costs without appreciably changing their heating habits.

We obtained the heating degree-day elasticity for total residential sales by use of a double-log regression of degree-days (*9*) and natural gas price (*10*) on sales per residential customer in the East North Central division for the nine heating-season quarters from 1974 through 1976. The resulting equation is ln (sales per customer) = 3.532 − 0.214 ln(price) + 0.706 ln(degree-days). The $R^2$ (correlation value coefficient) is 0.99. Thus we find heating degree-day and price $E$ values of 0.71 and −0.21, respectively, for total per capita residential use. As noted above, the negative effect of price rise is solely on the nonheating portion of the residential use.

Following a standard linear regression approach, we reached essentially similar conclusions with respect to all four divisions. We used degree-day values ($\bar{z}$) as one variable and the average quarterly price per $10^6$ Btu's ($P$) paid by residential customers as the other variable to explain the variation in quarterly consumption per customer ($S/C$)

$$S/C = a_0 + a_1\bar{z} + a_2P \qquad (10)$$

where $\bar{z}$ is obtained from Eq. 5 and the $x$ values in Table 2, and $P$ is obtained as the indexed ratio of quarterly revenues ($R$) to quarterly sales ($S$) as reported by AGA. A quarterly index $I_q$ permits the price to be expressed in terms of 1975 dollars (*11*) as

$$P = \frac{R}{S} I_q \qquad (11)$$

To estimate the coefficients, we rewrote Eq. 10 in stochastic form, adding the discrete variable $Q_3$ in order to handle third-quarter consumption shifts in the Middle Atlantic and West South Central divisions: $Q_3 = 1$ for third-quarter data and zero otherwise

$$S/C = a_0 + a_1\bar{z} + a_2P + e_1 + a_3Q_3 \qquad (12)$$

Results for the 12 quarters in 1974 to 1976 are presented in Table 4. All coefficients were significant to at least the 5 percent confidence level, and all $R^2$ values were 0.999, indicating that the variables completely explain the quarterly variation in gas consumption.

Thus, when seasonal usage trends are accurately incorporated by use of lag-corrected temperature data and quarterly sales data, the econometric model results are shifted and become consistent with those derived from the engineering models.

*Other implications*. The current and historical sales data compiled by the AGA are widely used by energy professionals. For many purposes other than demand forecast modeling, it is unimportant if the data lag the nominal calendar quarter by 2 to 4 weeks, but for conservation models, as indicated in this report, the lag can be very important. For those who need to correct the AGA data for lag, Eq. 6 provides a simple means of doing so. For each quarter, one makes use of the known $C$, $A$, and $B$ values and the appropriate $j$ and $k$ values, but substitutes 1.0 for the $x$ value in the equation. The resulting expression gives the sales for the true calendar quarter.

RICHARD L. LEHMAN

*Office of Ecology and Environmental Conservation, National Oceanic and Atmospheric Administration, Rockville, Maryland 20852*

HENRY E. WARREN

*Center for Climatic and Environmental Assessment, National Oceanic and Atmospheric Administration, Columbia, Missouri 65201*

**References and Notes**

1. K. S. Hu, *Temperature Sensitivity of Utility Gas Consumption in the Residential Sector* (Department of Statistics, American Gas Association, Arlington, Va., 1977).
2. The heating degree-day is a measure of the duration and intensity of winter coldness. The heating degree-day value per day is defined as the difference between 65°F and the mean daily outdoor temperature. When the mean outdoor temperature is 65°F or greater, the daily heating degree-day value is zero. The heating degree-day elasticity is the fractional change in fuel consumption per unit fractional change in accumulated heating degree-day value. The engineering model approach is discussed by E. J. Durrer and W. H. Somerton [*Am. Gas Assoc. Mon.* **58** (No. 2), 16 (1976)].
3. W. S. Chern and W. Lin, in *Proceedings of the American Statistical Association, Business and Economic Statistics Section* (American Statistical Association, Washington, D.C., 1976), pp. 250–254.
4. M. R. Seidel, *The Costs of Cold Weather and the Conservation of Residential Heating Gas* (Office of Policy Analysis, Federal Power Commission, Washington, D.C., 1977).
5. T. A. Ferrar and J. P. Nelson, *Science* **187**, 644 (1975).
6. H. E. Warren, *A Regression Model for Estimating Weekly Natural Gas Sendout in the State of Missouri* (CCEA Tech. Rep. 8, Center for Climatic and Environmental Assessment, Columbia, Mo., 1976).
7. The *Quarterly Report of Gas Industry Operations* (Bureau of Statistics, American Gas Association, Arlington, Va.) includes natural gas sales, customer, and revenue information for each of the nine U.S. census divisions; the annual *Househeating Survey* (American Gas Association, Arlington, Va.) contains househeating customer data.
8. It can be shown that $x$ is a unique function of $S$, $C$, $A$, and $B$; the apparent quadratic form $kx$ is thus misleading.
9. Calculated to match the exact lagged sales-reporting periods.
10. Normalized to 1975 dollars by use of the *Consumer Price Index* (Bureau of Labor Statistics, Department of Labor, Washington, D.C.) Smoothed to give a uniform rise each quarter.
11. The quarterly index $I_q = GI_qCI_{75}/GI_yCI_q$, where $GI_q$ is the price index for natural gas in quarter $q$ in year $y$, $GI_y$ is the average price index for gas in year $y$, $CI_{75}$ is the average consumer price index for the region in 1975, and $CI_q$ is the consumer price index for the region in quarter $q$. The source of index data is *Monthly Labor Review* (Bureau of Labor Statistics, Department of Labor, Washington, D.C.).

3 October 1977

# Localized Compressional Velocity Decrease Precursory to the Kalapana, Hawaii, Earthquake

Abstract. *A delay in the arrival times of compressional or* P *waves of 0.15 to 0.2 second from deep distant earthquakes has been detected at the closest seismograph station to the 20 November 1975 earthquake at Kalapana, Hawaii (surface-wave magnitude* $M_s = 7.2$*). This delay appeared approximately 3.5 years prior to the quake, and travel times returned to normal several months before it. The* P*-wave arrival times at other nearby stations remained constant during this period, an indication that the decreased velocity implied by the delay in travel time was associated with this normal-faulting earthquake and was confined to distances less than 20 kilometers from the epicenter.*

Since the original Russian reports (*1*) of seismic velocity decreases prior to earthquakes, workers in the United States, Japan, and other countries have searched for similar effects before other earthquakes in hopes of using this phenomenon as a predictive tool. A few successes have been reported (*2*) but only for small (surface-wave magnitude $M_s < 7$) thrust earthquakes (*3*), and negative findings are common (*4*). Therefore, the detection of decreased $P$-velocities preceding the normal-faulting earthquake ($M_s = 7.2$) near Kalapana, Hawaii, is of considerable interest for earthquake prediction research.

The data used to identify the velocity decrease were relative $P$-residuals from deep (> 500 km) Fiji-Tonga earthquakes (*5*) (see inset, Fig. 3). A residual is the difference between the observed and the computed arrival times of a seismic signal. One obtains a relative residual by subtracting from this value the residual of a nearby reference station. For a given earthquake, this process results in the near cancellation of contributions arising from ray path variability at the source, in the lower mantle, and in the upper mantle beneath the receiver. Near-receiver crustal variations, caused by any anomalous temporal behavior of interest, remain unchanged by this procedure and thus become detectable.

The residual data of stations WHA and MPR are presented in Fig. 1. Station MLO was chosen as the reference station because of its location on the stable southeastern flank of Mauna Loa volcano, well removed from most volcanic and earthquake activity. Station WHA, approximately 3.5 km from the computed Kalapana epicenter, was installed in March 1971. In mid-1972 its *P*-residual relative to MLO (Fig. 1A) increased from 0.1 second to nearly 0.3 second. This increase persisted into 1975 and diminished slightly in 1974; by late 1975, the residuals had returned to nearly the level of 1971. In contrast, the relative residuals between MPR and MLO (Fig. 1C) exhibit a remarkable 10-year stability, even though MPR is located on the frequently active east rift of Kilanea volcano and within the aftershock zone of the Kalapana earthquake.

Apparently MPR is stable with respect to MLO, and WHA is not; Fig. 1B illustrates the expected variation of WHA relative to MPR. This data set is not identical to that used in Fig. 1A since not all events are received equally well by the three stations. The same pattern of increased arrival times is evident, an indication that the crust beneath WHA changed in the period from 1972 to 1975 but the crust beneath MPR did not. The scatter in the WHA-MPR data is slightly greater than the scatter for the WHA-MLO data, even though MPR is less than 15 km from WHA. Perhaps this slight increase in scatter is caused by the fact that MPR is located on an active volcanic rift zone, whereas MLO is on more stable crust.

The travel time delay at WHA relative to MLO has a maximum magnitude of about 0.2 second. A long-term relative residual stability of approximately 0.1-second scatter is necessary to resolve such a feature. The MPR-MLO plot (Fig. 1C) includes 0.1-second limits to show that less than 10 percent of the relative residuals between two stations of the same seismic network scatter outside a 0.1-second band (the standard deviation is 0.04 second from the long-term mean). This travel time stability exhibited by MPR is representative of other stations of the Hawaiian network not included in this report (*6*). To achieve such low scatter, several conditions must be met. (i) Arrivals must be read to within a precision of 0.05 second. To this end, a timing system with the same clock for all stations, such as that used by the Hawaii Volcano Observatory (HVO), is highly desirable, for then timing corrections cancel when the relative residual is taken. Also, phase correlation of receiver and reference signals (see Fig. 2) was employed to avoid the possible misreading of emergent first motions. (ii) Error arising from hypocenter mislocation of source events must be negligible. I carried out an analysis based on work with Alaskan stations by Engdahl *et al.* (*7*) for the Tonga-Hawaii source-receiver configuration. I found that, because of the close receiver-reference station separations (~ 50 km) possible within the HVO network, a representative mislocation of ± 25 km would not introduce more than 0.02-second scatter in the relative residual. (iii) The source events must be confined to a volume restricted in both azimuth and distance from the closely spaced receivers—a condition satisfied by the deep Fiji-Tonga source zone used. Other workers using the relative residual technique have reported either a large data scatter (0.5 second) if this condition was neglected (*8*) or have introduced an empirical azimuthal term to correct for it (*9*).

The travel time increase (*P*-velocity decrease) identified for WHA can be formally tested for statistical significance. In Fig. 1A four time intervals, chosen visually, are demarked by bounds of ± 1 standard deviation from their respective means, as follows: I, + 0.11 ± 0.06 second, March 1971 through January 1972, 18 events; II, + 0.26 ± 0.07 second, January 1972 through November 1973, 32 events; III, + 0.21 ± 0.05 second, November 1973 through July 1975, 30 events; and IV, + 0.14 ±

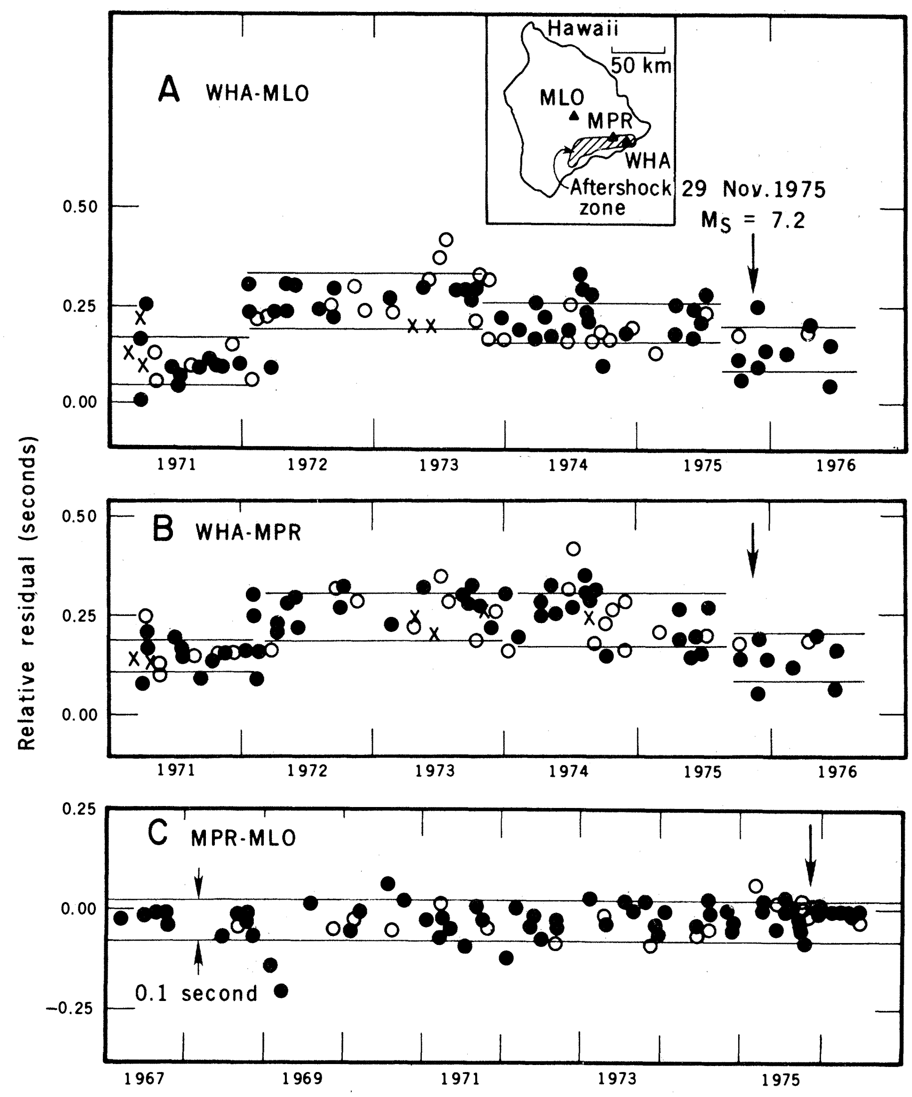



Fig. 1. Relative residuals versus time for (A) WHA-MLO and (B) WHA-MPR for the entire Fiji-Tonga zone; (C) relative residuals versus time for MPR-MLO, for events in the north Fiji-Tonga zone only. Note the different time scale of (C). Data begin in the year of installation of each station. Symbols: ●, excellent or good-quality reading (both stations); ○, fair or poor; x, other than first cycle; arrows designate the date of the Kalapana earthquake; horizontal lines mark off the bounds of ± 1 standard deviation from the average (see text). The inset is the island of Hawaii; on the scale of the inset, WHA overlies the Kalapana epicenter.

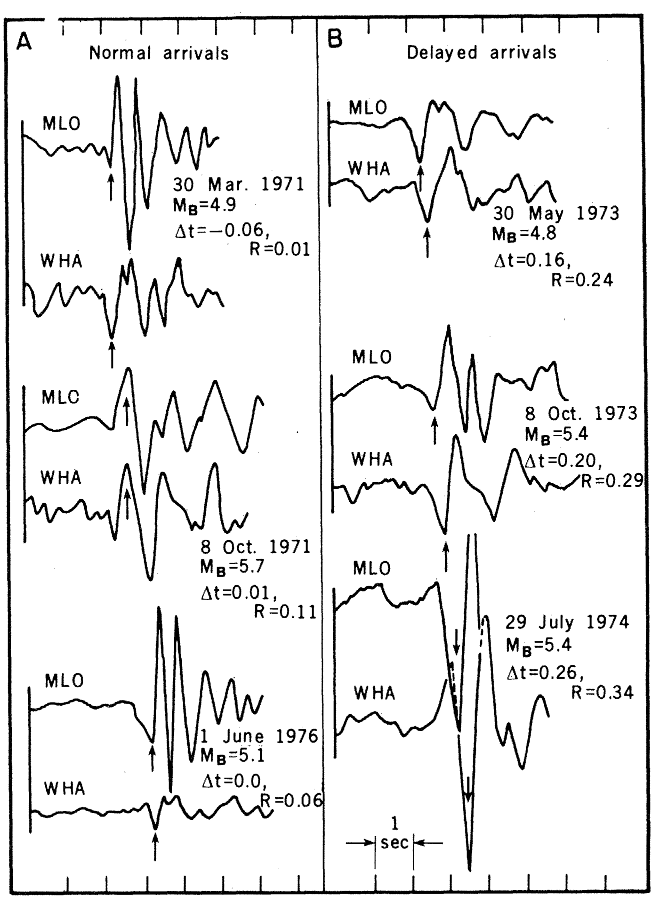
0.06 second, August 1975 through June 1976, 11 events. If the Fiji-Tonga events in the above intervals are a truly random sample from the entire Fiji-Tonga population (and no correlation of residual with depth, magnitude, or coordinates was found), the standard $t$-test for the difference between two sample means may be applied. For example, a test of the null hypothesis that the parent populations of samples I and II are the same (have the same average value) yields $t = 7.16$ with 48 degrees of freedom. From the $t$ tables this value of $t$ could arise less than one time in a thousand by chance alone. Thus, the difference in means between the "normal" interval I and the "delayed" interval II is highly significant (above the 99.9 percent level). Other interval pairs test as one would expect from visual inspection of Fig. 1A. For example, the difference between intervals I and IV is not significant, but the difference between intervals II and IV is highly significant. No station other than WHA within the Kalapana aftershock zone exhibits variation of $P$-residuals relative to MLO that were of statistical significance.

Sample seismograms (Figs. 2 and 3) from the entire data set (*10*) for the WHA-MLO station pair show that the HVO network, although designed to record short-period, local earthquake activity, also possesses an excellent teleseismic recording capability in the range from 0.5 to 1.0 second. The first clear peak or trough was read as indicated by the arrows. Although the differences between the normal and delayed arrivals may be qualitatively seen in Fig. 2, the quantitative measure of $R$, the relative residual, will depend on the computed arrival times at WHA and MLO.

It is also evident in Figs. 2 and 3 that signal correlation between the two stations was often poor, although the first prominent cycle in the signal generally exhibited good correlation. It was for this reason that only first-cycle readings were made except for a few events (marked by x's in Fig. 1) where this proved impossible. Part of the problem with correlation undoubtedly is due to differing crustal transfer properties beneath the two stations. Also gain changes were frequently made at all stations. However, such changes would not affect frequency-response characteristics; all the instruments of the HVO network are one of two types (*6*) with quite similar frequency response in the teleseismic range.

The data presented in this report must be considered preliminary in two respects: (i) a longer base line after the earthquake is necessary to more firmly establish normal travel times and (ii) arrivals for more HVO stations must be analyzed for comparison purposes (*11*). Nevertheless, the time delay observed at WHA is clear enough to warrant some further discussion.

The most recently available geological evidence (*12*) indicates that the Kalapana earthquake was a gravity-controlled slump event on the Hilina fault system. The faults of this system are thought to bottom at a depth of 4 km (*13*), the computed depth of the earthquake. If it is assumed that the travel time delay for a ray arriving from Fiji-Tonga was generated within these 4 km, a $P$-velocity decrease of 15 to 20 percent is required to produce the observed 0.2-second delay. Just as plausibly the anomalous zone could extend to twice this depth and require only



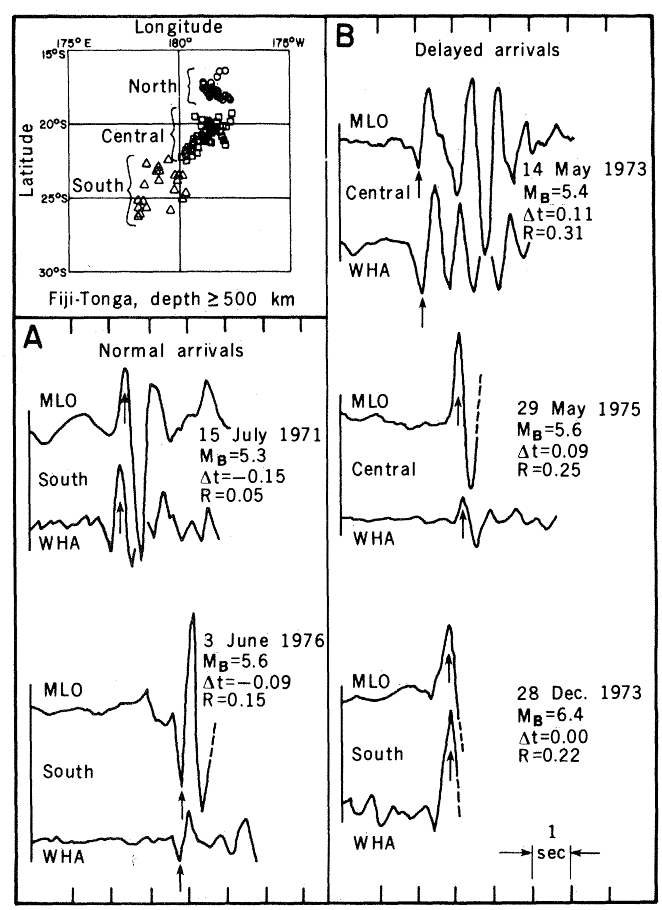




Fig. 2 (left). Tracings of $P$-arrivals at stations MLO (reference) and WHA, all from the north group of events of the deep Fiji-Tonga source region. Each signal set begins on an arbitrary real-time mark common to both stations; thus WHA is not shifted in time with respect to MLO. (A) Examples of normal (nondelayed) arrivals at WHA. (B) Delayed arrivals. Arrows denote the crest or trough measured. Although $\Delta t$, the arrival time difference, may be discriminated visually in this figure, the value of $R$ will depend on computed as well as observed arrival times. Fig. 3 (right). Tracings of $P$-arrivals similar to those in Fig. 2, except that examples are taken from the central and south Fiji-Tonga zones. The inset shows these zones with a portion of the epicenters used in this study. Dashed lines indicate that the trace deflected off scale.

an 8 to 10 percent velocity decrease. If dilatancy precedes the quake, then a theoretical treatment (*14*) based on parallel, vapor-filled cracks oriented vertically for a normal-faulting mechanism yields only a 5 percent velocity decrease for the Tonga rays which arrive at WHA at 25° off the vertical. However, inasmuch as both the depth of the anomalous zone and the degree of crack orientation are conjectural, the reported time delay is not unreasonable.

If cracks are present and are indeed vertically parallel, a horizontal seismic wave traveling to WHA would experience a maximum velocity decrease of about 17 percent (*14*). Local Hawaiian earthquakes could serve as sources for such horizontal paths, but increased relative residual scatter is anticipated since waves incident to WHA and the reference station will not, for this case, share a common ray path over the major part of the path length.

The very localized (less than 20 km) horizontal extent of the anomalous zone is much smaller than estimates for thrust earthquakes reported in the literature (*15*); indeed, it encompasses only a small fraction of the aftershock zone. Perhaps this is characteristic of normal and strike-slip faulting and is responsible for the negative reports of velocity changes preceding earthquakes with nonthrust mechanisms. Such a small anomalous region for a large earthquake could be explained in terms of a very restricted zone of intense stress buildup (*16*) where the break initiated, whereas the rest of the much larger rupture surface remained at a lower stress state throughout the observed precursory period. Then, as for the case reported here, only the rare occurrence of a large shallow earthquake beneath an existing, long-term seismic array will make possible the identification of a travel time delay small in both magnitude and horizontal dimension.

ARCH C. JOHNSTON

*Cooperative Institute for Research in Environmental Sciences, University of Colorado/National Oceanic and Atmospheric Administration, Boulder 80309*

### References and Notes

1. A. N. Semenov, *Izv. Acad. Sci. USSR Phys. Solid Earth* **3**, 245 (1969).
2. Examples (all for thrust earthquakes) are Y. P. Aggarwal, L. R. Sykes, J. Armbruster, M. L. Sbar, *Nature (London)* **241**, 101 (1973); J. H. Whitcomb, J. D. Garmany, D. L. Anderson, *Science* **180**, 632 (1973); M. Wyss and A. C. Johnston, *J. Geophys. Res.* **79**, 3283 (1974).
3. An exception is the report by R. Robinson, R. L. Wesson and W. L. Ellsworth [*Science* **184**, 1281 (1974)] of a *P*-velocity decrease prior to a strike-slip earthquake ($M$ = 5.0).
4. T. V. McEvilly and L. R. Johnson, *Bull. Seismol. Soc. Am.* **64**, 343 (1974); B. A. Bolt, *ibid.* **67**, 27 (1977).
5. The Fiji-Tonga region has been used for residual studies by other workers, in particular by E. R. Engdahl [*Geophys. Res. Lett.* **2**, 420 (1975)] and by C. H. Cramer, C. G. Bufe, and P. W. Morrison [*Bull. Seismol. Soc. Am.* **67**, 9 (1977)].
6. The seismic network operated by the HVO for the U.S. Geological Survey comprises some 40 stations on the island of Hawaii. For a full description, see R. Y. Koyanagi, A. T. Okamur, G. Kojima, *Hawaiian Volcano Observatory Summary* **63** (Department of the Interior, Washington, D.C., 1974).
7. E. R. Engdahl, J. G. Sindorf, R. A. Eppley, *J. Geophys. Res.* **82**, 5671 (1977).
8. W. L. Ellsworth, *Eos Trans. Am. Geophys. Union* **57**, 288 (1976).
9. C. H. Cramer, *Bull. Seismol. Soc. Am.* **66**, 1233 (1976).
10. Nearly 500 events $M_b \geq 4.7$ from the deep Fiji-Tonga source were scanned beginning in 1967 when the film records of the HVO array were started. Because of high wind, surf noise, and down periods, about 50 percent of these events could not be used.
11. A. C. Johnston, *Eos Trans. Am. Geophys. Union* **58**, 433 (1977). Additional data for station HLP on the Hilina fault system and within the aftershock zone of the Kalapana earthquake were presented which showed no temporal variation for 5 years prior to the earthquake. Two other stations, POL (25 km from the epicenter) and KAE (10 km), both located immediately south of the aftershock zone, show no temporal variation since having been installed in 1973.
12. R. I. Tilling *et al.*, *U.S. Geol. Surv. Circ. 740* (1976).
13. D. A. Swanson, W. A. Duffield, R. S. Fiske, *U.S. Geol. Surv. Prof. Pap. 963* (1976).
14. D. L. Anderson, B. Minster, D. Cole, *J. Geophys. Res.* **79**, 4011 (1974). The parameters used to compute the percent velocity decrease are: $\alpha$ (aspect ratio of ellipsoidal cracks) = 0.05, $\phi$ (porosity) = 0.01, $k_v$ (vapor bulk modulus) = 0.1 kbar, and a granite matrix. Any or all of these may be considerably different in the Hawaiian crust.
15. C. H. Scholz, L. R. Sykes, Y. P. Aggarwal, *Science* **181**, 803 (1973).
16. A theoretical model of such a feature, named the primary inclusion zone, has been proposed by B. T. Brady, *Pure Appl. Geophys.* **112**, 701 (1974).
17. Drs. E. R. Engdahl and M. Wyss contributed greatly to the initiation and development of this work. I am indebted to Dr. G. Eaton for making the facilities of the Hawaii Volcano Observatory available to me. I especially thank R. Koyanagi for his assistance in accumulating the data. This work was supported by U.S. Geological Survey contract 14-08-0001-15865.

11 July 1977; revised 31 October 1977

## Larval Dispersal and Species Longevity in Lower Tertiary Gastropods

Abstract. *Species longevity in Lower Tertiary volutids (Gastropoda) is primarily controlled by a combination of developmental type and environmental tolerance. Larval dispersal may be an important factor in molluskan evolutionary rates.*

Ecologic factors affecting evolutionary rates in invertebrates have been the subject of a great deal of discussion (*1*). Various rate controls have been proposed, including feeding type (*2*), environmental tolerance (*1, 3, 4*), and population size (*5*). We discuss here how evolutionary rates may be influenced by larval dispersal, in particular for Lower Tertiary Volutidae (Gastropoda).

Larval dispersal has a significant effect on the geographic distribution of mollusks (*6, 7*). Living species with long-lived planktonic larvae may regularly cross the Atlantic Ocean while those with short or no planktonic stages are unable to cross any oceanic basins. Even local geographic irregularities such as brackish water coves and inlets may be a barrier to dispersal (*8*). The pronounced effect of larval type on species biogeography has generated studies relating the dispersal of fossil invertebrates to modes of speciation (*9*) and evolutionary rates (*4, 7, 10*).

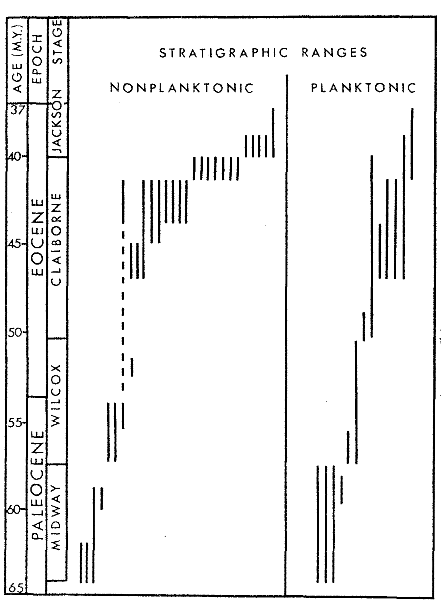



Fig. 1. Geologic ranges of species with nonplanktonic or planktonic larval stages.

The Paleocene-Eocene outcrops of the North American Gulf Coast provide a suitable framework for testing the effect of dispersal on species longevity. The stratigraphy has been extensively studied and molluskan fossils are generally well preserved.

In order to minimize the effect of factors other than dispersal (factors such as feeding type or morphologic complexity), a single family of gastropods, the Volutidae, was chosen for detailed analysis. Modern volutids are ecologically and morphologically a relatively homogeneous group (all burrowing carnivores-scavengers), and fossil species have an adequate proportion of both planktonics and nonplanktonics (living species have only nonplanktonic development).

Larval development for each species was determined by the criteria of Shuto (*9, 11*), and of the 42 taxa in the study


0036-8075/78/0224-0885$00.50/0 