AMERICAN METEOROLOGICAL SOCIETY:

A COLDEX Center for Oldest Ice Exploration PARTNER

Project Ice

Ice Core Science and Engineering

—

TEACHER'S GUIDE

Project Ice

This guide is one of a series produced by Project Ice, a National Science Foundation sponsored initiative of the American Meteorological Society (AMS). AMS is a subawardee of Oregon State University on its NSF Science and Technology Center institutional award (OPP-2019719), Center for Oldest Ice Exploration (COLDEX). The purpose of COLDEX is to “explore Antarctica for the oldest possible ice core records of our planet’s climate and environmental history, and to help make polar science more inclusive and diverse.” Project Ice is the annual K-12 teacher focused activity within COLDEX, and is offered via hybrid delivery that includes a one-week residency at Oregon State University. The goal of Project Ice is to create and train a diverse network of master teachers prepared to integrate paleoclimatology and polar science in their classrooms and provide peer training sessions. To support these teachers' educational experience, Project Ice develops and produces teacher's guides, slide sets, and other educational materials.

For further information, and the names of the trained master teachers in your state or region, please contact:

Project Ice
American Meteorological Society
1200 New York Avenue, NW, Suite 450
Washington, DC 20005
amsedu@ametsoc.org

This material draws from U.S. Ice Drilling Program School of Ice work supported by the National Science Foundation under Award #1836328. Some content is also based on AMS DataStreme course investigations, developed with support from the National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA).

Figure i. Ice cores stored at -36°C (-32.8°F) at the National Science Foundation - Ice Core Facility in Denver, CO. [Photo by Karen Pearce/NSF]

"Don't let anyone rob you of your imagination, your creativity, or your curiosity. It's your place in the world; it's your life. Go on and do all you can with it, and make it the life you want to live."

- Mae Jemison, Engineer, Physician and Former NASA Astronaut

"Life is an opportunity, benefit from it. Life is beauty, admire it. Life is a dream, realize it."

- Saint Mother Teresa of Calcutta (1910-1997)

Module: Ice core science and engineering
Instructor: Project Ice Instructor or Project Ice Graduate
Audience/Grade Level: K-12 Educators

Objectives: After completion of this module participants will be able to:

1. Implement scientifically accurate and pedagogically sound instructional resource materials focused on ***ice core science and engineering***;
2. Integrate engineering and the scientific method of pursuing questions related to ***ice core science and engineering*** into other educational settings;
3. Construct scientific explanations and demonstrate knowledge of engineering challenges for ***ice core science and engineering*** and relate/map these to the Climate Literacy Principles and NGSS.
4. Analyze and interpret scientific and engineering observations related to ***ice core science and engineering*** acquired through ice exploration, computer modeling, and previous ice core drilling expeditions
5. Conduct peer training sessions on ***ice core science and engineering*** on a continuing basis, with instructional resource materials, scientific guidance and opportunities to interact with scientists and professionals in the fields of climate science and polar exploration.

Ice Core Science - Basic Understandings:

IV. Ice as a Scientific Observatory (2, 3)

2. Instruments are sent down the boreholes left after drilling ice cores and also through fast-access holes. These logging instruments gather a wide array of information needed to fully understand the histories of climate and ice dynamics preserved within the ice (temperature, seismic, stratigraphy, ice hole tilt and deformation for example).

3. Future plans require multiple boreholes drilled to at least 150 m deep and some to 2,500 m deep to study the surrounding ice volume.

V. Technology

1. Scientists and engineers must work closely together to make long range plans for the drilling needs of scientists, the logistics for moving drills in extreme environments, and the funding needed for development and deployment of new technologies. The Ice Drilling Program (IDP) is a real- world example of the collaboration of scientists and engineers.

2. Scientists and engineers share practices:
- asking questions,
- developing and using models,
- planning and carrying out explorations,
- analyzing and interpreting data,
- using mathematics and computational thinking,
- constructing explanations and designing solutions,
- engaging in argument from evidence, and
- obtaining, evaluating, and communicating information

Applicable Climate Literacy Principles: 5.B
(from https://cleanet.org/clean/literacy/climate/index.html)

Next Generation Science Standards (NGSS)

Science and Engineering Practices
1. Asking questions (for science) and defining problems (for engineering)
3. Planning and carrying out investigations
6. Constructing explanations (for science) and designing solutions (for engineering)

Crosscutting Concepts
1. Patterns. Observed patterns of forms and events guide organization and classification, and they prompt questions about relationships and the factors that influence them.

4. Systems and system models. Defining the system under study—specifying its boundaries and making explicit a model of that system—provides tools for understanding and testing ideas that are applicable throughout science and engineering.
6. Structure and function. The way in which an object or living thing is shaped and its substructure determine many of its properties and functions.
7. Stability and change. For natural and built systems alike, conditions of stability and determinants of rates of change or evolution of a system are critical elements of study.

Disciplinary Core Ideas in Earth and Space Science
K-2: Water exists as solid ice—2-ESS2-3
3-5: Glacier processes—4-ESS2-1
6-8: Water movements both on land and underground (subglacial) MS-ESS2-2
9-12: Geologic record (relate to ice core record)—HS-ESS2-4

Engage | The scope of the challenge

Figure 1. Ice core scientists carry a recently drilled ice core in Antarctica. [Photo by Todd Anderson]

Antarctica is the coldest, driest, windiest, and highest elevation continent on Earth. It is largely uninhabited but is visited each year by researchers and support staff who perform different important research projects on the continent. Consider Figure 1, a photograph of ice core scientists carrying a recently drilled piece of ice core in a remote field camp in Antarctica. What are some of the questions this picture raises?

- Who are these scientists?
- What do ice cores actually tell us about the Earth's climate history?
- Where do scientists drill for ice cores in Antarctica?
- When is the earliest we can go back in Earth's history using the ice core record?
- Why do we care about Earth's climate history?
- How do we use science and engineering to drill for ice cores?

These scientific questions are likely accompanied by equally interesting logistical questions.

- Who are the scientists, engineers, and staff that make up Antarctic ice coring teams?

- What do people on ice coring teams need to do to prepare for life in Antarctica?
- Where do ice coring teams live in Antarctica?
- When does ice drilling generally take place in Antarctica?
- Why do we need so much equipment for ice coring?
- How do the people and equipment needed for ice coring get to Antarctica and how do the ice cores get back to research labs without melting?

Consider these questions as you continue through this module. Many of the questions you will still have after this module reflect the real challenges faced by the scientists and engineers that work to drill for ice cores in the remotest place on Earth.

Explore | Ice cores as a paleoclimate record

Ice cores can provide direct measurements of Earth’s past climate or “paleoclimate”. For example, when snow falls, the spaces between these snowflakes are filled with air. If this snow freezes into solid ice, the air gets trapped as bubbles. The air inside these bubbles are tiny samples of the atmospheric air at the time the ice froze. Bubbles in ice cores give scientists direct samples of past atmospheric chemistry. Scientists at COLDEX are particularly interested in measuring the concentration of greenhouse gases like carbon dioxide and methane. Greenhouse gases trap infrared or heat energy in the atmosphere, causing an increase in global temperatures. COLDEX scientists want to measure the concentration of these gases 1.5 million years ago and earlier when global temperatures were higher than they are today but similar to where we expect global temperatures to be in the future. Scientists can also measure the chemical composition of the ice itself, providing information about changes to the hydrological cycle due to climate.

COLDEX scientists are also interested in measuring the dust that gets trapped in ice cores. This dust can give scientists information about how dry the climate was at the time the ice formed as well as giving details about whether the Earth was in a colder glacial (more ice frozen on the surface) period or warmer interglacial (less ice frozen on the surface) period. The chemistry of the dust tells us where the dust came from, and we can also calculate the age of the dust, telling us the age of the ice it is found in. If the dust is volcanic ash, then we may be able to determine when and where the volcanic eruption was.

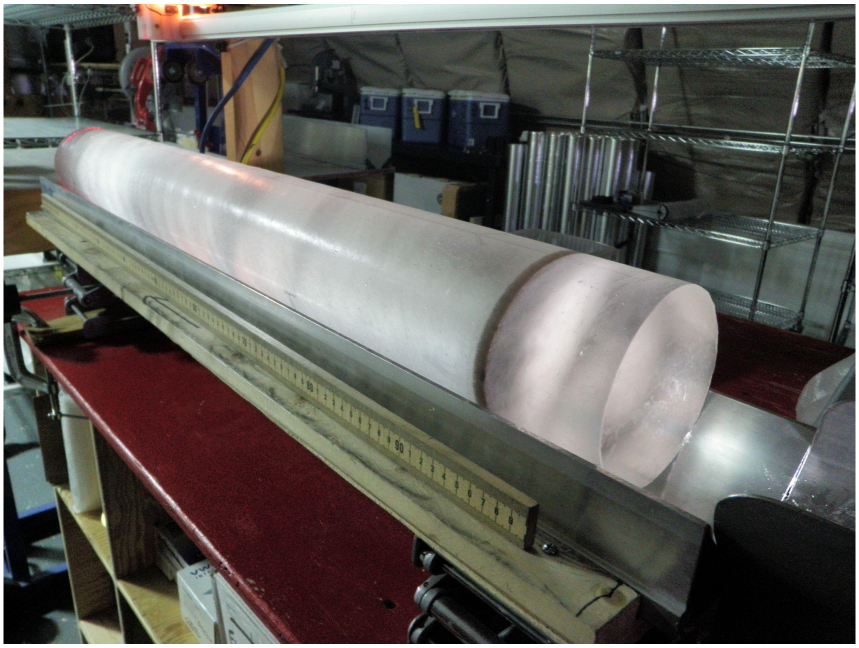

Figure 2. Ice core from the West Antarctic Ice Sheet. A new layer of ice accumulates each year, with the lighter layers accumulating in the summer and the darker layers accumulating in the winter. If undisturbed, the layers represent an increase in the age of the ice from the top to the bottom of the core. The very dark layer towards the bottom of the core is a layer of volcanic ash that fell approximately 21,000 years ago and became frozen in the ice sheet. [Photo by Heidi Roop]

These are just a few examples of the information we can learn about paleoclimate from ice cores. Most of these measurements will take place in science laboratories far away from where the ice was drilled in Antarctica. For the US Ice Drilling Program and COLDEX, the ice cores need to be transported back to the National Science Foundation Ice Core Facility (formerly the National Ice Core Laboratory) in Denver, Colorado where they will be stored until researchers are ready to make scientific measurements.

Group Review:

1.) Imagine you have drilled an ice core with a COLDEX science and engineering team. Now you and your team have to transport the ice from Antarctica to the Ice Core Facility in Colorado. What is your highest priority?

2.) Watch the following video ("The Long Haul") by the US Ice Drilling Program featuring Michael Davis, the US Antarctic Program Cargo Supervisor. How many steps need to be taken to get the ice cores from the field site (or "deep field") to Denver, Colorado?
https://www.youtube.com/watch?v=OMMOFZQMqsA&list=PLnGJdtH4AHvemsgCv0vf50BpiO1FurCkI&index=9

3.) Reflect on the scientific measurement: measuring the chemistry of the air in bubbles trapped in the ice. Considering this objective, why is it so important that the ice remains completely frozen throughout its transport from Antarctica to the research laboratories?

4.) Now, try to imagine drilling into the Antarctic ice sheet to retrieve cores of ice. Speculate on the potential challenges that face the ice coring team in the field.

Explain | Ice core science and engineering in Antarctica

Group Discussion of Responses from the Explore Section

In the Engage section, you speculated on the number one priority when planning to transport ice cores out of Antarctica. You then tried to list the many steps that US Antarctic Program Cargo Supervisor Michael Davis described in the US Ice Drilling Program video “The Long Haul”. Keeping ice cores frozen is a significant challenge but an important one. Even small, abrupt changes in the temperature the ice is exposed to could cause the ice to fracture, which may disrupt some of the characteristics important for scientific study. For example, you can think of the air bubbles in the ice as tiny pressurized capsules of the air that was in Earth’s atmosphere at the time the ice froze. Melting or fracturing of the ice could cause the air in these bubbles to escape.

There are many challenges to keeping the ice in good condition for scientific analysis while drilling the core. Keeping the ice core from fracturing at all is nearly impossible. Drilling teams need to consider not only the specific drills they will use but also use computer models and other techniques to predict the condition of the ice before drilling. In the coming Knowledge Check and Discussion sections, we will learn more about how scientists decide where to drill in the Antarctic ice sheet, the processes of drilling, and the challenges of living and working in Antarctica.

Knowledge Check and Discussion - Deciding where to drill for the oldest ice

The scientific objective at COLDEX is to drill a continuous core with at least 1.5 million year old ice at the bottom and to find pieces of older ice up to 5 million years old in shallower cores. To find ice older than the current oldest continuous ice core record of 800,000 years, scientists are focusing on the high elevation plateau region of the East Antarctic Ice Sheet (EAIS). Old ice may be found in the EAIS in one of two ways: as pieces of old ice folded upward from deep below the ice sheet into younger ice or as part of a continuous core of ice with the ice getting progressively older as you move from the top to the bottom of the core. Scientists can use instruments like radar that can image layers in the ice below the surface along with computer models that predict how ice flows to help them determine where old ice may be. Radar instruments send waves of microwave radiation through the ice, where the waves will bounce off of the layers below the surface, allowing scientists to calculate the depths to these layers. Radar instruments may be placed on the ground, where a snowmobile pulls the instrument across the snow surface, or flown over the ice surface from the air.

Another tool that is being developed in collaboration with COLDEX is the Ice Diver Probe. The Ice Diver is a thermal probe that can melt its way through ice layers quickly, collecting samples of dust embedded in the ice. By dating the age of this collected dust, ice core scientists get a better idea of how old the ice is.

COLDEX scientists input the data collected in the field about the ice sheet into computer models. These models use mathematical and physical calculations to estimate likely flow paths for the ice. This information gives scientists a way to predict how deformed or folded up the ice layers will be when drilling into the ice sheet.

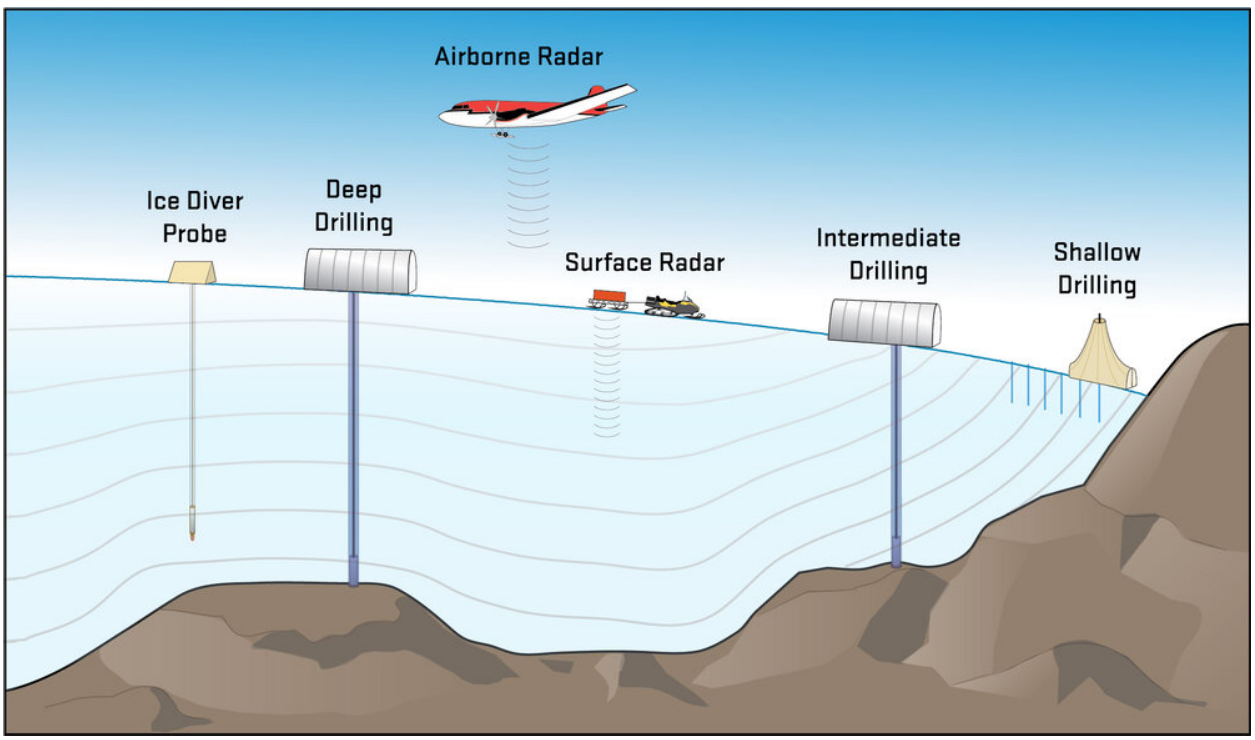

Figure 3. Some of the instruments used to explore potential old ice areas as well as deep, intermediate, and shallow drilling field stations. [From https://coldex.org/research]

You might notice from the figure above that COLDEX will use both deep and shallow drilling to find old ice. The depth of the ice core will be determined based on whether the ice coring team is looking for a continuous core or just pieces of old ice. Pieces of older ice folded upward into younger ice (called discontinuous ice) can often be found where ice flows up against topography such as the Transantarctic Mountain Range. As the ice flows against this mountain range, older ice is folded up into shallower depths beneath the ice sheet surface. Blue Ice Areas are often targets for pieces of old ice that can be found in shallower regions of the ice sheet. Blue Ice Areas are regions of the ice sheet where ice is being sublimated (the transition of solid ice directly into gaseous water vapor) at a greater rate than the accumulation of new snow. This means that older ice is being exposed at the surface due to this high rate of sublimation. Blue ice areas often look blue due to the way light is absorbed by the ice and air bubbles within the ice. One such blue ice area that COLDEX has investigated for old ice is in the Allan Hills region of the Transantarctic Mountain Range.

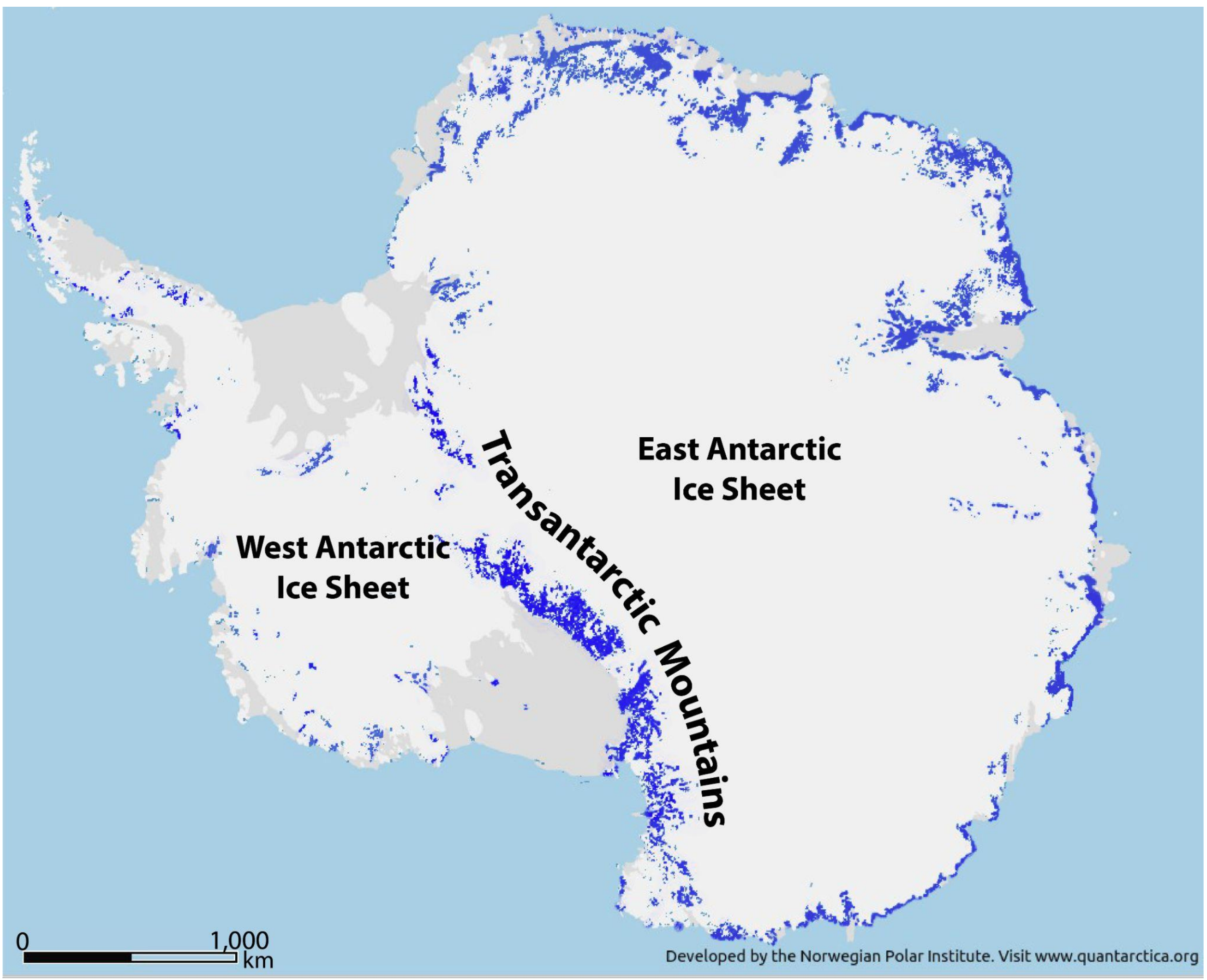

Figure 4. Blue ice areas (dark blue) across the East Antarctic Ice Sheet (EAIS) and West Antarctic Ice Sheet (WAIS). [Figure modified from the Norwegian Polar Institute]

Deep ice cores are often drilled near ice divides also called ice domes, where snow and ice is accumulating more than it is being lost due to melting or sublimation each year.

The snow and ice flows outward from the center of the dome, resulting in the center of the dome being the thickest part of the ice sheet and layers here relatively undisturbed from ice flow. In undisturbed ice layers, the oldest ice is found at the bottom of the ice sheet.

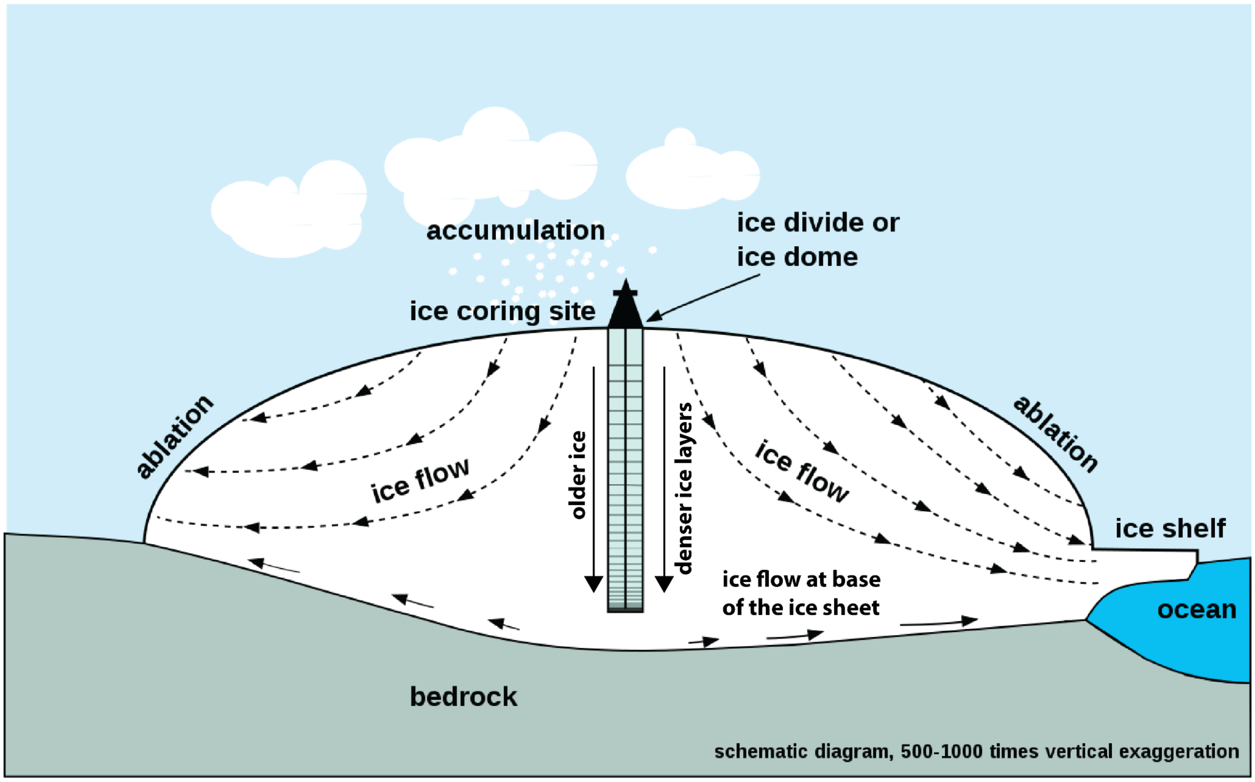

Figure 5. Ice divide or ice dome of an ice sheet.

How old this ice is will vary depending on the properties of the ice sheet, how fast the snow that formed the ice accumulated, and the topography of the bedrock the ice flows over. Figure 6 below shows the deep ice cores that have been drilled across Antarctica. The longest ice core drilled by a United States ice coring team was the West Antarctic Ice Sheet (WAIS) Divide core at 3,405 meters. This ice core covers 68,000 years of Earth's history (core "WD" in the figure below). The oldest deep ice core to date was drilled in the East Antarctic Ice sheet (EAIS) by the European Project for Ice Coring in Antarctica (EPICA) and although it is only 3,190 meters deep, this core covers 740,000 years of Earth's history (core "DC" in the figure below).

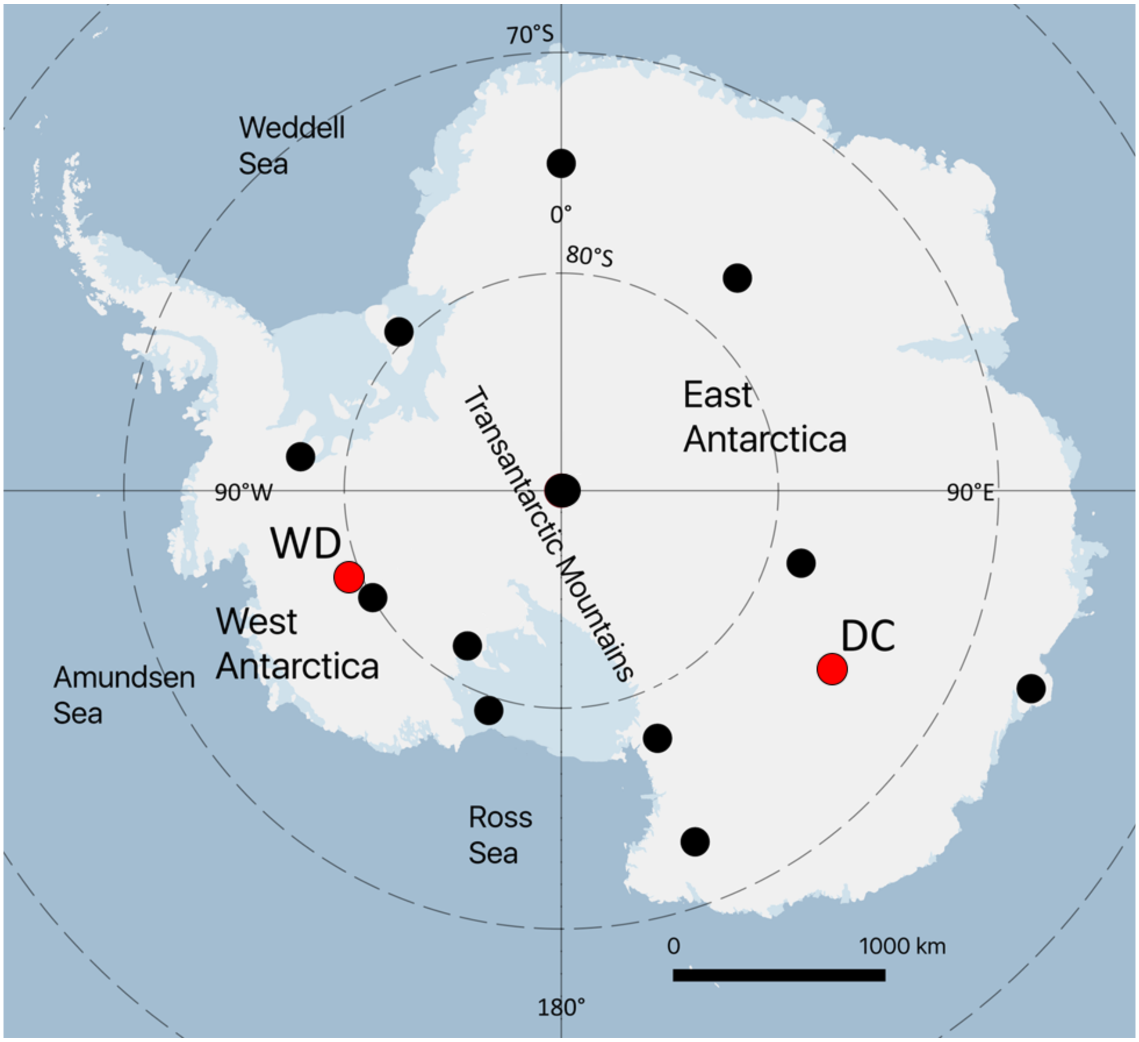

Figure 6. Location of deep ice cores (black circles) drilled to date across Antarctica. The red circles are the two deep cores discussed in the text: the WAIS Divide core (WD) and the EPICA Dome C core (DC).

Knowledge Check and Discussion - Getting to Antarctica

The US Antarctic Program has three stations on Antarctica: McMurdo, Amundsen-Scott South Pole, and Palmer Stations. McMurdo is the largest station and is home base for the US Antarctic Program. The average annual temperature at McMurdo Station is -18°C (0°F) with temperatures as high as 8°C (48°F) in the summer and as low as -50°C (-58°F) in the winter. Before even beginning their journey to Antarctica, members of an ice coring team must complete a medical, psychological, and dental health screening to ensure that they are physically and mentally able to withstand three months in the remotest and coldest location on Earth. Medical facilities and treatment options in Antarctica are limited, especially for teams that will be deploying to field locations outside the major stations.

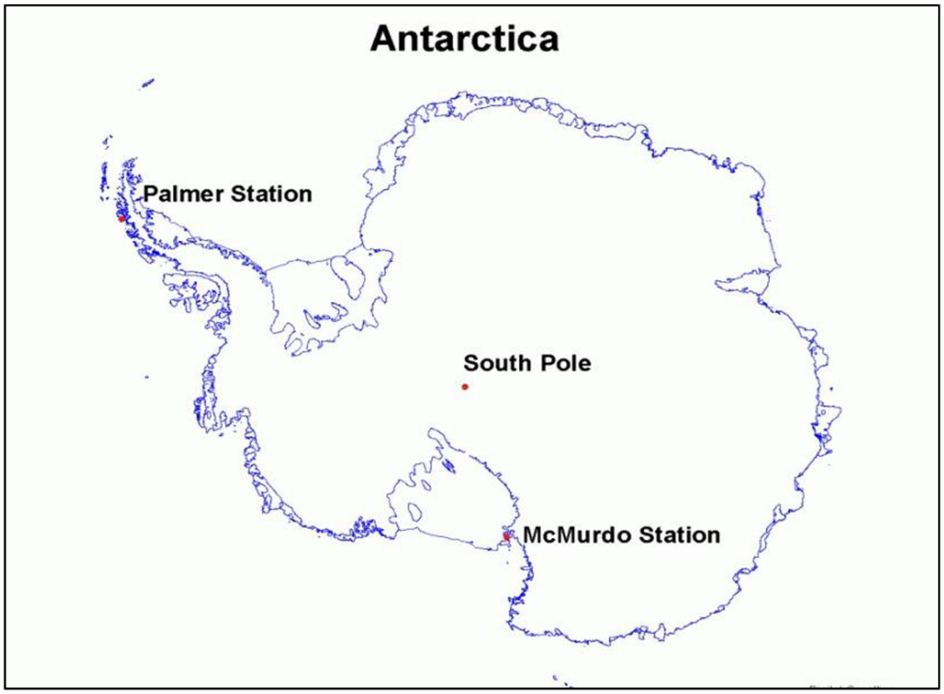

Figure 7. The locations of the three US Antarctic Program stations. [Figure from US Antarctic Program]

The scientists and engineers that make up an ice coring team will typically work during the Antarctic summer (October - February), when temperatures are warmer and the Sun never sets below the horizon. If scientists and engineers are traveling to McMurdo or South Pole stations, they will most likely travel to Antarctica on a flight from Christchurch, New Zealand. If traveling to Palmer station (on the Antarctic peninsula), they will most likely travel on a research ship from Punta Arenas, Chile.

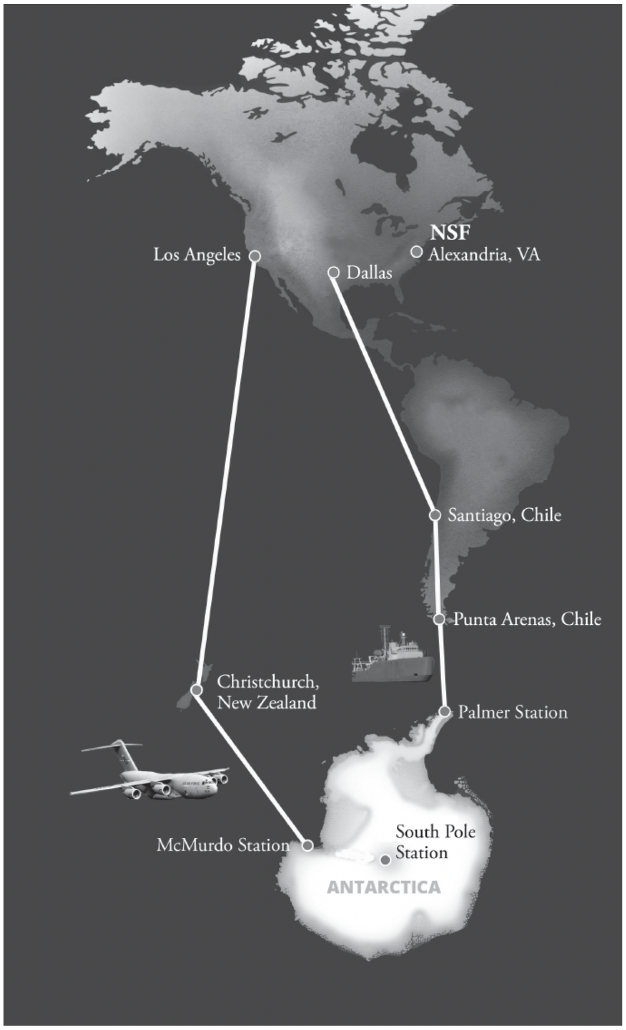

Figure 8. Typical routes taken by US scientists, engineers, and support staff traveling to Antarctica. [Figure from US Antarctic Program]

When an ice coring team arrives in either New Zealand or Chile, the scientists and engineers are given extreme cold weather gear to use while in Antarctica. From New Zealand, the ice coring team takes a 5 - 8 hour flight, called an “ice flight”, to McMurdo Station. If coming from Chile, an ice coring team would take a 4 - 5 day trip on a research ship to Palmer Station. Transportation to remote field camp locations outside of a station is done mostly using fixed-wing aircraft or sometimes helicopters. Snow mobiles may be used for transport around remote field camps.

Figure 9. Ice core scientists arriving at McMurdo Station in their US Antarctic Program issued extreme weather gear or “Big Reds”. [Photo by Austin Carter]

At remote field camps, members of an ice coring team live in tents. One of the challenges of living in a tent at a remote field camp is the wind and sometimes rapidly changing weather. Radios serve as the main method of communication. Ice coring teams at remote field camps must make multiple weather observation reports per day back to McMurdo station and must make daily check-ins with either the McMurdo or South Pole Station to ensure the continued safety of the field team.

Figure 10. The living quarters for an ice coring team in a remote field camp in Antarctica. [Photo by Jenna Epifanio]

Knowledge Check and Discussion - Drilling ice cores in Antarctica

After the ice coring team decides where to get their ice and then finally arrives at their remote Antarctic field camp, the next step is to drill the ice core! Successful drilling of an ice core requires immense teamwork between the ice core scientists and drilling engineers. The scientists decide on the scientific parameters they are looking for based on the questions they are trying to answer. These questions will determine how deep to drill, where to drill, and what features of the ice they are interested in studying. The engineers use their expertise to design the drilling practices used to make sure the highest quality ice core is retrieved.

Ice core drills are either electromechanical or electrothermal. An electromechanical drill uses cutters to mechanically cut a core from the ice sheet. The sonde is the part of the drill that goes down into the hole (called a borehole) in the ice sheet. The sonde is made up of an inner rotating barrel with cutters at the tip and an outer barrel. There is a motor that rotates the inner barrel so that it can cut through the ice. Chips of ice that form as the inner barrel cuts through the ice are removed away from the cutters using spiraled threads called flights. The sonde portion of the drill is suspended by a cable that is typically attached to a larger tower, allowing the sonde to be placed into and pulled back up through the borehole. The anti-torque system ensures that the only piece of the sonde that rotates is the inner barrel, keeping the cable from twisting and becoming tangled.

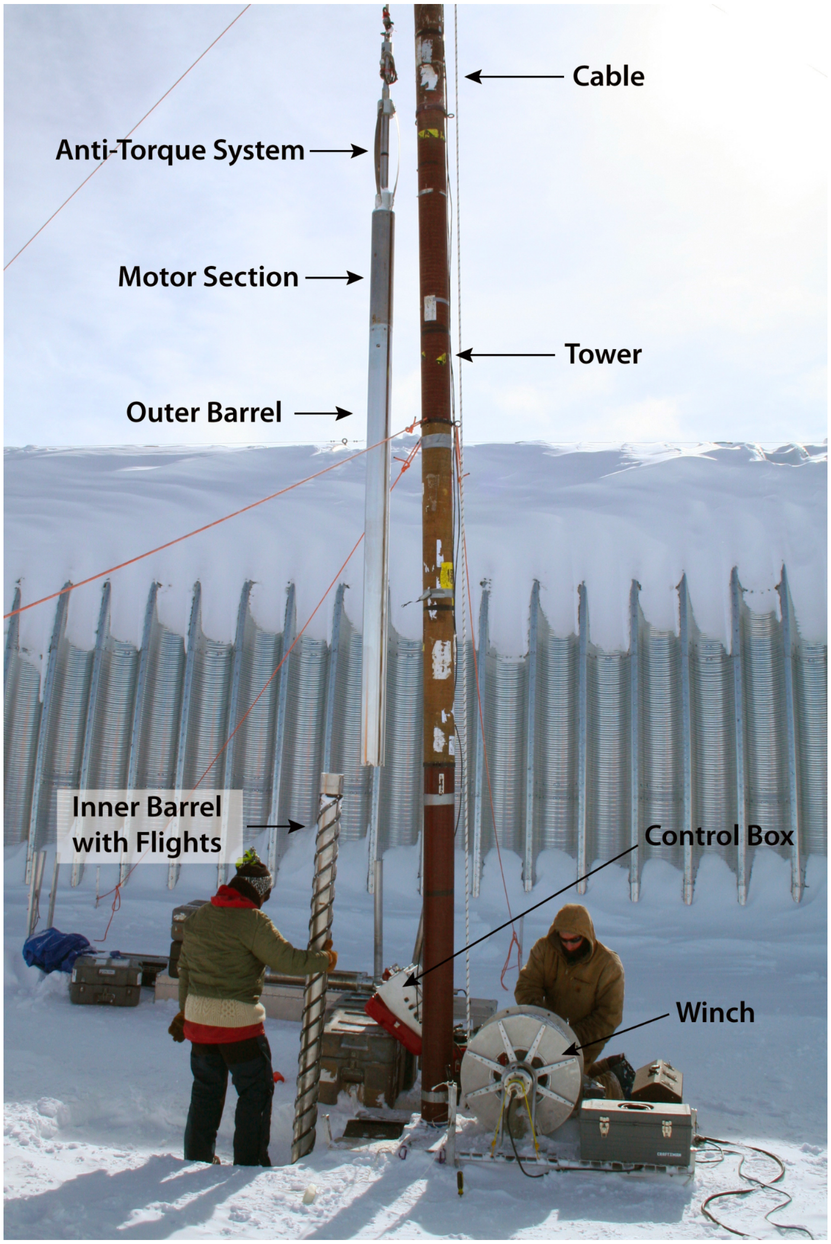

Figure 11. Major parts of an electromechanical drill. [Figure by Joseph Souney]

An electrothermal drill uses heat to melt through the ice surrounding where the ice coring team wants to core. Rather than mechanical cutters at the tip of the drill (called the drill head), an electrothermal drill head has a circular heating element. A benefit of electrothermal drills is that they have less moving parts than an electromechanical drill.

However, mixing heat and ice presents its own set of challenges. Electrothermal drills are typically only used for ice that is warmer than -10°C (+14°F). This is because the large temperature difference between the heating element and colder ice could cause thermal shock, resulting in fractures in the ice or changes to important ice chemistry.

There are many challenges facing the ice coring team. We learned in the previous section that ice flows. This means that the hole in the ice sheet where the drill is lowered into (called a borehole) may close if there is too much pressure on the sides of the borehole created by the flowing ice. The deeper the borehole goes, the more this force will push towards closing it. To help solve this problem, a special drilling fluid is used for most boreholes that reach depths of 300 m or more. There's an additional challenge to keeping the borehole open when using an electrothermal drill. With these drills, meltwater is produced as the drill melts down into the ice sheet. This meltwater can sometimes refreeze if left in the borehole, causing the hole to close. The ice coring team will add antifreeze to the meltwater or store the meltwater inside the drill. Both the presence of drilling fluid and antifreeze present further challenges that ice coring teams must consider, such as negative impacts on ice quality or environmental impacts.

Figure 12. An aerial photograph of a remote ice coring field camp in Antarctica. The long white tube with red ends is the tent where the drilling occurs. [Photo by The National Science Foundation]

Knowledge Check and Discussion - Transporting ice cores out of Antarctica

Once an ice core is drilled in the field, the core is removed from the inner barrel of the sonde and moved over to a station where it is logged. During logging, fractures and other physical properties of the core are noted. One of the major challenges that you may not think of is how to identify which way is “up” in the core! Arrows are drawn onto the core to show which way the ice core was oriented in the ice sheet. Why is this important? The chemical and physical properties of each ice layer contributes to our understanding of the climatic conditions on Earth at the time that layer was formed. Knowing how old ice layers are relative to the rest of the core is crucial to this story of how climate changes over time.

Figure 13. Recently drilled ice core sticking out of the drill sonde. Note the arrow helping the scientists to orient the core the same way it was oriented in the ice sheet. [Photo by Peter Neff]

In the video “The Long Haul”, you learned about all of the steps needed to get an ice core from a remote field camp in Antarctica all the way to long-term storage at the Ice Core Facility in Denver. The ice core must first be cut into 1 meter (3.28 feet) long sections and then put into a 1 meter long tube so that it will fit into the standard-sized insulated shipping containers used to send the ice out of Antarctica. The ice coring team may work at their remote Antarctic field site for close to two months to pack and ship the cores. The ice that has already been cored is stored in underground snow trenches until the cores are ready to be transported.

Figure 14. Ice core scientist cutting recently cored ice into a 1-meter length section for packaging and shipment out of Antarctica. [Photo by Mark Twickler]

Once the ice is cut into one meter pieces, it is placed in an insulated shipping container for transport to McMurdo Station. The shipping containers are flown back to McMurdo Station in an unheated aircraft cabin where they are put into the onsite freezers. The containers are then put in refrigerators on a cargo ship called “reefers” and transported to California before being transported to the National Ice Core Facility in Denver, Colorado. Currently the main freezer at the NSF-ICF is 55,000 cubic feet with over 17,000 meters of ice and is held at a temperature of -36°C (-33°F).

Figure 15. Silver tubes of ice stored in the freezer at the National Science Foundation Ice Core Facility in Denver, Colorado. Each tube contains 1 meter (3.28 feet) of ice and the white boxes contain recently-drilled ice from the West Antarctic Ice Sheet (WAIS). [Photo by Peter Rejcek]

New boxes arriving from the field are brought into the freezer quickly when they arrive in Colorado. The ice is allowed to equilibrate to the temperature of the freezer and then the tubes are removed from the boxes and placed on shelves for longer-term storage. All of the tubes are carefully inventoried and placed into a database so that researchers from around the world can access the ice for research. Scientists can visit the NSF-ICF to examine, log, measure, and cut pieces of the ice that can be shipped back to their laboratories for further scientific analyses. This step is called "core-processing" and takes place in a -25°C (-13°F) laboratory.

Figure 16. Ice core scientists at the NSF Ice Core Facility in Denver, Colorado planning how they will cut the ice core into sections that will be delivered to research laboratories across the country. [Photo by Danielle Whittaker]

Knowledge Check and Discussion - Ice core science and engineering

Elaborate | Drilling for ice cores in Antarctica

In the search for old ice, it is important for an ice coring team to consider many different features of the ice sheet and the bedrock (rock below) under the ice sheet based on the scientific question the team wants to answer. To find one long continuous core with the oldest ice at the bottom, scientists often search in areas where the ice is thick and the ice layers are believed to have remained mostly horizontal over time. Figure 17 shows a computer model of ice thickness across Antarctica.

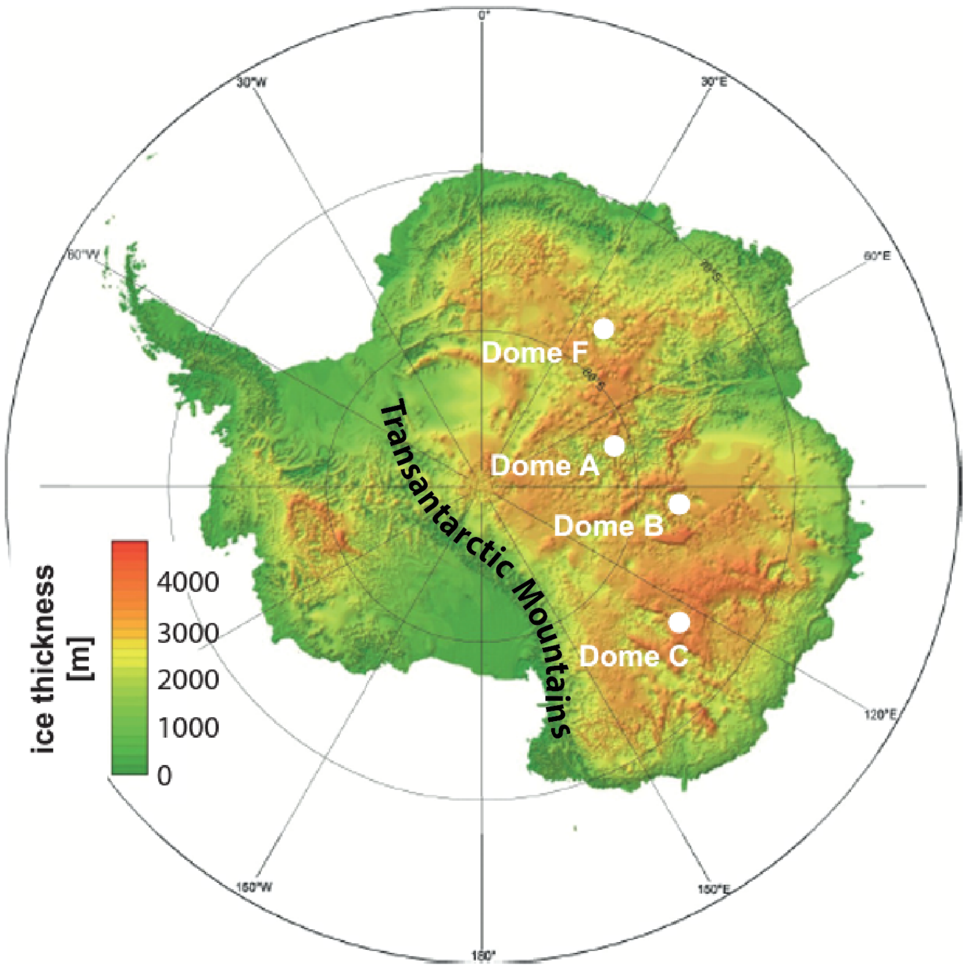

Figure 17. Computer model of ice thickness across Antarctica. The white dots are the location of some known ice domes. [Figure from Fischer et al. (2013)]

1. Recall that the Transantarctic Mountains separate the West Antarctic Ice Sheet (WAIS) to the West and the East Antarctic Ice Sheet (EAIS) to the East. Overall, thicker ice can be found…(select all that apply)

   a. In the WAIS
   b. In the EAIS
   c. At an ice dome
   d. At the coast

2. Dome F is also named Dome Fuji and is a location where an ice core was drilled. Based on Figure 17, which of the following describes the most likely length of the Dome Fuji ice core?

   a. Between 1,000 - 2,000 meters long
   b. Between 3,000 - 4,000 meters long

c. Greater than 4,000 meters long

As of 2023, the WAIS Divide ice core is the longest core ever drilled by a United States ice coring team. The core is 3,405 meters (11,171 feet). The figure below shows three potential locations (black stars) for where the WAIS divide ice core was drilled.

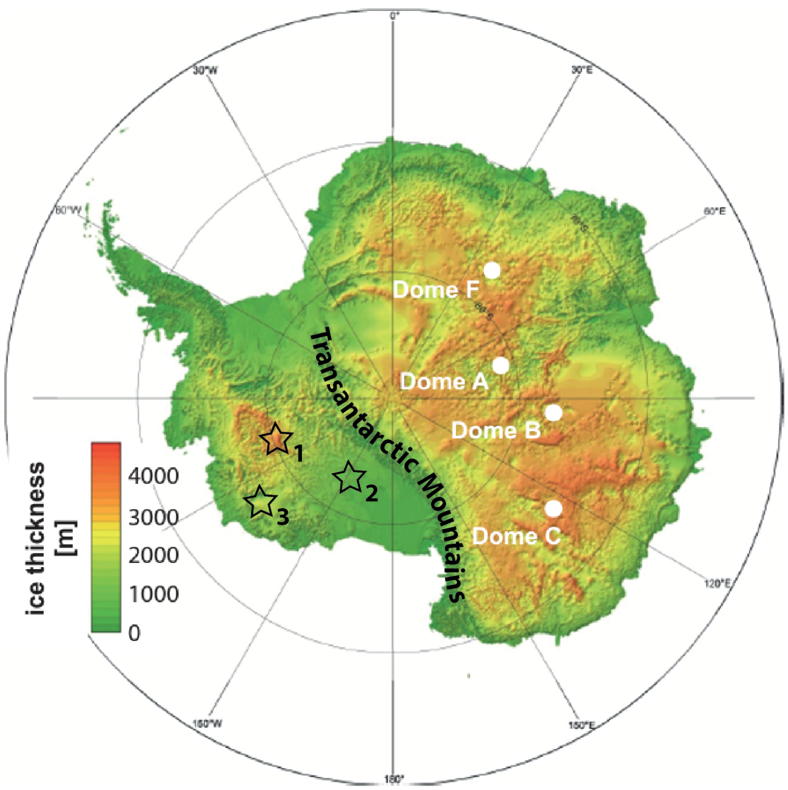

Figure 18. Computer model of ice thickness across Antarctica. The white dots are the location of some known ice domes. Black outlined stars are possible locations for the WAIS divide ice core discussed in question 3. [Figure from Fischer et al. (2013)]

3. Which location would likely produce the 3,405 meter WAIS divide ice core?
   a. Star 1
   b. Star 2
   c. Star 3

There are many different features of the Antarctic ice sheets to consider when planning where to drill for the oldest ice. Another piece of information that an ice coring team needs is the elevation of the bedrock or rock below the ice sheet. Ice that has to flow over mountainous terrain will likely have layers that have been deformed and are no longer horizontal, making the age of the layers more difficult to calculate. Figure 19 below shows a computer model of the bedrock elevation across Antarctica.

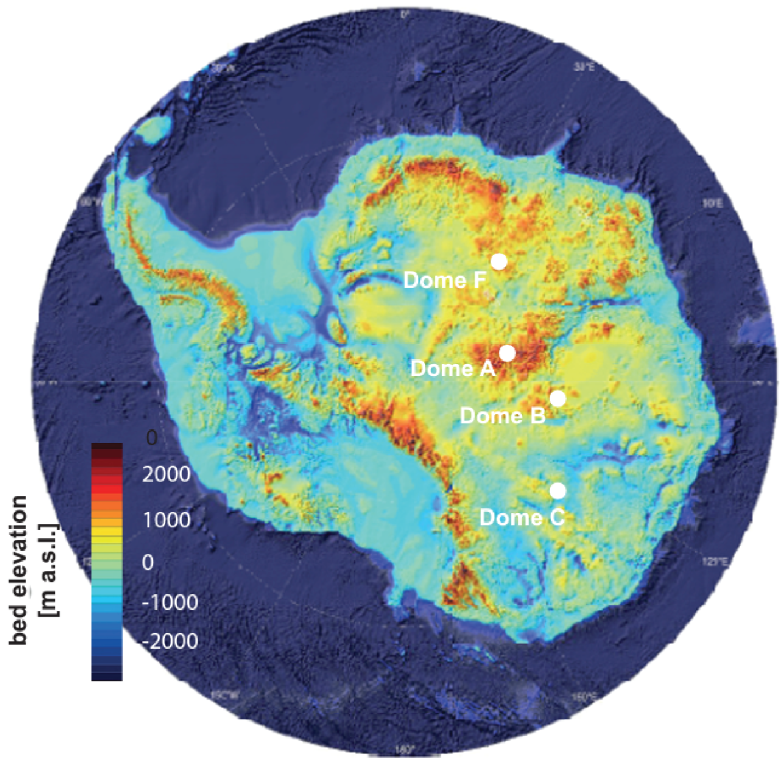

Figure 19. Computer model of bedrock elevation across Antarctica. The white dots are the location of some known ice domes. [Figure from Fischer et al. (2013)]

4. Which of the ice domes is located over the Gamburtsev Mountains, a mountain range that reaches an elevation of over 3,000 meters?
   a. Dome F
   b. Dome B
   c. Dome A

5. Sometimes ice core scientists are interested in drilling down to the bedrock below the ice sheet to get samples of the rock. Which conditions would you look for if this was your main scientific goal?
   a. High ice thickness, low bedrock elevation
   b. Low ice thickness, high bedrock elevation

Watch the following video “Polar Science and Engineering: Drilling Back Through Time” from the US Ice Drilling Program up to 6 minutes 30 seconds:
https://www.youtube.com/watch?v=EzJSJKBVE-Q&t=391s

6. Which of the following best describes the ice core scientists' main scientific question in this video?

a. Did a series of volcanic eruptions 18,000 years ago contribute to a change in the climate at that time?
b. Is it possible to drill a "replicate core", meaning an ice core that is drilled directly next to the borehole of a previously-drilled ice core (also called the "parent borehole")?
c. Can we extend the WAIS divide ice core depth even further than the already-drilled 3,405 meters?

7. Which of the following best describes the drilling engineers' main objective in this video?

a. Discover whether a series of volcanic eruptions 18,000 years ago contributed to a change in the climate at that time
b. Design a way to drill a "replicate core", meaning an ice core that is drilled directly next to the borehole of a previously-drilled ice core (also called the "parent borehole")
c. Extend the WAIS divide ice core depth even further than the already-drilled 3,405 meters

8. What was the difference in tilt between the "parent borehole" and the newly-drilled replicate borehole at the WAIS divide camp?

a. 5°
b. 10°
c. 1°

9. After a borehole is drilled, scientists can place instruments into the borehole to measure different properties of the ice. What do we call this group of scientists?

a. Ice core inspectors
b. Instrument droppers
c. Borehole loggers

An ice coring team has fun in Antarctica too! Watch this video of COLDEX scientist Peter Neff explaining the unexpected sounds you hear when dropping a piece of ice down a borehole: https://www.youtube.com/watch?v=SjGOmU8VnEk

10. As the ice moves down the borehole, the sounds coming to the surface change pitch due to the ___________________.

a. The Doppler effect
b. The Photoelectric Effect

c. The Domino Effect

Evaluate | Thinking like an ice core scientist

To review what has been presented and investigated during this module:

11. There are three United States stations in Antarctica: McMurdo, Amundsen-Scott South Pole, and _________
  a. Casey Station
  b. Palmer Station
  c. Syowa Station

12. Where an ice coring team drills for ice depends on the scientific questions being asked as well as the logistical requirements for drilling. Where would you search for old ice if you wanted to drill a shallow core (select all that apply)?
  a. In a Blue Ice Area
  b. At an ice dome
  c. Where the ice sheet flows up against a mountain range

13. Which ice coring drill would you use for ice that is colder than -10°C (+14°F)?
  a. An electrothermal drill
  b. An electromechanical drill

14. After an ice core is drilled, the ice coring team cleans off any drilling fluid on the ice core, takes notes on characteristics of the ice, cuts into 1-meter long pieces, and …which of the following?
  a. Melts off the bottom layer of ice
  b. Removes air bubbles in the ice
  c. Marks the “up” direction in the ice

15. Drilling engineers keep the whole drill setup from rotating and the cable from becoming tangled by using which of the following?
  a. Anti-torque system
  b. A sonde
  c. Flights

16. In “The Long Haul” video, US Antarctic Program Cargo Supervisor Michael Davis described that one of the most important engineering challenges is to keep the ice cores ___________ on their journey from Antarctica to the National Ice Core Facility in Denver, Colorado.

a. Clean
b. Frozen
c. Pressurized

17. An ice coring team typically works during the Antarctic summer, when the temperatures are warmer and the sun is constantly up. When is the Antarctic summer?
a. October - February
b. May - October
c. December - June

18. To find potential areas with old ice, COLDEX scientists are using tools such as (select all that apply):
a. Airborne and surface radar
b. Ice Diver Thermal Probe
c. Computer modeling
d. All of the above

19. The EPICA Dome C ice core currently covers the longest span of Earth's paleoclimate history. How many years does the ice in the Dome C core correspond to?
a. 400,000 years
b. 68,000 years
c. 740,000 years

20. In undisturbed ice layers, the oldest ice is found at the _______ of the ice sheet.
a. Bottom
b. Top

Workshop Extensions |
"The Long Haul Ice Core Challenge"
"Life Cores" (development activity)