A Far-Field Hydrothermal Plume from Loihi Seamount

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An extensive helium plume in the north central Pacific emanates from Loihi Seamount on the flanks of Hawaii. The maximum helium signal is found at a depth of about 1100 meters, the same depth as the near-field plume directly above Loihi Seamount. Although this helium plume is strongest near Hawaii, where the $^3He/^4He$ ratio at a depth of about 1100 meters reaches values 28 percent above the atmospheric ratio, it can be detected quite clearly at latitude 24°N, over 400 kilometers to the north. Excess ^3He is also present on the same isopycnal between 15°N and 20°N at 135°W, some 2000 kilometers east of the Hawaiian Islands.

Hydrothermal activity along the global mid-ocean ridge system introduces ^3He, Mn, Fe, and other tracers into the ocean that are useful for studying deep ocean circulation and mixing. One of the best examples is the extensive plume of ^3He that extends westward from the East Pacific Rise (EPR) at latitude ~15°S (*1*), suggesting that the flow in this region is westward, opposite to the eastward flow predicted by the geostrophic circulation model of Stommel and Arons (*2*). Plumes of hydrothermal ^3He also have been identified in the northeast Pacific emanating from the Juan de Fuca Ridge (JdFR) (*3*) and in the 10°N region of the EPR (*4*).

Although most studies of submarine hydrothermal venting have focused on mid-ocean ridge systems, there are a few studies of active hydrothermal systems on seamounts. Macdonald Seamount in the south Pacific underwent submarine eruptions in 1987 and 1989, and has active vents on its summit that inject volatiles into the overlying water column at a depth of about 130 m (*5*). Loihi Seamount, situated on the southeastern flank of the island of Hawaii, also has active vents near its summit at a depth of ~1000 m (*6*). Loihi lavas contain helium with a very primitive signature of $R \simeq 30\ R_A$ (where $R = {}^3He/{}^4He$ and $R_A = R_{air}$), which indicates an origin in the deep fertile mantle (*7*). Thus, the Loihi helium signature has elevated $^3He/^4He$ ratios as compared with those of mid-ocean ridge lavas, which contain helium with $R = 7$ to $9\ R_A$ (*8*). Because the helium and most of the volatiles in submarine hydrothermal fluids are derived directly from the volcanic rocks, it is not surprising that the fluids venting from the summit caldera of Loihi contain high concentrations of helium with an elevated isotope ratio of $\sim 27\ R_A$ (*9*, *10*). Several expeditions have detected a hydrothermal plume directly over Loihi that is characterized by enrichments in helium and methane (*11*–*13*).

Although hydrothermal venting on Loihi has been well documented, here I show that this venting generates a plume that, at least in the case of ^3He, can be detected at distances over 2000 km from the Hawaiian Islands. The existence of this plume provides an opportunity to map the shallow circulation in the vicinity of Hawaii and in the central Pacific basin.

The samples for this study were collected on several different expeditions (*14*). Water samples were collected in Niskin bottles mounted on a rosette, and then were sealed into copper tubing and stored until analyzed by mass spectrometry (*15*). Helium isotope ratios are reported as $\delta(^3He)\%$, which is the percentage deviation of the $^3He/^4He$ ratio from the ratio in air. None of the $^3He/^4He$ values have been corrected for the increase in $^3He/^4He$ due to the decay of tritium during the time the seawater samples were stored in copper tubing. However, for the typical 200-day storage time for these samples, this correction would be ≤0.01% in $\delta(^3He)$, assuming tritium values of ≤0.03 tritium units (TU) at a depth of 1000 m (*4*).

Evidence for a far-field helium plume emanating from the Hawaiian Islands was first seen in a series of profiles from NOAA expedition CGC-91 in 1991 and later in a similar suite of stations from NOAA expedition S94F in 1994 (Fig. 1). Individual $\delta(^3He)$ depth profiles immediately north of Hawaii exhibit a sharp maximum in $\delta(^3He)$ at a depth of ~1100 m, reaching values of $\delta(^3He) = 28\%$ for the stations nearest to Hawaii (Fig. 2). This relatively shallow helium signal is detectable at least 400 km north of Hawaii, but north of ~24°N this helium signal is not evident above background values. This shallow maximum in $\delta(^3He)$ is superimposed on the broader and more extensive maximum in $\delta(^3He)$ centered at a depth of ~2000 m that is produced by hydrothermal venting along the mid-ocean ridge system and from the JdFR in particular. The ^3He profiles from CGC-91 (1991) and from S94F (1994) are very similar, demonstrating that this shallow far-field plume is a long-lived feature of the water column.

Two aspects of the existing far-field plume data point strongly to an origin on Loihi Seamount: (i) the Loihi vents are

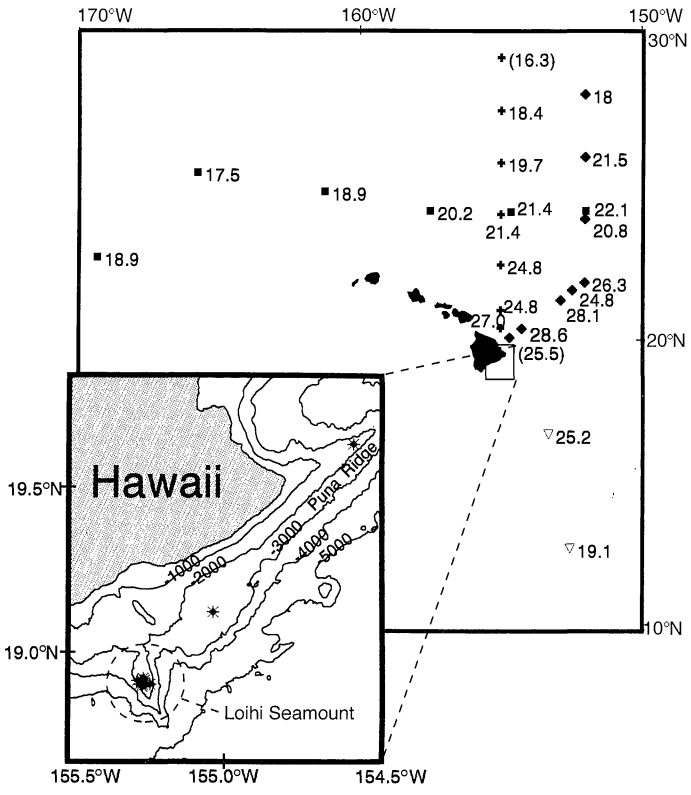

Fig. 1. Map of station locations for expeditions CGC-91 (diamonds), *Discoverer* S94F (crosses), TPS-24 (squares), and WOCE P16 (inverted triangles). The $\delta(^3He)\%$ values at a depth of 1100 m are indicated next to each station. The values indicated in parentheses are approximate because of less-than-ideal interpolation versus depth. The WOCE P16 data are from Jenkins (*24*). The insert shows detailed bathymetry on the southeastern flank of Hawaii, including Loihi Seamount and the Puna Ridge. Locations of casts taken during expedition TT-014 are indicated by stars. Bathymetry is from Moore and Chadwick (*25*).

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located at almost exactly the same water-column depth as the plume maximum, and (ii) the plume helium signal is strongest near Hawaii. Additional evidence concerning the origin of the far-field plume is provided by near-field hydrographic profiles collected directly over Loihi Seamount. The 1985 expedition by the R.V. *Hakuho Maru* detected hydrothermal plumes over Loihi that were highly enriched in methane, Fe, Mn, Ni, Co, and He (*12*, *13*). The 1985 Loihi plume had a two-layer structure with maxima at depths of ~1000 and 1100 m, possibly corresponding to separate injection from the shallow Pele's vents versus injection from deeper hydrothermal vents. In 1992, hydrographic work was conducted by the R.V. *T. G. Thompson* over Loihi Seamount as well as on the southeast flank of Hawaii and on the Puna Ridge (Fig. 1). A composite plot of $^3He/^4He$ values versus depth for all of these hydrocasts from expedition TT-014 (Fig. 3) shows $^3He/^4He$ values near background for southeast flank and Puna Ridge stations, whereas the samples collected over Loihi Seamount show very high enrichments in $^3He/^4He$ in the depth range between 1000 and 1250 m. Thus, these 1995 observations detected the plume at essentially the same depth as did the earlier 1985 work. Two of the 1995 samples have very high $^3He/^4He$ ratios of $\delta(^3He)$ = 470 and 410%.

The TT-014 helium data form a linear trend that is due to mixing between background seawater and the hydrothermal end-member (Fig. 4A). A least-squares linear fit to these data gives a slope of $^3He/^4He = (3.25 \pm 0.26) \times 10^{-5}$ or $R/R_A = 23.4 \pm 1.9$ (1σ errors), which corresponds to the helium isotope ratio of the pure end-member fluid. This value is in good agreement with the end-member helium ratio of $R/R_A = 23.1 \pm 2.3$ determined by Kodera *et al.* (*16*) from their 1985 samples and also agrees with direct measurements of helium isotope ratios in Loihi vent fluids (*9*, *10*). The fact that a near-field plume was observed over Loihi in 1983 (*11*), in 1985 (*12*, *13*), and again in 1995 (this work) indicates that the plume is being maintained by the Loihi vents in a steady-state mode at a depth of ~1100 m.

The elevated $^3He/^4He$ ratio ($R = 27\ R_A$) of the helium emanating from Loihi Seamount suggests that it might be possible to detect this elevated isotope ratio in the far-field plume samples. As shown in Fig. 4B, the shallow helium plume samples (at depths of 800 to 1400 m) from S94F are distinct from the other samples, corresponding to a higher enrichment in ^3He relative to ^4He. This is exactly what would be expected for a plume originating from an end-member fluid with elevated $^3He/^4He$ such as Loihi. Thus, the far-field plume samples are a diluted version of the near-field samples collected directly over Loihi (Fig. 4A). Because of the analytical uncertainty in the absolute concentrations, it is not possible to accurately determine the end-member $^3He/^4He$ ratios by means of linear regression fits to the data points in Fig. 4B. However, linear regression fits show that the shallow samples and the deep samples belong to two distinct populations at better than 70% confidence limits. This detectable isotopic anomaly relative to other Pacific water samples is a further indication that this shallow helium plume has its origin on Loihi Seamount.

The fact that the helium signal from

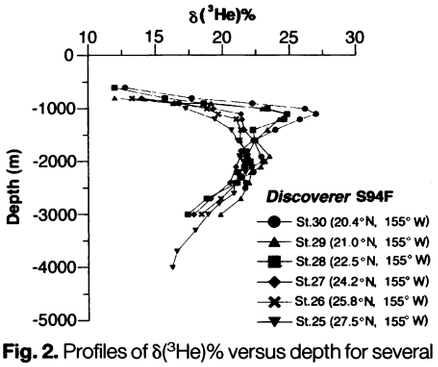

Fig. 2. Profiles of $\delta(^3He)\%$ versus depth for several stations from expedition S94F. Station (St.) locations are shown in Fig. 1. Note that stations 28, 29, and 30 all show a clear maximum in $\delta(^3He)$ at a depth of 1100 m, which is attributed to venting on Loihi Seamount. The deeper maximum at a depth of ~2000 m is due to hydrothermal venting on the JdFR and EPR.

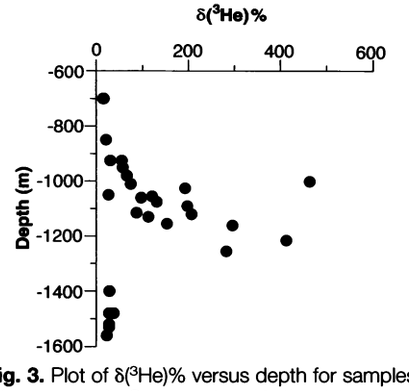

Fig. 3. Plot of $\delta(^3He)\%$ versus depth for samples taken over Loihi Seamount and in the vicinity during expedition TT-014 in 1992. Cast locations are shown in the insert in Fig. 1.

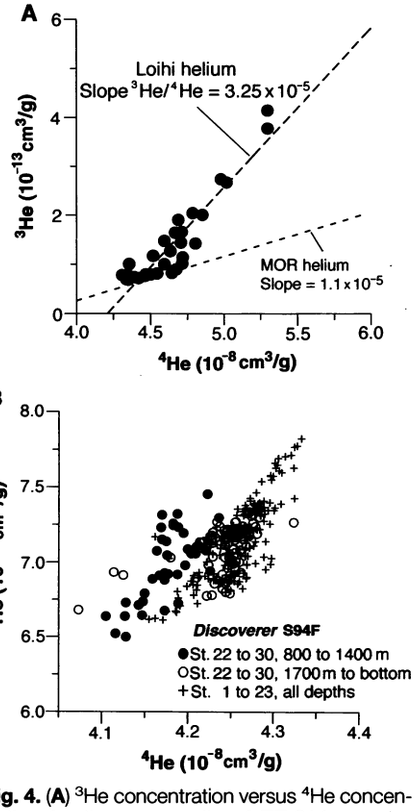

Fig. 4. (**A**) ^3He concentration versus ^4He concentration for the same suite of TT-014 samples shown in Fig. 3. Concentration units are in cubic centimeters per gram at standard temperature and pressure. A linear least-squares fit (long-dashed line) gave a slope of $^3He/^4He = (3.25 \pm 0.26) \times 10^{-5}$, or $R/R_A = 23.4 \pm 1.9$ (1σ errors). The correlation coefficient for this fit was $r^2 = 0.854$. For comparison, a short-dashed line indicates the slope of $^3He/^4He = 1.0 \times 10^{-5}$ expected for helium introduced along the mid-ocean ridges (MOR). (**B**) ^3He concentration versus ^4He concentration for far-field samples collected along S94F at stations 22 through 30. Shallow samples (at depths of 800 to 1400 m) are shown as solid circles; deeper samples (from 1700 m to the bottom) at the same stations are shown as open circles. For reference, all the remaining samples from the S94F expedition in the northeast Pacific are shown as crosses. Linear regression fits to these data groups show that the shallow Loihi plume samples belong to a distinct population.

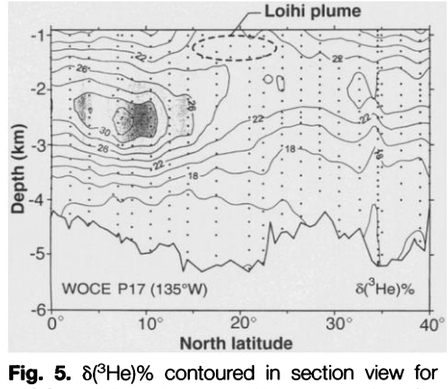

Fig. 5. $\delta(^3He)\%$ contoured in section view for WOCE line P17 along 135°W. In this section, the Loihi plume appears as an upturning of the $\delta(^3He)$ contours in the depth range from 900 to 1400 m, between latitudes 15° and 25°N as indicated by the dashed ellipse. The plume core centered at 8°N and a depth of 2500 m is helium from the EPR, whereas the weaker signal north of 32°N and at a depth of 2000 m is from the JdFR.

Loihi is detectable on the 1100-m depth horizon some 400 km north of Hawaii suggests that the Loihi plume might be much more extensive than previously imagined. One indication of the lateral extent of the Loihi plume is the excess ^{3}He above the regional background that is present at a depth of 1100 m on World Ocean Circulation Experiment (WOCE) line P17 at 135°W over 2000 km to the east of Hawaii (Fig. 5). The Loihi helium plume does not appear as a distinct maximum in these P17 profiles as it does in the stations closer to Hawaii (Fig. 2). Instead, the Loihi plume here is expressed as an upward turn of the $\delta(^3He)$ contours at depths of 1000 to 1500 m between 14°N and 24°N (Fig. 5). Because of the large distance between the proposed source and these P17 stations, it is difficult to demonstrate that this signal at 135°W is from Loihi. For example, this shallow ^{3}He could be due to shallow input from a hydrothermally active seamount at another location. However, the excess ^{3}He at 135°W is at the correct depth and latitude to be attributed to hydrothermal input on Loihi.

A more comprehensive view of the Loihi plume is provided when helium data from several different expeditions are combined. Figure 6, which shows $\delta(^3He)$% contoured on a surface at a depth of 1100 m (potential density $\sigma_\theta \cong 27.3$) (*17*), includes samples from expeditions CGC-91, S94F, and TPS-24, and WOCE lines P4, P16, P17, P18, and P19C (*14*). The Loihi ^{3}He signal is detectable in several of the TPS-24 stations north and east of Hawaii but is absent in all of the WOCE P4 samples along 8.5°N. Thus, it seems that the currents at this depth do not transport the Loihi hydrothermal signal as far south as 8°N.

The asymmetric ^{3}He distribution shown in Fig. 6 implies that transport is from west to east at latitude 20°N at depths of 900 to 1300 m. This flow is in the opposite direction to that suggested by the deeper ^{3}He plumes, which trend westward into the interior of the Pacific basin from injection sites along the EPR and JdFR. For example, the deep helium section along 10°N (*4*) clearly indicates westward transport of ^{3}He from venting sites on the EPR axis at ~105°W. This westward flow at 10°N is consistent with observations of asymmetric plume behavior during near-field investigations on the ridge axis (*18*). The helium plume from the JdFR also trends southwest into the interior of the Pacific basin from the injection sites in the far northeast Pacific (*3*). However, these plumes from mid-ocean ridge hydrothermal activity may be tracing a much different part of the circulation regime because they are much deeper (2000 to 2500 m in depth) than the Loihi plume.

The Loihi helium plume places some strong constraints on the intermediate depth circulation of the central north Pacific. The near-surface circulation of the north Pacific Ocean has been described in terms of two gyres: one large, midlatitude anticyclonic gyre, and another higher latitude, cyclonic gyre. Reid (*19*) notes that the centers of these two gyres move farther poleward with increasing depth. A map of steric height at 500 dbar relative to a 1500-dbar surface (*19, 20*) shows a flow that is westward in the vicinity of Hawaii, corresponding to the southern limb of this subtropical gyre. A similar map of steric height at 1000 dbar relative to 3000 dbar also indicates westward flow in the vicinity of Hawaii (*21*). These interpretations of the circulation are clearly at variance with the helium data. However, Yoshida and Kidokoro (*22*) and Reid and Mantyla (*23*) discuss an additional eastward flow at a depth of ~1000 m centered at ~20°N. This so-called subtropical counter-current agrees quite well with the eastward transport suggested by the Loihi helium plume distribution. Additional helium sampling planned in the vicinity of the Hawaiian islands will enhance our picture of the Loihi plume, thereby providing further constraints on the existence of this counter-current and the pattern of shallow circulation in the central Pacific basin.

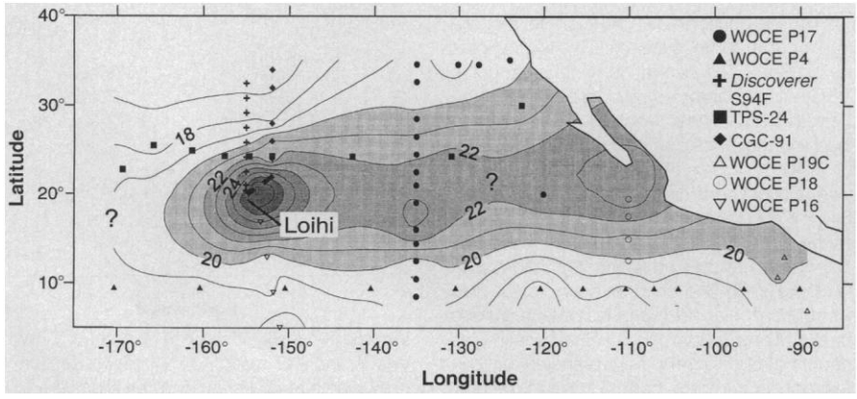

Fig. 6. $\delta(^3He)$% contoured on a surface at a depth of 1100 m, showing the broad lateral extent of the Loihi plume. In some cases, bottle data were interpolated to 1100-m deep surface. The contour interval is 1% in $\delta(^3He)$; the accuracy of the measurements is 0.25% (1σ). This figure includes data from eight different expeditions spanning the time interval from 1985 to 1994. Although these data are not synoptic, the sampling period is relatively short compared with the time scale for circulation at this depth. Helium data along WOCE lines P4 and P16 were provided by W. Jenkins (*4, 23*).

REFERENCES AND NOTES

1. J. E. Lupton and H. Craig, *Science* **214**, 13 (1981).
2. H. Stommel and A. B. Arons, *Deep-Sea Res.* **6**, 217 (1960).
3. J. Lupton, R. Feely, G. Massoth, *Eos* (fall suppl.) **70**, 1131 (1989); J. E. Lupton, *J. Geophys. Res.* **95**, 12829 (1990).
4. Helium and tritium data from WOCE line P4 have been reported by W. J. Jenkins in Data Release 6.0 (WHOI Helium Isotope Laboratory, 25 August 1995), which is available at http://kopernik.whoi.edu/data/tps.html; some of these data are also reported in S. E. Wijffels *et al.*, *Deep-Sea Res.*, in press.
5. H. Craig, V. Craig, R. Comer, J. Costello, K. Farley, *Eos* (fall suppl.) **69**, 1478 (1988); J.-L. Cheminée *et al.*, *Earth Planet. Sci. Lett.* **107**, 318 (1991).
6. A. Malahoff, in *Volcanism in Hawaii*, R. W. Decker *et al.*, Eds. (U.S. Government Printing Office, Washington, DC, 1987), p. 133; D. M. Karl, G. M. McMurtry, A. Malahoff, M. O. Garcia, *Nature* **335**, 532 (1988); P. N. Sedwick, G. M. McMurtry, J. D. Macdougall, *Geochim. Cosmochim. Acta* **56**, 3643 (1992); F. J. Sansone, C. G. Wheat, G. M. McMurtry, J. E. Lupton, G. P. Klinkhammer, *Eos* (fall suppl.) **75**, 313 (1994).
7. M. D. Kurz, W. J. Jenkins, S. R. Hart, D. A. Clague, *Earth Planet. Sci. Lett.* **66**, 388 (1983); W. Rison and H. Craig, *ibid.*, p. 407; I. Kaneoka, N. Takaoka, C. A. Clague, *ibid.*, p. 427.
8. J. E. Lupton, *Annu. Rev. Earth Planet. Sci.* **11**, 371 (1983).
9. H. Craig, J. A. Welhan, D. R. Hilton, *Eos* (fall suppl.) **68**, 1553 (1987).
10. P. N. Sedwick, G. M. McMurtry, D. R. Hilton, F. Goff, *Geochim. Cosmochim. Acta* **58**, 1219 (1994); J. E. Lupton, F. J. Sansone, C. G. Wheat, unpublished data from 1993 *Pisces* dives on Loihi Seamount.
11. Y. Horibe, K.-R. Kim, H. Craig, *Eos* (fall suppl.) **64**, 724 (1983); K.-R. Kim, H. Craig, Y. Horibe, *ibid.*, p. 724.
12. H. Sakai *et al.*, *Geochem. J.* **21**, 11 (1987).
13. T. Gamo, J.-I. Ishibashi, H. Sakai, B. Tilbrook, *Geochim. Cosmochim. Acta* **51**, 2857 (1987).
14. The data presented here were collected on nine separate expeditions as follows: TPS-24, R.V. *T. G. Thompson*, 1985; WOCE P4, R.V. *Moana Wave*, 1989; WOCE P17, R.V. *Thomas Washington*, 1991; WOCE P16, R.V. *Thomas Washington*, 1991; CGC-91, *NOAA Ship Discoverer*, 1991; TT-014, R.V. *T. G. Thompson*, 1992; WOCE P19C, R.V. *Knorr*, 1993; S94F, *NOAA Ship Discoverer*, 1994; and WOCE P18, *NOAA Ship Discoverer*, 1994.
15. With the exception of expedition TT-014, the samples in this study were hermetically sealed into the copper tubing by cold-welding under high pressure with a hydraulic press [C. Young and J. E. Lupton, *Eos* (fall suppl.) **64**, 735 (1983)]. This method provides long-term sample storage without loss of integrity. However, for expedition TT-014, samples were sealed into copper tubing with standard refrigeration clamps [J. E. Lupton, *Earth Planet. Sci. Lett.* **32**, 371 (1976)]. Helium isotope measurements were made on a dual-collector, statically operated mass spectrometer at the Hatfield Marine Science Center, Newport, OR. The estimated precision is 1σ = 0.25% in $\delta(^3He)$, and 1σ = 0.5% in ^{3}He and ^{4}He absolute concentrations. However, because of leak-

age through the refrigeration clamps, the absolute concentration measurements for the TT-014 samples are accurate to only about 1 to 2%. The mass spectrometer system employed a low-temperature (40°K) charcoal trap to separate helium from neon before analysis.
16. M. Kodera, G. Igarashi, M. Ozima, *Earth Planet. Sci. Lett.* **87**, 266 (1988).
17. Potential density is the density of seawater ρ corrected for adiabatic effects by the use of potential temperature θ instead of in situ temperature *T*. θ is the temperature of a parcel of water that has been brought adiabatically to the ocean surface without thermal contact with the surrounding ocean. In oceanography, density is usually expressed as the density anomaly $\sigma = (\rho - 1) \times 10^3$. Thus, a potential density of $\sigma_\theta = 27.3$ corresponds to $\rho_\theta = 1.0273$ g cm^{-3}.
18. E. T. Baker, R. A. Feely, M. J. Mottl, J. E. Lupton, *ibid.* **128**, 1 (1994).
19. J. L. Reid, in *Evolution of Physical Oceanography*, B. A. Warren and C. Wunsch, Eds. (MIT Press, Cambridge, MA, 1981), pp. 70–111.
20. V. A. Burkov, R. P. Bulatov, V. G. Neiman, *Oceanology* **13**, 325 (1973).
21. L. Talley, personal communication.
22. K. Yoshida and T. Kidokoro, *J. Oceanogr. Soc. Jpn.* **23**, 88 (1967); *ibid.*, p. 231.
23. J. L. Reid and A. W. Mantyla, *J. Phys. Oceanogr.* **8**, 946 (1978).
24. W. Jenkins, personal communication.
25. J. G. Moore and W. W. Chadwick Jr., in *Mauna Loa: A Decade Volcano*, J. M. Rhodes and J. P. Lockwood, Eds. (Geophysical Monograph Series, American Geophysical Union, Washington, DC, in press).
26. I thank K. Roupe, R. Greene, G. Paradis, G. Lebon, C. Massey, and M. Landsteiner for assistance with sample collections at sea; L. Evans, R. Greene, R. Kovar, and G. Paradis for the shore-based sample processing and helium isotope measurements; A. Bobbitt for assistance with the figures; L. Talley, D. Roemmich, J. Swift, J. Bullister, G. Johnson, and G. Cannon, who served as chief scientists on the expeditions involved and provided strong support for the helium work; W. Jenkins for making his WOCE P4 and P16 data available before publication; and L. Talley, J. Reid, and W. Jenkins for helpful discussions. Supported by the NOAA VENTS Program and by grants OCE91-05884 and OCE92-96169 from the Ocean Sciences Division of NSF. This is PMEL contribution number 1698.

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Selected Elastic Moduli of Single-Crystal Olivines from Ultrasonic Experiments to Mantle Pressures

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Ultrasonic interferometric measurements, developed for polycrystalline samples in a multi-anvil apparatus, were extended to single-crystal samples of San Carlos olivine and forsterite. The elastic moduli, C_{22} and C_{55} of San Carlos olivine and C_{55} of pure forsterite, were measured to about 13 gigapascals. These data on C_{22} for San Carlos olivine and C_{55} for forsterite are consistent with earlier measurements and extrapolations. The C_{55} for San Carlos olivine increases linearly as a function of increasing pressure, unlike the earlier nonlinear behavior observed at high pressure with impulsive stimulated scattering techniques.

Understanding the dynamics of Earth's mantle depends critically on the models of its mineralogical and chemical composition as a function of depth. Direct information on the composition comes from comparison of seismic profiles of the mantle with the sound velocities of candidate minerals measured in the laboratory. Olivine $[(Mg,Fe)_2SiO_4]$ is one of the major constituents of the upper mantle; this mineral transforms to a β phase (wadsleyite) and a spinal polymorph (ringwoodite) at the pressures and temperatures of the mantle transition zone (410 to 660 km). The significance of the sound velocities of olivine and its high-pressure polymorphs in the interpretation of the mantle composition has motivated measurements on this mineral to successively higher pressures. The earliest ultrasonic measurements were limited to pressures below 1 GPa (*1*, *2*). These low-pressure data for olivine have been used to construct mantle mineralogical models (*3*). Webb (*4*) measured the sound velocities of single crystals of San Carlos olivine $[(Mg_{0.9}Fe_{0.1})_2SiO_4]$ in a liquid-medium pressure vessel to 3 GPa using ultrasonic interferometry; she observed a slightly nonlinear dependence of certain elastic moduli (C_{ij}) with pressure. Using impulsive stimulated scattering (ISS), Zaug *et al.* (*5*) measured the elastic moduli of San Carlos olivine to 12.5 GPa in a diamond-anvil cell and observed a pronounced curvature in the variation of C_{55} as a function of increasing pressure. Their data suggest that the *P*- and *S*-wave velocities of olivine at a depth of 410 km are lower than those calculated from the third-order finite strain extrapolation of low-pressure elasticity data (*3*).

Recently, Duffy *et al.* (*6*) and Zha *et al.* (*7*) measured the sound velocities of single-crystal forsterite (Mg_2SiO_4) using Brillouin spectroscopy in a diamond-anvil cell; their results exhibit good agreement with those of Yoneda and Morioka (*8*) measured to 6 GPa. Neither of these studies indicated a nonlinear behavior of C_{55} versus pressure. However, the issue of whether this curvature exists for iron-bearing olivine is unresolved because Yoneda and Morioka and Duffy *et al.* used pure forsterite crystals; no pure mode directions were measured in the latter study (*6*).

We report here the results of ultrasonic interferometric measurements on single crystals of both San Carlos olivine and pure forsterite in a multi-anvil apparatus (*9*). The goals of these experiments were (i) to test the feasibility of using this technique with single-crystal samples and (ii) to understand the behavior of the C_{55} mode of olivine under high pressure. We also report measurements for the longitudinal mode C_{22}, for which there is good agreement between the data of Webb (*4*) and those of Zaug *et al.* (*5*).

We measured the acoustic travel times through the olivine and forsterite samples by ultrasonic interferometry (*10*). To convert the travel times to elastic moduli, we used thermoelastic identities:

$$C_{ij} = C_{ij}^0(\rho/\rho_0)(L/L_0)^2(t_0/t)^2$$

where the subscript or the superscript zero denotes the value at ambient pressure. The quantity C_{ij} is the corresponding elastic modulus (ij = 22 or 55 in the present study), ρ is the density, L is the sample length, and t is the travel time. The precision in the travel time measurements is better than 0.2%, and the effect of the gold foil bond introduces uncertainties in the travel time on the order of 0.1%. Published data (*4*) were used to calculate the density

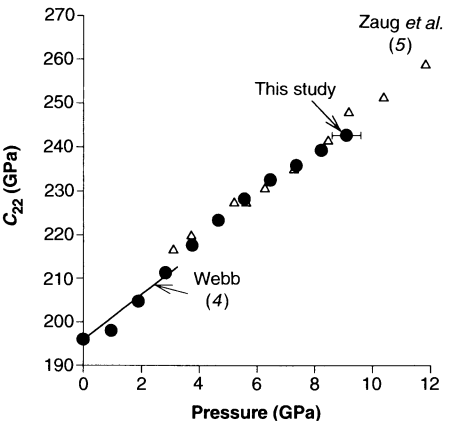

Fig. 1. Longitudinal elastic modulus C_{22} versus pressure for single crystals of San Carlos olivine. Filled circles, data from this study; solid line, data from (*4*); and triangles, data from (*5*). The uncertainties in pressures are indicated by the horizontal error bars shown for the highest pressure data points in all three figures. The uncertainties in the elastic moduli in this study are about the size of the symbol.

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