Chapter 19
Ancient Climates and Proxies

Abstract Paleoclimatology is the study of climates of the past. This study uses historical records, direct lines of evidence, and proxies to determine past climates. As we go back in time from the present, the less confidence we have in the data, so paleoclimatologists rely on converging data paths to increase confidence in the results and conclusions. Ice cores tell scientists a great deal about the ancient composition of the atmosphere by analyzing the air bubbles contain within them. These air bubbles within the ice contain samples of the atmosphere at the time they formed. Stable isotopes from ice and sediment samples reveal temperature data by proxy. Pollen, tree rings, coral growth, cave deposits, assemblages of organisms hold clues to past climates.

Keywords Pollen • Isotopes • ^{18}O • Radiocarbon • Trees • Rings • Corals • Dansgaard-Oeschger • Foraminifera • Cave • Organisms • Geochemistry • Fossil • Aeolian • Milankovitch • Tephrochronology • Dendrochronology • Dendroclimatology • Terrigenous • Sediment • Biogenic • Orbital • SMOW • Periglacial • Loess • Lacustrine • Glacial • Limnology • Palynology

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and each chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

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Things to Know	
Proxy	Orbital tuning
Paleoclimatology	Lëss
Stable isotopes	Biogenic sediment
Palynology	Periglacial material
Fossil pollen	Tephrochronology
Proxy types	Assemblages of organisms
Coral growth	Limnology
Terrigenous sediment	Dendroclimatology
Lacustrine	Biogenic sediment
Geochemistry	Uniformitarianism
Sr/Ca	Bipolar seesaw
Milankovitch	Foraminifera
Cave deposits	Mg/Ca
SMOW	Tree rings
Aeolian deposits	Dansgaard-Oeschger events

19.1 Introduction

Paleoclimatology is the study of ancient climates and involves using what is known about variables in present climate science to interpret past climates. In that sense, it uses the principle of uniformitarianism from geology, "the present is the key to the past." The opposite principle is also used, that the past is key to the present.

Proxies are substitutes for data directly obtained. Proxies are what paleoclimatologists gather from natural recorders of climate variability such as tree rings, ice cores, fossil pollen, ocean sediments, coral, isotope analysis, foraminifera and other fossil shells, and historical data. By analyzing records taken from these and other proxy sources, scientists can extend our understanding of climate changes far back beyond the 130+-year instrumental record that began in the 1880s. Paleoclimatologists try to obtain age information from multiple sources to reduce age uncertainty, and paleoclimatic interpretations must take into account uncertainties in time control or the interval of time the study encompasses.

Paleoclimatic reconstruction methods have advanced in the past several decades and range from direct measurements of past change, e.g., ground temperature variations, gas content of ice core air bubbles, ocean sediment pore-water change, and glacier size changes, to proxy measurements involving the change in chemical, physical and biological parameters that reflect past changes in the environment where the proxy entity grew or existed.

Many living creatures, such as insects, corals, and other organisms alter their growth and/or population dynamics in response to changing climatic conditions and these climate-induced changes are recorded in the past growth of living and

fossil specimens or assemblages of organisms. Tree rings, ocean and lake plankton, and pollen are some of the best-known and best-developed proxy sources of past climate going back centuries and millennia. Networks of tree ring width and density chronologies are used to decipher past temperature and other environmental factors based on comprehensive comparisons with overlapping instrument data. Distributions of pollen and plankton from sediment cores are used to derive quantitative estimates of past climate (e.g., temperatures, salinity, and precipitation) using statistical methods calibrated against their modern distribution and associated climate parameters.

Geochemistry of several biological and physical entities reflects well-understood thermodynamic processes that can be transformed into estimates of climate parameters such as temperature. Key examples include: oxygen isotope ratios (^{18}O and ^{16}O) in coral and foraminiferal carbonate to infer past temperature and salinity; magnesium/calcium (Mg/Ca) and strontium/calcium (Sr/Ca) ratios in carbonates for temperature estimates; alkenone (highly resistant organic compounds) saturation indices from marine organic molecules to infer past sea surface temperature (SST); and oxygen and hydrogen isotopes and combined nitrogen and argon isotope studies in ice cores to infer temperature and atmospheric transport.

Many physical systems (e.g., sediments and aeolian deposits) change in predictable ways that can be used to infer past climate change. There is ongoing work on further development and refinement of methods, and there are remaining research issues concerning the degree to which the methods have spatial and seasonal biases. Therefore, in many recent paleoclimatic studies, a combination of methods is applied since multi-proxy series provide more rigorous estimates than a single proxy approach, and the multi-proxy approach may identify possible seasonal biases in the estimates. No paleoclimatic method is foolproof, and knowledge of the underlying methods and processes is required when using paleoclimatic data.

The field of paleoclimatology depends heavily on replication and cross-verification between paleoclimate records from independent sources in order to build confidence in inferences about past climate variability and change. In this chapter, the most weight is placed on those inferences that have been made with particularly robust or replicated methodologies.

19.2 Historical Records

Historical records go back as far as drawings on the walls of caves. Most useful climatic records, however, are observations found in farmer's logs, diaries, old newspaper accounts, and other written records. These records are largely anecdotal and give only an overview or a general sense of climate prior to instrumental recordings in the 1880s.

Paleoclimatologists also use documentary data (e.g., in the form of specific observations and crop harvest data) for reconstructions of past climates.

19.3 Ice Cores

Ice cores have been taken from drilling into glaciers and ice caps in many parts of the world and those from Greenland and Antarctica are especially well known.

Recent studies (2010–2012) have shown that ice also forms by melt water from the glacial ice re-freezing at the bottom of glaciers. This does not affect data that are obtained above the re-freezing zone.

As glacial ice forms from snow which accumulates year after year, it entraps part of the environment from which it forms such as dust from volcanic eruptions and air trapped in atmospheric bubbles preserved in the ice. Thus, glacial ice cores tell scientists a great deal about Earth history at the time the ice was formed, especially the volcanic eruptions and composition of the atmosphere. Atmospheric concentrations of such atmospheric constituents as carbon dioxide, methane, and volcanic dust can be read directly from these ice cores. Other ice core constituents, such as certain stable isotopes, may also be important.

Reliable modern instrument records of climate only began in the 1880s and to obtain climate readings prior to then requires the use of proxies.

19.4 Stable Isotope Analysis

Oxygen and carbon stable isotopes are the two most used for environmental and climate change applications, although others are sometimes useful. They were discussed in detail in Chap. 14.

19.5 Ice Cores and Proxies

Ice cores are retrieved from glaciers and ice caps by a special coring or drilling method. The methods of obtaining and analyzing data from ice cores are discussed in Chap. 14.

19.6 Dating Ice Cores

Near the top of glacial ice, it is usually possible to identify annual layers of alternating light- and dark-colored bands. The light-colored bands represent summer and the dark-colored bands represent winter. The light- and dark-colored bands together represent 1 year.

Deeper below the ice surface, the original snow is recrystallized and the annual layers are indistinguishable. Dating the deeper ice becomes a much more difficult problem. Methods of dating ice cores are discussed in more detail in Chap. 14.

Gas synchronization uses records of gases that are well mixed in the atmosphere to link ice core records. This has been used with $\delta^{18}O$ to compare the timing of

deglacial changes recorded in Greenland and Antarctica. The rapid variations in atmospheric methane concentrations has allowed more accurate comparisons of the relationship between Dansgaard-Oeschger events in Greenland and warming events in Antarctica.

Tephrochronology uses the elemental composition and geochemical signature of volcanic ash (tephra) found in ice cores as stratigraphic markers. If the age of the volcanic eruption is known, tephra offer a means to date an ice core with radioisotopes and to correlate between ice cores in different parts of the world.

Correlation with other dated records allows researchers to establish relative chronologies between ice cores and with marine sediments.

19.7 Dendroclimatology

The study of the annual growth of trees and the consequent assembling of long, continuous chronologies for use in dating wood is called dendrochronology. The study of the relationships between annual tree growth and climate is called dendroclimatology. Dendroclimatology offers a high resolution (annual) form of paleoclimate reconstruction for most of the Holocene and Anthropocene.

The annual growth of a tree is the net result of many complex and interrelated biochemical processes. Trees interact directly with the microenvironment of the leaf and the root surfaces. The fact that there exists a relationship between these extremely localized conditions and larger scale climatic parameters offer the potential for extracting some measure of the overall influence of climate on growth from year to year. Growth may be affected by many aspects of the microclimate: sunshine, precipitation, temperature, wind speed and other factors.

A cross section of most forest tree trunks found in temperate regions will reveal an alternation of lighter and darker bands, each of which is usually continuous around the tree circumference (Fig. 19.1). Each seasonal increment consists of a couplet of early wood (a light growth band from the early part of the growing season) and denser late wood (a dark band produced towards the end of the growing season), and collectively they make up the tree ring. The mean width of the tree ring is a function of many variables, including the species, age, soil nutrients, and a host of other climatic factors. The problem facing the dendroclimatologist is to extract whatever climatic signal is available in the tree-ring data from the remaining background "noise." Figure 19.1 below shows the variability in widths of the tree rings.

19.8 Ocean Sediments

Billions of tons of sediment are carried off the land and accumulate in the ocean basins every year, and these sediments may be indicative of climatic conditions near the ocean surface or on the adjacent continents. Sediments are composed of both biogenic (organic) and terrigenous (inorganic, land derived) materials. The biogenic component includes the remnants of planktonic (ocean surface-dwelling) and benthic (deep-water- or

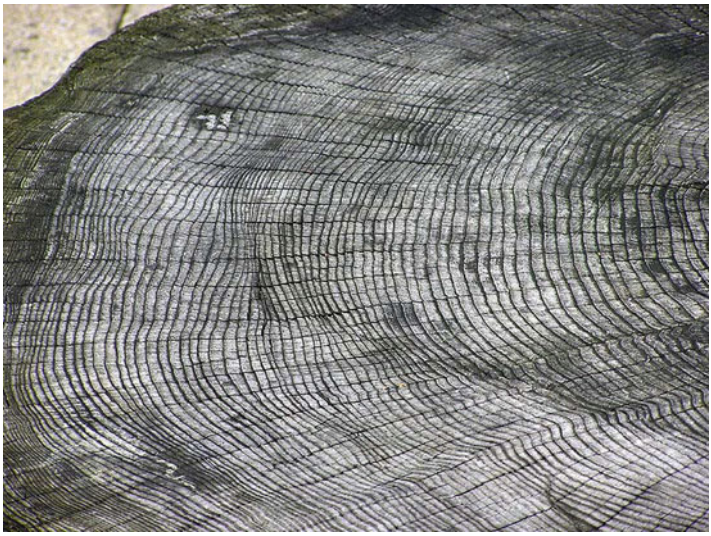

Fig. 19.1 Tree rings in a tree trunk in the Bristol Zoo, Bristol, England (Public Domain)

sea floor-dwelling) organisms which provide a record of past climate and oceanic circulation. Such records may reveal information about past surface water temperatures, salinity, dissolved oxygen and nutrient availability. By contrast, the nature and abundance of terrigenous materials may provide information about continental humidity-aridity variations, and the intensities and directions of winds. Ocean sediment records have been used to reconstruct paleoclimate changes over a range of time scales, from thousands of years to millions and even tens of millions of years.

19.9 Paleoclimate Reconstruction from Biogenic Material

Biogenic sea floor sediments are called oozes, and are usually either calcareous or siliceous in nature. Calcareous oozes consist mainly of the carbonate tests (hard parts) of millions of marine organisms, while siliceous oozes are made up of millions of silicate sources. For paleoclimatic purposes, the most important materials are the tests of foraminifera (calcareous zooplankton; Fig. 19.2), coccoliths (calcareous algae; Fig. 19.3), radiolarians and silicoflagellates (siliceous zooplankton; Fig. 19.4), and diatoms (siliceous algae; Fig. 19.5).

Paleoclimate reconstruction from the study of calcareous and siliceous tests has resulted from basically three types of analysis:

- Oxygen isotope composition of calcium carbonate ($CaCO_3$);
- Relative abundance of warm- and cold-water species; and
- Morphological variations in particular species resulting from environmental factors.

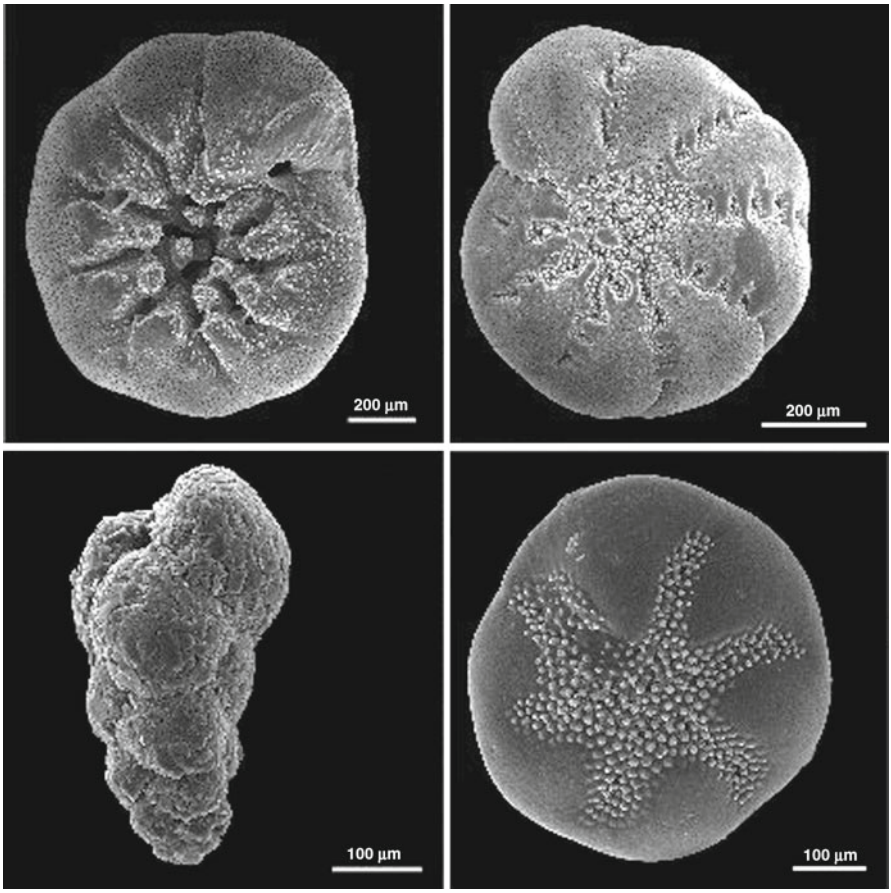

Fig. 19.2 Scanning electron microscope (SEM) images of tests (calcareous skeletons) of foraminifera (USGS, Public Domain)

Most work has concentrated on the study of the foraminifera, in particular oxygen isotopic analyses. Foraminifera ("forams" for short) are abundant and the oxygen content of their shells can be readily analyzed.

If calcium carbonate of a marine organism is crystallized slowly in water, the ^{18}O is slightly concentrated in the precipitate relative to that remaining in the water. This fractionation process is temperature dependent, with the concentrating effect diminishing as temperature increases. When the organism dies, the test sinks to the sea bed and is laid down, with millions of other tests, as biogenic sea floor sediment (calcareous ooze), thus preserving a temperature signal (in the form of an oxygen isotopic ratio) from a time when the organism lived. If a record of oxygen isotope ratios is built up from cores of ocean sediment, and the cores can be accurately dated, this provides paleoclimatologists with a method of paleoclimate reconstruction.

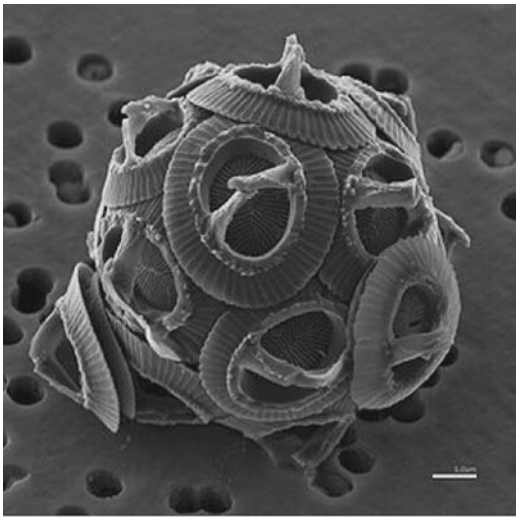

Fig. 19.3 Coccolith, calcareous algae (From Wikipedia, Licensed under the Creative Commons Attribution-Share Alike 2.5 Generic License, by Richard Bartz)

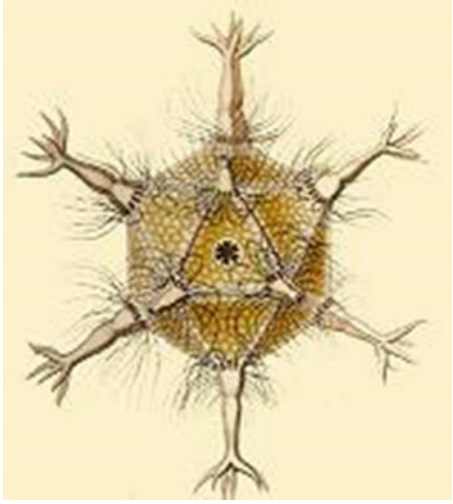

Fig. 19.4 A radiolarian from siliceous zooplankton ooze (Public Domain)

As for isotope ratios from ice cores, the oxygen isotopic composition of a sample is generally expressed as a departure, $\delta^{18}O$, from the $^{18}O/^{16}O$ ratio of an arbitrary standard, $^{18}O/^{16}O_{SMOW}$. SMOW is "standard mean ocean water" according to the following formula:

$$d^{18}O = \left(^{18}O/^{16}O\right)_{sample} - \left(^{18}O/^{16}O\right)_{SMOW} \times 10^3 \, \frac{0}{00} \div \left(^{18}O/^{16}O\right)_{SMOW}$$

The fractionation effect is much smaller than that which occurs during evaporation/condensation of water, and typically, $\delta^{18}O$ values are no more than a few parts per mille (‰) above or below the SMOW isotopic ratio.

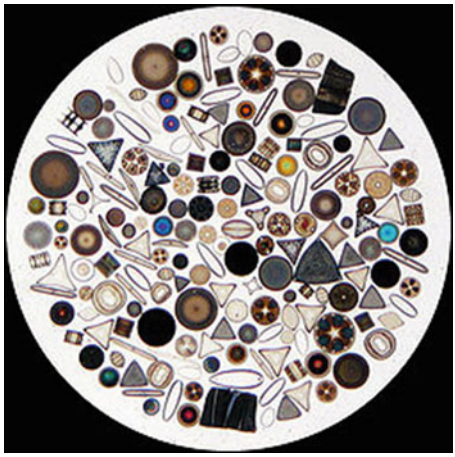

Fig. 19.5 Photomicrograph of diatoms on a slide (From Wikipedia, Licensed under the Creative Commons Attribution-Share Alike 2.5 Generic License)

Empirical studies relating the isotopic composition of calcium carbonate deposited by marine organisms to the temperature at the time of deposition have demonstrated the following relationship:

$$T = 16.9 - 4.2\left(\delta_c - \delta_w\right) + 0.13\left(\delta_c - \delta_w\right)^2$$

where T is the water temperature (°C), δ_c is departure from SMOW of the carbonate sample and δ_w is the departure from SMOW of the water in which the sample precipitated. For modern analyses, δ_w can be measured directly in ocean water samples; in fossil samples, however, the isotopic composition of sea water is unknown and cannot be assumed to have been the same as it is today. In particular, during glacial times, sea water was isotopically heavier (i.e., enriched in ^{18}O) compared to today; large quantities of isotopically lighter water were land-locked as huge ice sheets. Thus, the expected increase in δ_c due to colder sea surface temperatures during glacial times is complicated by the increase in δ_w at these times.

By analyzing isotopic records of deep water organisms, it is possible to resolve how much of the increase in δ_c for surface organisms was due to decreases in surface temperature and how much was due to continental ice sheet formation. It is expected that bottom water temperatures (≈1–2°C) have changed very little since glacial times (the last glacial maximum being 20,000–18,000 ka) and increases in δ_c for deep water organisms would reflect only changes in the isotopic composition of the glacial ocean. On this basis, some scientists have concluded that 70% of the changes in the isotopic composition of surface dwelling organisms were due to changes in the isotopic composition of the oceans, and only 30% due to temperature variations.

Unfortunately, changes in the isotopic composition of the ocean reservoirs are not the only complications affecting a simple temperature interpretation of δ_c variations. The assumption that marine organisms precipitate calcium carbonate from sea water in equilibrium is sometimes invalidated. Certain vital effects of marine

organisms, such as the incorporation of metabolically produced carbon dioxide, may cause a departure from the thermodynamic equilibrium of carbonate precipitation. However, by careful selection of species either with no vital effects or where the vital effects may be quantified, this problem can be avoided.

In addition to stable isotope analyses, the reconstruction of paleoclimates can also be achieved by studying the relative abundances of species, or species assemblages, and their morphological variations. In the case of the latter, test coiling directions (either right-coiling (dextral) or left-coiling (sinistral)) often reveal useful proxy information about paleotemperatures of the oceans. Other variations include differences in test size, shape and surface structure.

19.10 Paleoclimate Reconstruction from Terrigenous Material

Terrigenous material comes from land or continental areas. It is material picked up and transported by streams, mass wasting, or glaciers which finds its way into ocean waters and sinks to the bottom.

Weathering and erosion processes in different climatic zones on the continental land masses may produce characteristic sedimentary products. When these sediments (inorganic particles) are carried to the oceans (by wind, rivers, or ice) and deposited on the ocean floor, they may contain clues to the climate of their origin or transportation at the time of deposition.

Terrestrial sediment dilutes the relatively constant precipitation of calcium carbonate in warm waters; calcareous ooze shows an inverse relationship with the influx of terrestrial material. Because terrestrial sediment is related to climatic factors, the mixture of calcareous sediments with terrigenous sediment provides a paleoclimatic indicator. Therefore, times of high carbonate abundance indicate low terrestrial influx, i.e., low rates of continental weathering, transportation, and deposition. Conversely, less carbonate deposition may correspond to increased levels of continental weathering, erosion, and deposition which occur when the climate of the source region becomes warmer and wetter. Grain sizes and shapes may also be indicative of environments in which the particles originated or were deposited.

19.11 Terrestrial Sediments

Terrestrial sediments are those that come to rest on the continents or other land areas of the world. Streams (fluvial), lakes (lacustrine), wind (aerial), and ice (glacial) all show deposits on land where they are or have been active. Fluvial deposits occur along streams on the inside of meanders, as sand bars, and as deltas. Lacustrine deposits are characterized by annual alternating layers of light- and dark-colored material (varves); the light material is deposited in the warm summer months and the dark material in the winter months, the couplet marking a year's deposit. Aerial

or wind deposits are such things as dunes and loess (pronounced “lurss”). Glacial deposits are found where glaciers have receded or at the terminus or ends of glaciers and are called moraines.

19.12 Periglacial Features

Deposits and other features which occur around glaciers are known as periglacial features. Periglacial features are morphological features which are associated with continuous (permafrost) or discontinuous (diurnal or seasonal freezing) periods of sub-zero Celsius temperatures. Such features on which paleoclimatic inferences can be based include: fossil ice wedges; pingos; polygons; and periglacial involutions formed by multiple years of freezing and thawing. As the soil freezes and thaws over many hundreds of years in regions of permafrost, it is cracked and buckled to create ice wedges, polygons, thermo-karst lakes, and pingos.

Unfortunately, paleoclimate reconstructions based on such phenomena are subject to a fair degree of uncertainty. First, the occurrence of periglacial activity during the past can only indicate an upper limit on paleotemperatures, not a lower one. Second, periglacial features are generally difficult to date accurately; dating of the sediments with which they are associated provides only a maximum age estimate. Also periglacial features are destroyed when the glacier advances and are only found as the glacial ice recedes. But they are at best temporary features of the Earth’s surface. Subsequent to their formation, soil creep and erosion often destroy them.

19.13 Glacial Fluctuations

Glacial ice moves either under the influence of gravity or under its own weight. It recedes when ablation exceeds accumulation (Fig. 14.10) and expands when the opposite is true. When the two, ablation and accumulation, are equal the terminus or end of the glacier remains in place while the glacial ice within the glacier continues to move under the influence of gravity or its own weight. The material carried by the moving glacial ice piles up at the end of the glacier and forms an end moraine. A terminal moraine forms at the terminus or furthermost extent of the glacial ice and represents a period of equilibrium as the glacier begins to recede.

19.14 Lake-Level Fluctuations

The study of lakes is limnology. Climate is a major factor in the study of lakes as well as the lake water composition. Lakes in arid regions tend to be higher in salt content than lakes in humid areas due to the high rate of evaporation in arid regions

(e.g., Great Salt Lake, Utah). The condition of a lake at a given time is the result of the interaction of many factors: its watershed, climate, geology, human influence, and characteristics of the lake itself. With constantly expanding databases and increased knowledge, limnologists and hydrologists are able to better understand problems that develop in particular lakes, and further develop comprehensive models that can be used to predict how a lake might change in the future.

Lake levels fluctuate with the seasons of the year and with the amount of sediment carried into them. Lakes are temporary parts of the landscape in a geologic sense because streams flowing in carry sediment that will eventually fill up the lake. Also, if evaporation exceeds the amount of water being fed to the lake it will eventually dry up.

Lake levels fluctuate depending on the amount of water flowing into them and the amount of water flowing from them.

Lakes are by definition dammed structures, either man-made or natural. Dams fail, are overtopped or undercut and water flows from the lake.

Shorelines of ancient lakes are found in various parts of the world and are indicators of past climates. Sediment deposited in these lakes may also provide clues to ancient climates. Unfortunately with time, lake sediments are removed from Earth's surface quite readily and as a result are rare beyond a few thousand years in age. An exception is the lake discussed below.

19.14.1 Russia's Lake El'gygytgyn (Lake E)

During the week of June 17th, 2012, *Science* published a paper concerning first analysis of the longest sediment core ever collected on land in the Arctic that provides dramatic, "astonishing" documentation that intense warm intervals, warmer than scientists thought possible, occurred there over the past 2.8 million years at the beginning of the Pleistocene Epoch. This Russian lake, known colloquially as "Lake E" for rather obvious reasons, was created by a meteor impact around 3.6 million years ago and has been receiving terrigenous sediment almost continuously ever since. The core retrieved from the lake bed measured 318 m at which depth they encountered 3.6 million-year old impact rock.

The lead U. S. scientist, Julie Brigham-Grette of the University of Massachusetts Amherst, is quoted by *Science News* (June 21, 2012) as saying "What we see is astonishing. We had no idea that we'd find this. It's astonishing to see so many intervals when the Arctic was really warm, enough so forests were growing where today we see tundra and permafrost. And the intensity of warming is completely unexpected. The other astounding thing is that we were able to determine that during many times when the West Antarctic ice sheet disappeared, we see a corresponding warm period following very quickly in the Arctic. Arctic warm periods cluster with periods when the Western Antarctic ice sheet is gone."

These extreme inter-glacial warm periods correspond closely with times when parts of Antarctica were ice-free and also warm, suggesting strong inter-hemispheric climate connectivity, between the two Polar Regions.

The team of scientists has been analyzing sediment cores collected in 2009 from under ice-covered Lake El'gygytgyn in the northeast Russian Arctic. "Lake E" was formed 3.6 million years ago when a huge meteorite hit Earth and blasted out an 11-mile (18 km) wide crater. This crater has been collecting layers of sediment ever since. Fortunately it is located in one of the few areas in the Arctic not eroded by continental glaciers, leaving the thick sediment record remarkably undisturbed and continuous. Cores from Lake E reach back in geologic time nearly 30 times farther than Greenland ice cores covering the past 110,000 years.

The June 17th, 2012 paper in *Science* discusses four warm phases in detail; two of the oldest warm interglacials from about 1.1 million years ago and 400,000 years ago, and two of the youngest from 125,000 and about 12,000 years ago.

Pollen-based climate reconstructions (Table 19.1) suggest that summer temperatures and annual precipitation during the exceptional interglacials were about 4–5°C warmer and about 12 in. (300 mm) wetter than in other interglacials. Modeling and sensitivity tests for these warm periods also suggest it is virtually impossible for Greenland's ice sheet to have existed in its present form at those times.

Scientists using a state-of-the-art climate model show that the high temperature and precipitation during the "super interglacials" cannot be explained by Earth's orbital parameters or variations in atmospheric greenhouse gases alone, which geologists typically see driving the glacial/interglacial pattern during ice ages. This suggests that perhaps additional climate feedbacks were at work. The Lake E researchers suspect the trigger for intense interglacials might be in Antarctica. Earlier work in Antarctica by the international ANDRILL (Antarctic Geological Drilling; more information may be obtained at the following website: http://www.andrill.org/node/192) program discovered recurring intervals when the West Antarctic Ice Sheet melted. The Lake E study shows that some of these events match remarkably well with the super interglacials in the Arctic.

Brigham-Grette and colleagues discuss two scenarios for future testing that could explain inter-hemispheric climate coupling. First, reduced glacial ice cover and loss of ice shelves in Antarctica could have limited formation of cold water masses that flow into the north Pacific and well up to the surface, resulting in warmer surface waters, higher temperatures and increased precipitation on nearby land. Alternatively, disintegration of the West Antarctic Ice Sheet likely led to a significant global sea level rise and allowed more warm surface water into the Arctic Ocean through the Bering Strait.

Not only do results shed light on natural variability of the Arctic climate, but this view of the past may be a key to understanding climate in future centuries, the researchers said. "We have a lot more to learn," says Brigham-Grette. "But our results mesh with what glaciologists are seeing today. Seven of the 12 major ice shelves around the Antarctic are melting or are gone. We suspect the tipping point for the gradual de-glaciation of Greenland and the Arctic may be lower than glaciologists once thought."

The international Lake El'gygytgyn Drilling Project was funded by the International Continental Drilling Program (ICDP), the U.S. National Science Foundation's Division of Earth Sciences and Office of Polar Programs, the German Federal Ministry for

Table 19.1 Pollen zones recognized worldwide from the youngest (IX) on top to the oldest (Ia) at the bottom

Pollen Zones Recognized Worldwide					
Zone	Biostratigraphic division	Dates	Dominate plant type	Archeological periods	Geological stage
IX	Sub-Atlantic	500 BC to present	Spread of grasses and pine and beech woodland	Present iron age	Flandrian
VIII	Sub-Boreal	3000–500 BC	Mixed oak forest	Bronze age and iron age	Flandrian
VII	Atlantic	5500–3000	Mixed oak forest	Neolithic and bronze age	Flandrian
V and VI	Boreal	c. 7700–5500 BC	Pine/birch forest and increasing mixed forest	Mesolithic	Flandrian
IV	Pre-Boreal	c. 8300–7700 BC	Birch forest	Late upper paleolithic and early – mid mesolithic	Devensian
III	Younger dryas	c. 8800–8300 BC	Tundra	Late upper paleolithic	Devensian
II	Allerød oscillation	c. 9800–8800 BC	Tundra park tundra and birch forest	Late upper paleolithic	Devensian
Ic	Older dryas	c. 10000–9800 BC	Tundra	Late upper paleolithic	Devensian
Ib	Bølling oscillation	c. 10500–10000 BC	Park tundra	Late upper paleolithic	Devensian
Ia	Oldest dryas	c. 13000–10500 BC	Tundra	Late upper paleolithic	Devensian

Education and Research, Alfred Wegener Institute, GeoForschungsZentrum-Potsdam, the Russian Academy of Sciences Far East Branch, the Russian Foundation for Basic Research and the Austrian Ministry for Science and Research.

19.15 Pollen Analysis

The study of pollen is palynology. Pollen (Fig. 19.6) is plant material that has the consistency of ground up flour. It consists of microgametophytes of vascular seed plants that produce sperm cells. They have a resistant outer shell that protects them and is probably the main reason they are commonly found as fossils. Pollen is often discussed with spores, which are reproductive parts of lower plants, such as club mosses, horsetails, and ferns.

Pollen preserves best if the sedimentary environment lacks oxygen or is acidic, conditions unfavorable for the organisms that decompose pollen. Fossil pollen is an important kind of data for reconstructing past vegetation. Because vegetation is sensitive to climate, fossil pollen is a very important kind of proxy data for reconstructing past climates.

Pollen is widely dispersed by the wind and often occurs as fossils. It is useful for correlation purposes in the fossil record.

Pollen found in sediment cores are good indicators of the types of vegetation living at that particular time in Earth history and it is used to correlate horizons between deep-sea cores. It is possible to obtain high-resolution records of vegetation change with decadal resolution and to document plant community changes over the past few thousand years.

Palynologists also study orbicules, dinoflagellate cysts, acritarchs, chitinozoans, particulate organic matter, kerogen, and scolecodonts. These can all be found online or in textbooks of palynology. Palynology does not include diatoms, foraminiferans or other organisms with siliceous or calcareous exoskeletons.

Reasons why pollen is used in reconstructing past climates are as follows:

- Natural lakes contain abundant fossil pollen which is easily found. A cubic centimeter of lake sediment will typically contain tens or hundreds of thousands of pollen grains;
- Pollen is released to the air and is dispersed great distances and is representative of the vegetation from the region around the site;
- The pollen assemblage will represent a wide variety of plants from the region; and
- Pollen accumulates continuously year after year and can be used to reconstruct climate changes in the region in the past.

Peat deposits also contain abundant pollen and can be used to reconstruct past climatic conditions.

In the years before the First World War (WWI) a Swedish palynologist, Lennart von Post, analyzed pollen in core samples from peat bogs and noticed that different plant species were represented by bands throughout the cores. These bands offered a glimpse of past climates based on the differing species and quantities of the same species.

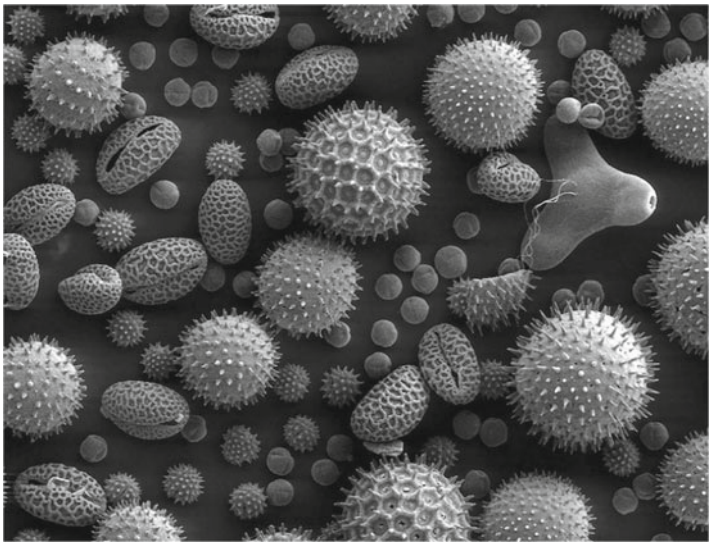

Fig. 19.6 Scanning electron microscope image of pollen grains from a variety of common plants (Magnification ×500, from Dartmouth Electron Microscope Facility, Public Domain)

In 1940, von Post's methods were applied to cores from the British Isles which produced the wider European pollen sequence stratigraphy used today. Von Post's method spread to the Western Hemisphere after WWII. Currently nine zones are recognized, numbered I–IX. They represent climatic and biological zones in the fairly recent geologic past from the present to 13,000 years ago. The table (Table 19.1) below lists the pollen zones with the youngest at the top (IX) to the oldest at the bottom (Ia).

19.16 Sedimentary Rocks

Certain types of sedimentary rocks provide clues as to the climatic conditions under which they formed. For example, limestone (made mainly of the mineral calcite [$CaCO_3$]) is formed only under warm, shallow sea environments where it is forming today. It indicates those conditions in the past.

Coal is a sedimentary rock that forms under oxygen-free conditions in areas that have abundant vegetation. The vegetation and coal itself indicate past climatic conditions.

Paleoclimatic conditions can often be determined by a study of paleogeography which involves identifying ancient geographic positions of shorelines, shallow seas, and delta deposits, for example. Sizes, shapes, and composition of particles making up sedimentary rocks may also indicate the climatic conditions under which a rock has formed.

The weathering processes result in different types of material ending up as sediment and these sediments may be indicators of climate in the geologic record.

The sedimentary rock record may show signs of sea level rise and fall. Features such as "fossilized" sand dunes can be identified. Scientists can get a grasp of long term climate by studying sedimentary rock going back thousands, millions, and billions of years. The division of Earth history into separate periods is largely based on visible changes in sedimentary rock layers that are based on major changes in conditions. Often these include major shifts in climate.

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