Reports

"Internal Waves" Advancing along Submarine Canyons

Abstract. *Patterns of alternating up- and downcanyon currents have been traced along the axes of submarine canyons off California. The patterns arrive later at stations nearer the heads of coastal canyons. Where a canyon heads between two islands, the patterns advance down the axis. The propagation speeds of these patterns were estimated as 25 to 88 centimeters per second. Internal waves are the probable explanation.*

During the past 5 years we have obtained 79 records of the currents near the floors of submarine canyons along the coasts of California and Baja California. In earlier work Shepard and Marshall (*1*) discovered that currents of less than 50 cm/sec move alternately up and down the canyon floors with periods of oscillation varying from less than 1 hour to about 8 hours at depths of less than 200 m, but usually around 12 hours at greater depths, which suggests possible tidal influence. Net movement during our measurements of about 3 to 15 days was almost always downcanyon, and the downcanyon flows usually lasted longer and had higher velocities than the upcanyon ones.

Although our earlier records indicated a possible correlation of flow patterns between adjacent stations when taken simultaneously, the only information for establishing such a relation was from records of two stations only 200 m apart. We have now obtained records from stations separated by 1 km to as much as 7.5 km. Also, we have been taking many records to compare currents near the canyon floor with those as much as 34 m above it. With this new information, we have a much clearer idea of the nature and cause of the normal currents in submarine canyons. Knowing that internal waves progress across the continental shelf (*2*), we have suspected that they might also move along submarine canyon axes. By fitting together the current patterns at adjacent stations, as has been done for internal waves on the continental shelf, it should be possible to determine if there is any propagation of wave patterns up the canyons. Our records providing this information came from the axes of La Jolla, Santa Monica, Santa Cruz, Hueneme, Carmel, and Monterey canyons, all off California (see Fig. 1).

Our first piece of substantial evidence came from Hueneme Canyon, a somewhat U-shaped valley off the point at the tip of the Santa Clara delta (*3*) (Figs. 1 and 2). Current meters were emplaced in three stations at depths of 174, 375, and 448 m, separated, respectively, by 6.3 and 3.1 km along the axis. Using plots of the speeds and durations of up- and downcanyon currents for each station, we could fit the resulting curves together by plotting the record of the deep station 103 minutes to the right of the record from the middle station, and, with less assurance, by moving the record from the middle station 252 minutes to the right of the record from the shallow station (Fig. 3, A and B). This seems to indicate that, during the taking of the records, internal waves were advancing up Hueneme Canyon at an average speed of 50 cm/sec between the two outer stations and 42 cm/sec between the inner stations.

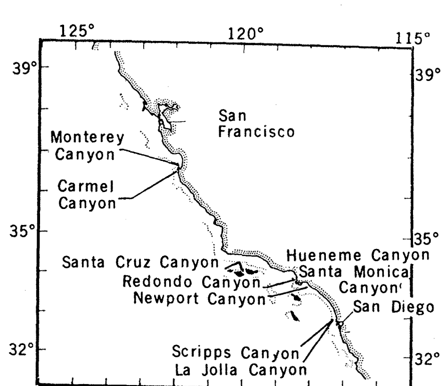


Fig. 1. Locations of the various canyons from which currents have been measured in California.

The next substantial evidence came from Santa Cruz Canyon, which is unique in heading into the narrow passageway between Santa Rosa and Santa Cruz islands, rather than into the coast as do other California canyons (Fig. 2). The predominant northwest winds drive water through the strait from Santa Barbara Channel, north of the islands (*4*). The stations in Santa Cruz Canyon were at axial depths of 357 and 585 m, separated along the axis by 7.5 km. The only good fit is obtained by moving the curves from the deeper station 170 minutes to the left of those from the shoaler station (Fig. 3C). Thus, internal waves were probably moving downcanyon away from the strait at the canyon head and progressing diagonally to the southeast along the slope leading to Santa Cruz Basin. The average rate was 73 cm/sec.

Our next opportunity came from measurements in Carmel Canyon, where a steep-walled valley cuts deeply into the embayment between the granitic rocks of Monterey Peninsula and Point Lobos (*5*). Two stations separated by 1.2 km were established at axial depths of 205 and 348 m. Current meters were placed at 3 and 18 m above the bottom at the shoaler station, and at 3 and 30 m above the bottom of the deeper station. Thus it was possible to match the curves between the stations in four different ways; the best fit was obtained between the two shoaler current meters (Fig. 4A). The results showed time lags between meters of 16, 20, 30, and 34 minutes, with the deeper station getting the waves first in all cases. Using an aver-

Scoreboard for Reports: In the past few weeks the editors have received an average of 68 Reports per week and have accepted 12 (17 percent). We plan to accept about 12 reports per week for the next several weeks. In the selection of papers to be published we must deal with several factors: the number of good papers submitted, the number of accepted papers that have not yet been published, the balance of subjects, and length of individual papers.

Authors of Reports published in *Science* find that their results receive good attention from an interdisciplinary audience. Most contributors send us excellent papers that meet high scientific standards. We seek to publish papers on a wide range of subjects, but financial limitations restrict the number of Reports published to about 15 per week. Certain fields are overrepresented. In order to achieve better balance of content, the acceptance rate of items dealing with physical science will be greater than average.

age of 25 minutes, we calculate that the waves advanced upcanyon at 83 cm/sec, considerably faster than in Hueneme and Santa Cruz canyons.

In nearby Monterey Canyon, which heads near the beach at Moss Landing in Monterey Bay (*6*), we placed current meters at three stations, 155, 357, and 384 m deep. The shoalest station was on the canyon wall near the axis, and the other two were in the axis, with a separation of 1.3 km between the two deeper stations and 5.5 km between the two shoaler stations. The curves for the two deeper stations can be reliably matched with a time difference of 84 minutes (Fig. 4B), but a match is less certain between the two shoaler stations, with a difference of 244 minutes (Fig. 4C). This indicates an average advance upcanyon of 25 cm/sec for the deeper portion and 38 cm/sec of the shoaler. Here, the propagation apparently is somewhat faster in the shoaler parts of the canyon.

The current meter measurements in La Jolla Canyon (*1*) provided many comparisons between the two stations at 167 and 206 m, separated by only 200 m. These are too close for good comparisons, but the peaks in all but one out of seven cases were definitely displaced, so that the waves were arriving later at the shoaler station. Figure 16 of Shepard and Marshall (*1*) indicated that the opposite was true, but an examination of the original data showed that the two stations had been erroneously labeled. The average displacement was 10 minutes, and the propagation speed was 33 cm/sec.

Two current meters placed in Santa Monica Canyon, which heads along the outer shelf off the city of Santa Monica, were positioned at depths of 174 and 375 m, separated by 7.4 km. Unfortunately, only the deeper station shows a record with both velocity and direction, but from the directional plots it is possible to get a fairly good relation of times of direction change be-

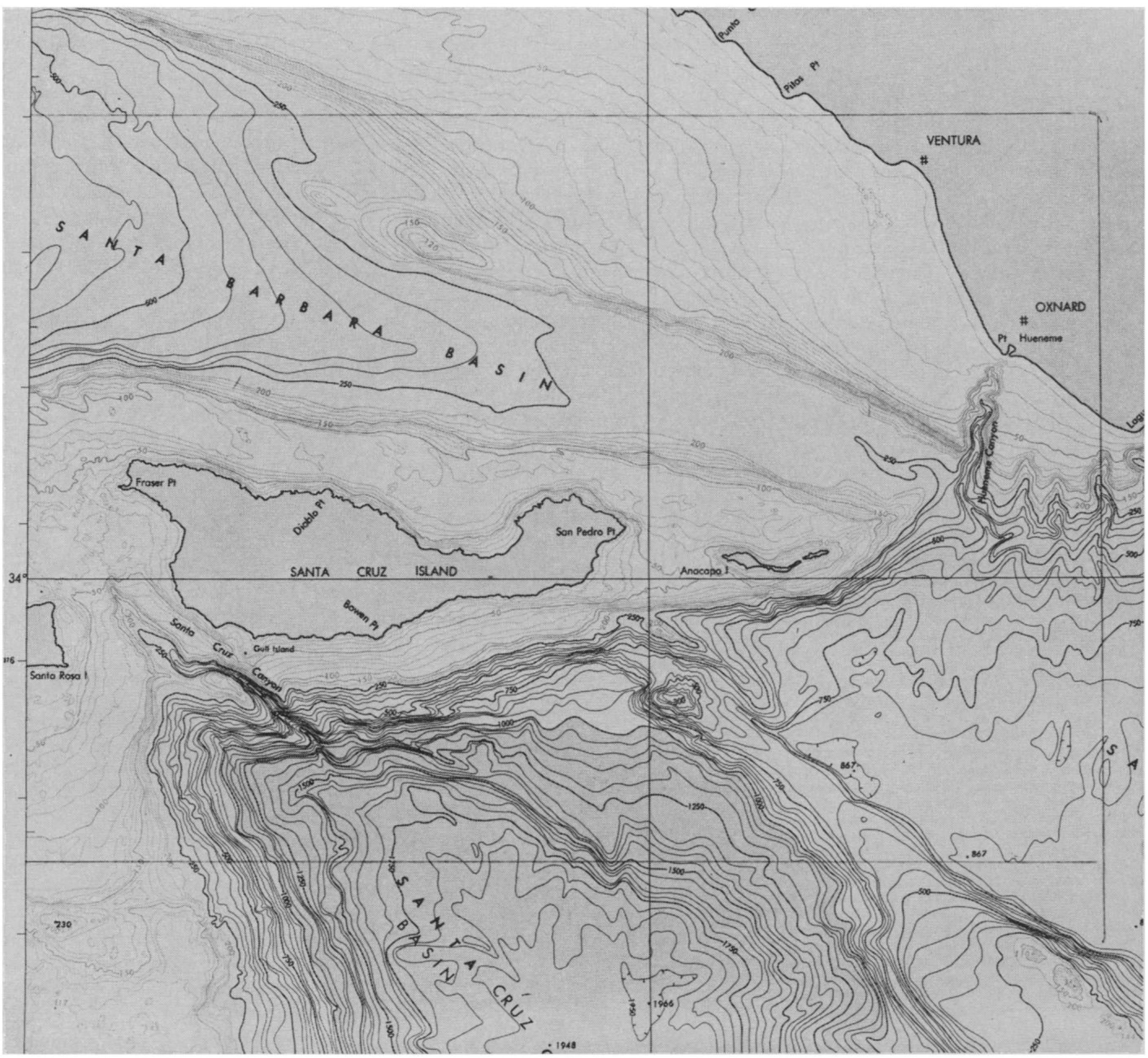


Fig. 2. Relation of the head of Santa Cruz Canyon to the sill between Santa Barbara and Santa Cruz basins. Hueneme Canyon is shown at the right. The contours are in meters. [Data from Environmental Science Service Administration Chart]

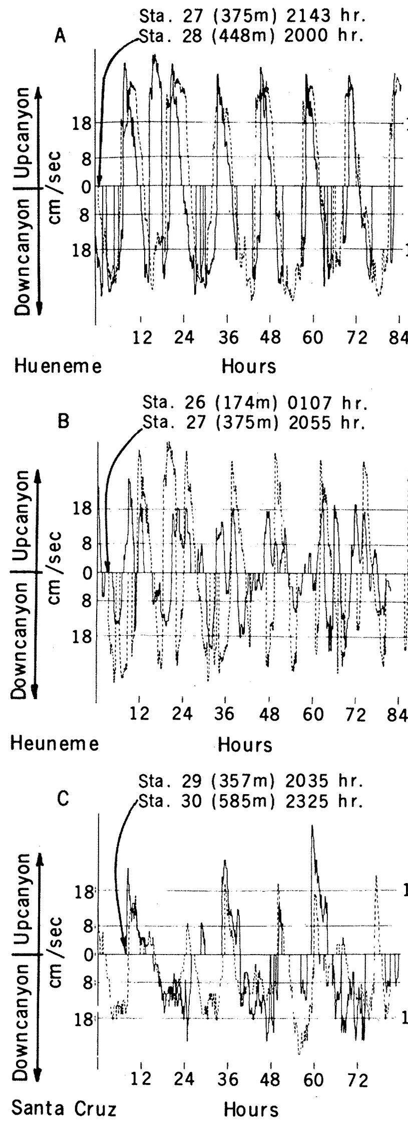
tween the two records, with 140 minutes displacement to the right for the deeper station and a speed of 88 cm/sec.

Also, we attempted but failed to match the patterns between stations at 78 and 167 m in the axis of La Jolla Canyon, and between stations at 92 and 283 m in Redondo Canyon. This may indicate either that the internal waves do not propagate into the heads of the canyons or that reflecting internal waves near the canyon heads may complicate the patterns sufficiently that they cannot be recognized.

In summary, we have evidence from five submarine canyons off California that internal waves are propagated along the axes. The speed of propagation cannot be measured very accurately, but it appears to vary from 25 to 88 cm/sec. The landward propagation speed of internal waves along the shallow continental shelf off Mission Bay, San Diego, is about 22 cm/sec (*2*), which suggests that internal waves advance faster up submarine canyons. As suggested by LaFond (*7*), the faster rate of advance may be due to the constriction of internal waves as they move into the narrow confines of the canyons.

A rather close relationship in the direction of flow patterns at various heights above the canyon floors up to 34 m has been established (*8*). Here, we have a resemblance to wind waves, where the landward motion at the wave crest extends down to the bottom, as does the seaward motion under the wave trough. However, at greater heights above the canyon floors, the flows may be reversed in direction compared to those nearer the bottom.

The evidence now available that the observed currents are due to internal waves and internal tides includes the following. (i) The current patterns advance along the canyons with velocities much greater than the current velocities. (ii) The phase velocity is not that of surface waves but is of the right order of magnitude for internal waves. (iii) Similar types of currents and phase velocities occur on the continental shelf (*2*). (iv) The currents oscillate coherently at various heights above the bottom. (v) Internal waves move upcanyon in all but one example, in agreement with the general landward propagation of internal waves across the shelf. The one exception, in Santa Cruz Canyon, is expectable since water probably comes into the head of this canyon from the Santa Barbara Channel.



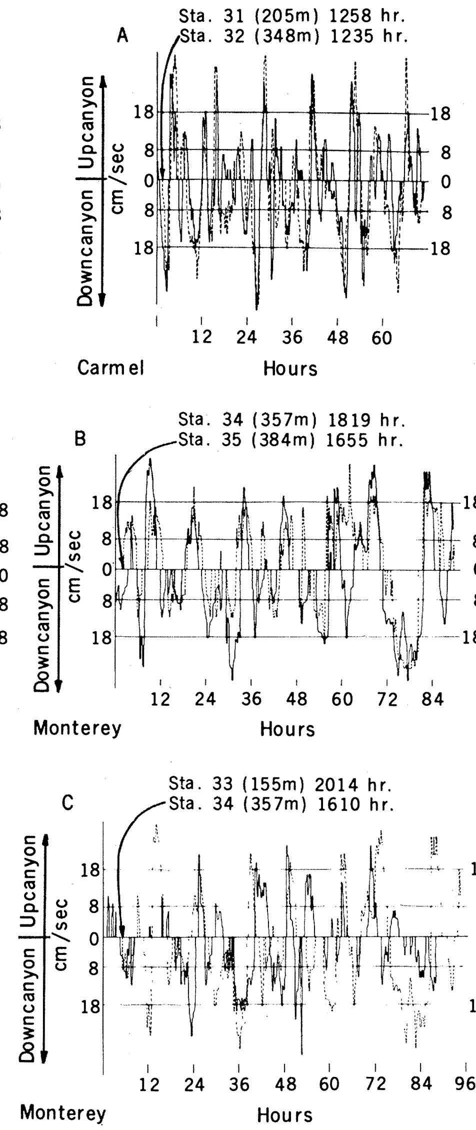


Fig. 3 (left). (A) Upcanyon and downcanyon velocity curves displaced in time to show the best fit between stations at 375 and 448 m (axial depth) along Hueneme Canyon. In these curves, crosscanyon currents are given with zero velocity to accentuate the up- and downcanyon flows. The offset indicates upcanyon progradation. (B) Comparison between Hueneme Canyon stations at 174 and 375 m; the poorer fit reflects the greater distance between stations than in (A). (C) Comparisons between stations at 375 and 595 m in Santa Cruz Canyon. Note that the times are later at the deeper station, indicating the one example of downcanyon progradation. Fig. 4 (right). (A) Comparison of up- and downcanyon currents between nearby stations in Carmel Canyon at depths of 205 and 348 m. (B) Comparison of up- and downcanyon currents in Monterey Canyon at depths of 357 and 384 m. Again, the good fit is related to the closeness of the two stations. (C) Comparison of up- and downcanyon currents in Monterey Canyon at depths of 155 and 357 m. The long distance between the stations is responsible for the relatively poor fit.

Perhaps it is unwise to suggest that all, or even most, of the currents are caused by internal waves. The tides, or at least the internal tides, are factors that may be important, especially below the 200-m depth. Much more information is required before we can thoroughly understand these internal waves in the canyons. Whether they show any relation to the occasional turbidity currents that are believed to develop high-speed flows down the canyons remains to be seen. However, internal waves may be an important agent in the transport of sediment along the canyon axes.

FRANCIS P. SHEPARD
NEIL F. MARSHALL
PATRICK A. MCLOUGHLIN
Geological Research Division,
Scripps Institute of Oceanography,
University of California,
La Jolla 92037

References and Notes

1. F. P. Shepard and N. F. Marshall, *Am. Assoc. Pet. Geol. Bull.* **57**, 244 (1973).
2. E. C. LaFond, in *Encyclopedia of Oceanography*, R. W. Fairbridge, Ed. (Reinhold, New York, 1966), pp. 402–408.
3. Hueneme Canyon is located directly off the artificial Navy harbor at Hueneme. The canyon crosses the narrow shelf, terminating at a depth of about 550 m. It is cut into soft formations.
4. Santa Cruz Canyon has steep rocky walls and a twisting axis. It extends diagonally down the slope into Santa Cruz Basin about 22 km and terminates at a depth of 1350 m.
5. Carmel Canyon has steep granite walls. It heads a stone's throw from the beach at the head of an embayment. It extends seaward past the Monterey Peninsula, joining Monterey Canyon at a depth of about 2000 m.
6. Monterey Canyon, the largest on the California coast, has walls of unconsolidated sediments in the inner portion where we worked, but is rock-walled at greater depths. The axis is essentially meandering and can be traced for more than 100 km.
7. E. C. LaFond, personal communication.
8. F. P. Shepard, N. F. Marshall, P. A. McLoughlin, in preparation.

9. Supported by NSF contract GA-19492 and by ONR contract Nonr-2216(23). Ship time was given us on *Velero IV* by the Hancock Foundation of the University of Southern California, and on the *Acania* by the U.S. Naval Postgraduate School at Monterey, California. The cooperation of D. E. Drake and R. E. Andrews is appreciated, as are the field work of G. G. Sullivan (Scripps Institution of Oceanography) and ideas contributed by C. S. Cox and R. S. Arthur (both of Scripps Institution of Oceanography) and E. C. LaFond (Naval Undersea Center, San Diego).

1 October 1973

Atmospheric Concentrations and Sources of Trace Metals at the South Pole

Abstract. *The chemical composition of atmospheric particulate material collected at the geographic South Pole indicates that Al, Sc, Th, Sm, V, Mn, Eu, Fe, La, Ce, Co, Cr, Na, K, Mg, and Ca are derived from either crustal weathering or the ocean. The relatively volatile elements Zn, Cu, Sb, Se, Pb, and Br are apparently derived from other sources. Because of their volatility, vapor-phase condensation or a high-temperature dispersion source is suspected for these elements or their compounds.*

Considerable interest has been directed recently toward measurements of the distribution and composition of atmospheric particles in remote regions of the earth. This interest has developed largely out of concern that man might inadvertently modify the earth's climate by changing the distribution of particles in the atmosphere on a global basis (*1*) and also as a result of the need to determine, for both geochemical and environmental reasons, the atmospheric input of many substances into the oceans (*2*).

The Antarctic polar plateau offers one of the best locations on earth for studying the composition of the background aerosol since it is isolated, both geographically and meteorologically, from the major sources of anthropogenic emissions in both the Northern Hemisphere and the Southern Hemisphere. Most measurements of trace substances of atmospheric origin from Antarctica have been confined to snow and ice (*3*, *4*). The primary advantage of direct atmospheric collection is that the investigator is aware of, and has some control over, the history of the sample being collected. On the basis of current meteorological conditions and local activities, he can determine whether or not a sample is truly representative of a background aerosol.

In October 1970, extensive atmospheric sampling was begun in Antarctica at Amundsen-Scott (or South Pole) Station at 90°S, 2800 m above sea level. We collected the atmospheric particulates on polystyrene filters (20.3 by 25.4 cm Delbag, type 99/97), using high-volume pumps (Gelman Hurricane) at a sampling rate between 1 and 2 standard cubic meters (SCM, 298°K, 1 atm) per minute. Samples were also collected on 47-mm and 90-mm filters (Millipore Celotate type EA, 0.5-μm pore radius). The filter holders for all filter types were constructed entirely of polyethylene or Teflon and were located approximately 8 m upwind from the pumps. Typical sample volumes ranged from 10,000 SCM for the Delbag filters to 100 SCM for the 47-mm Millipore filters. The samples were collected about 400 m upwind of South Pole Station. The winds were predominantly (over 90 percent of the time) from the 0° to 90°E longitude quadrant during the 7-week period of sample collection. Continuous records of wind speed and direction were obtained from the U.S. Navy weather station during each sampling interval. Four samples were collected simultaneously over each 3-day period, two on Delbag filters and one on each size of the Millipore filters. Numerous filter blanks were measured to correct for filter impurities and collection contamination. Although the Millipore blanks were generally higher, their variability was considerably less than that for the Delbag filters, and the agreement between samples collected on the two types of Millipore filters and samples collected on the Delbag filters was good.

One of the two Delbag filters was used for analyses of Pb, Na, Mg, Ca, and K by atomic absorption, the acid-soluble fraction having been removed from the polystyrene filter matrix with nitric acid prior to analysis with an atomic absorption spectrophotometer (Perkin-Elmer model 303). For the Pb analysis we used a heated graphite atomizer (Perkin-Elmer HGA-70) and for Na, Mg, Ca, and K we utilized standard flame techniques. The other filters were analyzed by nondestructive instrumental neutron activation analysis (INAA) for as many elements above the blank value as possible. Filters were pressed into pellets in a Ni-nylon die before being irradiated in the National Bureau of Standards reactor ($\phi_{\rm thermal} = 6 \times 10^{13}$ neutron cm^{-2} sec^{-1}) along with standards for each element determined. After appropriate decay periods, radiation from the samples was measured with Ge(Li) γ-ray detectors of large volume and high resolution (full width at half maximum, 2.2 kev for the 1.33-Mev γ-ray of ^{60}Co). The γ-ray spectra were analyzed by computer, with the small peaks being checked by manual integration to obtain the final concentrations.

There were ten 3-day sampling periods during which the winds were favorable for the collection of atmospheric samples without contamination from the camp. The results presented below are confined to these ten sampling periods only. For virtually all the elements measured by INAA, the final result for each sampling period represents the average of the analyses of two Millipore and one Delbag filter that were collected in parallel.

The average trace element concentrations and concentration ranges for the ten sampling periods are presented in Table 1. The uncertainty given for the concentrations is the standard deviation of the mean concentration found for each element in the ten sampling periods.

There are two major obvious natural sources for trace elements in atmospheric particulates—crustal weathering and the sea. In an effort to ascertain whether either of these sources is re-