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Gases in Glaciers

Gas trapped in the bubbles of glacier ice may originate from two different sources, depending on the manner in which the ice was formed. If the temperature is always below freezing in the area of ice formation, as in parts of Greenland and Antarctica, there is no melting, and the ice is formed simply by compaction of snow crystals. Air is trapped between the crystals, and the composition of the gas in such ice should be uniform and the same as that of the atmosphere (Table 1) at the time the ice was formed. If there are no losses or additions, it seems probable that the air will be preserved in its original state for the life of the ice.

If melting is involved in the formation of the ice, as in the case of the more temperate glaciers, the gas will have a different composition. Water equilibrated with air at 0°C contains 2.9 percent (by volume) of dissolved gases (Table 1). Since gas is insoluble in ice (*1*), the gas will separate from the water, on freezing, and will contribute to the gas content of the ice. Since meltwater is not evenly distributed in the firn, there will be variations in the composition of the gas enclosed in the ice thus formed.

Because the atmospheric gases dissolve in water in proportions that differ from their proportions in the air, it is possible to estimate the amount of water involved in formation of the ice (*2*). For this purpose the ratio of the inert gases—that is, the ratio of argon to nitrogen—is considered to be constant. Such an estimate gives, therefore, evidence about the climate at the time the ice was formed and, in theory, should also yield information about the composition of the atmosphere at that time.

The gas enclosed in a temperate glacier in Norway has been systematically examined (*3*). When the ice was formed, it contained a gas which was mostly air, with a small admixture of gas that had been separated from water by freezing. This was evident from the variations in composition from bubble to bubble and from elevated carbon dioxide values. However, during their life in the glacier, the oxygen, argon, and carbon dioxide components of the gas had been systematically removed. This was attributed to a leaching process which takes place during the warm summers of the temperate climate, when the temperature of the ice approaches 0°C and slight films of water containing dissolved gas may migrate through intercrystal boundaries.

In glaciers or icecaps where the temperature of the ice remains below zero, it would appear that the ice is an excellent preservative of the enclosed gas. Glacier ice is pure and comparable in salt content to distilled water (*4*), and there is not enough contaminating matter in the ice to produce a chemical reduction of the oxygen. Also, gas diffusion through ice is extremely slow—less than that of helium through glass (*5*)—and because of the enormous distances within a glacier it seems unlikely that the composition of the gas could change appreciably by diffusion through the ice, even over long periods of time.

It is well established that there have been climatic cycles since the last ice age, with temperatures warmer and colder than at present (*6*). The composition of the atmosphere has been known, through analysis, for only about 100 years, during which time the carbon dioxide content seemingly has not increased measurably (*7*). The theory has has been postulated, though, that a high carbon dioxide content would result in a warm climate, through a "greenhouse" effect (*8*); this theory lends special interest to the study of the carbon dioxide content of the air.

Table 1. Composition of dry gas.

Component	Atmospheric air (% by volume)*	Water equilibrated with air at 0°C, 760 mm-Hg† (% by volume)
Nitrogen	78.09	61.54
Oxygen	20.94	34.90
Argon	0.94†	1.86
Carbon dioxide	0.03	1.75

* Data from R. J. Hock *et al., J. Meteorol.* 9, 441 (1952).
† Data from *Handbook of Chemistry and Physics* (ed. 36, 1954–55).

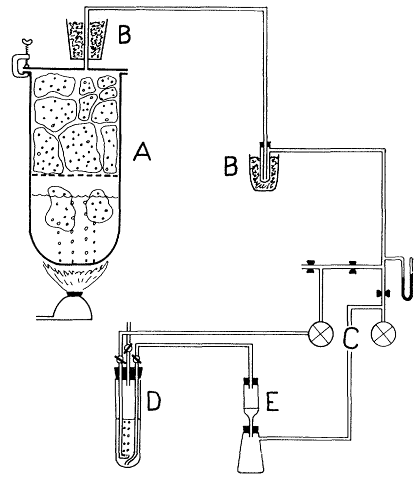

Fig. 1. Schematic diagram of equipment for extraction of carbon dioxide: *A*, 130-lit vacuum-tight ice-melting pot; *B*, vapor traps containing salt-snow mixture; *C*, high-vacuum pumps for taking vacuum and transporting the gas; *D*, barium hydroxide absorption tube; *E*, filtration unit for collecting and washing barium carbonate.

What was the climate and what was the composition of the atmosphere in ages past? Greenland and Antarctica are covered by large ice sheets, in which some of the ice may be 20,000 years old or more. It seems likely that analysis of the gas contained in this ancient ice may provide some answers to these questions.

Samples of glacier ice from three locations near Thule, northwest Greenland, have been collected and analyzed for enclosed gas (*2*). The amounts of oxygen, argon, and carbon dioxide in these samples were all equivalent to, or higher than, those of these gases in air and varied within each piece of ice. This indicated that the ice was formed in a period when the summers, at least, were warm in these latitudes. Using the ratio Ar/N_2, we calculated values for oxygen and carbon dioxide and compared these calculated values with the observed values. The oxygen content of the gas was close to that expected, but the values for carbon dioxide were scattered around a value twice as high as that for present-day air. One explanation might be that the composition of air was different with respect to carbon dioxide when this ice was formed.

Information thus obtained about ancient atmosphere and climate is of little value unless the age of the ice is known. When it was found that the carbon dioxide content of the Greenland ice samples was relatively high, a method was developed to extract and collect the carbon dioxide gas component from ice for radiocarbon dating. The technique was to melt the ice under vacuum and boil the meltwater, all the while removing the gas through a solution of barium hydroxide (Fig. 1).

This technique was tested during April 1957 on Storbreen, the Norwegian glacier examined previously. About 5000 kg of ice (approximately 50 "runs" of the extraction apparatus) were required to obtain enough C^{14} for a reasonably accurate count. Three weeks were required for mining and transporting the ice and for extracting the gas.

The resulting barium carbonate was taken to the Physical Laboratory at the University of Groningen for measurement of the age of the carbon dioxide (*9*). The age obtained for terminal Storbreen ice was 710 ± 120 years. Since only 0.3 g of carbon was available, the sample was counted twice during 5 days (*10*). The age is in excellent agreement with age estimates made by the Norwegian Polar Institute. It appears that this is a suitable technique for the dating of glacier ice.

In conclusion, glacier ice contains gases in sufficient quantity for accurate analysis. Present evidence indicates that, although changes may occur in the gas enclosed in temperate glaciers, the gas trapped in high-polar ice is well preserved. The composition of the enclosed gas yields information on the amount of meltwater that was present in the firnification process, and hence on the climate at the time the ice was formed.

Information on the composition of the atmosphere at the time of ice formation is also obtained. An investigation of gas in icebergs (*11*) showed one of the icebergs to have an absolutely uniform gas composition with respect to oxygen, indicating unchanged atmosphere. It would seem that, through further investigation in Greenland with the techniques now available, it may be possible to locate, analyze, and date ancient atmosphere in its original state.

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Sensitivity to Oxygen During Postembryonic Development of the Wasp Habrobracon

Work on the effects of oxygen gas upon *Habrobracon juglandis* (Ashmead) has shown that pupae are injured by exposure to oxygen whereas larvae appear to be unaffected (*1*). Pupae exposed to 30 lb of oxygen for 1 minute showed an immediate and marked decrease in oxygen uptake as well as arrested development. Since pupae and larvae differ considerably in their sensitivity to oxygen gas, it seemed pertinent to determine at what stage the change from oxygen-resistance to oxygen-sensitivity occurred. Since injury from exposure to oxygen in *Habrobracon* can be established by measuring the oxygen consumption or by determining the incidence of embryos that are able to develop to the adult stage (*1, 2*), we decided to study the stage-sensitivity to oxygen gas, using these criteria. In the present report the effects of exposure to oxygen upon the oxygen consumption at various stages of postembryonic development is reported (*3*).

The wasp *Habrobracon* is parasitic upon the larvae of the Mediterranean flour moth, *Ephestia kuhniella* (Zeller). Female wasps were placed in dishes containing *Ephestia* larvae and were permitted to lay eggs upon them. After a 2-hour period the wasps were transferred to other dishes containing fresh *Ephestia* larvae. Cultures were allowed to develop to the desired stage for treatment with oxygen (Table 1). The life-cycle from egg to imago takes about 8½ days at 31°C. The cultures used consisted entirely of haploid males and were obtained parthenogenetically from unmated mothers.

Individuals of known age and stage of development were placed in plastic chambers of approximately 100 cm^3 volume. Oxygen gas was flushed through the chamber for 1 minute in order to remove the air and was then applied for an additional minute at 30 lb pressure. The cultures were then removed from the chambers, flushed with air, placed in a flask, and measured for oxygen consumption about 1 hour after treatment, by means of the Warburg apparatus. Determinations were made on groups of 25 wasps for a 3-hour period. Measurement of oxygen consumption for an additional 3 hours showed no change from the first 3 hours. The oxygen-treated groups were paired with air-exposed control groups so that a measure of the degree of injury could be obtained by determining the ratio of oxygen consumed by experimentals to that consumed by the controls (see Table 1, column 5). Other individuals in the cultures were examined in order to determine whether the oxygen-treated embryos could develop to the adult stage.

The oxygen consumption for *Habrobracon* exposed to air or to 30 lbs of oxygen at certain stages of postembryonic development is presented in Table 1. Each value and standard error is based upon from three to six experiments. Comparison of the "oxygen consumed" values for experimentals and controls shows that for some stages of development there is no significant difference while for others the difference is large. Comparison of the values for magnitude of oxygen consumption, with age, for the controls shows the U-shaped curve that has been reported for many insects. Cultures that are oxygen-treated as larvae in cocoons or as prepupae show no decrease in oxygen consumption from that of their control groups. Furthermore, cultures at these stages were able to develop normally and to emerge as adults. Cultures consisting of a mixture of prepupae and white pupae show a significant difference in oxygen consumption between controls and experimentals. This difference is more pronounced for white pupae (120 hours and 144 hours old) and for pigmented pupae (168 hours old). The oldest pigmented pupae (192 hours) show a decrease in sensitivity (Table 1).

The decrease in oxygen consumption reported here for the oxygen-treated pupae is a permanent decrease. Experiments reported elsewhere (*2*) have shown that there is no subsequent increase in oxygen consumption for these pupae, even after 24 and 48 hours. The effect reported here is irreversible.

Wasps in these stages of development show not only a decrease in oxygen consumption after oxygen treatment but arrested development as well, so that most of these insects do not reach the adult stage. Exposure of white pupae to 30 lb of oxygen for 1 minute will cause over 95 percent of these wasps to remain as white pupae (*2*). This procedure is now