior to the exercise [or question can be omitted]).

   For example, if the mean height in a population of 21-year-old men is 1.75 meters, and one randomly chosen man is 1.80 meters tall, then the "error" is 0.05 meters; if the randomly chosen man is 1.70 meters tall, then the "error" is −0.05 meters.

3. What is the average error for this location (Mt. Rea)? ___0.2 x10^3 years__ this means that the rocks sampled here could represent a range of years during which the glacier retreated enough to expose the rocks. This could have happened anytime between __2.4 x 10^3 years (2,400 yrs.)_ and __2.0 x 10^3 years (2,000 yrs.) ago_______________________.

4. Consider the data plotted on your graph for the Ford Ranges in Marie Byrd Land, Antarctica. Of these seven locations, the Boyd and Balchen glaciers are retreating at varying rates. List the locations in order from the slowest retreat to the most rapid retreat.

    a. Slowest_____Mt. Van Valkenberg: Clark Mtns.____________________________________
    b. ____________Mt. Blades; Sarnoff Mtns.___________________________________
    c. ____________ Mt. Darling/Mt. Spencer: Allegheny Mtns.____________________________
    d. ____________ Fleming Peaks: Eastern Sarnoff Mtns._________________________________
    e. ____________ Mt. Rea: Western Sarnoff Mtns ______________________________
    f. ____________Migmatite Ridge: Eastern Fosdick Mtns._____________________________
    g. Most rapid__ Mt. Passel: Denfeld Range ____

5. One would expect a glacier to begin retreating at its terminus as well as along its margins. The terminus for each of these glaciers (Boyd and Balchen) is to the west. Looking at your map, list the sample locations from the farthest east to the most westerly.

    a. Farthest east__ Mt. Van Valkenberg: Clark Mtns _________________________________
    b. ______________ Mt. Darling/Mt. Spencer: Allegheny Mtns.________________________
    c. ______________ Fleming Peaks: Eastern Sarnoff Mtns ______________________________
    d. ______________ Migmatite Ridge: Eastern Fosdick Mtns ___________________________
    e. ______________ Mt. Passel: Denfeld Range ____________________________________
    f. ______________ Mt. Blades; Sarnoff Mtns ____
    g. Most westerly__Mt. Rea: Western Sarnoff Mtns._________________________________

6. Do you see any pattern in the rates of retreat and the sample location relative to the glacier's terminus? __Yes____ Hint: look for increasing or decreasing rates of retreat as you move inland from the glacier's terminus as well as patterns related to the elevations of sample locations. If so, explain the pattern(s) you see.

    For the most part, those sample locations closest to the glacier's edge, have the most rapid rates of retreat. There is one exception: Mt. Blades has the 6th slowest rate of retreat and it is further west than one would expect it to be. Mt. Rea is the most westerly and has a slightly slower rate than Migmatite Ridge and Mt. Passel. It does have the highest elevation of these three peaks so there may be something related to elevation and sample site location that relate to the slower rate of retreat.

7. Why do you think Mt. Darling/Mt. Spencer may have one of the oldest ages of exposure?

   Higher elevations would be exposed earlier on as a glacier shrinks in size.

8. Mt. Van Valkenberg is the furthest east and therefore, the furthest from the glacier's terminus. It also has the highest elevation of all the sample sites. Why do you think is has a younger exposure age than the Mt. Darling/Mt. Spencer sample site? In other words, why do you think it is younger than you would expect?

   Students answers will most likely vary – accept any reasonable answer. Acceptable answers may include: sampling errors (maybe the sample location is recorded incorrectly, samples have been dislodged from higher elevation/rolled downhill); snow/ice may have remained in an isolated spot while rest of glacier retreated; they may have been shielded by surrounding topographic features; Laboratory errors.

Reedy Glacier, Antarctica

9. Looking at the data, are there any samples at lower elevations that have greater ages than samples collected at higher elevations? __Yes_____ At which location(s)?

   Quartz Hills bench and Reedy shear margin

10. Explain why these ages might be greater than expected. Please give at least two reasons.

    This is a similar question to #8. Students answers will most likely vary – accept any reasonable answer. Acceptable answers may include: sampling errors (maybe the sample location is recorded incorrectly, samples have been dislodged from higher elevation/rolled downhill); snow/ice may have remained in an isolated spot while rest of glacier retreated; they may have been shielded by surrounding topographic features; Laboratory errors.

    The purpose of these questions (#8 & #10) is to get students thinking about the complexities of science in the real-world. Fieldwork is difficult and there are many more variables to account for than within a controlled laboratory setting.

11. What is a shear force? It is force where two planes are sliding past one another.

12. A glacier's shear margin is usually found at the edges where the glacier is moving past the surrounding rock. What is most likely happening along these edges that would cause the samples here to exhibit the youngest exposure ages?

    The glacier is probably churning up rocks from depth. These samples may be periodically exposed to the atmosphere by the motion of the glacier and then disappear down the associated crevasses, only to resurface after a period of time. They would only be accumulating changes from cosmic rays when they are exposed at the surface. When they have disappeared into the glacier, they wouldn't be accumulating ^{10}Be due to a lower production rate.

13. Quartz Hills has the oldest exposure age of the four sampling sites (12,600 years – 10,200 years). Why do you think this is even though it is much further from the glacier's terminus than the other sites?

    The elevation of Quartz Hills is much greater than the other sites: 1313.7 m versus 738.6 m. Quartz Hills is a little over 1.8x higher than the other sampling sites.

    (Taking this into consideration, the determined exposure age of 11.4 x 10^3 years would be the equivalent of 6.3 x 10^3 years if the influence of elevation were removed. If the glacier were uniformly shrinking, even though Quartz Hills if farther inland, it would be losing volume (thickness) at an equal rate and the sole difference in ages would be due to elevation.)

Rate of Retreat in Antarctica:

14. Which of the three locations would have most affected by geomagnetic latitude?

    Reedy Glacier and Mt. Rigby on the Scott Glacier because it is at a higher latitude than the Ford Ranges.   (85° S versus 77° S)

15. In general, does the data from all of the sample sites (Ford Ranges, Reedy Glacier, and Mt. Rigby on Scott Glacier) reflect the idea that as a glacier begins to retreat, higher elevations are exposed first? Hint: Look at the data tables and your graphs to analyze the elevation vs. exposure age data.

    Overall, yes. The higher the elevation, usually the exposure ages are much older. There are a few exceptions, but these are few in comparison to the majority of the data. These exceptions could be due to a variety of factors (see answers for questions #8 and #10).

16. Order the three sample sites from their oldest average exposure age to the youngest. Include their average age.
    a. Oldest: ___ Reedy Glacier (5.8 x 10^3 yrs.)______________________________________
    b. __________ Mt. Rigby, Scott Glacier (5.2 x 10^3 yrs.)_____________________________
    c. Youngest: _Ford Ranges (4.0 x 10^3 yrs.)____

17. Scientists have found that the ice in Western Antarctica is melting much more rapidly than in Eastern Antarctica. How might this research and associated data help with climate change predictions?

    Answers will probably be highly variable. Accept any reasonable explanation. If scientists begin to see younger and younger exposure dates as well as increasing rates of retreat, they may be able to extend (extrapolate) these findings into the future. The creation of models helps substantiate climate change predictions and helps society plan for future environmental issues such as sea level rise, and to develop modifications in infrastructure to offset climate related threats.

Be^{10} Exposure Ages of Glacial Erratics, Ford Ranges, Marie Byrd Land, Antarctica

Location	Latitude	Longitude	Exposure Age (1 x 10^3 yr)	Elevation (m)	Error ± 1 x 103 yr	Rate of Retreat (m/1,000 yr)
Migmatite Ridge: Eastern Fosdick Mtns	76° 33' S	144° 28' W	4.7	1042	0.4	
			4.1	991	0.3	
			2.3	817	0.2	
Mt. Passel: Denfeld Range	76° 53' S	144° 59' W	3.6	726	0.3	
			1.8	569	0.1	
			1.8	443	0.3	
Fleming Peaks: Eastern Sarnoff Mtns.	77° 16' S	144° 26' W	4.9	691	0.3	
			4.3	660	0.3	
Mt. Blades: Western Sarnoff Mtns.	77° 10' S	145° 19' W	6.8	632	0.5	
			3.7	506	0.3	
			3.0	482	0.4	
Mt. Rea	77° 5' S	145° 35' W	18.6	685	1.2	
			3.3	489	0.3	
			3.4	433	0.2	
			2.8	404	0.2	
			2.7	287	0.2	
			2.6	172	0.2	
			2.4	162	0.2	
			2.4	351	0.2	
			1.9	245	0.2	
			0.6	237	0.1	
			0.3	226	0.1	
Mt. Van Valkenberg: Clark Mtns.	77° 19' S	142° 7' W	6.3	1126	0.4	
			3.8	1071	0.4	
			3.3	1052	0.2	

Mt. Darling/Mt. Spencer: Allegheny Mtns.	77° 27' S	143° 20' W	9.3	1076	0.6
			6.9	988	0.4
			4.6	884	0.3
			3.8	849	0.3

Be^{10} Exposure Ages of Glacial Erratics, Ford Ranges, Marie Byrd Land, Antarctica

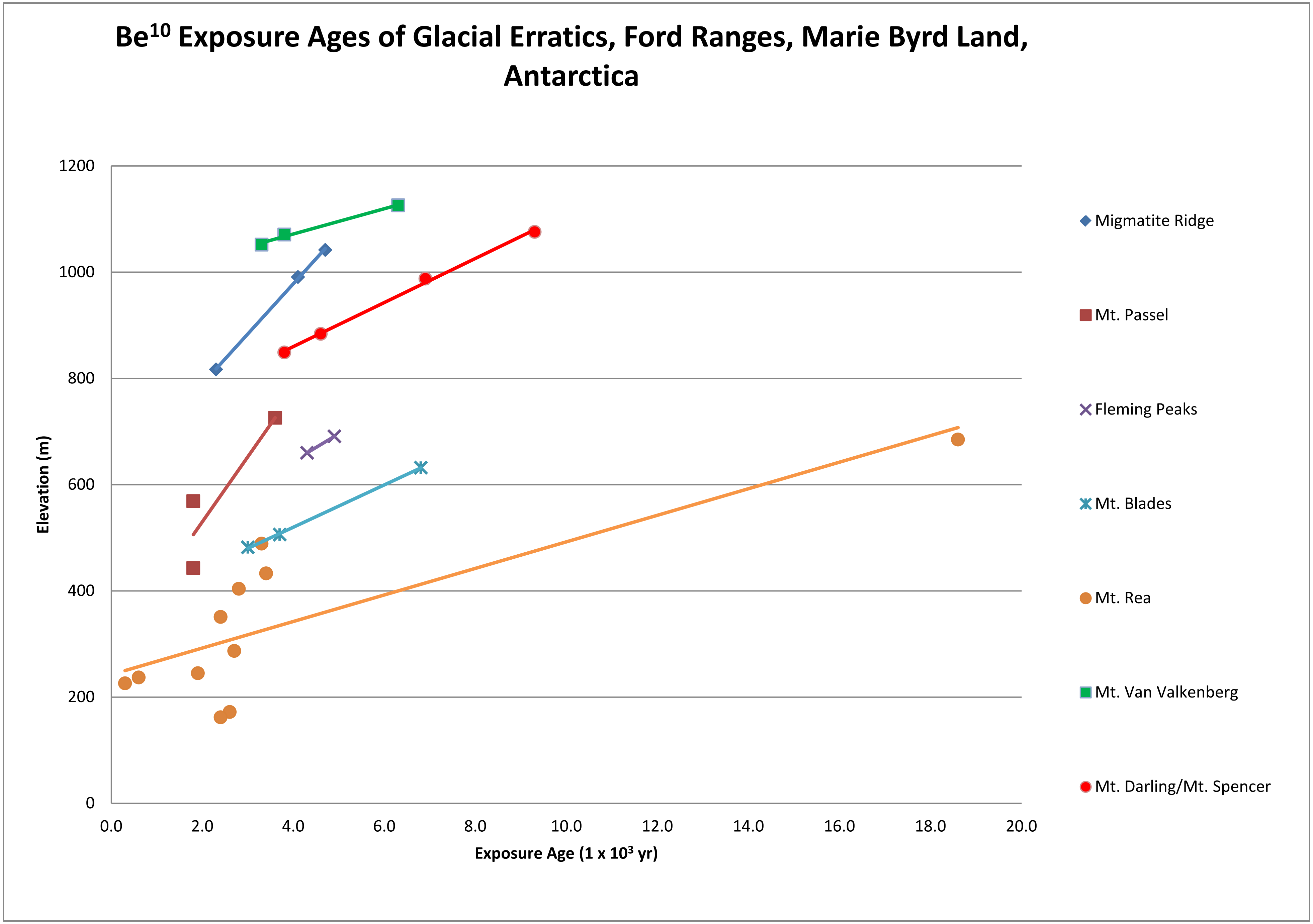
Location	Latitude	Longitude	Exposure Age (1×10^3 yr)	Elevation (m)	Error $\pm 1 \times 10^3$ yr	Rate of Retreat (m/1,000 yr)
Migmatite Ridge: Eastern Fosdick Mtns	76° 33' S	144° 28' W	4.7	1042	0.4	
			4.1	991	0.3	
			2.3	817	0.2	
Mt. Passel: Denfeld Range	76° 53' S	144° 59' W	3.6	726	0.3	
			1.8	569	0.1	
			1.8	443	0.3	
Fleming Peaks: Eastern Sarnoff Mtns.	77° 16' S	144° 26' W	4.9	691	0.3	
			4.3	660	0.3	
Mt. Blades: Western Sarnoff Mtns.	77° 10' S	145° 19' W	6.8	632	0.5	
			3.7	506	0.3	
			3.0	482	0.4	
Mt. Rea	77° 5' S	145° 35' W	18.6	685	1.2	
			3.3	489	0.3	
			3.4	433	0.2	
			2.8	404	0.2	
			2.7	287	0.2	
			2.6	172	0.2	
			2.4	162	0.2	
			2.4	351	0.2	
			1.9	245	0.2	
			0.6	237	0.1	
			0.3	226	0.1	
Mt. Van Valkenberg: Clark Mtns.	77° 19' S	142° 7' W	6.3	1126	0.4	
			3.8	1071	0.4	
			3.3	1052	0.2	
Mt. Darling/Mt. Spencer: Allegheny Mtns.	77° 27' S	143° 20' W	9.3	1076	0.6	
			6.9	988	0.4	
			4.6	884	0.3	
			3.8	849	0.3	

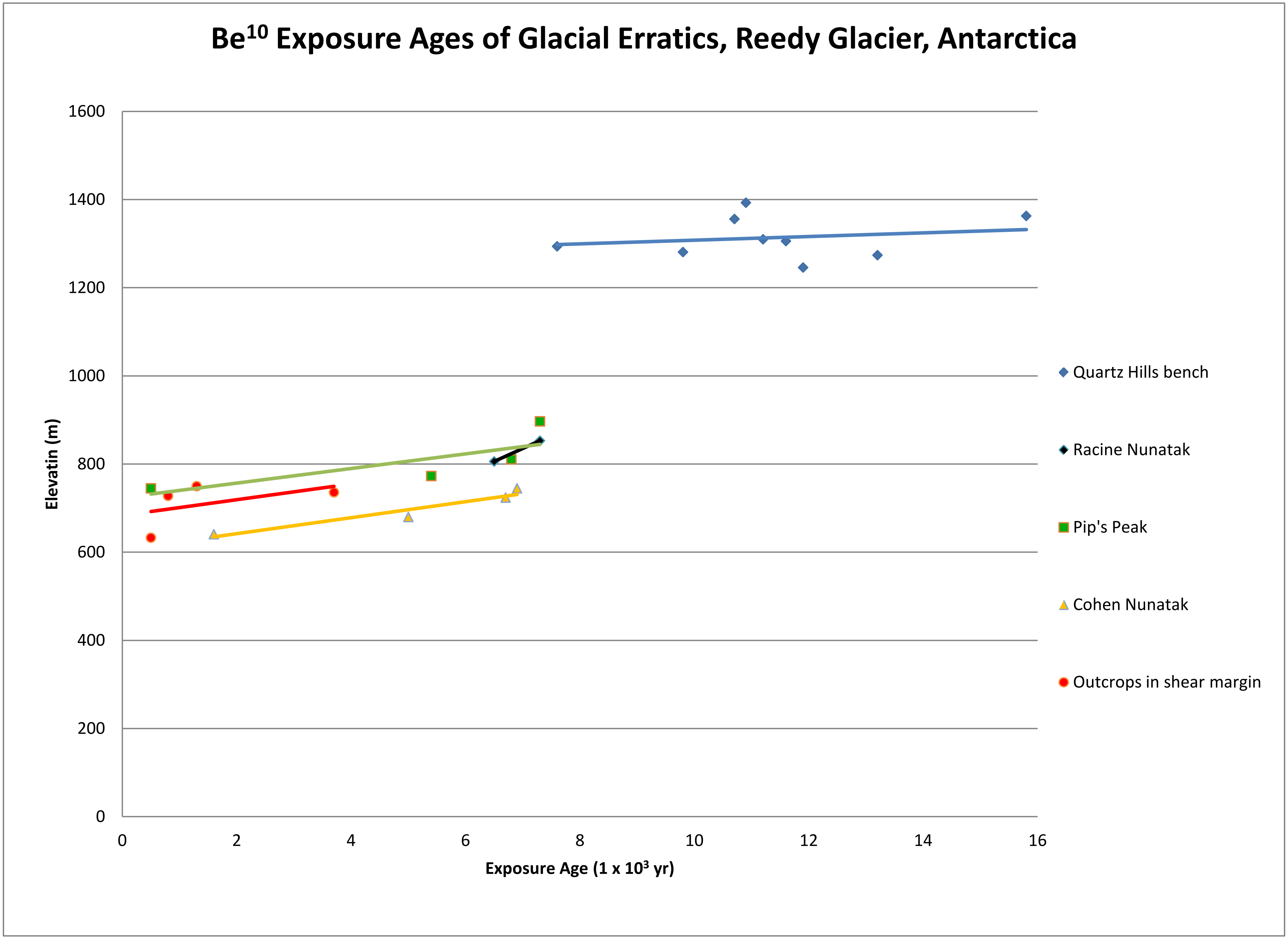
Be^{10} Exposure Ages of Glacial Erratics, Reedy Glacier, Antarctica

Location	Latitude	Longitude	Exposure Age (1×10^3 yr)	Elevation (m)	Error $\pm 1 \times 10^3$ yr	Rate of Retreat (m/1000 yr)
Quartz Hills bench	85° 54' S	132° 36' W	15.8	1363	1	
			10.7	1356	1.7	
			10.9	1393	2.7	
			11.2	1310	0.8	
			11.6	1306	0.7	
			7.6	1294	0.7	
			9.8	1281	1.7	
			13.2	1274	0.6	
			11.9	1246	0.8	
Racine Nunatak	85° 28' S	136° 14' W	7.3	853	0.5	
			6.5	806	0.4	
Pip's Peak	85° 26' S	135° 55' W	7.3	897	0.5	
			6.8	811	0.4	
			5.4	773	0.4	
			0.5	745	0.1	
Cohen Nunatak	85° 25' S	136° 12' W	6.9	745	0.5	
			6.7	724	0.4	
			5	680	0.3	
			1.6	641	0.2	
Glacier's shear margin	85° 25' S	135° 56' W	1.3	750	0.1	
			3.7	736	0.3	
			0.8	728	0.1	
			0.5	633	0.1	

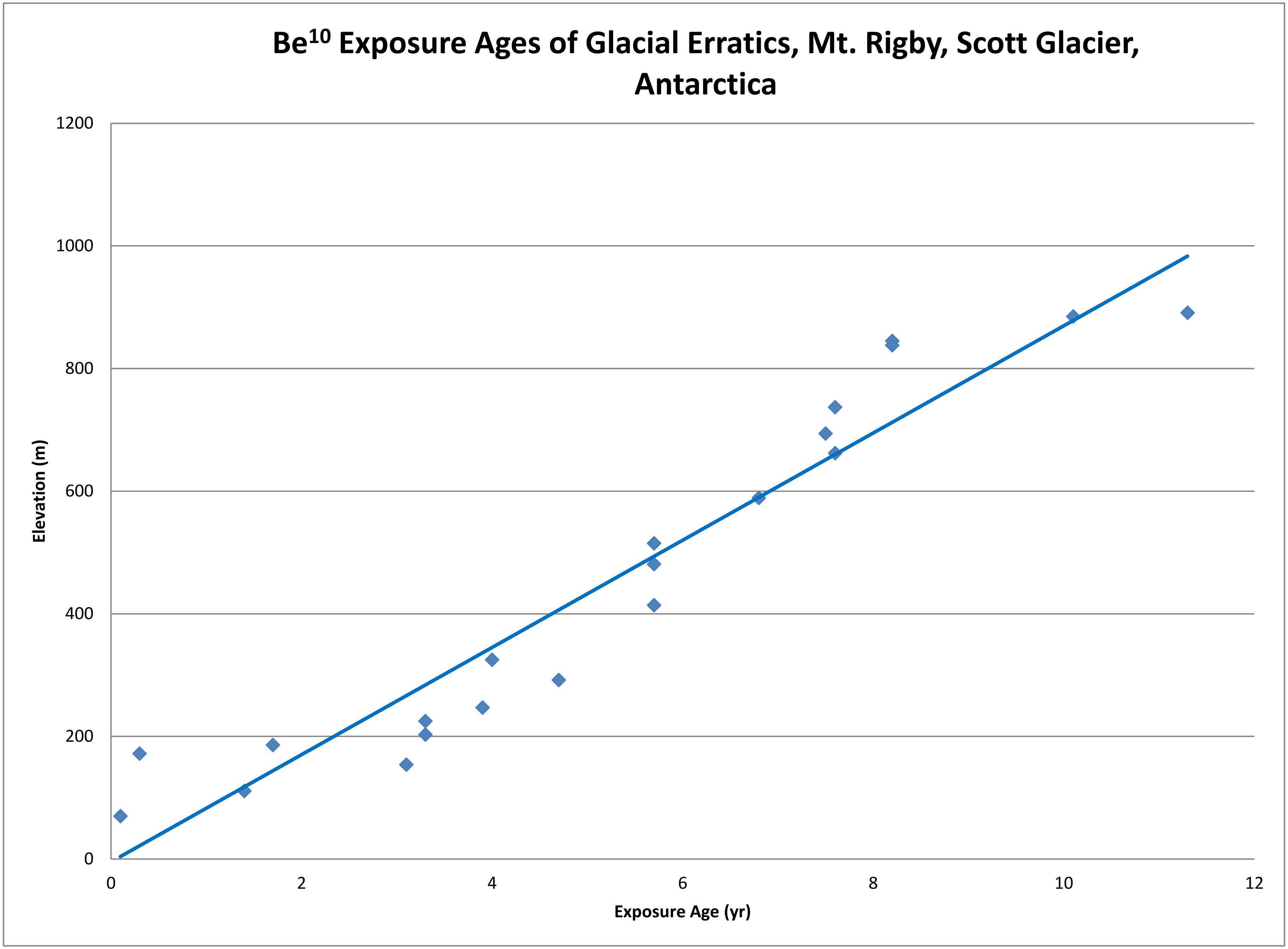
Be^{10} Exposure Ages of Glacial Erratics, Mt. Rigby, Scott Glacier, Antarctica

Latitude	Longitude	Exposure Age (1×10^3 yr)	Elevation (m)	Rate of Retreat (m/1000 yr)
85° 30' S	154° 32' E	11.3	891	
		10.1	885	
		8.2	845	
		8.2	838	
		7.6	737	
		7.5	694	
		7.6	662	
		6.8	589	
		5.7	515	
		5.7	481	
		5.7	414	
		4	325	
		4.7	292	
		3.9	247	
		3.3	225	
		3.3	203	
		1.7	186	
		0.3	172	
		3.1	154	
		1.4	111	
		0.1	70	


Be10 Exposure Ages of Glacial Erratics, Ford Ranges, Marie Byrd Land, Antarctica
Elevation (m)
Exposure Age (1 x 10³ yr)
1200
1000
800
600
400
200
0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
Migmatite Ridge
Mt. Passel
Fleming Peaks
Mt. Blades
Mt. Rea
Mt. Van Valkenberg
Mt. Darling/Mt. Spencer



Be10 Exposure Ages of Glacial Erratics, Reedy Glacier, Antarctica
1600
1400
1200
1000
800
600
400
200
0
0
2
4
6
8
10
12
14
16
Elevatin (m)
Exposure Age (1 x 103 yr)
Quartz Hills bench
Racine Nunatak
Pip's Peak
Cohen Nunatak
Outcrops in shear margin



Be10 Exposure Ages of Glacial Erratics, Mt. Rigby, Scott Glacier, Antarctica
1200
1000
800
600
400
200
0
Elevation (m)
0
2
4
6
8
10
12
Exposure Age (yr)

Teacher Answer Key

Be^{10} Exposure Ages of Glacial Erratics, Ford Ranges, Marie Byrd Land, Antarctica

Location	Latitude	Longitude	Exposure Age (1×10^3 yr.)	Elevation (m)	Error ± 1 x 10 yr.	Rate of Retreat (m/1,000 yr.)
Migmatite Ridge: Eastern Fosdick Mtns	76° 33' S	144° 28' W	4.7	1042	0.4	**93.8**
			4.1	991	0.3	
			2.3	817	0.2	
Mt. Passel: Denfeld Range	76° 53' S	144° 59' W	3.6	726	0.3	**157.2**
			1.8	569	0.1	
			1.8	443	0.3	
Fleming Peaks: Eastern Sarnoff Mtns.	77° 16' S	144° 26' W	4.9	691	0.3	**51.7**
			4.3	660	0.3	
Mt. Blades: Western Sarnoff Mtns.	77° 10' S	145° 19' W	6.8	632	0.5	**39.5**
			3.7	506	0.3	
			3.0	482	0.4	
Mt. Rea	77° 5' S	145° 35' W	18.6	685	1.2	**25.1**
			3.3	489	0.3	
			3.4	433	0.2	
			2.8	404	0.2	
			2.4	351	0.2	
			2.7	287	0.2	
			1.9	245	0.2	
			0.6	237	0.1	
			0.3	226	0.1	
			2.6	172	0.2	
			2.4	162	0.2	
Mt. Van Valkenberg: Clark Mtns.	77° 19' S	142° 7' W	6.3	1126	0.4	**24.7**
			3.8	1071	0.4	
			3.3	1052	0.2	
Mt. Darling/Mt. Spencer: Allegheny Mtns.	77° 27' S	143° 20' W	9.3	1076	0.6	**41.3**
			6.9	988	0.4	
			4.6	884	0.3	
			3.8	849	0.3	

Teacher Answer Key

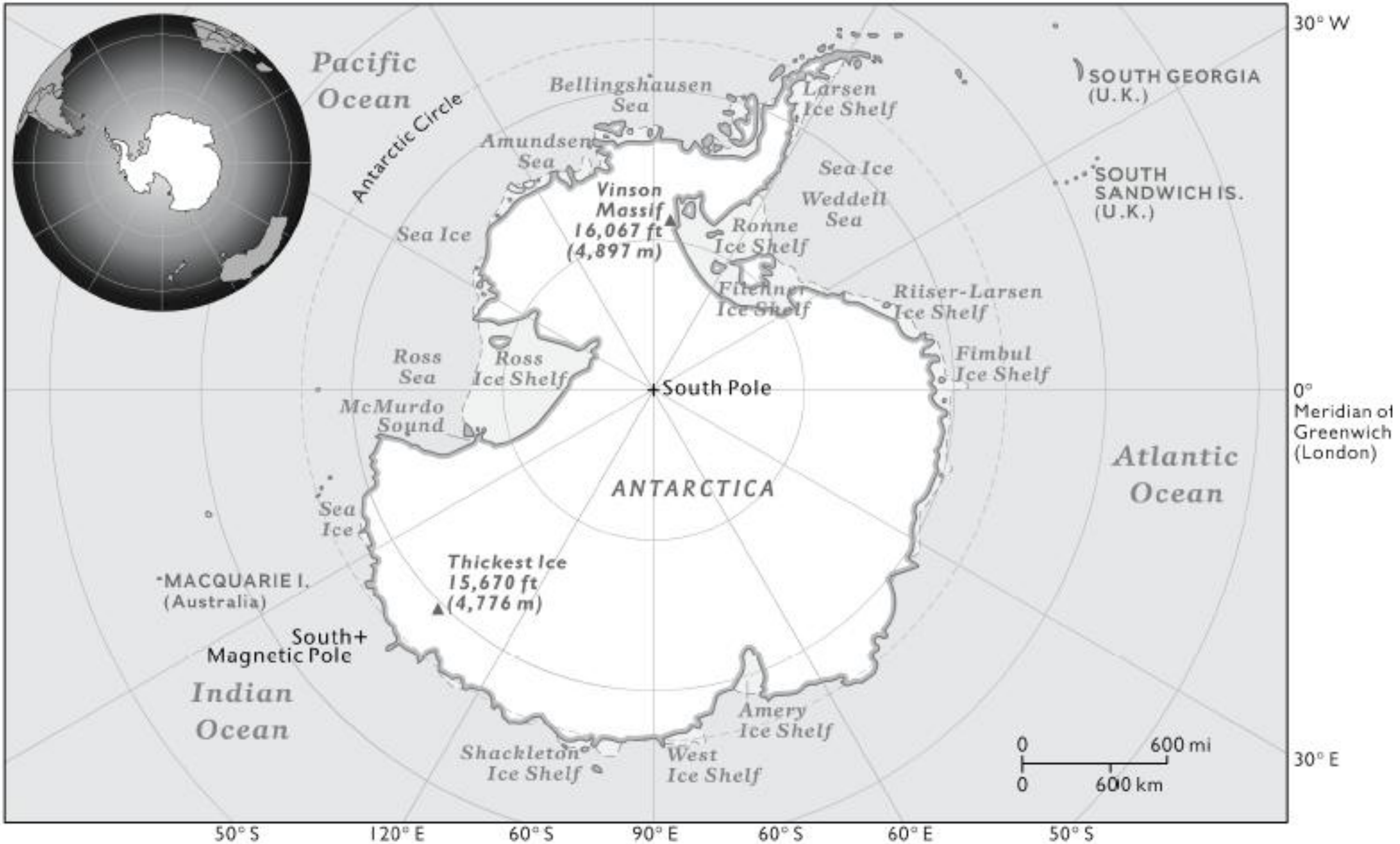
Be^{10} Exposure Ages of Glacial Erratics, Reedy Glacier, Antarctica

Location	Latitude	Longitude	Exposure Age (1 x 10^3 yr.)	Elevation (m)	Error ± 1 x 10^3 yr.	Rate of Retreat (m/1000 yr.)
Quartz Hills bench	85° 54' S	132° 36' W	10.9	1393	2.7	**8.4**
			15.8	1363	1	
			10.7	1356	1.7	
			11.2	1310	0.8	
			11.6	1306	0.7	
			7.6	1294	0.7	
			9.8	1281	1.7	
			13.2	1274	0.6	
			11.9	1246	0.8	
Racine Nunatak	85° 28' S	136° 14' W	7.3	853	0.5	**58.8**
			6.5	806	0.4	
Pip's Peak	85° 26' S	135° 55' W	7.3	897	0.5	**22.4**
			6.8	811	0.4	
			5.4	773	0.4	
			0.5	745	0.1	
Cohen Nunatak	85° 25' S	136° 12' W	6.9	745	0.5	**19.6**
			6.7	724	0.4	
			5	680	0.3	
			1.6	641	0.2	
Reedy shear margin	85° 25' S	135° 56' W	1.3	750	0.1	**32.2**
			3.7	736	0.3	
			0.8	728	0.1	
			0.5	633	0.1	

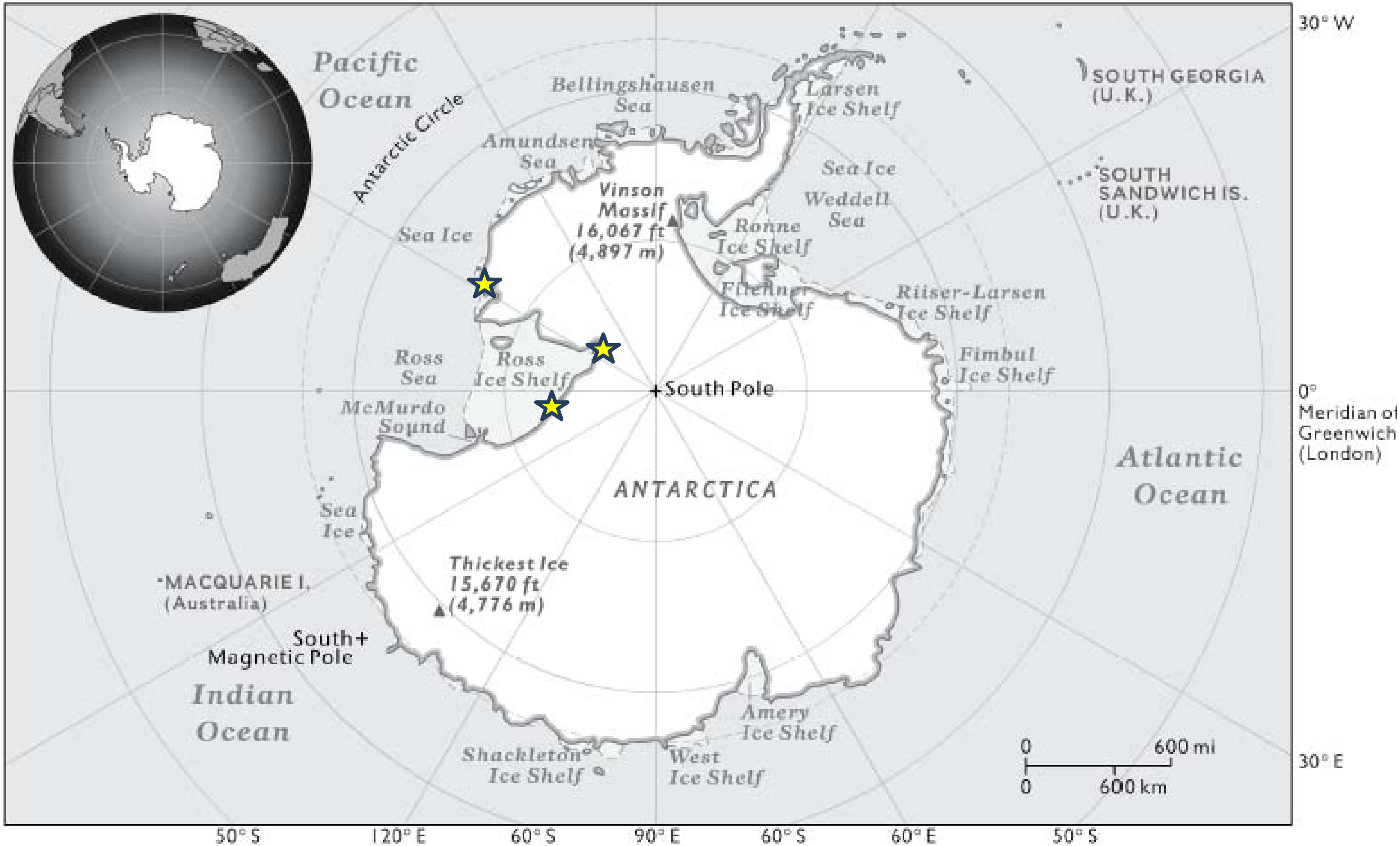
Teacher Answer Key

Be^{10} Exposure Ages of Glacial Erratics, Mt. Rigby, Scott Glacier, Antarctica

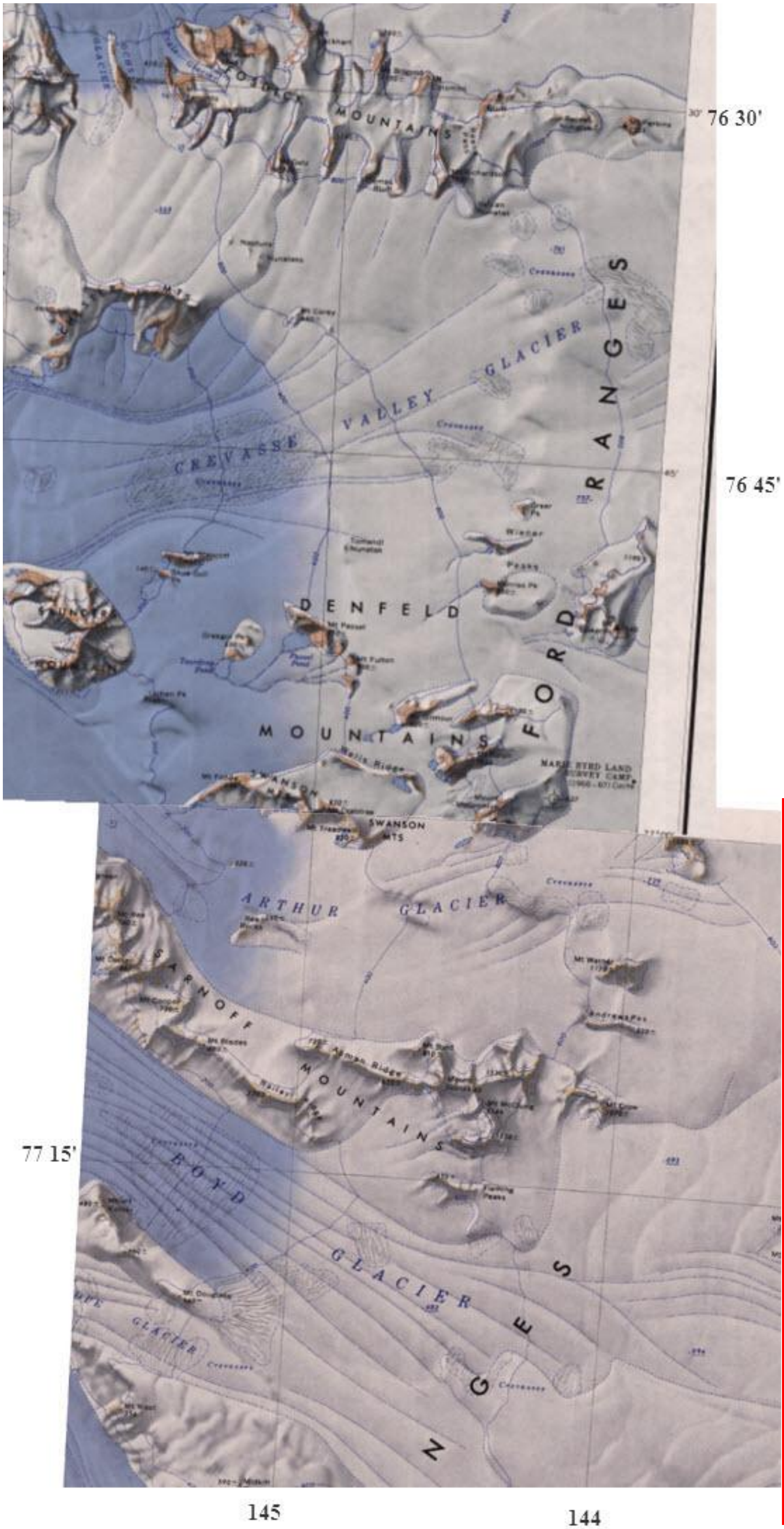
Latitude	Longitude	Exposure Age (1×10^3 yr)	Elevation (m)	Rate of Retreat (m/1000 yr)
85° 30' S	154° 32' E	11.3	891	**73.3**
		10.1	885	
		8.2	845	
		8.2	838	
		7.6	737	
		7.5	694	
		7.6	662	
		6.8	589	
		5.7	515	
		5.7	481	
		5.7	414	
		4	325	
		4.7	292	
		3.9	247	
		3.3	225	
		3.3	203	
		1.7	186	
		0.3	172	
		3.1	154	
		1.4	111	
		0.1	70	



Antarctic Sample Site Map



Antarctic Sample Site Map key



FORD

RANGES

MAP

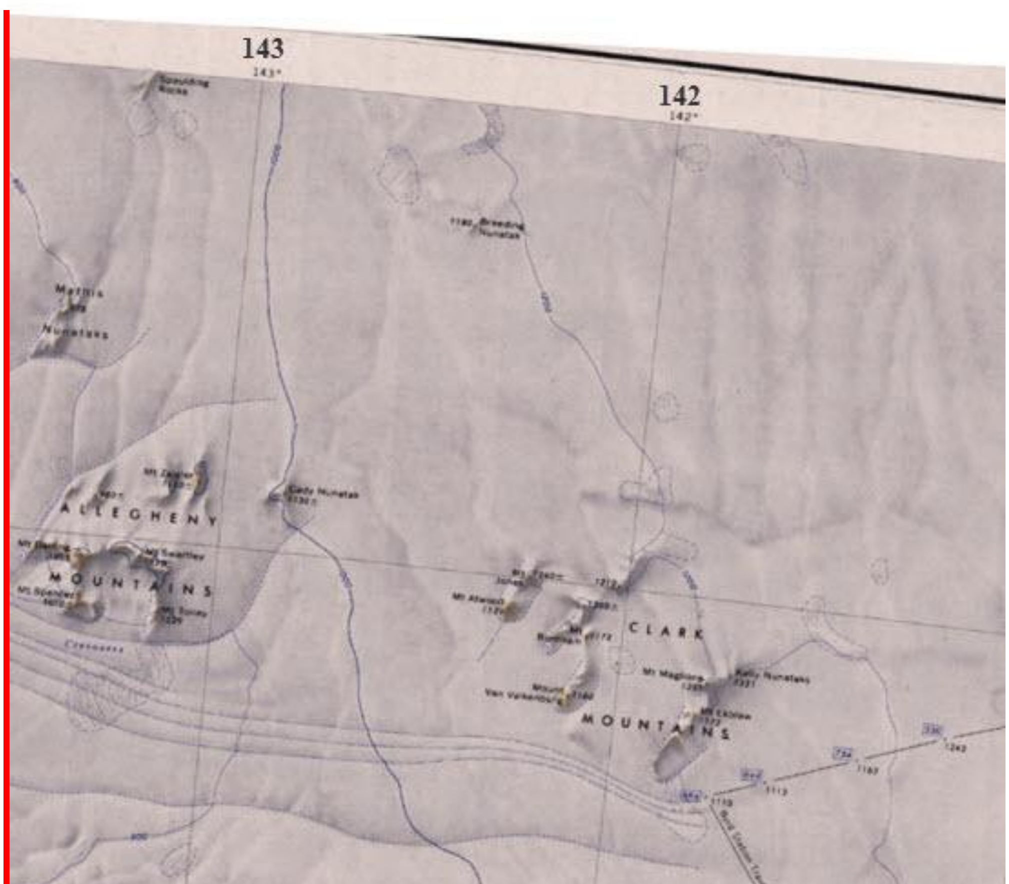
LEFT SIDE

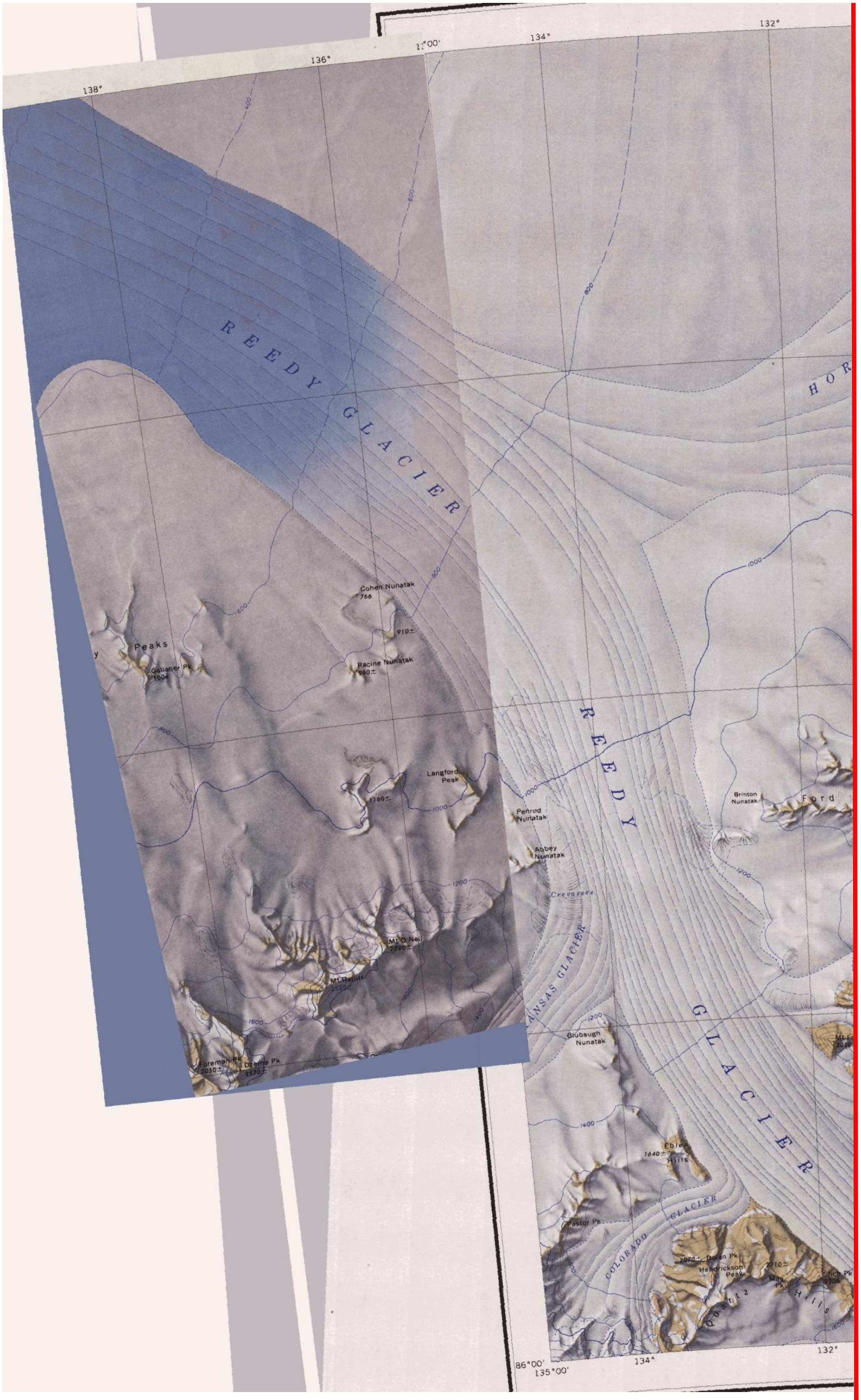
(match red lines together)

5'

FORD RANGES MAP RIGHT SIDE

(Match red lines together)





REEDY

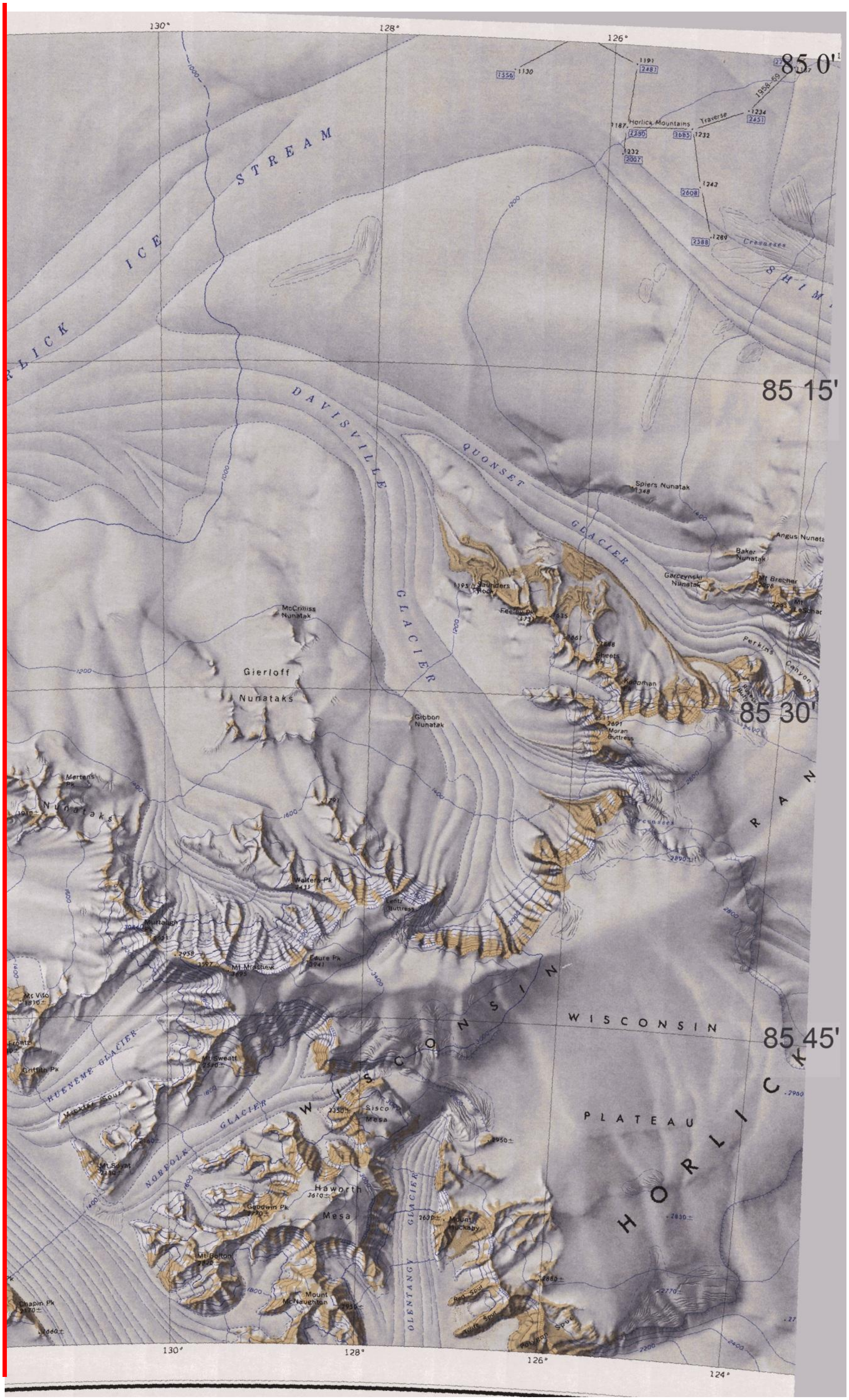
GLACIE

MAP

LEFT SID

(Match red

lines togethe



REEDY GLACIER MAP RIGHT SIDE

(Match red lines together)

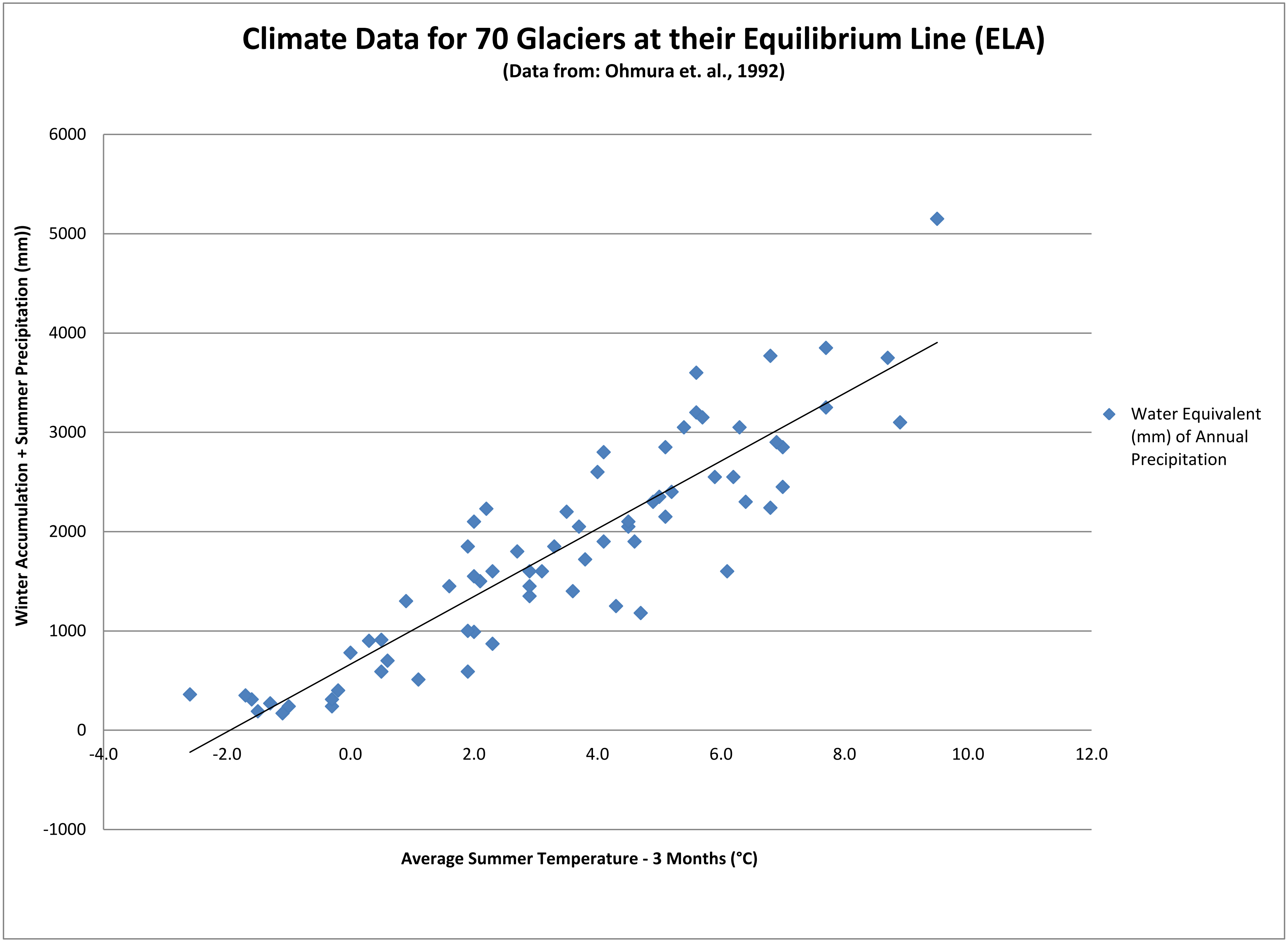
Climate Data for 70 Glaciers at Their Equilibrium Line Altitudes

Source of data: Ohmura et al. 1992

Region	Glacier	Average Summer Temperature [^oC]	Winter accumulation + summer precipitation [mm] at ELA
Canadian Arctic	Ward Hunt Ice Shelf	-1.0	240
	Gilman Glacier	-1.1	170
	Per Ardua	-1.5	190
	White Glacier	-1.6	310
	Baby Glacier	-1.7	350
	Laika Glacier	0.5	590
	Devon Island ice cap, northwest slope	-0.3	240
	Barnes Ice Cap	1.9	590
	Decade Glacier	-0.3	310
Greenland	Greenland ice sheet	0.6	700
	Greenland ice sheet	1.1	510
	Qapiarfiup sermia	2.9	1350
	Greenland ice sheet	2.0	990
	Greenland ice sheet	2.3	870
Iceland	Vatnajökull, south-east slope	4.0	2600
Svalbard	Austfonna	0.5	910
Alaska and Cordillera	Gulkana Glacier	7.0	2450
	Wolverine Glacier	5.6	3600
	Lemon Creek Glacier	7.0	2850
	Alexander Glacier	3.7	2050
	Yuri Glacier	3.3	1850
	Andrei Glacier	5.1	2150
	Ram River Glacier	4.7	1180
	Peyto Glacier	6.1	1600
	Bench Glacier	6.4	2300
	Tiedemann Glacier	6.2	2550
	Woolsey Glacier	8.9	3100
	Sykora Glacier	4.5	2050
	Bridge Glacier	4.5	2100
	Zabisha Glacier	4.1	1900
	Place Glacier	6.8	2240
	Helm Glacier	5.0	2350
	Sentinel Glacier	8.7	3750
	South Cascade Glacier	6.9	2900
	Nisqually Glacier	9.5	5150

Scandinavia	Blaisen	4.6	1900
	Storsteinfjellbreen	3.1	1600
	Cainhavarre	2.9	1600
	Storglaciären	3.8	1720
	Trollbergdalsbreen	5.6	3200
	Engabreen	6.3	3050
	Högtuvbreen	7.7	3850
	Alfotbreen	6.8	3770
	Nigardsbreen	4.9	2300
	Grasubreen	1.9	1000
	Hellstungubreen	2.9	1450
	Tunsbergdalsbreen	5.2	2400
	Austre Memurubre	2.1	1500
	Vestre Memurubre	2.3	1600
	Vesledalsbreen	5.9	2550
	Hardangerjökulen	3.5	2200
	Folgefonni-East	5.7	3150
	Folgefonni-West	5.4	3050
	Bondhusbreen	5.1	2850
Alps	Vernagtferner	2.0	1550
	Hintereisferner	2.0	2100
	Rhonegletscher	2.2	2230
	Careser	1.6	1450
	Griesgletscher	2.7	1800
	Marmolada	4.3	1250
Causacus	Dzankuat	4.1	2800
Tianshan	Tsentrainyy Tuyuksu	3.6	1400
	No. 1 Glacier Urumqi	-0.2	400
Himalaya	Rikha Samba Glacier	-1.3	270
	Gyajo Glacier	0.3	900
	EB050 (E09)	0.9	1300
Southern Hemisphere	Tasman Glacier	7.7	3250
	Hodges Glacier	1.9	1850
	Glacier, Deception Island	0.0	780
	Law Dome	-2.6	360

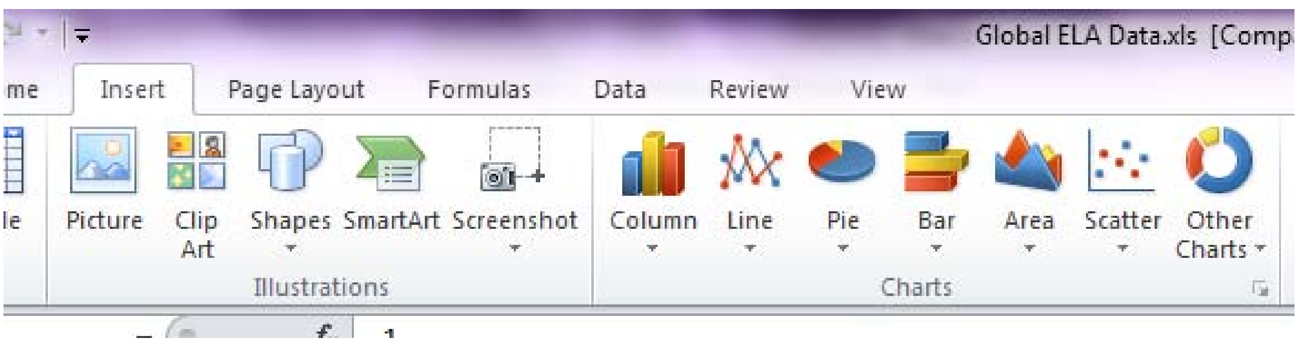
Teacher Answer Key



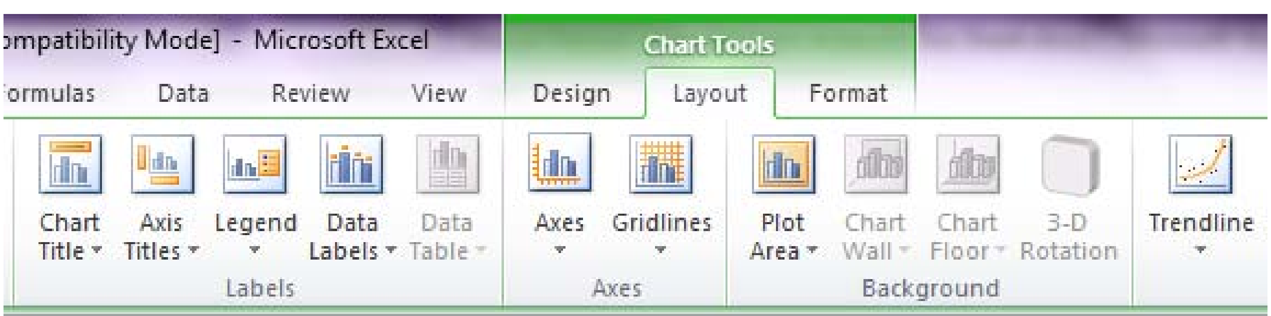
1. Alternatively, you can use the Excel file to create a computer generated scatter plot. To do this:
   a. Select (highlight) the Exposure Age and Elevation columns together.

Exposure Age (1×10^3 yr)	Elevation (m)
11.3	891
10.1	885
8.2	845
8.2	838
7.6	737
7.5	694
7.6	662
6.8	589
5.7	515
5.7	481
5.7	414

   b. Go to the "Insert" menu and select 'Scatter' from the chart menu (choose the first scatter option – the one that <u>does not</u> show points connected by a line).



   c. To format the scatter plot with a title, axis labels, and key, select "Layout" under the chart tools.

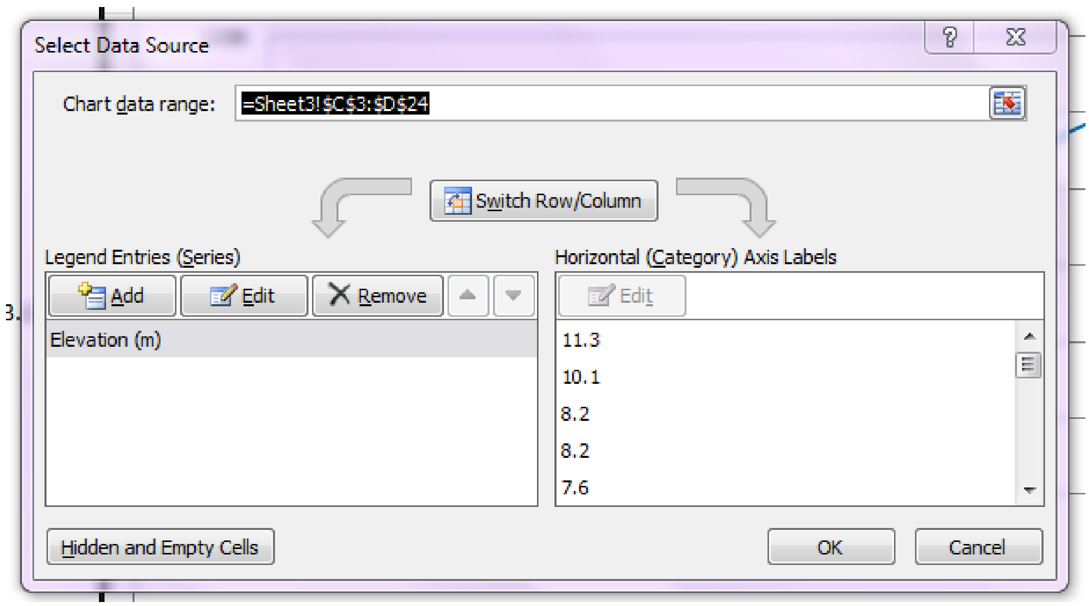


   d. Insert a linear trend line, by selecting "Trendline" in the "Layout" section of the "Chart Tools" (see diagram above).

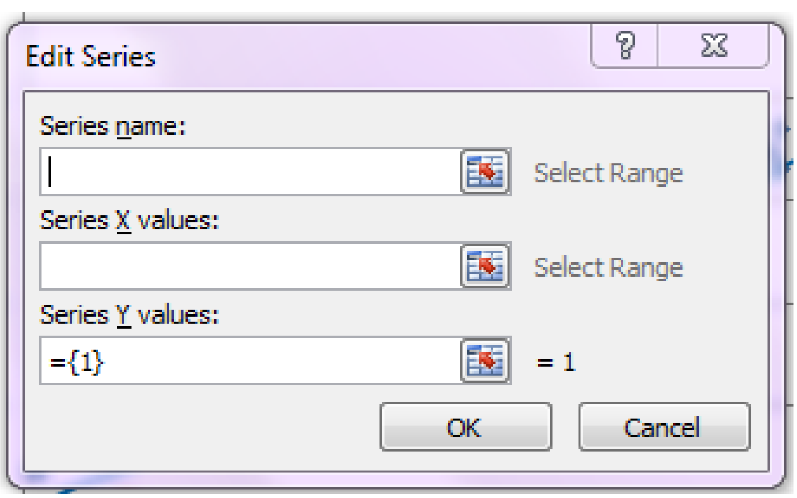
2. To plot multiple data sets on the same graph, you will need to add a new series to the graph.

   a. Right click on the graph. At the top of the page, you'll see "Chart Tools". Click on the "Design" tab. Click on "Select Data".

   b. This will open up a box where you can specify which data you want to include on the graph.



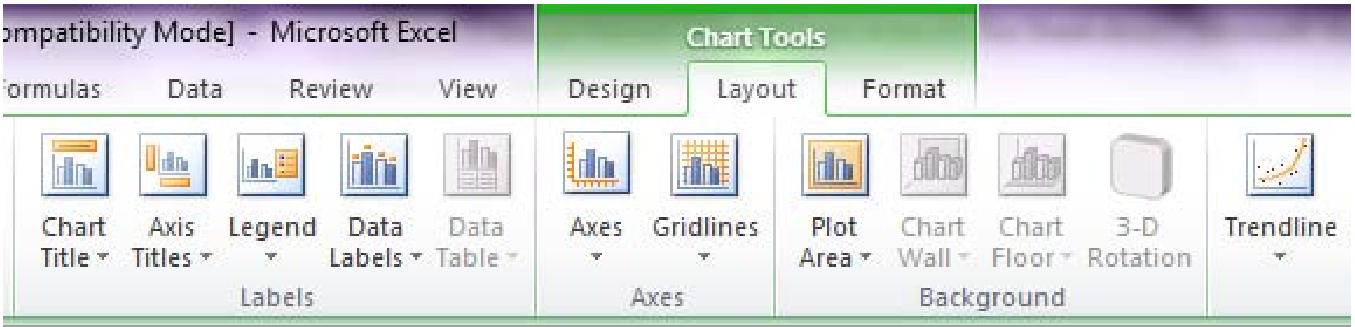
   c. Click on the "Add" button. This will open up a box where you can enter the range of the data and edit any information about it.



   d. For "Series Name", enter the location of the data samples.

e. For “Series X values”, highlight the range of data that will fall on the x-axis (Exposure Age).
f. For “Series Y values”, delete the “={1}” and then highlight the range of data that will fall on the y-axis (Elevation).
g. Enter “OK”.

3. Create a trend line (line of best fit) for each data set.
   a. Click on one of the points for a data set.
   b. Select “Trendline” in the “Layout” section of the “Chart Tools”.

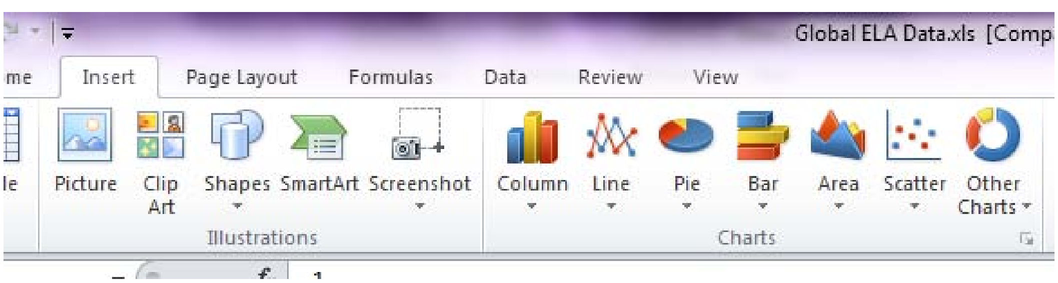


   c. To format the trend line (make the line color match the data points or any other desired modification), right click on the trend line. Select “Format Trendline” and make any modifications you desire.

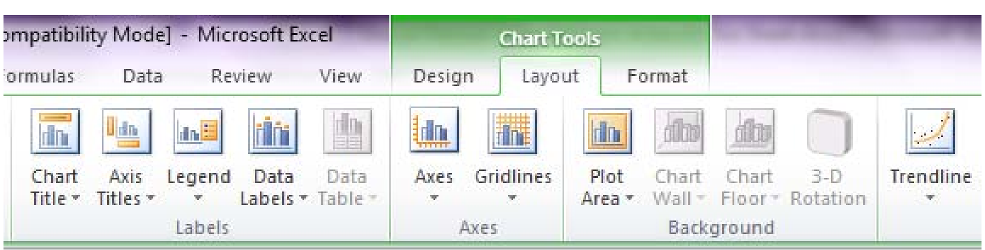
1. Alternatively, you can use the Excel file to create a computer generated scatter plot. To do this:
   a. Select (highlight) the temperature and precipitation columns together.

Temperature of three summer months at ELA [^{o}C]	Winter accumulation plus summer precipitation [mm] at ELA
-1.0	240
-1.1	170
-1.5	190
-1.6	310
-1.7	350
0.5	590
-0.3	240
1.9	590
-0.3	310
0.6	700
1.1	510
2.9	1350
2.0	990
2.3	870

   b. Go to the "Insert" menu and select 'Scatter' from the chart menu (choose the first scatter option – the one that <u>does not</u> show points connected by a line).



   c. To format the scatter plot with a title, axis labels, and key, select "Layout" under the chart tools.



   d. Insert a linear trend line, by selecting "Trendline" in the "Layout" section of the "Chart Tools" (see diagram above).