Reports

Variations in the Rate of Rotation of the Earth

Abstract. *Variations observed in the length of the day can be divided into three types: seasonal, irregular, and long-term. The astronomical data examined here for the years 1956–1969 suggest that the seasonal terms hitherto assumed are slightly in error, that the irregular variations probably share the same source with the seasonal variations, and that the long-term variations may be linked to earthquake activity.*

The atomic clock, introduced in 1955, has made possible precise timing of the rotating earth. Astronomical observations of the earth's rotation and comparison of universal time (defined by this rotation) with atomic time lead to information about the position of the earth's spin axis and rate of rotation.

That the earth's spin axis moves with respect to the earth's surface has been known for some time (*1*). In the main, this motion consists of a movement, around the mean, of the instantaneous rotation pole, with a period of approximately 14 months. This circulation of the rotation pole is known as the Chandler wobble.

This report is concerned with the rate of rotation of the earth around the mean pole, not the motion of the pole itself. In order to discount the Chandler wobble, we compare atomic time (A.T.) not with basic universal time (U.T.0) but with U.T.1, which is derived from U.T.0 by removing contributions to its variations caused by the wobble. By subtracting U.T.1 from A.T., a measure of the "lateness" (if positive) or "earliness" (if negative) of the earth with respect to the atomic clock is derived. A daily increase of this quantity means that the earth is taking longer than 24 hours of atomic time to complete a revolution. In other words, the length of the day, in excess of 24 hours, is the change in 1 day of the quantity A.T. – U.T.1.

Variations observed in the length of the day can be divided into three types: seasonal, irregular, and long-term. Data obtained during the years 1956–1969 are examined here, with a view to establishing some characteristics of these types of variations.

Seasonal variations. Daily observations of A.T. – U.T.0 have been made at the U.S. Naval Observatory continuously since 1956. These values are obtained daily from observations of the transit of as many as 30 stars at each of two stations, and A.T.–U.T.1 is derived from the adopted values by removal of the Chandlerian terms.

The daily values of A.T. – U.T.1 were obtained from the U.S. Naval Observatory. These values have been used here to calculate the mean monthly values of the length of the day for each month of the years 1956–1969, and to calculate the annual means. The results are shown in Fig. 1. These data have been subjected to a harmonic analysis to determine the seasonal terms of the variation of the length of day. The results of this analysis are depicted in the "harmonic dial" of Fig. 2. This figure shows the amplitudes and phases of the annual, semiannual, and 4-month components for each year of the 14-year period, and the same components for the complete 14-year period (labeled "mean" in the figure). Also shown are the values adopted by the Bureau Internationale de l'Heure (BIH), obtained from the U.S. Naval Observatory data, and those given by Stoyko (*2*) for the years 1952–1958. Third and higher-order harmonics were sought but found to be insignificant.

Note first that there are significant differences between the seasonal components derived here, those derived by Stoyko for the years 1952–1958, and those adopted by the BIH. The components derived from analysis of 14 years of continuous data (the so-called "mean" values) are described by the following expression:

$$\text{LOD} - 24 \text{ hours} = 0.342 \cos \frac{2\pi (d - 15)}{365.25} + 0.345 \cos \frac{4\pi (d - 113)}{365.25} + 0.105 \cos \frac{6\pi (d - 7)}{365.25} \text{ msec}$$

where LOD is length of day and d is the number of days after 1 January.

This may be compared with the expansion for Stoyko's results for 1952–1958:

$$\text{LOD} - 24 \text{ hours} = 0.45 \cos \frac{2\pi (d - 35.3)}{365.25} + 0.24 \cos \frac{4\pi (d - 118.1)}{365.25}$$

which is nearly the same as the expression for the BIH-adopted variation.

It is now generally accepted that the

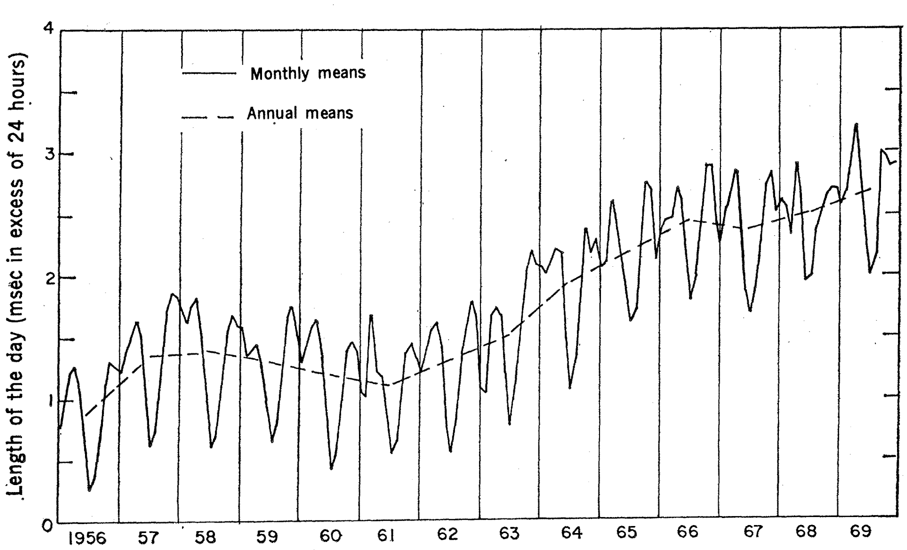


Fig. 1. Variations in the length of the day, derived from A.T. – U.T.1, for the years 1956–1969.

main cause of the annual variation in the length of the day is the similar variation of the angular momentum of the atmosphere. The semiannual variation is caused mainly by bodily tides. Mintz and Munk (*3*) have calculated the contributions of these effects, and their work predicts the following form for the seasonal variation:

$$\text{LOD} - 24 \text{ hours} = 0.38 \cos \frac{2\pi\,(d-30)}{365.25} + 0.22 \cos \frac{4\pi\,(d-81)}{365.25}$$

We note that both amplitude and phase of the annual term are in good agreement with both new and old observed values. However, the new semiannual term, although it agrees reasonably with the predicted phase, is more than 50 percent greater than the predicted amplitude, in contrast with Stoyko's result.

Irregular variations. The nonseasonal variations in the length of the day may be examined after removing the seasonal terms. Universal time 2 (U.T.2) is a defined time scale, which is derived from U.T.1 by removal of the BIH-adopted 12-month and 6-month periodic terms. The nonseasonal variations may therefore be deduced from the quantity A.T. − U.T.2. However, we have shown above that the seasonal terms are subject to significant variations, and, in any case, there is a discrepancy between the adopted seasonal terms and those found in this study.

Figure 3 depicts the nonseasonal variations for the years 1956–1969, derived (i) from A.T. − U.T.2 and (ii) from A.T. − U.T.1 in conjunction with the "mean" 12-month and 6-month terms found in this study. Comparison of these two sets of variations shows that the short-term irregular fluctuations that result from removal of the seasonal terms depend greatly on the seasonal terms adopted. Since we cannot assume that the seasonal variations are constant and always consist of only an annual and a semiannual term, it seems reasonable to surmise that the short-term irregular fluctuations are merely residuals of the inadequately represented seasonal terms. The magnitude of the fluctuations are such that they could well share the same cause as the seasonal variations—namely, fluctuations of the mean zonal momentum of the atmosphere. In other words, I propose here that the seasonal and short-term variations in the rate of rotation of the earth are but one phenomenon, separated into two by a mathematical convenience.

In the above discussion, the irregular fluctuations have been assumed to be real and not simply the results of imprecise original data. The standard deviation of the A.T. − U.T. data is rarely better than 10 msec; over a 30-day month, a precision better than 0.3 msec cannot be assumed. The fluctuations must therefore be treated with caution. The number of cases of "negative persistence" substantiates this view. Such cases, where an exceptionally high value of the length of the day is followed or preceded by an exceptionally low one, could well arise from imprecise raw data. (We recall that the length of the day is derived from the difference between succeeding measurements of A.T.−U.T.)

Danjon (*4*) has reported a sudden change in the rotation rate of the earth, coincident with the large solar flare of 15 July 1959. This has been the subject of some dispute (*5*). The data presented here show no unusual events in July 1959, and there is no evidence here to support this report.

Long-term variations. In the search for causes of longer-term variations in the length of the day, it is of interest to examine the basic A.T. − U.T.2 data, the length of the day, and the rate of change of the length of the day (that is, the deceleration of the earth's rotation). The first and third quantities are, respectively, the integral and first time derivative of the second quantity.

Note that the average length of day for the period under consideration is about 1.75 msec longer than 24 hours (see Fig. 1). This contributes to a progressive increase in the value of A.T. − U.T.2, which may be removed, to a certain extent, by plotting A.T. − U.T.2 − 0.00175 (d − 1959.0), where d − 1959.0 is the number of days after 1 January 1959. This device is merely a convenience that enables the basic data to be more easily represented graphically.

In Fig. 4 the continuous variation of A.T. − U.T.2 − 0.00175 (d − 1959.0),

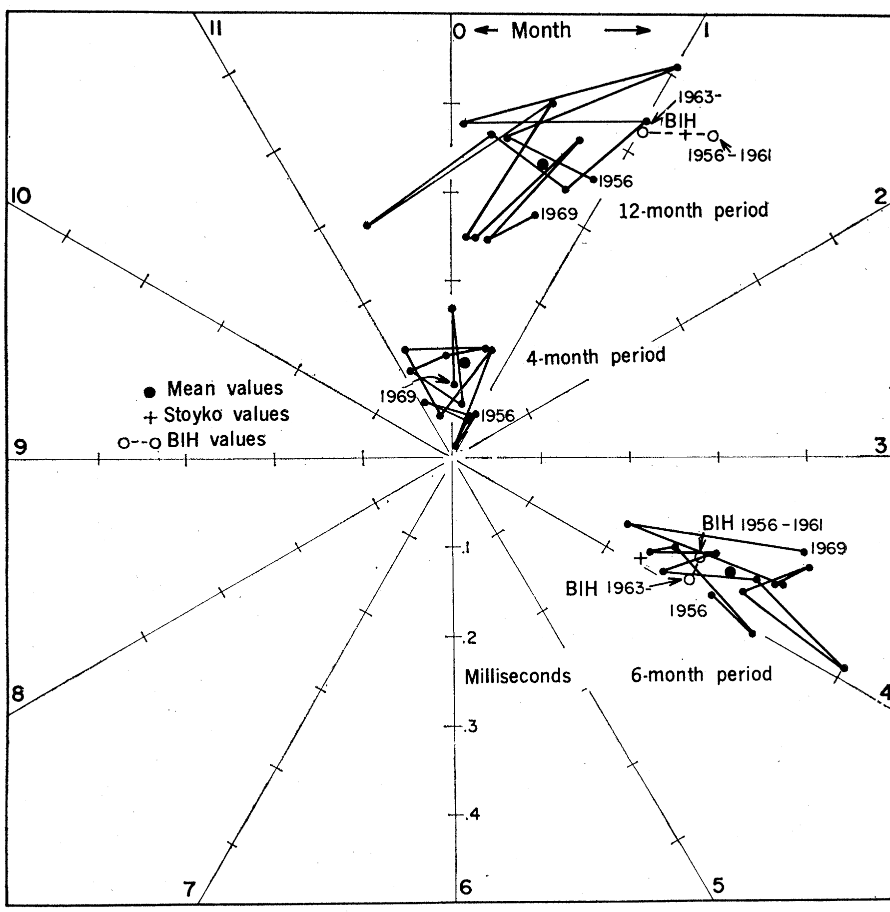


Fig. 2. Harmonic dial showing the amplitudes and phases of the first three terms in the seasonal variation of the length of the day. Derived values for each of the years 1956–1969 are shown, as well as those for the complete period 1956–1969 (labeled "mean"). These are compared with the terms adopted by the BIH and those given by Stoyko (*2*). The phase of each term is defined as the time of year when the particular term reaches a maximum value.

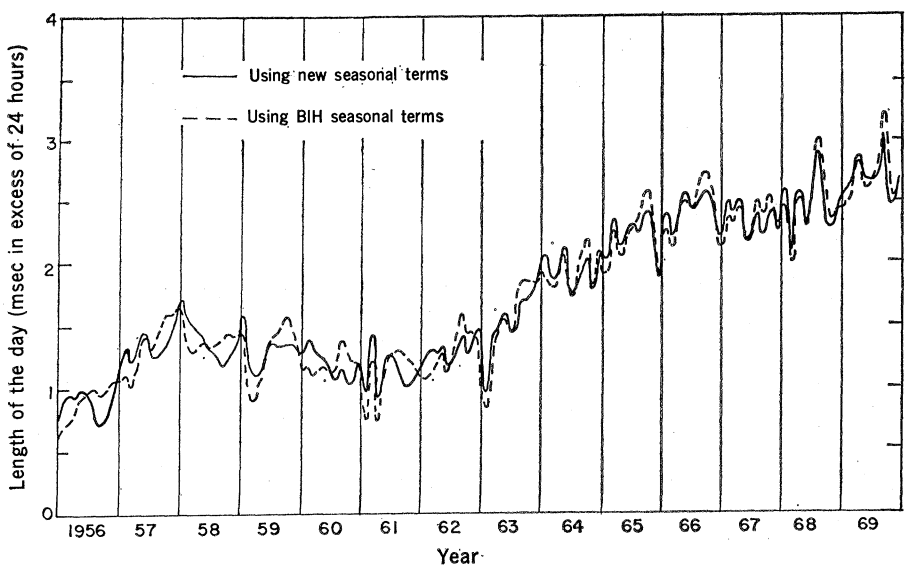


Fig. 3. Variations in the length of the day, after removal of the first two seasonal terms, for the years 1956–1969.

the annual means of the length of the day, and the annual mean rates of change of the length of the day (that is, the positive sign deceleration of the rotating earth) are plotted, for the period 1956–1969, against the annual mean sunspot numbers for these years and the dates of occurrence of earthquakes of magnitudes greater than 7.5 for the period 1957.0 to 1968.0.

Several features of these variations should be noted. First, the curve in Fig. 4c shows no sudden changes in acceleration during the period examined. This is in contrast to the findings of Brouwer (*6*), who used older and less accurate data to fit the A.T.–U.T.2 variation to a series of parabolas and found sudden changes in acceleration about every 10 years. Markowitz (*7*), who used a similar curve-fitting technique, found sudden changes in acceleration about every 4 years. The technique of fitting the observed data to a series of parabolas is bound to reveal sudden changes in acceleration; however, it is extremely dangerous to assume that they are real. The more precise the data and the required degree of "fit," the shorter the period over which the fit can be accepted and, consequently, the shorter the time between sudden changes in the derived acceleration. The data examined here show, if anything, a periodic variation in acceleration.

Danjon (*8*) has suggested a relationship between the rate of rotation of the earth and solar activity, and has supported this by comparing A.T. – U.T.2 with the (linearized) time-integrated cosmic-ray nucleonic component. A simpler, and more direct, comparison can be made between the length of day and the sunspot number. In Fig. 4 slight correlations are apparent between the mean annual sunspot numbers and both the length of the day and the acceleration of the earth's rotation. The first correlation is of the same nature and sense as that suggested by Danjon; however, the better correlation seems to be the positive one between solar activity and the earth's rotational acceleration.

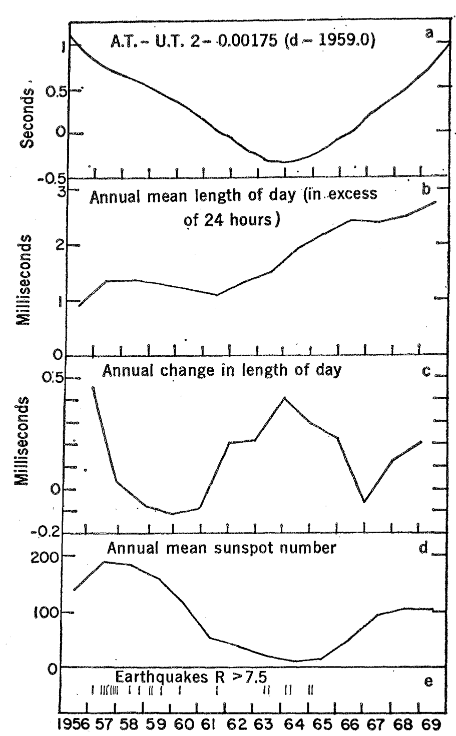


Fig. 4. Comparison of three parameters related to the earth's rotation rate with the annual mean sunspot numbers and the incidence of large earthquakes.

A possible link between the earth's rotation rate and the solar activity is the circulation of the atmosphere. As we have seen, small changes in the global atmospheric circulation lead to the large seasonal variations and possibly short-term fluctuations in the length of the day. There is some evidence (*9*) to suggest a solar influence on atmospheric circulation; if such an influence is apparent on a global scale, this may provide a clue to one cause of the long-term variations on the length of the day. However, there are not enough global meteorological data available at present to enable a proper investigation of this possibility, which touches, in any case, on the disputable question of solar-weather relationships.

The possibility that the earth's rotation is affected by earthquakes has been the subject of many studies. Most recently, Mansinha and Smylie (*10*) have found tentative evidence of a correlation between earthquakes and sudden changes in position of the earth's rotation pole. However, no successful attempt has been made to correlate earthquakes with sudden changes in rotation rate. The data used here show no such effect. However, Fig. 4 does suggest a slight correlation of general earthquake activity (the number of large earthquakes that occur during a given period) with the length of the day.

Three possible correlations, apparent from the data presented, between long-term variations in the rate of rotation of the earth and other geophysical phenomena have been suggested. It would be very dangerous, however, to surmise that all of these exist. To do so would, among other things, suggest a relationship between earthquakes and solar activity. Many more years of data will be needed before a proper assessment of the various possibilities can be made.

R. A. CHALLINOR*

Department of Physics,
University of Toronto,
Toronto 5, Ontario, Canada

References and Notes

1. S. C. Chandler, *Astron. J.* **11**, 65 (1891).
2. N. Stoyko, *C.R. Acad. Sci. Ser. B* **249**, 99 (1959).
3. Y. Mintz and W. Munk, *Mon. Notic. Roy. Astron. Soc. Geophys. Suppl.* **6**, 566 (1954).
4. A. Danjon, *C.R. Acad. Sci. Ser. B.* **249**, 2254 (1959); *ibid.* **250**, 1399 (1960).
5. S. Yeh and B. Shaw, *Acta Astron. Sinica* **8**, 68 (1960); S. Iijima and S. Okazaki, *Publ. Astron. Soc. Jap.* **13**, 125 (1961).
6. D. Brouwer, *Astron. J.* **57**, 125 (1952).
7. W. Markowitz, paper presented at the NATO Advanced Study Institute, London, Ontario, 1969.

8. A. Danjon, *C.R. Acad. Sci. Ser. B* **254**, 2479 (1962); *ibid.*, p. 3058.
9. D. Woodbridge, *J. Geophys. Res.* **64**, 331 (1959); N. Macdonald and W. Roberts, *ibid.* **65**, 529 (1960).
10. L. Mansinha and D. Smylie, *Science* **161**, 1127 (1968).
11. Supported by the National Research Council of Canada under grant A3940. I thank C. O. Hines for suggesting this investigation.
* Present address: Channel Data Processing, 19 James Street, St. Helier, Jersey, Channel Islands, United Kingdom.

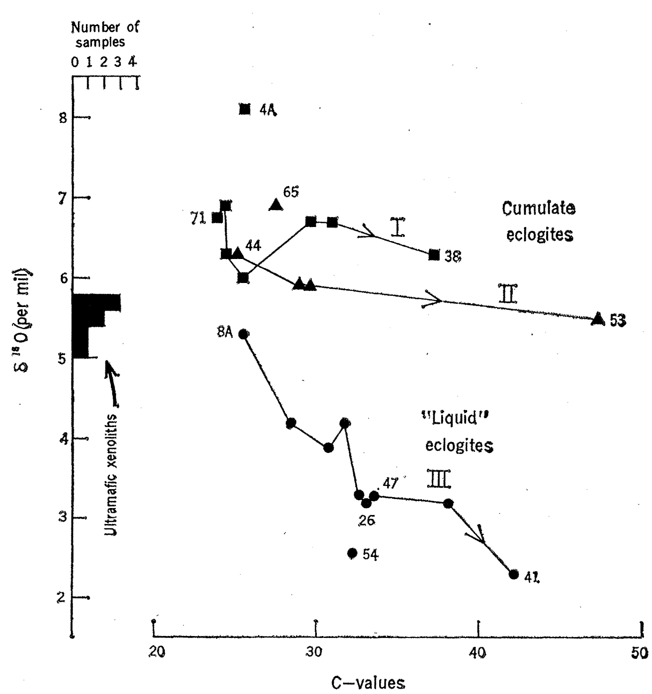
29 January 1971

Oxygen Isotope Ratios in Eclogites from Kimberlites

Abstract. *The oxygen isotope compositions ($\delta^{18}O$) of eclogitic xenoliths from the Roberts Victor kimberlite range from 2 to 8 per mil relative to SMOW (standard mean ocean water). This surprising variation appears to be due to fractional crystallization: the eclogites rich in oxygen-18 represent early crystal accumulates; the eclogites poor in oxygen-18 represent residual liquids. Crystal-melt partitioning probably exceeded 3 per mil and is interpreted to be pressure-dependent. Anomalous enrichment of oxygen-18 in cumulate eclogites relative to ultramafic xenoliths suggests that crystal-melt partitioning increased after melt-formation but prior to crystallization.*

Ultramafic xenoliths from kimberlite pipes have $\delta^{18}O$ values ranging from 5 to 6 per mil relative to SMOW (standard mean ocean water) (Fig. 1). The great majority of ultramafic and mafic igneous rocks from other parts of the world have $\delta^{18}O$ values between 5 and 7 per mil (*1*). The upper mantle thus appears to be fairly uniform in isotopic composition. The $\delta^{18}O$ values less than 5 per mil found in a few igneous rocks have been attributed to isotopic interaction with meteoric waters at igneous temperatures (*1, 2*). They have not been attributed to fractional crystallization because measured phenocryst-groundmass fractionations in lavas are very small (*3*) and because there is seldom any simple relation between isotopic compositions and the differentiation sequence (*1*). However, the $\delta^{18}O$ values of eclogitic xenoliths from the Roberts Victor kimberlite, South Africa, range from 2 to 8 per mil, and the evidence shown in Fig. 1 and described below leaves little doubt that isotopic fractional crystallization has been operative at eclogitic pressures within the mantle.

The Roberts Victor eclogites can be subdivided into three groups on the basis of their textures and chemistries (*4*): group I, a set of early crystal accumulates containing clinopyroxene and garnet; group II, a set of subsequent crystal accumulates containing subordinate amounts of kyanite or rutile in addition to clinopyroxene and garnet; and group III, a set of "liquids" which resulted from the progressive removal of the above-mentioned crystals (these "liquids" solidified into assemblages of clinopyroxene and garnet). The probable sequences of differentiation within these groups are shown in Figs 1 and 2. The differences in oxygen isotope compositions between the three groups and the variation within group III can be accounted for by a progressive depletion of ^{18}O in the melt due to removal of ^{18}O-enriched crystals (*5*). Although it is not possible to uniquely associate specific crystal accumulates with specific "liquids," changes in the chemical trends (*4*) suggest that the transition from group I eclogites to group II eclogites occurred when the liquid had a composition similar to that of samples 26 and 47. The trends in Fig. 1 imply that isotopic partitioning between crystals and melt increased during differentiation and amounted to 3.0 per mil at the time of the transition. We submit that the isotopic partitioning increased in response to an increase in pressure, although we are aware that the influence of pressure on isotopic fractionation is generally assumed to be negligible. An interpretation invoking



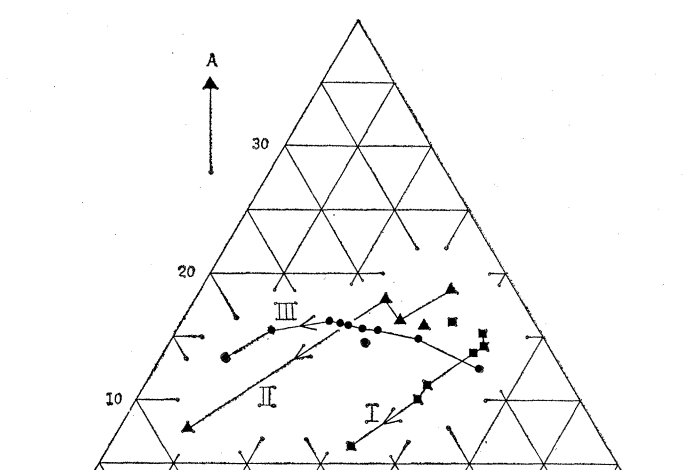


Fig. 1 (left). Oxygen isotope composition of Roberts Victor eclogites plotted against their C values (C = CaO, see Fig. 2). Samples 4A, 65, and 54 do not conform to the chemical and isotopic patterns determined for the other rocks and may represent independent magmatic episodes. The histogram shows $\delta^{18}O$ values of ultramafic xenoliths from South African kimberlites. Fig. 2 (right). An ACF diagram showing the projected chemistries of eclogites from the Roberts Victor mine (*4*). Arrows indicate the directions of differentiation within the three groups. The three off-trend samples are 4A, 65, and 54 (see Fig. 1). In molecular proportions, $A = Al_2O_3 + Fe_2O_3 - Na_2O - K_2O$; $C = CaO$; and $F = MgO + FeO + MnO$.