pare *Salpingacantha* sp.) containing the apparent protoplast of the ciliate was identified in the materials from 200 m.

Metazoan forms observed included naupliar (at 20 m) and postnaupliar (at 20 and 110 m) copepods of the family Oithonidae (Fig. 2). The estimated abundances at 20 m were 6 nauplii and 18 postnauplii per cubic meter; and at 110 m, there were 7 postnauplii per cubic meter. The nauplii seen were all early stages (that is, the first and second stages). Postnauplii observed included a female carrying a pair of spermatophores and several specimens that appeared to have large oil sacs. In addition to the copepods, two specimens of another segmented metazoan, probably a polychaete larva, were found in the sample at 20 m.

Unconcentrated preserved samples from 20, 66, 110, 154, and 200 m were examined for small microplankters using the Utermöhl inverted microscope procedure at ×400 magnification. Samples (100 ml) were stained with rose Bengal, and an area corresponding to 4 ml of seawater settled was viewed. Cells identified as probable monads were seen, the sample from 200 m having the largest number ($1.1 \times 10^4$ per liter). A few naked dinoflagellates (10 to 20 $\mu$m in length) were observed in the samples from 66 and 110 m.

Thus, albeit in low abundances, several components of what might comprise a planktonic food web were found in the waters under the Ross Ice Shelf at J9. With the data available, we cannot state whether these microbial organisms represent an indigenous population or if they represent the remnants of populations advected from the Ross Sea. Currents up to 17 cm sec$^{-1}$ were measured at the drill site, but the main component was tidal, and hence the net flux cannot be determined. Tritium and $^{14}$C measurements from the J9 site indicate that the water below the ice shelf has exchanged with Ross Sea water within the last 20 years (*17*). The level of activity of these microbial organisms and their interactions cannot be determined at present and await studies in which dynamic factors such as rates of production and trophic transfer are investigated.

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## Terrestrial Ages of Four Allan Hills Meteorites: Consequences for Antarctic Ice

Abstract. *The terrestrial ages of three Allan Hills meteorites are between $3 \times 10^4$ and $3 \times 10^5$ years and one is $(1.54^{+0.14}_{-0.28}) \times 10^6$ years old. The Antarctic ice sheet is therefore older than $(1.54^{+0.14}_{-0.28}) \times 10^6$ years and the meteorite accumulation process at Allan Hills probably began between $3 \times 10^4$ and $3 \times 10^5$ years ago.*

Allan Hills is a 100-km$^2$ area in Antarctica where many distinct meteorites lie exposed on the ice (*1, 2*). The first meteorite locale of this type was discovered on the other side of the continent near the Yamato Mountains chain (*3, 4*). On the basis of the glaciological and geological settings at the two sites, the following reasonable picture (*1, 3*) has emerged. Meteorites that fall on the Antarctic ice sheet are preserved and carried along with the flow of ice to the continental margin. If the ice flow is halted at a barrier where the ice is sufficiently dissipated by wind ablation, exposed meteorites accumulate in front of the barrier. The terrestrial ages of the Allan Hills and Yamato meteorites are important time markers for the history of Antarctic ice.

Terrestrial ages for meteorites are based on the amount of a cosmic-ray-produced radioactivity in the sample and the amounts in observed falls that have similar cosmic-ray exposure histories. The cosmic-ray exposures are obtained from stable cosmic-ray-produced noble gas isotopes. Terrestrial ages for seven Yamato and seven Allan Hills meteorites have been estimated from their $^{53}$Mn ($3.7 \times 10^6$ year half-life) activities (*5*). Six of the Yamato and six of the Allan Hills specimens have $^{53}$Mn activities indistinguishable from those of contemporary falls, and hence $^{53}$Mn terrestrial ages of less than $\sim 2 \times 10^6$ years estimated from the scatter in $^{53}$Mn data for falls. One Yamato specimen, number 7301, has a $^{53}$Mn activity about one-quarter of that of the others, so that its $^{53}$Mn terrestrial age is approximately $7 \times 10^6$ years; however, the $^{10}$Be and $^{26}$Al activities in Yamato 7301 were measured and gave terrestrial ages of $\sim 1 \times 10^6$ years (*5*). The inconsistency makes the $7 \times 10^6$ year terrestrial age questionable. The low $^{53}$Mn activity could be caused by weathering. Manganese-53 is produced in iron and is more affected by weathering than are the radioactivities produced in silicates.

We measured the terrestrial ages for Allan Hills specimens 5, 6, 7, and 8 by determining the radioactivities of $^{14}$C ($5.74 \times 10^3$ year half-life) and $^{26}$Al ($7.3 \times 10^5$ year half-life) and the contents of stable noble gases. The precision of the terrestrial ages is better than that in previous determinations because of the


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Table 1. Carbon-14 and $^{26}Al$ terrestrial ages and $^{21}Ne$ exposure ages for four Allan Hills samples.

| Allan Hills meteorite | $^{14}C$ activity, melt plus remelt (dpm/kg) | $^{14}C$ terrestrial age ($10^3$ years) | $^{26}Al$ activity (dpm/kg) | $^{26}Al$ terrestrial age ($10^5$ years) | $^{21}Ne$ exposure age ($10^6$ years) |
|---|---|---|---|---|---|
| 5 (eucrite) | <1.0 | >32 | 88.9 ± 1.5 | <1.9 | 6.2 ± 1.5 |
| 6 (H6 chondrite) | <1.7 | ≥30 | 50.6 ± 0.8 | <2.0 | 19.9 ± 2.0 |
| 7 (L6 chondrite) | <1.2 | >32 | 45.2 ± 1.0 | <3.0 | 22.1 ± 2.0 |
| 8 (H6 chondrite) | <1.7 | ≥30 | 11.4 ± 0.4 | $15.4^{+1.4}_{-2.8}$ | 1.5 ± 0.2 |

Table 2. Noble gas contents in Allan Hills meteorites.

| Allan Hills meteorite | Content ($10^{-8}$ cm$^3$ STP/g)* | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $^3He$ | $^4He$ | $^{20}Ne$ | $^{21}Ne$ | $^{22}Ne$ | $^{36}Ar$ | $^{38}Ar$ | $^{40}Ar$ |
| 5 (eucrite) | 9.05 | 1150 | 1.62 | 1.71 | 1.98 | 1.22 | 1.66 | 1400 |
| 6 (H6 chondrite) | 42.7 | 1610 | 8.6 | 9.4 | 10.35 | 1.58 | 1.44 | 6100 |
| 7 (L6 chondrite) | 45.3 | 345 | 8.8 | 9.5 | 10.8 | 1.36 | 1.35 | 263 |
| 8 (H6 chondrite) | 2.8 | 1430 | 0.75 | 0.77 | 0.81 | 0.72 | 0.26 | 6180 |

*STP, standard temperature and pressure.

more appropriate half-lives and because $^{14}C$ and $^{26}Al$ are both produced in silicates. Carbon-14 is produced almost entirely from oxygen and $^{26}Al$ from silicon and aluminum.

We extracted the carbon from ~ 10 g of material by heating at successively higher temperatures and then melting and remelting the samples under vacuum conditions. The extraction and counting procedures are the same as those we used for lunar samples (*6*). Before and after measuring $^{14}C$ in the Allan Hills samples, we measured the $^{14}C$ in a specimen of Bruderheim, a 1960 chondrite fall. Carbon-14 has been measured (*7–11*) in more than a dozen recently fallen stony meteorites including Bruderheim; the average value is 60 dpm/kg. Our values for Bruderheim, 57 ± 3 and 60 ± 3 dpm/kg, agree with previous determinations (*7, 8*). The $^{14}C$ released at low temperatures ($\lesssim$ 800°C) is from a combination of terrestrial contaminants including absorbed atmospheric $CO_2$. The $^{14}C$ released at high temperatures (~ melting) is cosmic-ray–induced activity. For the Allan Hills specimen the $^{14}C$ activities are below our detection limit. We used 60 dpm/kg for the $^{14}C$ content of the Allan Hills specimens at fall and obtained their $^{14}C$ terrestrial ages, $\gtrsim 3 \times 10^4$ years, from the sum of the activities obtained on melting and remelting the samples (Table 1).

The $^{26}Al$ activities in the Allan Hills samples were measured by nondestructively counting the specimen in anticoincidence-shielded multidimensional NaI (Th) $\gamma$-ray spectrometers (*12, 13*). The isotopic contents of the noble gases were measured by high-sensitivity mass spectrometry. The $^{26}Al$ activities are given in Table 1, the noble gas contents in Table 2. The $^{21}Ne$ exposure ages, calculated with the production rates of Cressy and Bogard (*14*), are also given in Table 1. Aluminum-26 has been measured in more than 30 observed falls (*15*). The activities are quite constant for each class of meteorites, unless the cosmic-ray exposure age is insufficient for $^{26}Al$ saturation. Eucrites are a class of meteorites with higher silicon and aluminum contents than ordinary chondrites and therefore have higher $^{26}Al$ contents. The average $^{26}Al$ activity for eucrites is 100 dpm/kg; that for chondrites is 60 dpm/kg.

Allan Hills 5 is a eucrite (*16*). Aluminum-26 has been measured in five saturated eucrite falls (*15*). From the lowest and highest $^{26}Al$ activities in eucrite falls, we obtained a terrestrial age of less than $1.9 \times 10^5$ years for Allan Hills 5. Allan Hills 6, 7, and 8 are chondrites (*16*). Although the average $^{26}Al$ activity for chondrite falls is 60 dpm/kg; values as low as 45 dpm/kg have been reported (*15*). Terrestrial ages of less than $2.0 \times 10^5$ and $3.0 \times 10^5$ years for Allan Hills 6 and 7 follow from the lowest and the average $^{26}Al$ values in chondrite falls. The $^{26}Al$ activity in Allan Hills 8, 11.4 ± 0.4 dpm/kg, is far less than that in chondrite falls with $^{26}Al$ saturation. From its $^{21}Ne$ exposure age of $1.5 \times 10^6$ years, the $^{26}Al$ activity in Allan Hills 8 was 76 percent saturated. The expected $^{26}Al$ activity in Allan Hills 8 at fall is $(50^{+6}_{-12})$ dpm/kg. The uncertainty arises largely from the scatter in $^{26}Al$ data for chondrite falls. Allan Hills 8 has a terrestrial age of $(1.54^{+0.14}_{-0.28}) \times 10^6$ years on the basis of its present activity and an activity of $(50^{+6}_{-12})$ dpm/kg at fall. The effect of shielding on the terrestrial ages was estimated from our measured $^{21}Ne/^{22}Ne$ ratios (*17*) and found to be unimportant compared to the scatter in $^{26}Al$ data for meteorite falls.

A very low $^{53}Mn$ activity has been reported (*5*) for Allan Hills 8, 22 ± 3 dpm/kg; this is one-third of the value that we anticipated from our $^{26}Al$ and exposure age measurements. This $^{53}Mn$ inconsistency is similar to that in Yamato 7301 (*5*). Allan Hills 8 is highly weathered, and approximately half of its total iron has been oxidized to $Fe_2O_3$ (*16*). If $^{53}Mn$ was lost from $Fe_2O_3$, then the $^{53}Mn$-$^{26}Al$ inconsistency would be essentially eliminated.

More than 300 meteorites and no terrestrial rocks have been found at the Allan Hills sites; therefore, the Antarctic ice sheet is older than specimen 8 or $(1.54^{+0.14}_{-0.28}) \times 10^6$ years. Assuming that the meteorite fall rate is constant, the terrestrial age distribution reflects the history of ice movement. If the four determined terrestrial ages are fairly representative of the Allan Hills meteorite assemblage, then meteorites were collected at the site more efficiently during the recent $3 \times 10^5$ year period than during the previous $1.2 \times 10^6$ years. This result requires either that the recent period was one of much more rapid ice inflow and ablation than the previous period, or that during the past ~ $3 \times 10^5$ years ice covered Allan Hills and meteorites that had accumulated earlier were removed. The second possibility is more likely. Ice ages have occurred in other regions of the earth during the past $3 \times 10^5$ years; furthermore, the ice level needs to rise by only ~ 200 m to cover Allan Hills. The meteorite with the $1.5 \times 10^6$ year age would then have spent between $1.2 \times 10^6$ and $1.5 \times 10^6$ years traveling to Allan Hills or being stored on ice at other locations.

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## Sea-Level Fluctuations and Deep-Sea Sedimentation Rates

Abstract. *Sediment accumulation rate curves from 95 drilled cores from the Pacific basin and sea-level curves derived from continental margin seismic stratigraphy show that high biogenous sediment accumulation rates correspond to low eustatic sea levels for at least the last 48 million years. This relationship fits a simple model of high sea levels producing lower land/sea ratios and hence slower chemical erosion of the continents, and vice versa.*

A preliminary study based on sediment thickness (*1*) indicates that there have been large-scale fluctuations in the average sedimentation rate in the major ocean basins and that these fluctuations are synchronous and global in extent. In that study, rates were expressed in meters per million years and were uncorrected for compaction with increasing burial depth. Consequently, in this analysis, younger and less compacted sediments appear to have higher sedimentation rates than older, more compacted ones, even though the total flux of material to the sea floor might have remained constant. We have therefore recalculated Pacific Ocean sedimentation rates in terms of mass per unit area per unit time (grams per square centimeter per $10^3$ years) in the manner suggested by van Andel *et al.* (*2*) for both total accumulation rate and carbonate accumulation rate. The basic data are taken from the published *Initial Reports of the Deep Sea Drilling Project* (*3*) and from the files of the DSDP data base in La Jolla, California.

The procedure used in calculating sedimentation rates is relatively simple (*4*). Basically, it consists of determining the age (in years) of every level below the sea floor at each location and then using compositional and porosity data to calculate the total mass and bulk composition of the sediment that has accumulated at each locality during a particular time interval. In this study we used 3-million-year time increments. The results shown in Fig. 1a are simple arithmetic averages from 95 sites in the Pacific Ocean.

Figure 1a also compares the results from the two methods of expressing the Pacific Ocean sedimentation rates. The recalculated data do not refute the basic conclusion of the earlier study of Davies *et al.* (*1*) that the ocean apparently alternates between periods of high and low sedimentation, but there are significant changes in the relative amplitudes and sometimes the phase of the fluctuations. For instance, the ratio of the total sedimentation rate in the latest Pliocene and Quaternary (0 to 3 million years) to that in the Upper Oligocene (24 to 27 million years) is about 5:1 as calculated by Davies *et al.* (*1*) and only 2:1 in the present recalculation. Similarly, the carbonate sedimentation rate ratios obtained by the two methods are 3:1 and 1:2, respectively, for the same two intervals. Although such differences may be due in part to the slightly inequivalent time intervals used to average the rates in the studies, it is clear that they are mainly due to differential compaction. We therefore believe that our curve represents the best currently available estimate of the Pacific Ocean sediment accumulation rate through time.

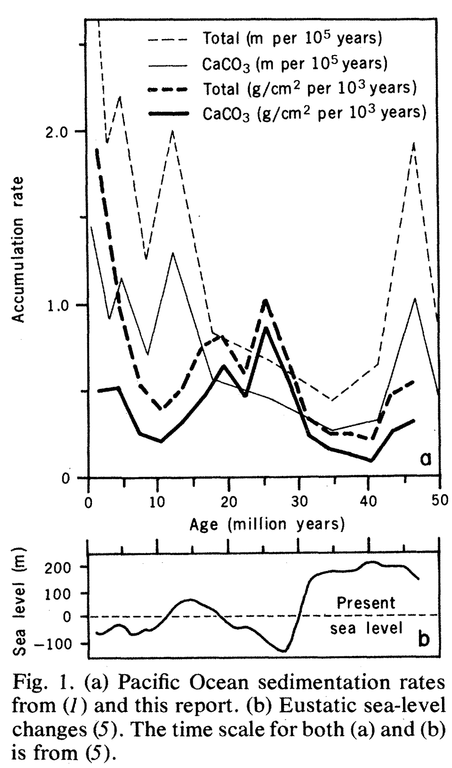


Fig. 1. (a) Pacific Ocean sedimentation rates from (*1*) and this report. (b) Eustatic sea-level changes (*5*). The time scale for both (a) and (b) is from (*5*).

Figure 1 shows that the sedimentation rates are correlated with the global sea-level fluctuations postulated by Vail *et al.* (*5*), with high accumulation rates occurring at times of low sea level and vice versa. This correlation is especially significant because the sea-level curve was derived from continental-shelf seismic data and sea-floor spreading rates and, therefore, is completely independent of the data base used in calculating the oceanic sedimentation rates. In constructing Fig. 1b we modified the sea-level curve by sampling it at 0.5-million-year intervals and smoothing it by using a seven-point moving average in order to compare it with our results, which were calculated for 3-million-year intervals. Furthermore, as the sediment accumulation curve was quantitatively calculated from deep-sea core data and the sea-level curve was interpreted from seismic data, we have more confidence in the phase than in the amplitude correlation of the two.

As pointed out by Rona (*6*), a correlation between sea level and sedimentation rate suggests that at times of high sea level, material eroded from the continents is trapped on the continental shelves. During times of low sea level the shelf sediments are exposed, and previously deposited shelf sediment is weathered and eroded. The resulting erosion products are then flushed to the deep sea. However, order-of-magnitude calculations (*7, 8*) suggest that the continental erosion rates are so high and the shelf so small that some material must almost always bypass the shelf.

Because of the limited drainage area of the Pacific basin and the fact that the deep Pacific is surrounded by trenches, which prevent bottom transport of continental detritus (*9*), we propose that the sea level–sedimentation rate correlation represents mainly biogenous precipitates (carbonate and opal) and not erosional detritus. In this model, high sea levels allow high rates of biogenous precipitation on the shelves, thus starving the ocean basins, whereas low sea levels permit dissolved river loads to reach the deep sea and foster chemical erosion of material to the seafloor might have remained contrast, the detrital load of rivers always enters the ocean at point sources

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