pregnancy or perhaps even in the process of giving birth, thereby obtaining both cow and calf. Such a hunting pattern might have been particularly rational if the giant buffalo were seasonal breeders so that locating pregnant cows, at least as part of a seasonal round, was not especially difficult. In any case, over time such a pattern could have endangered the survival of the species, and it is interesting that giant buffalo remains become progressively less numerous relative to Cape buffalo ones upward through the sequence at Klasies. In the terminal Pleistocene (LSA) deposits of Nelson Bay Cave, which contain the latest known record of the giant buffalo (*4*), its bones are far less numerous than those of the Cape buffalo.

For the other Klasies and Die Kelders species which became extinct in the terminal Pleistocene, there is insufficient material to establish age distributions or time trends in relative frequencies. The coincidence of extinctions with now well-established environmental changes at the end of the Pleistocene (final last glacial) and in the early Holocene (*18*) suggests a causal role for such changes. But environmental changes by themselves are an insufficient explanation of extinction, insofar as the extinct creatures clearly survived the presumably analogous environmental changes at the end of the penultimate glacial, about 125,000 years ago (*17*). The contrasts between the Klasies and Die Kelders MSA faunas on the one hand and LSA ones on the other suggest that the new and critical factor at the end of the last glacial may have been the presence of significantly more competent predatory hominids.

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Late-Quaternary Climatic Trends and History of Lake Erie from Stable Isotope Studies

Abstract. *Oxygen and carbon isotope measurements on mollusk and carbonate shells separated from a long sediment core in central Lake Erie document climatic changes of the Great Lakes region and the evolution of Lake Erie since deglaciation. On the basis of ^{18}O data, two major climatic improvements are recognized, one occurring between 13,000 and 12,000 years before the present (B.P.) and the other between 10,000 and 8,000 years B.P. Changing drainage patterns are also reflected in the ^{18}O contents of the Lake Erie water. Carbon isotopes reflect changes in aquatic vegetation and water depth. The settlement and industrialization of the Lake Erie drainage basin is documented in the ^{13}C and ^{18}O contents of modern mollusks.*

Paleotemperatures obtained from ^{18}O analyses of the carbonate skeletons or shells of marine organisms (*1*) and the results of isotope work on ice cores from Antarctic and Greenland ice sheets (*2*) are widely known. This report presents the results of ^{18}O and ^{13}C analyses on carbonate shells separated from the sediments in a long core from Lake Erie. An attempt is made to show that such ^{18}O analyses also can provide a rather detailed picture of climatic and water budget changes which occurred in the Lake Erie basin during the past 15,000 years. It is assumed that these shells were deposited in isotopic equilibrium with Lake Erie water and therefore reflect the composition of this water at the time of growth of these animals (*1, 3–5*). Furthermore, it is assumed that the ^{13}C contents of the shells analyzed reflect environmental conditions existing within the habitat of the various carbonate-depositing animals and depend primarily on the origin of the inorganic, dissolved carbon in the lake water (*4*).

The core site (core 13194) is located in the cental basin of Lake Erie, 22.5 km southeast of Erieau, Ontario, at a water depth of 24.4 m. It is one of several borehole sites in this area investigated by the Geological Survey of Canada and the Consumers' Gas Company, Toronto, Ontario, to determine the stratigraphy, history, and engineering properties of Lake Erie offshore sediments (*6, 7*).

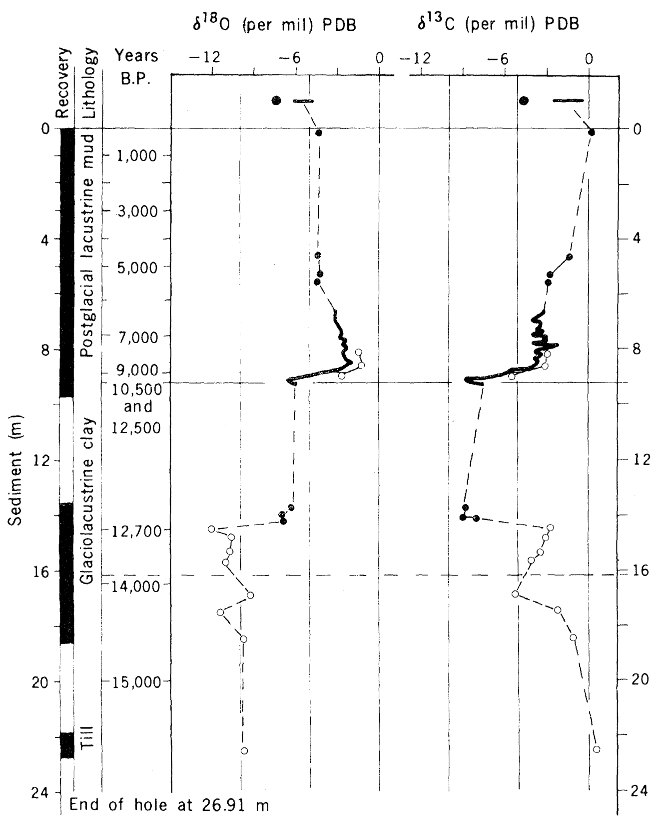
The stratigraphic sequence, the inferred chronology, and a summary of the isotope data are shown in Fig. 1. Figure 2 gives a comparison of $\delta^{18}O$ and $\delta^{13}C$ values from all samples analyzed (*8*). Pollen studies encompass the upper half of the glaciolacustrine and Holocene sediments and provide the necessary chronologic control since the sediments contain insufficient organic matter for radiocarbon dating. We derived time horizons for specific pollen boundaries by correlating the pollen data with various radiocarbon-dated pollen records in Lake Erie and in the surrounding area.

The oldest samples obtained for this study are from a dark, grayish-brown, silty clay, "till-like" sediment from a depth of 26.5 m. These oldest "Lake Erie" sediments are interpreted as lodgement till deposited during the Port Bruce advance of the Erie lobe and are assigned an age of 13,800 years before the present (B.P.) (*9*). During the time that the ostracods lived in the pre–Port Bruce glacial lakes, "Lake Erie" had the lowest ^{18}O concentration in its history. This is not surprising since these glacial lakes received not only ^{18}O-depleted meltwaters from nearby glacial ice but also precipitations with lower ^{18}O contents than that of average present-day precipitations (*10*).

The high $\delta^{13}C$ values of the ostracod shells almost certainly indicate that at this time the dissolved inorganic carbon in the lake water was in, or close to, isotopic equilibrium with atmospheric CO_2. Pollen and other plant remains are absent; consequently, little if any plant life was established at this early stage.

The "till-like" sediment grades upward into partially laminated, dark grayish-brown glaciolacustrine silty clay with reddish-brown clay inclusions. These lake clays accumulated during the existence of several high-level glacial lake stages (Arkona to Lundy) through to the earliest postglacial lake phase, Early Lake Erie. Inferred ages for the sediment column during this time interval are 12,730 ± 200 years B.P. (sample I-3665) (*11*) for the rise in *Picea* (spruce) pollen at 14.5 m and 12,500 years B.P. for the top of the glaciolacustrine sediments at 9.2 m.

The rise in *Picea* pollen implies an advancing spruce forest and coincides with a



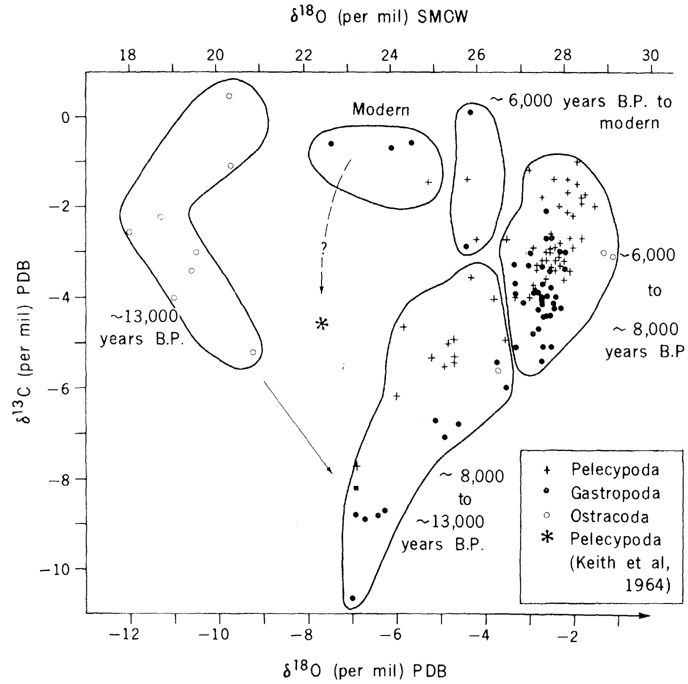


Fig. 1 (left). Stratigraphy, inferred chronology, sediment recovery, and results of ^{18}O and ^{13}C isotope analyses on Lake Erie core 13194. Open circles signify analyses on ostracods; closed circles and heavy lines denote analyses on mollusks. Fig. 2 (right). Summary diagram of the ^{18}O and ^{13}C isotope analyses on Lake Erie core 13194, illustrating an evolutionary "cycle" beginning more than 14,000 years B.P. and continuing to the present; *SMOW*, standard mean ocean water isotope standard.

sharp break in the fossil fauna and isotope records. Gastropods are now well established and show considerably higher ^{18}O and lower ^{13}C contents in their shells than the earlier ostracods.

The low ^{13}C values probably reflect an abundance of aquatic vegetation which through aerobic decay or respiration adds isotopically light CO_2 to the lake system. The higher ^{18}O contents could reflect two processes: a climatic improvement, which probably accounts for the spruce invasion at this time, or higher evaporation rates from a rather shallow lake, or both. If this increase were due solely to a climatic improvement, the increase in ^{18}O (5 to 6 per mil) in the average annual precipitation would correspond to an increase in the average annual land surface temperature by 7° to 10°C (*10*). A very rapid change in climatic conditions occurred in Britain approximately 13,000 years ago (*12, 13*). Changes in *Coleoptera* (beetle) assemblages suggest that after 12,850 ± 250 years B.P. the average July temperature rose by about 7°C, and there is evidence that "the change came with dramatic swiftness" (*12*). Although a similar increase might have been expected in Ontario after the retreat of the last ice sheet, it is probably a combination of a change in both evaporation rate and precipitation input which accounts for the observed ^{18}O trend. After this increase, at least in Britain, temperatures slowly fell again, possibly by as much as 7°C, until the next rapid increase occurred about 10,000 years B.P. (*12, 13*). Unfortunately, this low-temperature episode is not recorded in the analyzed samples from Lake Erie but there is good evidence for the second climatic improvement.

The glaciolacustrine sediments are unconformably overlain by soft, mottled, dark gray-brown postglacial clay with some layers rich in iron sulfide. The unconformity represents a period of subaerial exposure of the glaciolacustrine sediments and a hiatus in sedimentation during the existence of low-level Early Lake Erie about 12,500 years B.P. (*6, 14*). The unconformity is recognized from engineering studies (*6*) and also by a sharp break in the pollen record. *Picea* pollen declined from 60 to 28 percent while *Pinus* (pine) pollen increased sharply from 5 to 38 percent over the contact. The dominance of *Pinus* pollen implies that postglacial deposition did not commence until approximately 10,500 years B.P. (*15*). The hiatus between glaciolacustrine and earliest postglacial deposition therefore may have lasted as long as 2,000 years.

The fine-grained sediments between 9.2 and 6 m were largely derived from the erosion of the older tills and glaciolacustrine clay by wave activity in a steadily rising residual lake which occupied the central basin during a low-level Early Lake Erie (*16*). However, sediment input was extremely low between 10,500 and 8,000 years B.P., according to the pollen record.

After reaching a maximum at 8.9 m, about 9,000 years ago (*17*), pine pollen declined sharply and was replaced by increased percentages of *Quercus* (oak) and other deciduous hardwood pollen at 8.7 m, about 7,620 ± 70 years B.P. (sample GSC-1816) (*15*). This change implies a climatic maximum during deposition of the early Holocene sediments. The isotope data support this interpretation since the ^{18}O concentration in the lake water rose another 4 to 5 per mil and reached a maximum between 7,500 and 8,000 years B.P. As the deepening of Lake Erie continued during this period, this increase must be largely due to a climatic improvement rather than to changing evaporation rates. Thus, if the ^{18}O content of the average annual precipitation increased by 4 to 5 per mil (*10*), this rise corresponds to an increase in the average annual temperature of 5° to 8°C. This estimate is considerably higher than the temperature changes determined by Stuiver (*3*), who assumed an increase of about 2°C in the central and eastern United States. The discrepancy could reflect either differences in the water budgets of the lakes and ponds considered or could indicate that between 10,000 and 8,000 years B.P. in the Great Lakes region the climatic improvement occurred with a steeper temperature gradient than to the east and south.

The ^{18}O increase is paralleled by increasing $^{13}C/^{12}C$ ratios (Fig. 1). These $\delta^{13}C$ values could reflect a decreasing importance of aerobically decomposing organic matter and aquatic vegetation in the deepening Lake Erie, a relative increase of the exchange with the atmospheric CO_2 reservoir, or a more significant input of isotopically heavy CO_2 produced in a reducing environment within the bottom sediments (*4*, *18*). Significant amounts of CH_4 are produced in Lake Erie sediments (*19*), and thus this latter possibility cannot be discounted a priori.

After the sharp increases in both ^{18}O and ^{13}C between 10,000 and 8,000 years B.P., the $\delta^{13}C$ values in the carbonates increased gradually and eventually attained a maximum close to ± 0 per mil in the surface sediments (Figs. 1 and 2). Changes in the ^{18}O curve, however, are probably associated with changes in the water budget of Lake Erie. The ^{18}O concentrations decreased upward in small but clearly visible steps, possibly reflecting an increased rate of flushings and a decrease in the relative evaporation intensity with the increased deepening of Lake Erie. According to the pollen data (*20*), the decrease in ^{18}O by about 2.5 per mil around 6,000 years B.P. is correlated with increasing sedimentation rates and changes in sediment type at the time of increased flow through Lake Erie when Nipissing Great Lakes drainage was diverted from the North Bay to the Sarnia outlet (*21*). The ^{18}O shift could then be explained in terms of the increasing amounts of ^{18}O-depleted water passing from Lake Huron to Lake Erie at that time.

Unfortunately, with the exception of a few shell fragments in the surface sediments, we were unable to recover sufficient fossil material for isotope analyses from the strata above the 5-m level. Therefore a detailed discussion of younger shell samples is not yet possible. However, ^{13}C analyses of the organic matter in Lake Erie sediments revealed significant differences between old and modern organic carbon deposited, reflecting the increased "terrestrial" input from man's activities since forest clearance and settlement of the drainage basin (*22*).

This change in carbon input is possibly documented in some of the modern mollusks. Published isotope data (*5*) from a number of pelecypods and gastropods collected in Lake Erie have revealed considerably lower ^{13}C contents than observed in the modern samples in this study (Fig. 2). The lower values could be due to habitat differences since the mollusks were collected from areas characterized by significant inputs of isotopically light "terrestrial" carbon (*22*), whereas the samples analyzed in the present study were collected off the relatively nonpolluted north shore of central Lake Erie.

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Precambrian Paleomagnetism: Magnetizations Reset by the Grenville Orogeny

Abstract. *Paleomagnetic results from iron-rich metasediments folded during the Grenville orogeny (~1000 million years ago) indicate that stable remanence was acquired after folding as the rock cooled from above 615°C through 550°C. As well as imparting a new remanence, the thermal event destroyed any preexisting magnetizations. In a proposed model, virtually all Grenville paleomagnetic poles have been reset and can provide no evidence of plate tectonic processes before 1000 million years ago. The polar sequence suggested by potassium-argon age trends within the Grenville province does, however, indicate rapid drift of North America between 1000 and 900 million years ago.*

Metamorphic rocks pose special problems for the paleomagnetist. Frequently, the natural remanent magnetization (NRM) is weak and unstable, and its direction may have been deflected by the magnetically anisotropic fabric of the rock. A more subtle problem is dating the NRM within limits that are not intolerably broad. Potassium-argon and rubidium-strontium ages can be reset during a metamorphic event if the peak temperatures are of the order of 250° to 350°C and 700° to 800°C, respectively (*1*). Furthermore, the NRM itself may be partially or totally reset. The heating accompanying a major metamorphic event may be very prolonged for deeply buried rocks. A single event may involve more than one heating episode, especially in the presence of igneous activity. Rocks will generally be exposed to high pressures as well as high temperatures, and the original magnetic minerals will be altered.

Following metamorphism, the reset NRM may comprise one or more generations of thermoremanent magnetization, viscous partial thermoremanent magnetization, or crystallization remanence. Nor