NLR methods

Plant reproductive organs have little inherent climatic signal but climate may be deduced from extrapolation of the tolerances of their NLRs. Following Axelrod & Bailey (1969), four steps are required in NLR analysis:

1. NLR of all taxa in an assemblage should be identified to modern genus level.
2. NLR determinations should also be attempted at species level (because generic tolerances are too broad).
3. The average MAT and average mean annual range of temperature (MAR) are estimated based on habit 'preferences' of modern NLRs.
4. The effective temperature (average temperature at the beginning and end of a period free from frost or chill) and equability of the palaeoclimate are calculated using the average MAT and MAR.

References


4.19.2 Temperature from Oxygen Isotope Ratios

T. F. ANDERSON

Introduction

Oxygen isotope ratios ($^{18}\text{O}/^{16}\text{O}$) of well preserved marine calcareous fossils are indicative of the temperature of ancient ocean waters. This approach is based on the fact that the difference in $^{18}\text{O}/^{16}\text{O}$ ratios between calcium carbonate and the water from which it precipitates is a function of temperature. Oxygen isotope ratios are expressed in the δ notation:

$$\delta^{18}\text{O} = \left( \frac{^{18}\text{O}/^{16}\text{O}_{\text{sample}} - ^{18}\text{O}/^{16}\text{O}_{\text{standard}}}{^{18}\text{O}/^{16}\text{O}_{\text{standard}}} \right) \times 10^3. \quad (1)$$

Units are per mil or parts per thousand. The standard material for carbonates is PDB, a late Cretaceous belemnite from the Pee Dee Formation of South Carolina; for water, the standard is SMOW, i.e. standard mean ocean water (see Anderson & Arthur 1983). Oxygen isotope palaeotemperatures for calcite can be calculated from:

$$T^\circ C = 16.0 - 4.14\Delta + 0.13\Delta^2, \quad (2)$$

where $\Delta = \delta^{18}\text{O}$ calcite (vs. PDB) − $\delta^{18}\text{O}$ water (vs. SMOW) (Anderson & Arthur 1983). Thus, $\delta^{18}\text{O}$ of calcite increases as temperature decreases. Palaeotemperature estimates can be made with an uncertainty of $\pm 0.5^\circ C$, because $\delta^{18}\text{O}$ values are measured to within 0.1 per mil.

Factors other than analytical precision control the uncertainty in isotopic palaeotemperatures:

1. The manner in which isotopic fractionation between biogenic calcium carbonate and water varies with temperature must be known. Equation (2) applies to inorganic precipitation of pure calcite at isotopic equilibrium and to a number of low-magnesium calcite fossil groups including bivalves, belemmites, brachiopods, and planktic foraminifers. Slightly different equations apply to preserved aragonite and high-magnesium calcite shells (Anderson & Arthur 1983). In addition, physiological effects during shell secretion in some organisms result in departures from equilibrium fractionation; notable examples are corals and echinoids.

2. It is necessary to estimate the $\delta^{18}\text{O}$ of the water in which the shell grew. In the hydrologic cycle, evaporation preferentially removes $H_2^{16}\text{O}$ from water, while precipitation and runoff returns $H_2^{18}\text{O}$. Local variation in the hydrologic balance of ocean waters of normal salinity can produce small variations in $\delta^{18}\text{O}$. (The range for modern seawater is 2.5 per mil.) This effect is normally ignored in estimating isotopic palaeotemperatures because hydrologic data on ancient ocean water is lacking. Also, because $H_2^{16}\text{O}$ is preferentially stored in polar icecaps and continental ice sheets, oceans are enriched in $^{18}\text{O}$ during glacial epochs relative to nonglacial epochs. For example, the growth and decay of continental ice
sheets during the Late Quaternary produced excursions of at least 1 per mil between glacial and interglacial oceans. The effect of Palaeozoic glaciations on the $\delta^{18}O$ of contemporaneous seawater was probably similar.

3 Reliable isotopic palaeotemperatures can be obtained only from those fossils that have been preserved from diagenetic alteration. Cemented or partially recrystallized fossils will generally give erroneous palaeotemperatures, because secondary carbonates reflect the temperature and isotopic composition of diagenetic solutions.

Isotopic palaeotemperatures from the Cenozoic and Late Cretaceous

The most continuous record of marine temperature variations for the past 100 million years has been constructed from isotopic analyses of well preserved foraminifera in deep-sea sediments. Diagenetic alteration of foraminiferal tests is minor and relatively easy to determine microscopically. In addition, the effects of continents on the temperature and $\delta^{18}O$ of ocean water in the pelagic realm is minimal.

The Quaternary oxygen isotope record of foraminifera shows oscillations with periods of about $10^5$ years between $\delta^{18}O$ maxima during glacial and $\delta^{18}O$ minima during interglacials (see Savin 1977, fig. 8; Anderson & Arthur 1983). Although the direction of these isotope shifts is qualitatively compatible with temperature changes, it is now generally accepted that the amplitude of Quaternary $\delta^{18}O$ oscillation reflects changes in continental ice volumes more than changes in seawater temperatures.

Marine temperatures for the Tertiary and Late Cretaceous have been estimated from isotopic data on Deep Sea Drilling Project cores. Composite oxygen isotope records for planktic and benthic foraminifera from subtropical sites in the North Pacific illustrate the major features of palaeoclimatic changes over the past 130 million years (Fig. 1). The planktic record reflects temperature and $\delta^{18}O$ variations in low-latitude surface waters; the benthic record reflects conditions at the high-latitude source regions of deep-water masses. The data suggest general cooling in the Pacific over the past 100 million years. Temperatures of subtropical surface waters were evidently warmer in the Albian/Cenomanian and the Eocene than in intervening times. Temperature trends in deep waters are correlated with those of surface waters from the Middle Cretaceous through the Early Tertiary. However, bottom waters during this interval (especially during the Cretaceous) were considerably warmer than at present. In other words, the latitudinal contrast in ocean temperatures had increased during the Tertiary, resulting principally from apparent cooling at high latitudes. Abrupt positive shifts in the Tertiary benthic $\delta^{18}O$ trend probably reflect the initiation (Eocene–Oligocene) and rapid expansion (Middle Miocene) of the Antarctic icecap, as well as a decrease in high latitude surface temperatures.

Palaeotemperature trends from shallow-marine bivalves from northwest Europe (Fig. 2) are similar to those for Pacific low-latitude surface waters (Fig. 1), suggesting that global palaeoclimatic changes were not obscured by the influence of continents on the temperature and $\delta^{18}O$ of nearshore seawater. In contrast to the deep-sea record, the isotopic data from bivalves suggest that the shallow
Fig. 2 Oxygen isotope record of shallow-marine bivalves from northwest Europe for the past 100 million years. δ²⁶O and temperature scales are the same as Fig. 1. (Data from Buchardt 1977 and Burdett, J. & Arthur, M. pers. comm. 1987.)

Fig. 3 Oxygen isotope record for Palaeozoic brachiopods and marine cements. The temperature scale (right vertical axis) is for ice-free oceans. (After Popp et al. 1986, by permission of the Geological Society of America, and Veizer et al. 1986.)

Oceans of northwest Europe were significantly warmer during the Eocene than during the Middle Cretaceous.

Isotopic palaeotemperatures from the Palaeozoic

Isotopic palaeotemperature determinations on Palaeozoic fauna are limited necessarily to shallow-marine taxa. The most serious problem with Palaeozoic fossils is the preservation of the original isotopic signal through early diagenesis and long-term burial. Several recent studies have suggested that trace element compositions and microscopic textural characteristics can be used to identify isotopic preservation in fossil brachiopods (Popp et al. 1986; Veizer et al. 1986). Specifically, portions of brachiopods which are not cathode luminescent and whole brachiopod shells with low Mn and Fe contents have probably suffered only minimum diagenetic alteration. Data on well-preserved brachiopods from a range of locations, supplemented with estimates for primary marine cements, indicate that δ¹⁸O values increased irregularly during the Palaeozoic, with a major positive shift from the Devonian to the Carboniferous (Fig. 3). The extent to which this and similar δ¹⁸O age trends for cherts and sedimentary phosphates represent decreasing temperatures or increasing δ¹⁸O of ocean water is a major controversy in stable isotope geochemistry. The resolution of this controversy will have a profound impact on our interpretation of surface temperature variations and hydrosphere-lithosphere interactions through time (Anderson & Arthur 1983; Veizer et al. 1986).
4.19.3 Salinity from Faunal Analysis and Geochemistry

J. D. HUDSON

Introduction

Salinity is one of the main controls on the distribution of the aquatic biota, and the estimation of palaeosalinities has concerned many palaeoecologists. Most work has involved benthic invertebrates with calcium carbonate hard parts, although palynology has important applications. Fossil occurrences of particular taxa or assemblages may be compared to modern distributions. Alternatively, fossils can be analysed geochemically, as convenient samplers of the waters they inhabited. Sedimentological evidence also should be sought.

The usual result of such studies is an empirical estimate of the palaeosalinity, or range of salinities, experienced by the organisms, and is generally expressed in parts per thousand or in the 'Venice System' (Fig. 1). The recognition of fully-marine faunas is generally not controversial; nor, in Mesozoic and Cenozoic rocks, is that of freshwater lake faunas. Most palaeoenvironmental interest thus centres on the brackish water and hypersaline faunas of estuaries and other coastal environments, and of saline lakes.

Most brackish systems are labile, and the range and rate of salinity change may have as great an effect as mean salinity. Water bodies whose salinity varies are commonly also variable in temperature, depth, food supply, etc., and are often underlain by soft, organic-rich substrates. Therefore effects on biotic distribution caused directly by salinity are hard to disentangle from those which are due to other controlling factors.

Besides palaeoenvironmental interpretation, more fundamental questions concern: the mechanism(s) by which salinity control operates; whether there is a special brackish water fauna as opposed to merely a reduced-marine one; the evolutionary origin of brackish water faunas; and the relationship of brackish water faunas to the invasion of freshwaters or land by various groups of organisms. On the long time-scale, there is also the possibility that the composition of seawater itself may have changed. Palaeontology supplies essential historical data bearing on these biological and geochemical questions.

Faunal analysis

The normal palaeoecological precautions about working with in situ assemblages obviously apply; in particular, because salinity in estuaries and lagoons can vary so rapidly, the importance of finely-controlled collecting cannot be overstressed. Even so, some time-averaging of fine-scale variation inevitably occurs.

Many higher taxa of plants and animals today are effectively marine-stenohaline and their occurrence, especially in combination, can be used to infer fully marine salinity: viz. corals, cephalopods, echinoderms, bryozoans, articulate brachiopods, planktic and larger benthic foraminifera, and many calcareous red and green algae. Most of these, however, include some partially euryhaline forms extending into polyhaline waters. Only a small number of higher taxa thus account for most of the modern brackish and freshwater shelled fauna, i.e. bivalves, gastropods, ostracodes, smaller benthic foraminifera, and charophyte algae. Non-calciﬁed arthropods are important but seldom preserved except as trace fossils (conchostracans being an exception). Many ‘fish’ are and have been euryhaline, although often also migratory and subject to vagaries of preservation. Even among these groups, few lower taxa have given rise to genera or species tolerant of mesohaline or more dilute waters. Most freshwater taxa are strictly stenohaline.

It follows from these considerations that brackish and freshwater faunas are of low taxonomic diver-