Lakes occur across the globe and are sensitive to climatic change. Analysing the sediments that have accumulated at the bottom of lakes over time can help us to reconstruct past environmental change. Here, we focus specifically on the use of oxygen isotopes from lake sediments to reconstruct climate change (Fig.1).

Figure 1 Lake Nar in central Turkey is a lake where the isotope composition of the water is dependent on the balance between the amount of summer evaporation versus winter recharge (precipitation or inflow of water to the lake). The oxygen isotope composition of calcite crystals that form in the lake water can be used as a record of how this balance might have changed over time.

What are isotopes?

Isotopes are variations of a particular chemical element. It is all to do with the number of neutrons. Oxygen has two main isotopes: ^{18}O which has 10 neutrons and 8 protons; and ^{16}O which has 8 neutrons and 8 protons. Although these variants have a different number of neutrons (and therefore a different atomic mass), the number of protons remains the same, and they are still classed as the same element.

Isotopes are analysed in terms of ratios such as $^{18}O/^{16}O$ which is shortened to $\delta^{18}O$ (δ is the symbol for 'delta' and means 'change') and are measured in parts per thousand or 'per mil' (‰).

^{18}O is said to be 'heavier' than ^{16}O, because it is carrying more neutrons. The greater the number of neutrons, the heavier the isotope.

Isotopes in rainfall and lakewaters

The ratio of $^{18}O/^{16}O$ can change depending on a number of factors. On a global scale, average annual values for $\delta^{18}O$ in precipitation (rain or snow, for example) largely correspond to different temperature zones. In general, the isotopically heavier (higher) values occur at the equator and the lighter (lower) values at the poles.

At the local scale, isotopes in precipitation are controlled mainly by:

1) the source of the rainfall (e.g. Atlantic vs. Arctic rain)

2) the amount of rainfall

3) the temperature.

Rainfall enters lakes, and in open lakes where there is a throughflow of water (i.e. the water is replenished regularly; it has a short 'residence time') $\delta^{18}O$ of lakewater will reflect $\delta^{18}O$ of precipitation. This is particularly prevalent in high latitude and high altitude regions.

However, in closed lakes with longer residence times (where there is less inflow and outflow), especially in semi-arid environments, $\delta^{18}O$ of lakewater will be modified further due to evaporation. Because ^{16}O is lighter than ^{18}O (as it has fewer neutrons), it is preferentially evaporated, leading to an increase in $\delta^{18}O$ of the water remaining in the lake. Therefore, in oxygen isotope studies of lake sediments, it is vital to assess the hydrological setting. This allows us to understand whether the oxygen isotope ratios of the lakewaters change in response to the source/amount/temperature of precipitation (in general lakes with short residence times), or to variations in precipitation/evaporation (in general lakes with long residence times).

Lake sediments as archives of past climate

A number of different components form or grow in lakewaters and eventually sink to the bottom of the lake and are depositied in the sediments at the lake bed. (Fig. 2). For example: shells; fine grained calcium carbonate crystals (which form due to chemical processes in the lake water); diatoms (a type of algae made of silica); and organic parts of plants and animals, as well as sand, silt, and clay. The $\delta^{18}O$ of the components that formed within the lake can tell us a great deal about the lake environment at the time they formed. The $\delta^{18}O$ of carbonates and diatoms, for example, depends on the $\delta^{18}O$ of the lakewater (and therefore temperature).

Figure 2 Typical components of lake sediments that can be analysed for oxygen isotope ratios. From left to right: chemically precipitated crystals of calcite, diatom frustules composed of silica and ostracod valves composed of calcite.

Figure 3. Laminated (layered) sediments deposited in Lake Nar in central Turkey. The laminations are distinguishable by differences in colour. The white layers comprise summer-precipitated calcium carbonate while the darker layers represent organic matter which settled to the bottom of the lake in the winter months.

By looking at changes in $\delta^{18}O$ through time, and depending on the characteristics of the lake in question, we can reconstruct past environmental conditions (e.g. temperature, precipitation source, and precipitation or evaporation amount) for a particular location. Sometimes the different components can form layers or 'laminations' within the lake sediment, which are often distinguishable by differences in colour. In Figure 3, the white layers contain calcium carbonate crystals which formed in the summer months, while the darker layers represent organic matter which settled to the bottom of the lake in the winter months.

Getting to grips with age

We need to find the age of the lake sediments that we are analysing so that we can understand *when* the environmental changes took place. Depending on the timescale that we are interested in, there are a number of different dating tools available to us. With laminated sediments (like in Fig. 3) we can simply count back the number of layers like tree rings, assuming that they are annual. With sediments from the 20th century, radioisotopes found in sediments such as ^{137}Cs can be used to provide age markers. This is because there were known fallout peaks in 1963/4 from atmospheric nuclear weapons testing and in Europe in 1986 associated with the Chernobyl incident, leaving distinct markers. Radiocarbon dating can be used on sediments going back thousands of years. This uses the radioactive decay of ^{14}C to estimate the age of organic matter. Most lake sediments contain a lot of organic matter, either the fine grained material that formed within the lake and settled out through the water column, or seeds and leaves from plants that were washed into the lake. We can also use layers of volcanic ash from a known volcano. In theory, each ash layer corresponds to a specific volcanic eruption. We can identify precisely which one by analysing the chemical composition of the ash shards that make up the layer, and if the age of the eruption is known from historical records then this provides an age marker in the sediment similar to the ^{137}Cs peaks.

Examples of how oxygen isotope analysis of lake sediments has been used to reconstruct past environmental change:

Lake Nar

Changes in climate were reconstructed from the oxygen isotope composition of carbonates from Lake Nar in central Turkey. The lake has limited inflow and outflow and the waters are evaporating, so the main control on the $\delta^{18}O$ of carbonates through time has been the balance between precipitation and evaporation. Higher values of $\delta^{18}O$ suggest more evaporation and/or less rainfall. The isotope record revealed that it was relatively drier in Roman times, it got wetter in the Medieval period and then it was drier at the time of a cool period known in Europe as the 'Little Ice Age' (Fig. 4). By comparing this record to others from around the world, they were able to show that changes in circulation patterns, in particular the North Atlantic Oscillation and Indian Monsoon, have important influences on the hydroclimate of central Turkey.

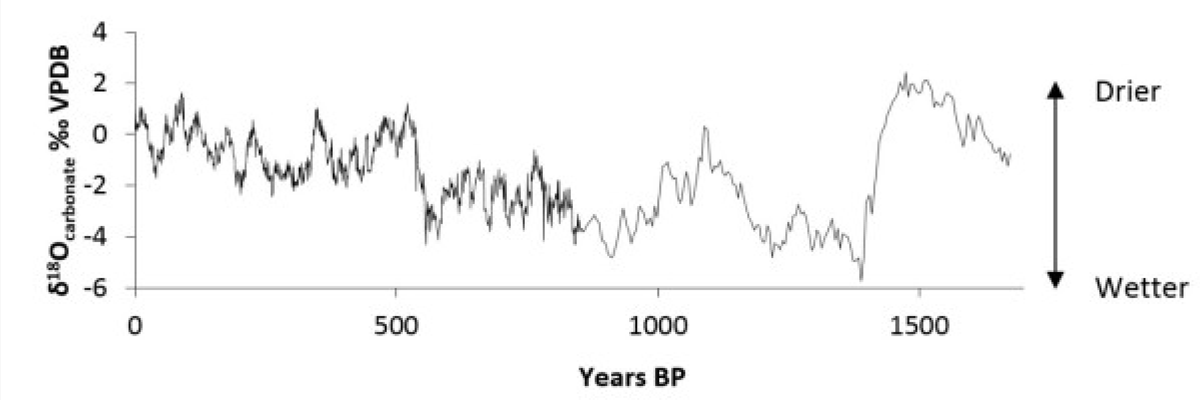

Figure 4. The oxygen isotope record from a closed lake, Nar in central Turkey, which is used to reconstruct the balance between precipitation and evaporation over the last 1720 years. Climate variations in Roman times and the Medieval period can be deduced, as well as a dry interval at the time of the Northern European 'Little Ice Age'.

Lake Tibetanus

Figure 5. Lake Tibetanus in northern Sweden is an excellent example of an open lake where the oxygen isotope composition of the lake waters is similar to precipitation.

A high-resolution record of climate variation based on the $\delta^{18}O$ of carbonates was constructed from a lake sediment record from Lake Tibetanus in northern Scandinavia (Fig. 5). Modern lakewater isotope data indicate that controls on its $\delta^{18}O$ are not due to changes in evaporation or temperature, and its variations must therefore reflect changes in precipitation. Periods of very low $\delta^{18}O$ values have been discovered at: ~200, 500, 1300, 1600 and 2900 years ago (Fig. 6). These all coincide with major peaks in North Atlantic ice rafted debris deposition (glacier advances) in the North Atlantic. The $\delta^{18}O$ minima in Lake Tiberanus are therefore likely to represent colder conditions, possibly as a result of more precipitation of rain/snow from the Arctic (as occurs in the UK when it gets winter snowfall). These winter, Arctic-like conditions are a result of changes in atmospheric circulation patterns probably associated with the North Atlantic Oscillation.

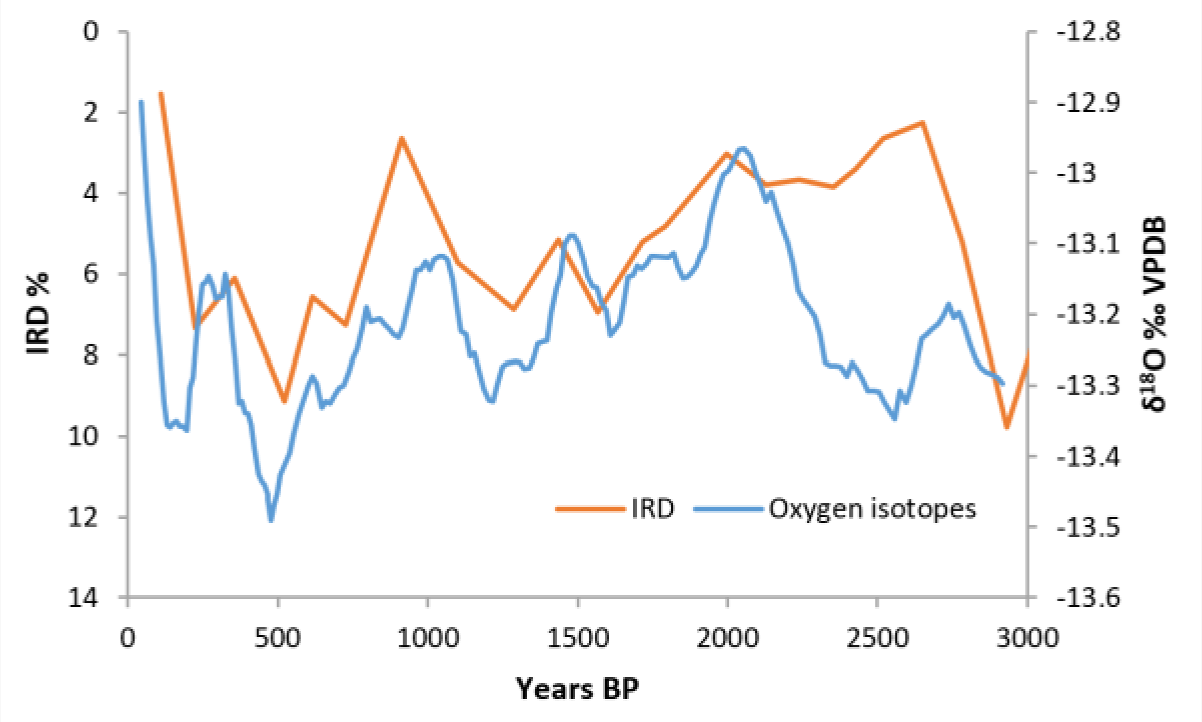

Figure 6. Calcites precipitated in Lake Tibetanus vary in response to the source of the rain/snowfall, in this case reflecting changes in the North Atlantic Oscillation.

Further information can be obtained from: Leng, M.J. and Marshall, J.D. 2004. Palaeoclimate interpretation of stable isotope data from lake sediments. Quaternary Science Reviews, 23, 811-831.

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