Last of the West Ford Dipoles

Abstract. *Radar measurements confirm that the several hundred million individually orbiting West Ford dipoles reentered the lower atmosphere in precise accord with predictions. Calculations indicate that these tiny copper wires survived reentry and floated gently back to Earth; unfortunately, the probability of finding one is minuscule. Some dipole clusters remain in orbit but almost all should return to Earth within the next 2 years.*

In 1958 Morrow and Meyer discussed the possible use of a belt of orbiting dipoles as a passive medium to facilitate world-wide military radio communications (*1*). This proposal developed into Project West Ford which was undertaken at the M.I.T. Lincoln Laboratory to determine the feasibility of such a communications system and its possible impact on other branches of science. After careful study indicated that no harm would ensue, an experiment was carried out by placing about 480 million tiny copper wires (dipoles) in orbit in May 1963 (*2, 3*). The probability of such dipoles puncturing spacecraft was easily shown to be negligible; the dipoles could possibly have been a hazard only insofar as they might have interfered with optical or radio astronomical observations by reflecting solar rays or man-made radio signals. Again calculations showed that the interference would be negligible (*4*) and the experiment verified these predictions. No radio observatory detected signals reflected from the dipoles at any frequency despite several cooperative experiments in which radio telescopes were directed at radar-illuminated spots on the dipole belt (*5*). Optical astronomers were only slightly more successful: an exceedingly faint photographic image of the dipoles was obtained 1 day after launch, when they were concentrated in the immediate vicinity of the dispenser (*6, 7*). Some astronomers (*8*) using sensitive photoelectric equipment were able to detect sunlight reflected from the dipoles, but only during the first week before the dipoles had spread more fully around the orbit. One group (*9*) did report additional photoelectric detections. Careful examination of the original data shows little justification for this interpretation; indeed, more reliable radar evidence (as well as theoretical considerations) demonstrates that no dipoles were present in the part of the sky from which some of these optical reflections were allegedly observed (*7*). Of course the dipoles continued to be detectable with sensitive *X*-band radar systems tuned to the resonant frequency of the dipoles, and many communications experiments conducted between the Lincoln Laboratory facilities in Westford, Massachusetts and Camp Parks, California, corroborated predictions with remarkable accuracy (*10*).

To prevent the copper wires from interfering in the future with some type of scientific observation not yet conceived, they were placed in an orbit carefully designed so that the individual dipoles would return to Earth within 3 years. In such a resonance orbit (*7*) the pressure of sunlight gradually drives the dipoles back to the Earth's surface.

A thorough description of these and other aspects of the West Ford experiment from launch through January 1964 was given previously (*11*). The remainder of this report summarizes the subsequent results.

Because of delay in ejection of the unit containing the dipoles from the parent satellite, normal dispensing of individual wires was not completed, and about half remained in electrically connected clusters (*12, 7*). We discuss, in turn, the fates of the clusters and the individual dipoles. Because of their greater electrical length, the clusters were more readily detectable by radars operating at frequencies below *X*-band. The largest clusters observed repeatedly at UHF (*13*) had combined radar cross sections of only about 1 m^2; the total geometric cross section was probably substantially smaller. Because of the relatively small area-mass ratio (A/M) of these clusters, their orbital lifetime will be extremely long, but they will cause far less interference than the multitude of other larger satellites traveling in similar orbits.

More numerous, smaller clusters have been observed at *L*-band with the Millstone Hill radar (*14*). Although not well determined, the orbits of the clusters are known to be spread between those of the individual dipoles with higher A/M and the orbit of the parent satellite whose A/M is lower. The decrease in the right ascension of the ascending nodes of the dipoles being greater causes them to pass overhead earlier than the parent satellite. Therefore, the clusters could be detected by directing the radar beam, say, nearly overhead at a time when the belt was expected to pass through it, and by allowing the Earth's rotation to cause the beam to search the region between the belt and the orbit of the parent satellite. With observations made in this manner, only a small fraction of the clusters pass through the radar beam making it difficult to estimate

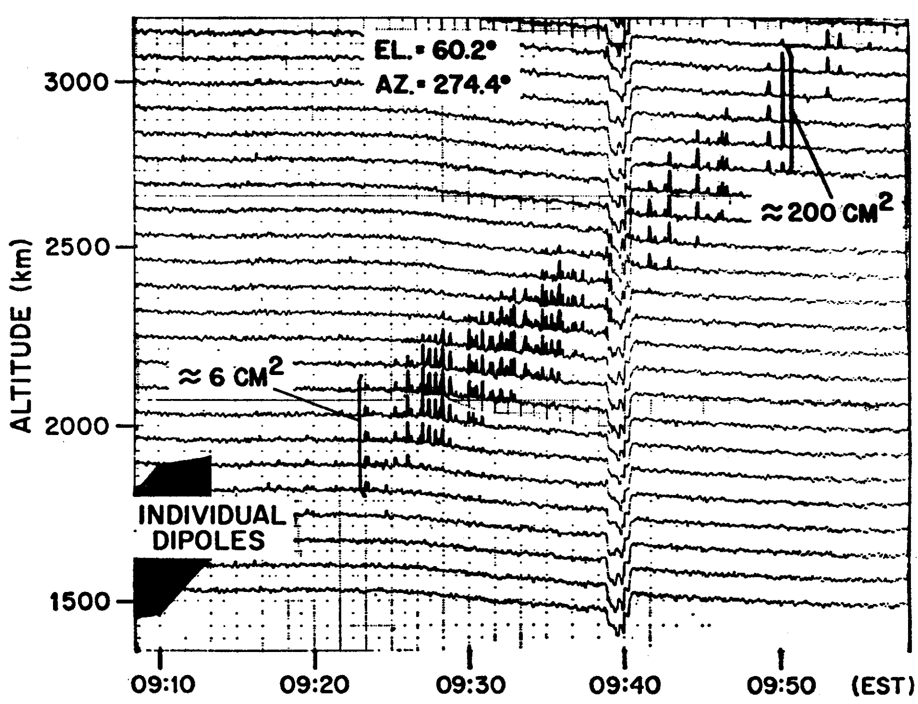
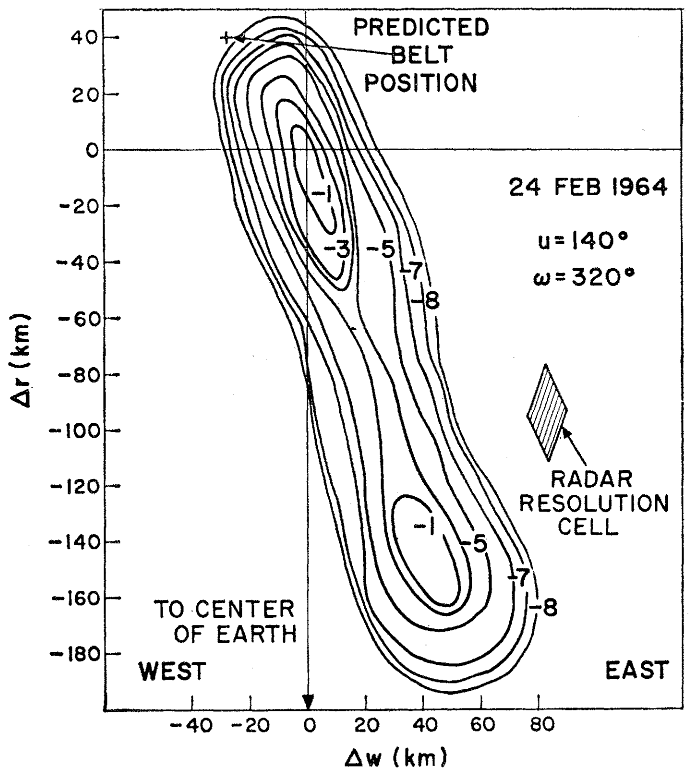


Fig. 1. Millstone Hill radar observations of dipole clusters at 1295 Mcps.



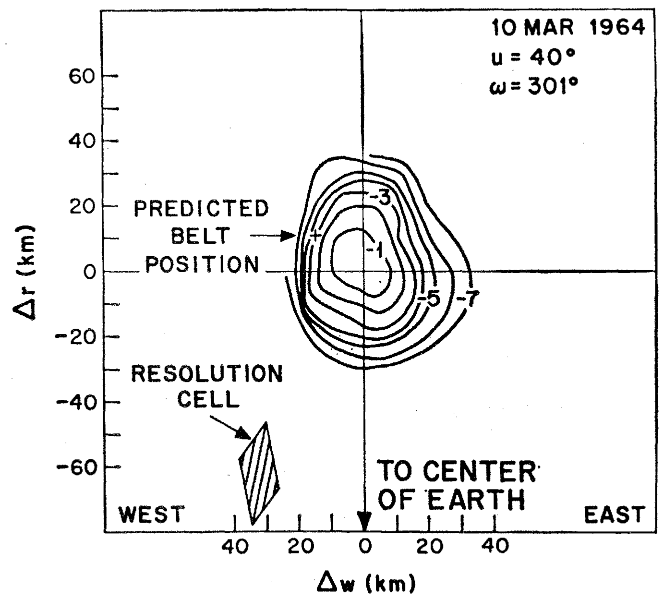


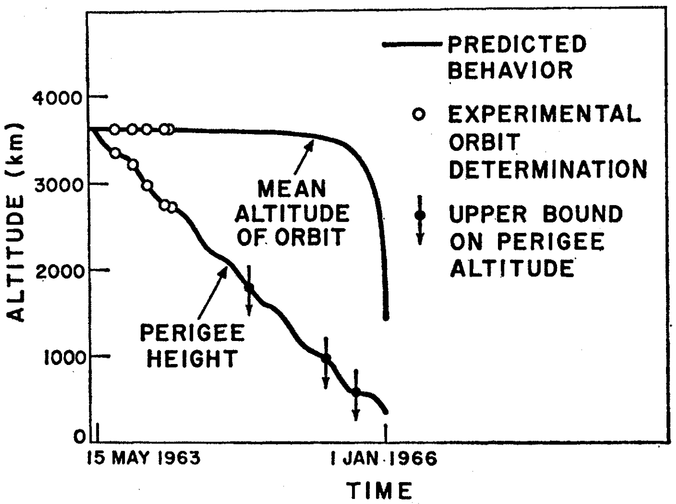
Fig. 2 (left). Physical cross section of the dipole belt at apogee. Contours of equal dipole density are labeled in decibels referred to the density at the origin. The angle u denotes the argument of latitude of the observation whereas ω denotes the argument of perigee. Fig. 3 (above). Same as Fig. 2, except here the observed section was near a semilatus rectum point of the orbit.

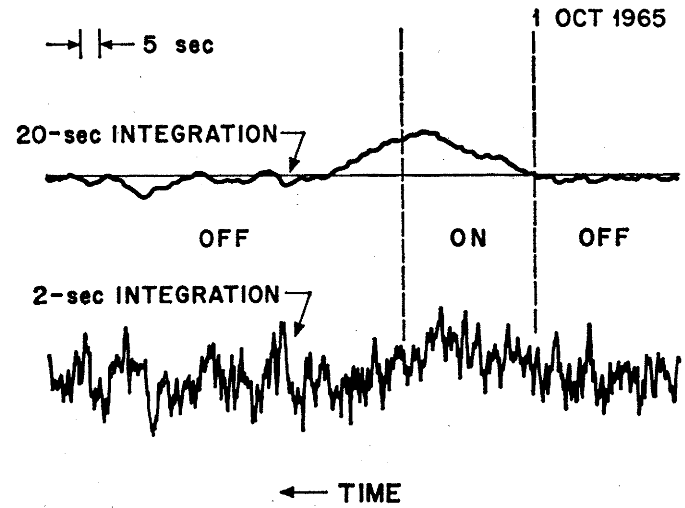
their total radar cross section. A further complication is introduced because detection depends not only on the spatial coordinates of a cluster but also on its radial velocity which affects the echo frequency. The necessary use of a narrow Doppler filter may therefore prevent the detection of some targets. (Using a very wide filter, on the other hand, could lower the signal-to-noise ratio sufficiently to prevent all targets from being detected.) The results from one of these observations are shown in Fig. 1, with each curve representing the echo power (plus noise) received from the altitude given on the ordinate scale. In each line the vertical deviations from the average are proportional to the logarithm of the received signal power and are related to the radar cross section of the target as indicated. Since 2-msec pulses were transmitted, the echo from a given cluster in general appears on four of the lines which are separated by 0.5 msec in delay (that is, in range). The downward drift and anomalous dip apparent on each curve were caused by receiver-gain changes which are readily accounted for in estimating cross sections.

The difficulties mentioned, compounded in later observations by the greater dispersion in cluster orbits, imply that the desired estimate of the total radar cross section at L-band was not too accurate. Nevertheless, extrapolation over the entire "orbit" always led to substantially the same estimate—about 50 m^2. The geometric or physical cross section is most likely several orders of magnitude lower. Since the portions of the orbit explored in these measurements were often near perigee, the orbital lifetimes of the clusters could be inferred from the distribution of altitudes. The latest observation (in October 1965) confirmed previous estimates indicating that most of the clusters contributing to the L-band radar cross section will cease to orbit within the next 2 years; only a minute fraction will orbit indefinitely. In any event, the orbital planes of all objects remaining will spread differentially around the Earth (*7*) and present widely separated small radar targets that will be difficult to distinguish from the orbiting remnants of other space launchings.

The differential velocities imparted to the individual dipoles during dispensing caused them to diffuse along their "common" orbit and form a belt around the earth (*7*). The physical cross section of the belt increased with time under the influence of differential gravitational and sunlight-pressure perturbations, thereby making detection increasingly more difficult. However, by transmitting *cw* from Camp Parks via the belt to Westford, one could measure accurately the physical cross section (Figs. 2 and 3) until October 1964 (*15*). The growth of the cross section was predicted to be greatest in the radial direction at apogee and perigee and least at the semilatus rectum points in the orbit (*7*, *16*). The shape and the orientation of these contours are in qualitative agreement with the predictions. But lateral growth of the belt was, in fact, substantially less rapid than anticipated on the basis of currently accepted values for the dust-particle flux near Earth. (Dipole—dust particle collisions were expected to "randomize" the dipoles' tumbling axes, which initially had been preferentially oriented in the direction of the dispenser's spin axis, and hence to produce a larger spread between orbits because of the concomitant increase in differential sunlight-pressure perturbations.) Although a quantitative statement is difficult to formulate, and would require an enormous investment in computer time, it is nonetheless apparent that the dipoles were not detectably affected by dust particles. Their flux near Earth may well be significantly less than is currently assumed.

What may we conclude about the orbital lifetime of the dipoles? At launch the expected behavior of the average dipole's perigee height and mean altitude (Fig. 4) were calculated (*17*). Through January 1964, five independent orbital determinations were made solely from pulse radar data (*12*); the agreement with predictions was excellent. Thereafter, the dipole





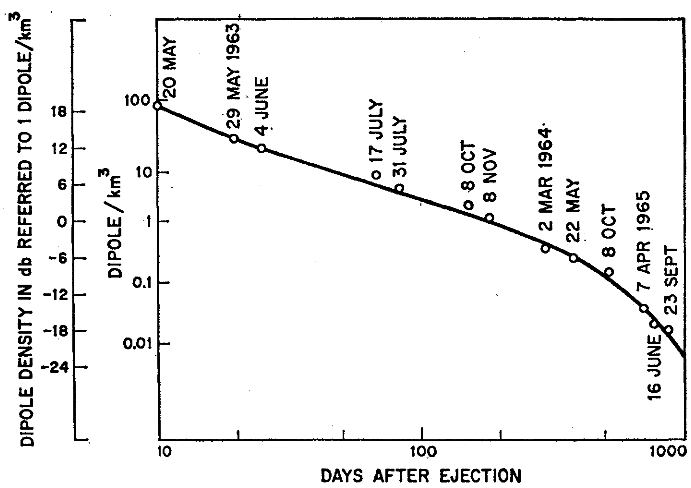


Fig. 4 (above). Orbital behavior of the West Ford dipole belt: comparison between theory and observation.

Fig. 5 (top right). Last radar detection of the dipoles. Curves are from a strip-chart recording of the received power at Haystack (Tyngsboro, Mass.) when the belt was illuminated in an on-off fashion by the Camp Parks radar (Pleasanton, Calif.). System difficulties caused the signal strength to be about 5 db lower than expected.

Fig. 6 (bottom right). Observed average dipole density versus time.

density was too low and the echo power consequently too weak for such determinations to be made. The contour maps, however, enabled the locations of the densest part of the belt to be compared with the predictions. On the 16 contours obtained between January and May 1964, the differences were generally about several tens of kilometers *(15)*. One observation made near perigee provided a useful upper bound on the perigee altitude. During the summer of 1964 the antenna drives, the antenna pointing program, and the method of boresighting were improved. On the three contours obtained thereafter, the predicted and observed centers were more nearly coincident, implying that the larger earlier differences may well have been errors in measurement rather than in prediction. Although the dipole density was too low for useful contour maps to be obtained *(18)*, observations between October 1964 and October 1965 did confirm the predicted belt position. Each observation detected dipoles exactly where predicted, but, when the antennas scanned away from the predicted location, the echo strength invariably decreased. (Upper bounds on perigee altitudes determined from these observations are also shown in Fig. 4.)

The penultimate detection of the dipoles with the receiver at Westford was made very close to perigee on 16 June 1965. At the center of the belt only three dipoles on average were in the common volume of the two antenna beams. Nevertheless, an attempt to determine the radial extent of the belt indicated a dimension of about 400 km between regions where the dipole density was 5 db lower than the maximum observed. The last Camp Parks–Westford observations on 23 September 1965 were also near perigee, but the low altitude of the latter allowed little more than the determination of the average dipole density. The final detection was made on 1 October 1965, with the Haystack facility in Tyngsboro, Massachusetts replacing the Westford terminal. The greater sensitivity of Haystack could not be fully utilized in this situation, however, because its larger antenna resulted in a substantial decrease in the common volume illuminated by the two antenna beams. Part of the chart recording made during this observation is reproduced in Fig. 5 *(15)*. The received power at Haystack increased by as much as five times the standard deviation of the noise when the Camp Parks transmitter was on. Detection was achieved with an average of only one dipole in the common volume only about 75 percent of the time.

To underscore the decrease in dipole density within the belt during the course of the experiment, measured macroscopic average dipole densities at the centers of the contours are shown in Fig. 6 *(19)*. Between the 10 days after the dipoles were dispensed and the final detection, the density can be seen to have decreased by a factor of 10,000 *(20)*. Later attempts to detect the dipoles (19 November and 2 December 1965) failed. The possibility of systems problems was eliminated by careful bistatic experiments employing the moon as a target. If the dipoles followed the predicted orbits, their macroscopic density at these times would have been below the detection threshold because of the rapid increase in dispersion attributable to air-density perturbations, which become severe during the final months in orbit. Despite being negative, the results of these attempts were thus in good accord with expectations. There can be little doubt that the dipoles reentered the dense lower atmosphere during a period of several months, centering about the predicted reentry date of 1 January 1966 for the average dipole.

Unfortunately, New Year's celebrations were not punctuated by a display of tiny fireballs. Calculations show that because of their high A/M value and shallow reentry angle, the dipoles were able to radiate heat rapidly enough to avoid disintegration (*7*), and most probably floated back to Earth essentially unharmed. Even had they disintegrated during reentry, the dipoles would have produced trails far too faint to have been visible.

What is the probability of finding a dipole? Since the spread in orbital lifetimes is long, in comparison with 24 hours, the dipoles were distributed almost uniformly along each latitude circle; their density per unit surface area should therefore be greatest in the polar regions. A simple calculation (*7*) demonstrates that the maximum macroscopic surface density is about 5 dipole/km^2. Search of a sufficiently large area (and depth of snow) to ensure a probability of 0.9 of recovering at least one dipole in the arctic is feasible, but expensive (*21*). However, no funds were solicited for such a recovery operation.

This report on the fate of the dipoles is intended to be the last. Our gratification at having seen experimental results in agreement with predictions is tempered by the realization that little can be done to clear the clouded reputation of Project West Ford. For, as was observed long ago, the (alleged) evil that projects do lives after them; the good is oft interred with their bones. So let it be with West Ford.

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References and Notes

1. C. F. J. Overhage, W. H. Radford, *Proc. IEEE (Inst. Elec. Engrs.)* **52**, 452 (1964).
2. Each dipole was 1.78 cm in length and 0.00178 cm in diameter; the ensemble was placed in a nearly circular, nearly polar orbit at an altitude of about 3650 km. The combined mass of all dipoles was only 20 kg.
3. The first attempted experiment in October 1961 was unsuccessful because the dipoles did not separate individually [P. Waldron, D. C. MacLellan, M. C. Crocker, *Proc. IEEE (Inst. Elec. Engrs.)* **52**, 571 (1964)].
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13. D. C. MacLellan, W. E. Morrow, I. I. Shapiro, *ibid.*, p. 564.
14. L. G. Kraft and J. C. Henry, private communication.
15. D. Karp, private communication.
16. As discussed in reference 7, the double-peak nature of the dipole density distribution, most pronounced at perigee and apogee (Fig. 2), is most likely the result of the manner in which the dipoles separated from their dispenser.
17. The decreases in perigee height and mean altitude are attributable almost exclusively to the effects of sunlight pressure and air drag, respectively; the contribution of charge drag is negligible [I. I. Shapiro, *J. Geophys. Res.* **69**, 4693 (1964)].
18. One might think that since the dipole density is greatest at the semilatus rectum points, signal-to-noise considerations would allow contours to be made there much later than at, say, apogee or perigee. However, the enhancement does not vary simply as the ratio of the densities, because the velocity (hence, the Doppler) spread is widest at the semilatus rectum points. (Differences in range are not too important because the increase with range of the number of dipoles in the common volume of the two antenna beams nearly compensates the inverse fourth power range dependence of the echo strength of a given target.)
19. Since the densities depended on where along the belt the measurements were made, a smooth average curve is also shown in the figure.
20. The final communication experiment between Camp Parks and Westford involved one teletype channel and was performed on 9 April 1964 after the density had decreased by a factor of nearly 10^3. A 40-kw transmitter was used, and about 52 words per minute were sent over this channel from the West Coast to the East Coast.
21. E. Fireman, private communication.
22. I thank D. Karp for making, collating, and explaining all *X*-band observations of the dipoles, and L. G. Kraft for preparing the *L*-band observations. Lincoln Laboratory is operated with support from the U.S. Air Force.

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Deep-Sea Pleistocene Biostratigraphy

Abstract. *The first detailed paleontological analysis of a deep-sea pistoncore from the Caribbean Sea has been completed. The core, P6304-8, was raised from 3927 meters, east of Beata Ridge at 14°59′N, 69°20′W. Formerly, stratigraphic works in this area were based on studies of paleotemperature, measured by the oxygen isotope mass spectrometry method, or on micropaleontological analysis by means of rapid or cursory examinations. For core P6304-8, samples for foraminiferal analysis were taken at 10-centimeter intervals and split into smaller samples containing an average of 710 individuals (smallest sample, 517 individuals); all individuals were then identified and counted. By use of data derived from populations of this size, a statistical reliability was insured within a 5 percent limit. Temperature oscillations, the best method of portraying Pleistocene stratigraphy, were shown by using ratios of the relative abundances of tropical and subtropical planktonic foraminifera to those found in temperate and cooler waters. These ratios correlate well with existing paleotemperature measurements for the same core, obtained by the oxygen isotope mass spectrometry method.*

World-wide climatic fluctuations caused by Pleistocene glaciation are well documented by both terrestrial and marine geological evidence (*1*). Land evidence includes soil horizons, tills, moraines, pollen, and mammalian successions. In the marine environment, Pleistocene stratigraphy has been based

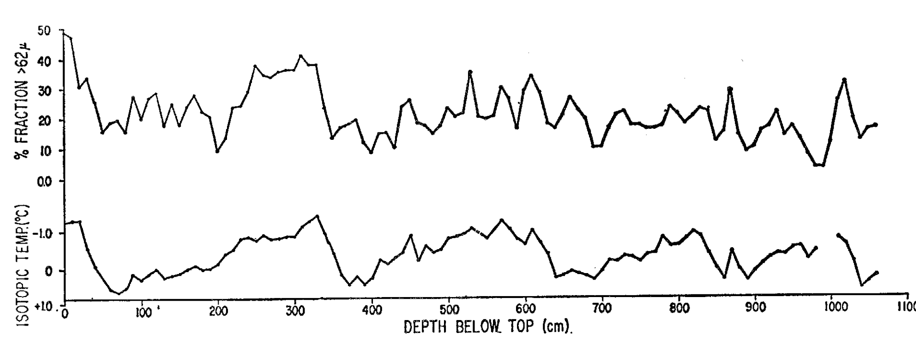

Fig. 1. Core P6304-8. $O^{18}:O^{16}$ ratios in the pelagic foraminiferal species *Globigerinoides trilobus sacculifer* (Brady) (δ per mil with respect to the Chicago standard PDB-1) and weight percentages of the sediment fraction larger than 62 μ (from Emiliani, 1966).