semble of events all peaked in the same direction, we may be able to do better.

If accurate time records are kept, one can perform a time-of-flight experiment with neutrinos (9). This can be done by comparing the neutrino time to optical or gamma observation times, or by comparing peaks in the time distribution. In principle, if the neutrino has a mass its time-of-flight difference will be

$$\Delta t = \frac{1}{2}\;\frac{m_1^2 - m_2^2}{p^2}\,t$$

Where m_1 and m_2 are the two masses to be compared and t is the total travel time. For $m = 10$ eV and $p = 10$ MeV at 1 kpc $= 10^{11}$ seconds, one gets $\Delta t = 50$ msec. With modest timing accuracy one can compare the arrival with signals observed at gravitational-wave detectors (10) and perhaps gamma-ray satellites.

Since the neutrinos have a continuous energy spectrum this may not be distinct. To some extent the situation is helped by the E_ν^2 dependence of the cross section, which tends to narrow the effective spectrum for interacting neutrinos.

If separate neutrino mass peaks are observed, it may be possible to combine this information with the asymmetry information and measure the $\bar\nu_e$ component of the neutrino mass eigenstates—that is, $\langle\,\bar\nu_e\mid\nu_1\,\rangle$, $\langle\,\bar\nu_e\mid\nu_2\,\rangle$, and so on. Although the signal from individual neutrino interactions is too weak to be detected, some of these will activate the proton decay electronics and be recorded. From these one can hope to learn something about the neutrino energy spectrum itself, which is related to the temperature in the star at the time it became transparent to neutrinos.

One can contemplate major improvements in the detector for studying stellar collapse. The use of more and larger photomultiplier tubes would increase the detector's range and aid in reconstructing more events but would be very expensive. One can increase the light collection by a factor of 3 inexpensively through the use of reflecting walls and wavelength shifters. While this would increase the range of sensitivity, it would destroy the structure of the Cerenkov light and prevent reconstruction and would make the detector unsuitable for studying proton decay.

Our signal is dominated by the charged current reaction $\bar\nu_e p \rightarrow e^+ n$. It may be possible to dissolve a good ν_e detector in water and boost the detector's sensitivity to other components of the burst. Other advantages of adding a salt to the detector are that the density would increase, giving greater sensitivity to proton decay, and the index of refraction

would go up, yielding more Cerenkov photons per centimeter. This effect would be offset by the increase in dE/dx, resulting in a shorter range.

For example, it is known that NaCl does not adversely affect the attenuation length of light in water. It is highly soluble: 8000 tons of water dissolve 3200 tons of NaCl. This yields 3.3×10^{31} ion pairs. The chlorine has a modest cross section for ν_e interactions (11):

$$\sigma(\nu_e \times {}^{37}Cl) = 8.1 \times 10^{-41}\ cm^2$$

The natural abundance is 25 percent ^{37}Cl. For a collapse at 1 kpc, this yields 1.1×10^4 ν_e-Cl interactions. This rate is small compared to the 1.2×10^5 from the water but is comparable to the number of νe scatterings. The observed signal in this case is dominated by the excitation and subsequent decay of a low-lying argon state.

It is concluded that the 8000-ton water IMB detector would be an effective stellar collapse detector. It has a large mass of hydrogen, which gives it a large $\bar\nu_e$ cross section. Detector noise would not be a problem for signals originating in a large portion of our galaxy.

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Major Carbon-14 Deficiency in Modern Snail Shells from Southern Nevada Springs

Abstract. *Carbon-14 contents as low as 3.3 ± 0.2 percent modern (apparent age, 27,000 years) measured from the shells of snails* Melanoides tuberculatus *living in artesian springs in southern Nevada are attributed to fixation of dissolved HCO$_3^-$ with which the shells are in carbon isotope equilibrium. Recognition of the existence of such extreme deficiencies is necessary so that erroneous ages are not attributed to freshwater biogenic carbonates.*

Carbon-14 dating is a useful and precise technique only in cases where both the initial ^{14}C concentration of the sample and the magnitude of postdepositional changes in isotope ratio unrelated to radioactive decay are known. Wood has played an important role in ^{14}C dating because of its ubiquity on land, its incorporation of ^{14}C in near equilibrium with the atmospheric pool, and its relative resistance to alteration. Interpretation of the ^{14}C contents of other materials is not as simple, and many attempts have been made to define and compensate for the range of processes that affect isotopic composition. For example, studies of freshwater biogenic carbonates should account for the possible effects of contamination, fractionation, reservoir deficiencies including hard water effect (1), exchange, and measurement and sampling errors. Despite this range of processes, most measurements of modern freshwater biogenic carbon are at least 70 percent modern ^{14}C, although the largest reported deficiency is in *Potamageton illinoensis*, a living subaquatic plant with 4.72 ± 0.2 percent modern ^{14}C (2). Carbon-14 concentrations as low as 3.3 ± 0.2 percent modern, measured in shells of the aquatic snail *Melanoides tuberculatus* (Müller) collected live from three springs in Nevada, are the lowest recorded.

Crystal Pool, Big Spring, and King Spring, three major artesian springs, are
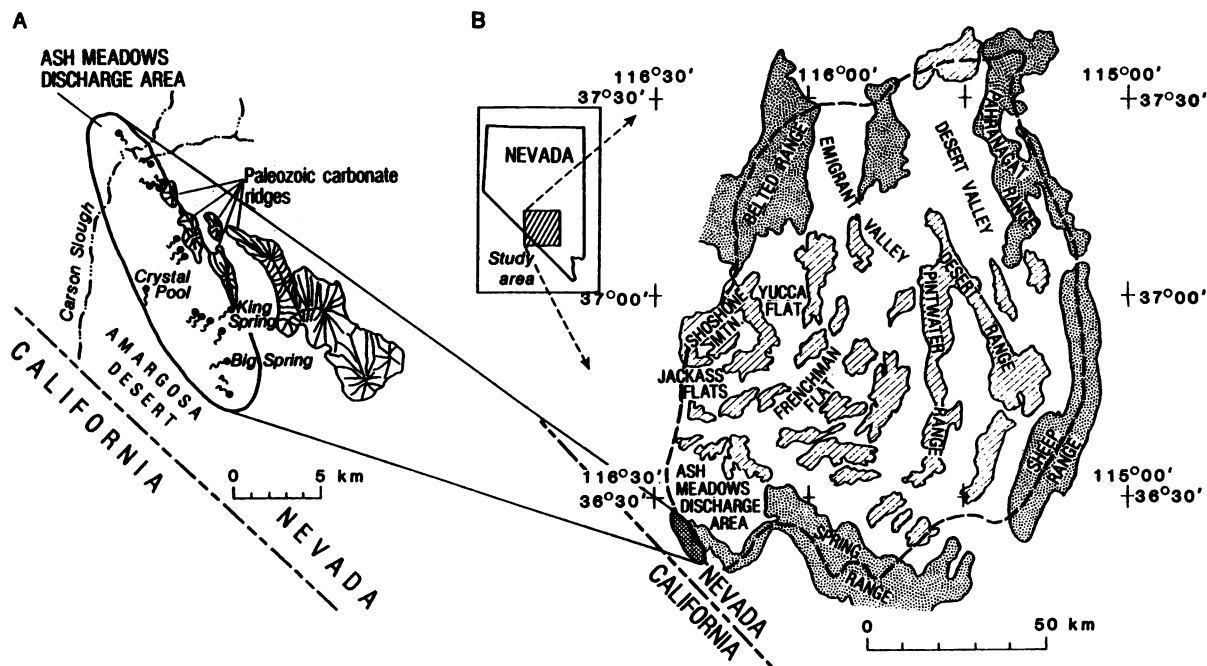
Fig. 1. (A) Extent of Ash Meadows discharge area showing relation of springs to Paleozoic carbonate ridges. Discharge is from spring pools developed in Plio-Pleistocene lake beds that slope gently to the west-southwest. Redrawn from U.S. Geological Survey topographic maps. (B) Relation of Ash Meadows discharge area to its recharge areas and to the state of Nevada. The majority of the recharge occurs at higher elevations in the mountains. Redrawn from (3, 12, 23). (———)Approximate boundary of Ash Meadows ground-water system: (▓▓▓) mountain ranges high enough so that some parts receive in excess of 30 cm of rain per year; and (▨▨▨) other mountains.

part of the Ash Meadows discharge area (16 by 3 km) that is situated along the slope between the Amargosa Desert and ridges of Paleozoic carbonate rock in the extreme southern portion of Nevada (Figs. 1 and 2). Crystal Pool and Big Spring are large (about 15 m in diameter by 5 m deep) glory hole springs, each having a single orifice and a well-defined outflow channel (Fig. 2). The pools lie about a meter below the surface of the Plio-Pleistocene lake bed sediments that form their walls and bottom; both springs are about 3 km from the nearest Paleozoic carbonate ridge. King Spring, smaller and shallower (about 8 m in diameter by 1 m deep), lies at the boundary between the lake beds and a tufa mound deposited on the Paleozoic carbonates. It has multiple small orifices in its flat, predominantly tufa floor.

All of these springs are fed by the same regional Paleozoic carbonate aquifer, which is recharged by precipitation infiltrating the upper elevations of several mountain ranges in a region extending at least 100 km to the north and east (Fig. 1) (3). After underground courses that for some branches of the aquifer take thousands of years and reach depths of thousands of meters, the waters rise at Ash Meadows as a multicomponent mixture, saturated with calcite, that has constant chemical, physical, and flow characteristics (3) (Table 1). These artesian springs are the habitat of M. tuberculat-

us, an exotic mollusk species [introduced into Big Spring about 1970 (4)] composed entirely of parthenogenetic females that bear postmetamorphic young (2-mm long) (5). The adults are most abundant under rotting algal mats, where they apparently feed on decaying organic matter at the mat and sediment interface; these food habits are consistent with Starmülhner's observations (6).

There are three carbon reservoirs of

different ^{14}C contents available to the snails. One is the Plio-Pleistocene lake bed and Paleozoic carbonate rock reservoir which is much older than can be measured by radiocarbon dating and lacks measurable ^{14}C. Another is the atmospheric CO_2–subaerial plant reservoir with 95 to 100 percent modern ^{14}C. Finally, there is the dissolved HCO_3^- and algal mat reservoir that ranges from 1.7 percent modern ^{14}C in King Spring to
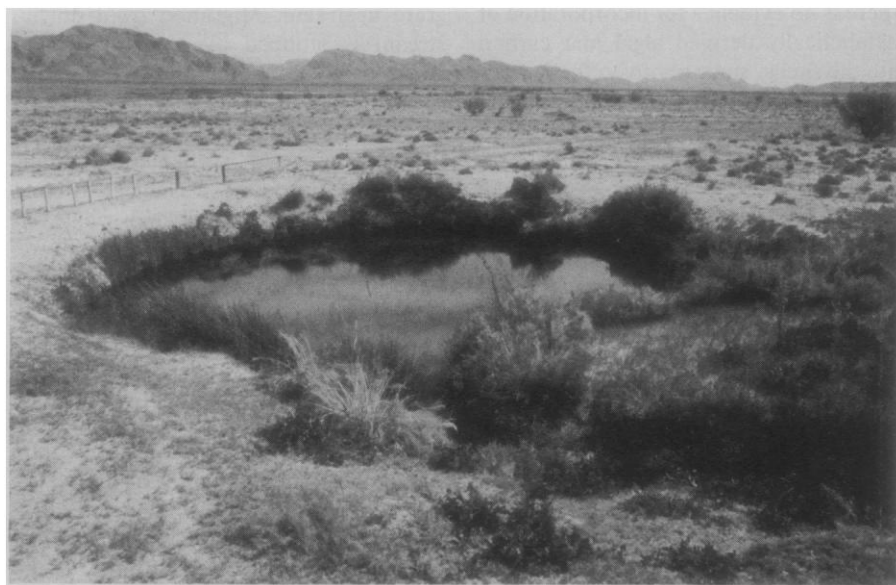

Fig. 2. Big Spring showing spring pool, outlet channel, character of local vegetation, and lake bed plain sloping slightly upward to Paleozoic carbonate ridges in the distance. Big Spring's natural configuration has not been modified in attempts to increase flow. [A. C. Riggs photo]

Table 1. Physical, isotopic, and chemical characteristics of the three Nevada springwaters and snail shells. All values except shell ^{14}C and ^{14}C contents are from (3).

Discharge (m³/day)	Temperature (°C)	^{14}C* content (% modern)		^{13}C† content (per mil PDB)		pH	Alkalinity (meq/liter)
		Water	Shell‡	Water	Shell		
Big Spring							
5,500	27	3.9 ± 0.3 (WRD199) 2.9 ± 0.4 (WRD236) 2.8 ± 0.2 (WRD285)	3.3 ± 0.2 (WRD296)	−4.6 ± 0.1	−1.9 ± 0.1 −2.7 ± 0.1	7.4	5.21
Crystal Pool							
15,300	31	11.6 ± 0.7 (WRD198) 10.6 ± 0.3 (WRD231)	10.6 ± 0.2 (WRD297)	−5.0 ± 0.1	−2.8 ± 0.1 −2.95 ± 0.1	7.4	5.11
King Spring							
8,200	32	1.7 ± 0.4 (WRD234)	5.9 ± 0.2 (WRD298)	−4.7 ± 0.1	−2.8 ± 0.1 −2.95 ± 0.1	7.4	5.00

*Numbers in parentheses are the sample numbers in (15).   †Upper shell ^{13}C value for each spring was measured by F. J. Pearson and the lower by T. Coplen, U.S. Geological Survey Water Resources Division (WRD) laboratory, Reston, Virginia.   ‡Shell ^{14}C values determined in the U.S. Geological Survey WRD laboratory under F. J. Pearson.

11 percent modern ^{14}C in Crystal Pool— a vast range compared to the uniformity of the other solutes and a probable indication of megascale heterogeneities in ground-water flow (3) (Table 1).

Originally, metabolic by-products were generally believed to be the most likely source of shell carbonate, but it has become increasingly clear that many mollusk shells are precipitated in equilibrium with carbon isotopes in solution (7). Fritz and Poplawski (8) demonstrated that some freshwater mollusk shells are deposited essentially in equilibrium with the isotopic composition of the solution, with metabolically derived carbon present in only minor amounts. Analyses of the Nevada spring snails yield results that are consistent with these findings. There is no evidence for incorporation of metabolically derived algal mat carbon into the shells, since photosynthetic fractionations would lead to a reduction in shell ^{13}C of about 25 per mil relative to dissolved carbon [*Lyngbya* sp. and *Spirogyra* sp., the predominant algae in Crystal Pool, have ^{13}C = −28.0 ± 0.1 per mil relative to Peedee belemnite (PDB)] (9, 10). No such depletion in shell ^{13}C is seen; in all springs the shells have about 2 per mil more ^{13}C than the water (Table 1). Observation and experiment both suggest that fractionation on precipitation will cause solid carbonate to have about 2 per mil more ^{13}C than does dissolved HCO_3^- in equilibrium with solid carbonate (10). Although ^{14}C fractionates twice as much as ^{13}C (11), no ^{14}C fractionation is seen (the shells and dissolved carbon in Crystal Pool and Big Spring are essentially identical in ^{14}C content) since measurement uncertainty

overshadows the small (4 per mil) expected fractionation.

The King Spring shells, with only 5.9 ± 0.2 percent modern ^{14}C, have more ^{14}C than the springwater. This anomaly is explained by the fact that King Spring pool receives perennial inflow amounting to a third of its discharge from adjacent springs and seeps (12). Before flowing into King Spring, the waters traverse a marshy area that supports abundant subaerial vegetation whose eventual decay should release ^{14}C (13). This contamination was avoided in the water analyses by sampling directly from a major orifice, while shell carbonate apparently represents conditions in the pool at large or a combination of the pool and marsh inflow if the snails migrate upstream. Migration from downstream is stopped by irrigation headworks at the pool outlet.

Neither Big Spring nor Crystal Pool receives any perennial inflow, nor are there any apparent dry channels draining into them, but both are subject to contamination from rainfall and whatever sheet flow they intercept after the rare rainstorms [average annual precipitation is 10 cm (12)]. All three springs are local topographic lows that catch both organic litter and inorganic dust blown in by winds. Another source of contamination prevalent in all the springs is the carbon-bearing debris that people throw into these sites. Contamination of the water by exogenous carbon would seem inevitable, but the springs rapidly flush out dissolved materials. Big Spring, for instance, flows so rapidly that, in the absence of mixing, the water in the pool would be replaced every 2 hours; Crystal

Pool would turn over in less than half an hour (14). King Spring's perennial contaminating inflow overwhelms the flushing action. Thus, with the exception of King Spring, contamination by carbon originating above the water surface is masked by high turnover rates and natural carbonate saturation of the springwaters.

Since dissolved HCO_3^- and shell carbonate are in isotopic equilibrium, there is no gradient to drive exchange and no evidence of exchange. Measurement error does not seem to be a problem since the results of different sets of measurements are consistent and the King Spring deviation has been explained (15).

Since aquatic mollusk shells are not favored material for ^{14}C dating, it is tempting to dismiss these results as interesting curiosities of no particular consequence. There are at least three reasons for rejecting this view. The first is that reservoir deficiencies are not limited to snails but occur in all plants and animals that incorporate ^{14}C in disequilibrium with the atmosphere. The submerged plants *Chara* sp. (11.61 ± 0.57 percent modern ^{14}C) and *P. illinoensis* (4.72 ± 0.2 percent modern ^{14}C), and the Sonoran mud turtle *Kinosternon sonoriense* (16 ± 2.6 percent modern ^{14}C), all from Montezuma's Well, Arizona (2, 16), are proof that organisms ranging from primary producers to carnivores get much of their carbon from the water (6.46 ± 0.42 percent modern ^{14}C). The second reason is that waters deficient in ^{14}C are available to aquatic life in many places around the world. Ground waters and springwaters with less than 5 percent modern ^{14}C (apparent age, 22,000 years) are reported from such diverse locations as the United States (17), Hungary (18), Great Britain (19), Libya and Morocco (20), and Chile (21). Ground water with ^{14}C indistinguishable from 0 percent modern has been reported from Qatar (22). Further, desert springs are commonly deficient in ^{14}C and are especially important for ^{14}C dating since they are usually hubs of biological activity. The third reason is that mollusk shells can be satisfactory dating material if initial ^{14}C levels and magnitudes of postdepositional alterations are known.

In the cases where the magnitude of ^{14}C deficiencies is unknown or underestimated, the potential for misdating is extreme. For instance, if the ^{14}C depletion in Big Spring were attributed entirely to hard water effect (1), shells from the spring would date at least 22,000 years too old. Since there is no limit to the size of reservoir deficiencies, the potential for misdating, particularly of samples

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from arid areas, is also unlimited. It is probable that living plants and animals that naturally completely lack ^{14}C are unreported only because the proper environments have yet to be tested.

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1. The hard water effect is a dilution of ^{14}C content by the dissolution of dead mineral phase carbonate that buffers the acidity caused by dissolution of modern soil zone CO_2 into the infiltrating ground water. For stoichiometric reasons, the amount of mineral carbon dissolved cannot exceed the amount of soil zone carbon present. Dilution of the soil zone carbon is therefore limited to 50 percent, or one half-life of ^{14}C (about 5700 years). For the original description see E. Deevey, Jr., et al., *Proc. Natl. Acad. Sci. U.S.A.* **40**, 285 (1954).
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Enhanced Atmospheric Circulation over North America During the Early Holocene: Evidence from Lake Superior

Abstract. *Profiles of grain sizes in five cores recovered from Lake Superior show that grain size increased with burial depth to the postglacial-glacial contact. The results reflect a substantial reduction in bottom-current velocity and the corresponding wind velocity from 9500 to 6500 years ago.*

Some models of atmospheric circulation and of paleoclimate predict that the midlatitude westerlies over North America were stronger during early Holocene as compared with late Holocene because of enhanced anticyclonic circulation over the Laurentide ice sheet (*1–4*), but little direct evidence supports them. The morphology of the Nebraskan sand dunes suggests that the north-northwest winds during the late Pleistocene were stronger than the southwest winds during the mid-Holocene, but the stratigraphic record lacks a definite and continuous chronology (*5*). The fluvial deposits in the driftless area indicate that there were more episodes with high runoff in early than late Holocene time; these may reflect storm frequency (*6*).

We present evidence of major fluctuations in atmospheric circulation throughout the Holocene over Lake Superior. The prevailing signal is one of decreasing wind intensity or storm frequency beginning 9500 years ago. The results are based on analyses of sediments from a deep-water environment just north of the Keweenaw Peninsula in Lake Superior. Seismic profiles (3.5 kHz) and side-scan sonar records, collected along 500 km of shiptrack, plus 2 piston (P), 10 gravity (G), and 12 box (B) cores recovered from 220 to 260 m water depth revealed sedimentary features that indicate weak bottom currents 25 km offshore and progressively stronger bottom currents southeastward toward the base of the slope off the peninsula (*7, 8*). A scoured trough, 20 m deep, 2 km wide, and 20 km long, is at the base of the slope where bottom currents may be strongest. The bottom currents probably intensify during major storms, particularly in the spring and fall when the lake is isothermal and the wind-driven Keweenaw current may extend to depths exceeding 200 m (*9, 10*).

Sediment cores were recovered along two 15 km-long transects perpendicular to the shoreline and to the direction of bottom-current flow inferred from geophysical data (*7, 8*) (Fig. 1). An additional core, 37P, was recovered from the western arm of Lake Superior, outside the main study area (Fig. 1). Surface sediment samples from all cores in the study area and subsurface samples from cores 14G, 23P, and 24P, were analyzed for percentages of sand, silt, and clay by sieve and pipette techniques. The subsurface samples extended downcore to below the postglacial-glacial contact (*11*), or for the length of the core if the contact did not exist. The silt fraction (5.85 to 71.44 μm) of all subsamples plus additional subsurface samples from cores 4G, 8G, and 37P were analyzed for grain size with an Elzone electronic particle analyzer (*12, 13*), which determined the relative abundance of particles in 128 discrete increments of approximately 0.03 phi (*14*). All samples were analyzed at least in duplicate and in triplicate if the median grain size of the first two analyses was not within 0.09 phi. The average of the individual analyses was used to calculate the median grain sizes reported. The average deviation of the median grain size between duplicate analyses was 0.05 phi, which is 1.0 to 1.5 μm at this size range.

Cores 23P and 24P were dated paleomagnetically—the best technique available for dating Holocene sediments in the Great Lakes (*15–17*). The downcore profiles of the magnetic declination and inclination variations provide chronostratigraphic events for correlation between adjacent cores.

It has been shown that dominant grain size of surface samples changes from sand in the trough to clay farther offshore (*18*). The median grain size of the silt fraction for the same samples changes from 36 to 15 μm—a change attributed to regional variation in bottom-current intensity.

Downcore analyses show a noisy but significant coarsening in median grain size of the silt fraction with burial depth in five of six cores examined (Fig. 1). The exception is core 14G, which may be anomalous because of localized current eddies at this site (*18*). The increase in grain size downcore may be the result of (i) a change in lake level during postglacial times that altered bottom currents or the sediment source; (ii) a change in vegetation during the Holocene that affected sediment influx; or (iii) a decrease in bottom-current velocity through the Holocene. Fluctuations in the lake level during the Holocene apparently influenced the grain size of sediments in the lower Great Lakes (*19*). Lake level in our