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TWO-STATION MEASUREMENTS OF RAYLEIGH WAVE GROUP VELOCITY ALONG THE HAWAI'IAN SWELL

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Abstract. Two-station measurements of Rayleigh wave group velocity between Midway Atoll and O'ahu provide a useful constraint on lithospheric thickness along the Hawai'ian Swell. Comparison of the observed dispersion curve with age-dependent, regionalized dispersion curves suggests that the swell acts as 50-110 m.y. old lithosphere, and not as 20-50 m.y. old lithosphere as is predicted by the currently favored hypothesis for the swell's formation. A preliminary isotropic shear velocity model for the swell suggests that the lithosphere may be as thick as 100 km. This value is difficult to reconcile with the lithosphere being substantially thinned during its passage over the Hawai'ian hotspot.

Introduction

The first two-station measurements of Rayleigh wave group velocities along the Hawai'ian Swell, a region of anomalously shallow seafloor between Hawai'i and Midway Atoll, provide knowledge about its deep seismic velocity structure. Such information introduces a new constraint for models of the swell's formation, which have been based primarily on its shape and subsidence rate, its gravity and geoid signatures, and its heat flow.

These measurements thus afford the prospect of testing the currently favored "lithosphere reheating" model [*Detrick and Crough*, 1978] (Figure 1). Estimates of the thinning required to explain the above observables indicate that the lithosphere can be only ~ 40-50 km thick at the hotspot [*Crough*, 1978; *Von Herzen et al.*, 1982]. Consequently, surface wave group velocities should be slower along the swell than along unperturbed lithosphere because they are controlled largely by lithospheric thickness [*Forsyth*, 1975; *Leeds*, 1975]. Until recently, the short distance between seismic stations on Hawai'i and O'ahu (~360 km) has precluded dispersion studies with data having sufficiently long wavelength to sample the depth of interest. To address this question, among others, we installed a three-component seismic station on Midway (MWY, 28.212° N, 177.371° W) in December 1988. By using Rayleigh waves recorded at MWY and at either the *IRIS/GEOSCOPE* station KIP or the *DWWSSN* station HON, both on O'ahu, classical two-station analysis over distances ~ 2100 km can isolate the swell's deep velocity structure and avoid the uncertainties due to poorly known group delays at the source.

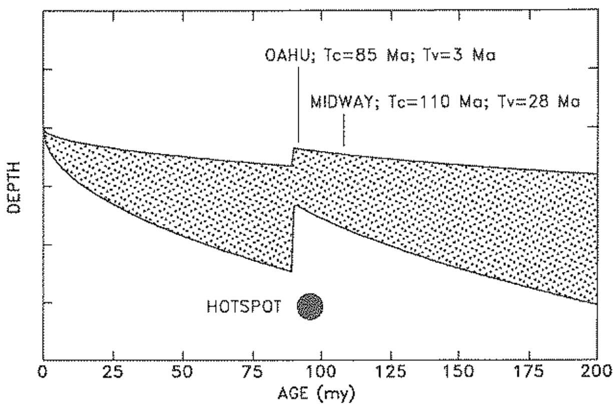

Fig. 1. Cartoon of lithosphere reheating model. Lithosphere thickens with age until it passes over hotspot, where it is thinned and rises isostatically, forming swell. Thereafter, lithosphere cools and again thickens; swell subsides. Positions of O'ahu and Midway are indicated, showing values of crustal age t_c, established from seafloor magnetic lineations, and age of volcanic edifices t_v, established radiometrically [after *Detrick and Crough*, 1978].

Data Selection and Analysis

The principal selection criterion for data was that the difference in propagation azimuths, δAZM, to stations MWY and either KIP or HON be less than 2° (Table 1). Because the data had wavelengths that were small ($\lambda \leq 200$ km) compared with the swell's 600 km width, this criterion insured that the data sampled the structure. Thus, three of the propagation paths lie virtually along the swell's longitudinal axis; only path 1 is slightly off the axis (Figure 2). This path, however, provided Rayleigh waves that propagated from SE to NW, whereas the other wavetrains traveled from NW to SE. Thus, we are confident that the results are not biased by clock errors or by deviations from great circle propagation due to velocity heterogeneities outside the common, interstation path. Moreover, by rotating the available NS and EW seismograms to the great circle azimuth we satisfactorily decoupled the Love and Rayleigh energy. This observation implies that local propagation azimuths equaled the great circle values, and argues against the possibility that the Rayleigh waves were refracted into

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TABLE 1: Earthquakes Used in This Study

Path	Date	Origin Time	Lat. °N	Lon. °E	m_b	δAZM	Station Pair
1	89 Jan 19	03:17:47.8	-4.010	-105.707	5.4	1.8	HON-MWY
2	89 Jan 28	07:26:55.2	33.257	141.484	5.4	0.7	MWY-KIP
3	89 Sep 05	11:25:57.7	29.418	128.753	5.2	0.6	MWY-KIP
4	89 Sep 05	13:03:39.1	29.531	128.583	5.0	0.5	MWY-KIP

the presumably low-velocity swell from the surrounding unperturbed lithosphere.

To eliminate relative instrumental phase delays from the signals, we deconvolved the KIP and HON data and reconvolved them with the MWY transfer function. The cross-correlograms of these signals with those recorded at MWY showed excellent coherence, and their amplitude spectra demonstrated reasonably good signal-to-noise ratios (S/N_{max}~10) for periods $30 \leq T \leq 50$ s. To extract group velocities from these spectra, we applied multiple filter analysis (MFA) by passing them through a sequence of narrow-band Gaussian filters, and selecting the group-delay times that maximized the instantaneous amplitudes at the filters' center frequencies [*Dziewonski et al.*, 1969]. We chose filter bandwidths that optimized the trade-off between time and frequency domain resolution [*Cara*, 1973]. We also corrected the instantaneous amplitudes for bias caused by convolving the symmetric Gaussian filters with sloping spectra; these corrections were largest for $T \geq 40$ s, where the spectral slopes are as large as -26 dB / octave. Up to $T \sim 55$ s, the four spectra yielded consistent group velocities (Table 2), with a peak $U_{max} \sim 4.09 \pm 0.01$ km/s at $T \sim 47$ s, but at longer periods, where the signals were weaker, the results were more variable and did not define a clear trend. We therefore take $T = 55$ s as the maximum period of reliability using this technique.

To check the MFA results, we recomputed the group velocities using phase-match filters [*Herrin and Goforth*, 1977] implemented with the frequency-variable approach (FVF) of *Russell et al.* [1988], and allowing for a 10% bias in estimated amplitudes due to spectral curvature. This iterative procedure requires an initial estimate of group velocity dispersion, so to test the sensitivity of the computations to the pilot dispersion curve, we analyzed each cross-correlogram twice: once using *Nishimura and Forsyth's* [1989] curve for oceanic lithosphere with age 20-52 Ma as the pilot, and once using their 52-110 Ma curve. In each case the solution converged within 3 iterations, and we again obtained consistent results for the eight trials (Table 2), regardless of which curve was used as the pilot. Using this technique, we determined that there was no significant contamination from overtones or multipathed arrivals, and found $U_{max} \sim 4.08 \pm 0.01$ s at $T \sim 41$ s for the fundamental mode.

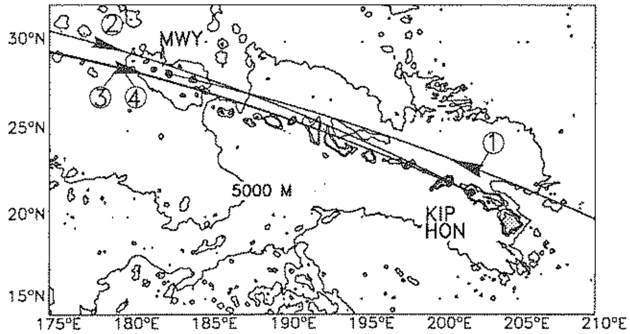

Fig. 2. Geometry of experiment showing Hawai'ian Swell, seismic stations, and propagation paths. Swell delineated by 5000 m contour of SYNBAPS bathymetric values. For clarity, propagation paths terminate at second station along great circle; arrows show propagation direction. Path numbers correspond to event numbers in Table 1.

The mean dispersion curves derived from the MFA and FVF are illustrated in Figure 3. Immediately apparent is the good agreement of the results obtained with the two techniques, particularly for $30 \leq T \leq 50$ s, where the signal was strongest. Even outside this range, where the two curves differ most, they agree within 0.5%. Toward longer periods, the MFA errors grow larger due to the decreasing S/N ratio. The FVF have better ability to extract information from low amplitude signals, so the FVF dispersion curve extends to $T = 70$ s, and has slightly smaller standard errors. The smoother shape of the FVF dispersion curve is due primarily to the initial smoothness of the pilot curves and the subsequent 4 segment b-spline interpolation of the curves in the algorithm.

Discussion

Contrary to our expectations based on the reheating model, the average group velocities along the swell are consistent with values for unperturbed, mature oceanic lithosphere. This can be seen by comparing the measure-

TABLE 2: Average Midway-O'ahu Group Velocities

Period (s)	U_{MFA} (km/s)	Std. Error (km/s)	Period (s)	U_{FVF} (km/s)	Std. Error (km/s)
26.3	3.977	0.019	31.0	4.036	0.007
27.5	3.992	0.011	32.0	4.044	0.007
28.8	3.996	0.010	33.0	4.052	0.008
30.1	4.009	0.009	34.1	4.060	0.008
31.5	4.020	0.012	35.3	4.066	0.009
33.0	4.023	0.012	36.6	4.072	0.009
34.7	4.042	0.006	37.9	4.076	0.010
36.2	4.050	0.006	39.4	4.079	0.010
38.3	4.067	0.009	41.0	4.080	0.010
39.8	4.081	0.002	42.7	4.079	0.010
41.8	4.087	0.004	44.5	4.077	0.010
44.0	4.093	0.008	46.5	4.072	0.010
46.0	4.088	0.009	48.8	4.066	0.010
48.2	4.088	0.014	51.2	4.057	0.009
50.6	4.064	0.018	53.9	4.046	0.009
53.2	4.029	0.015	56.9	4.032	0.008
55.4	4.014	0.021	60.2	4.016	0.007
			64.0	3.997	0.006
			68.3	3.975	0.006

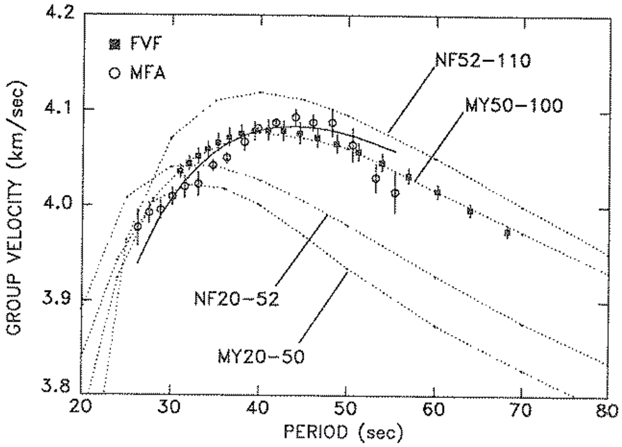

Fig. 3. Summary of Rayleigh wave group velocities observed along Hawai'ian Swell. Symbols: average values (± 1 standard error) of individual curves from four earthquakes, constructed using MFA or FVF techniques. Dashed lines: pure-path dispersion curves for age provinces in the Pacific Ocean Basin. Curves with MY prefix from *Mitchell and Yu*, [1980]; curves with NF prefix from *Nishimura and Forsyth*, [1989]; numbers following prefix correspond to ages spanned by curve. Solid line: fit to observations from inverse model (Table 3, Figure 4).

ments (Figure 3) with two sets of regionalized dispersion curves established by pure-path analyses of large suites of Rayleigh waves travelling through different age provinces of the Pacific Ocean Basin [*Mitchell and Yu*, 1980; *Nishimura and Forsyth*, 1989]. The two regionalized curves for each province span slightly different age ranges, which helps explain the small (~1%) systematic differences between them. Within this uncertainty, however, the group velocities observed between Midway and O'ahu agree with values for seafloor having ages $50 \le t \le 110$ Ma. If we consider the variation of crustal age, t_c, along the swell, this observation might be expected. From seafloor magnetic lineations [*Cande et al.*, 1989] we infer that t_c around O'ahu is ~ 85-95 Ma, the uncertainty being due to the proximity of the Molokai fracture zone. The crustal age around Midway is ~ 110 Ma. This range, $85 \le t_c \le 110$ Ma, is toward the upper bound of the older age province.

However, in the context of the reheating model we must also consider the lithosphere's *thermal* age, t_{th}, which we presume to have been reset during passage over the hotspot. The K-Ar age of the volcanic edifice, t_v, from O'ahu's shield-building stage averages 3 Ma [*Doell and Dalrymple*, 1973]. Therefore, according to the reheating model, 3 m.y. ago the lithosphere at O'ahu acquired the thermal and mechanical characteristics of 25 m.y. old lithosphere, and so now should have $t_{th} = 28$ Ma. Similarly, the radiometric age of the volcanic edifice underlying Midway is 28 Ma [*Dalrymple et al.*, 1977], so the lithosphere at Midway should have $t_{th} = 53$ Ma. Because the variation of thermal age predicted by the model, $28 \le t_{th} \le 53$ Ma, nearly matches the bounds of the younger of the illustrated age provinces, $20 \le t \le 50$ Ma, we would expect that group velocities along the swell should follow the lower set of regionalized dispersion curves. As they do not, it appears that dispersion along the Hawai'ian Swell depends on t_c, rather than on t_{th}.

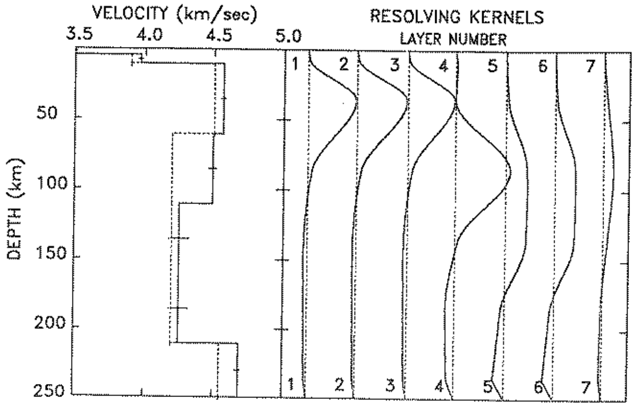

Fig. 4. Shear velocity model for Hawai'ian Swell, obtained by inverting group velocities. Dashed line is 7-layer starting model; solid line is final result (Table 3). Resolving kernels demonstrate that only the lithosphere (layers 3 & 4) is well resolved. The solution is particularly insensitive to the ocean and crust (layers 1 & 2). The large change between the starting and final velocities for layer 4 suggests thick lithosphere between Midway and O'ahu.

The simplest interpretation of these comparisons is that the lithosphere has not been appreciably thinned by the hotspot. This conclusion appears to be supported by a shear velocity model of the swell, obtained by inverting the averaged MFA group velocities with a generalized least-squares algorithm that employs singular value decomposition of the data kernel matrix (Figure 4). For this inversion we computed initial partial derivatives from a starting model that consisted of an ocean, a single crustal layer, a high-velocity upper mantle lid, and a three-layer low-velocity zone (LVZ) overlying a halfspace (Table 3). We assumed that all layers were flat, with constant, isotropic velocities. To fit the observed dispersion curve using this parameterization, the shear velocity in the uppermost layer of the LVZ had to increase from 4.20 km/s to 4.49±0.02 km/s, which is consistent with values found in the lid. The shear velocities in the two deeper layers of the LVZ remained, however, within one σ of their starting value.

The resolving kernels demonstrate that the data's bandwidth was sufficient to resolve the velocity structure down to ~ 100 km. The lid and the uppermost layer of the LVZ (layers 3 and 4), having large, compact kernels, were clearly resolved, but the deeper layers, having smaller, broader kernels were not. Moreover, with this parameterization there was little trade-off between the crust and upper

TABLE 3: Starting and Final Inverse Models

Layer N	Thickness (km)	β_{start} (km/s)	β_{final} (km/s)	σ (km/s)
1	4.5	0.0	0.0	0.0
2	6.0	3.90	3.97	0.02
3	50.0	4.50	4.57	0.02
4	50.0	4.20	4.49	0.02
5	50.0	4.20	4.26	0.07
6	50.0	4.20	4.26	0.07
7	---	4.55	4.68	0.02

mantle velocities, or between the lid and the LVZ. If the lithosphere was thinned as much as predicted by the reheating model, our data should have sensed the transition between lithosphere and asthenosphere easily. To further substantiate this conclusion, we are processing more data as they become available. We are computing group and phase velocities, and are continuing to refine the inverse model, specifically to investigate the precise depth of the lithosphere-asthenosphere boundary, possible crustal thickening along the Hawai'ian Ridge, and the effects of anisotropy. For now, however, the observed group velocities indicate that the lithosphere, as defined by shear velocity, is ~100 km thick between Midway and O'ahu.

Other geophysical evidence suggests that the deep structure beneath the Hawai'ian Swell is neither anomalously slow nor warm. *Sipkin and Jordan* [1980] noted that travel-time residuals of multiple ScS phases having bounce points along the swell's northern flank indicated a normal velocity structure. *Zhang and Tanimoto's* [1989] tomographic study of the Pacific Basin demonstrated that a low velocity region indeed exists, but is confined to the immediate vicinity of Hawai'i; it does *not* extend NW along the swell. *Von Herzen et al.* [1989] offered evidence that heat flow over the swell may not be higher than over "unperturbed" seafloor of equal crustal age, again counter to predictions by the reheating model. Despite crossing the swell where the reheating model predicts the largest anomalous surface heat flux (~ 700 km ESE of Midway), a new survey revealed no variation that could be correlated with the swell's axis. Considering this lack, and reevaluating older data from a profile along the axis [*Von Herzen et al.*, 1982], the authors concluded that a heat flow anomaly over the swell, previously taken to support the reheating model, may not actually exist. Heat flow anomalies for at least one other swell have also been questioned. *Stein and Abbott* [1990] have recently shown that, given the scatter of existing measurements, no HF anomaly can be identified unambiguously over the South Pacific Superswell. With the Rayleigh wave group velocities presented above, these lines of investigation present serious difficulties for the reheating model.

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