campsite along the route to natural pastures at even higher elevations. At different times of the year, people of the same general culture may have made use of extremely high sites such as Lauricocha, sites at moderate elevations such as Quishqui Puncu, and perhaps even coastal sites such as those found near Ancón (*5*). Lanning has recently stressed that the *lomas* vegetation of the desert coast comes to life only when sea fog (*garúa*) blankets the low hills from about May through November. In contrast, the season of maximum precipitation in the highlands corresponds to our winter. The seasonal variations in temperature are not great either in the highlands or on the coast, but in both zones there is marked seasonality in moisture availability and growth of vegetation. The relatively neat alternation of seasons would favor transhumance, or seasonal migrations, through the steep gradient of Andean altitudinal zones, at least until the time of really productive, settled agriculture. Seasonal movements would clearly benefit hunter-gatherers, but incipient horticulturalists (particularly of root crops) might also find transhumance attractive. Finally, whether Andean camelids are the game animals or the subjects of initial domestication, they should be expected to follow, or be improved by, seasonal changes in pasture. Andean agriculture may have its beginnings elsewhere than at the sedentary coastal midden sites where it is best documented at present.

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Seismic Delay Times: Correlation with Other Data

Abstract. *Travel-time residuals of seismic* P-*waves were expanded in spherical harmonics to determine their global variations. The expansion coefficients were correlated with similar coefficients of geopotential, variations in heat flow, and the surface topography of Earth. Although none of the correlation coefficients is very high, best values are between the seismic delay times and variations in gravitational potential and between heat flow and surface topography.*

Recently an increasing number of worldwide data have been obtained and analyzed on heat flow (*1*), gravitational potential (*2*), and more recently the delay times of seismic *P*-waves relative to a worldwide average (*3*). Variations of these quantities laterally on Earth indicate the presence of heterogeneities in Earth's crust or mantle, or in both. The nature and causes of these lateral heterogeneities, as well as the depth to which they extend, constitute an important problem in geophysics; understanding and solution of the problem require more than one set of data and a joint interpretation of various observations.

As a first step in this direction we have chosen to investigate correlation between the various sets of data. The global distribution of each set can best be expressed by spherical harmonic expansion, and the correlation coefficient can be computed by use of the harmonic coefficients. These coefficients exist for Earth's heat flow, gravitational potential, and surface topography. We now describe spherical harmonic analysis of seismic travel-time residuals.

Travel times of seismic *P*-waves from earthquakes and explosions, determined at many stations, indicate certain deviations from the standard Jeffreys-Bullen tables (*4*). Part of the anomaly is systematic, varying as a function of epicentral distance, and probably due to slight inaccuracies of the tables; part is station dependent. In other words, regardless of distance, the seismic arrivals at certain stations are consistently early; at others, consistently late. Our interest is in these deviations from the average which are controlled by crust and mantle structures under the stations.

Seismic travel times and their residuals have been extensively analyzed statistically by Herrin and Taggart (*3*), who have determined residuals at 260 primary stations. Each determination was based on at least ten events at teleseismic distances. Thus azimuthal and lateral variations were averaged, and it can be assumed that the resid-

Table 1. Spherical harmonic expansion coefficients of seismic travel-time residuals.

M	$n=0$		$n=1$		$n=2$		$n=3$	
	C_{nm}	S_{nm}	C_{nm}	S_{nm}	C_{nm}	S_{nm}	C_{nm}	S_{nm}
0	0.320	0	−0.116	0	−0.016	0	−0.049	0
1			− .266	−0.144	.090	0.099	− .364	0.005
2					− .091	.210	.185	.083
3							.115	− .127

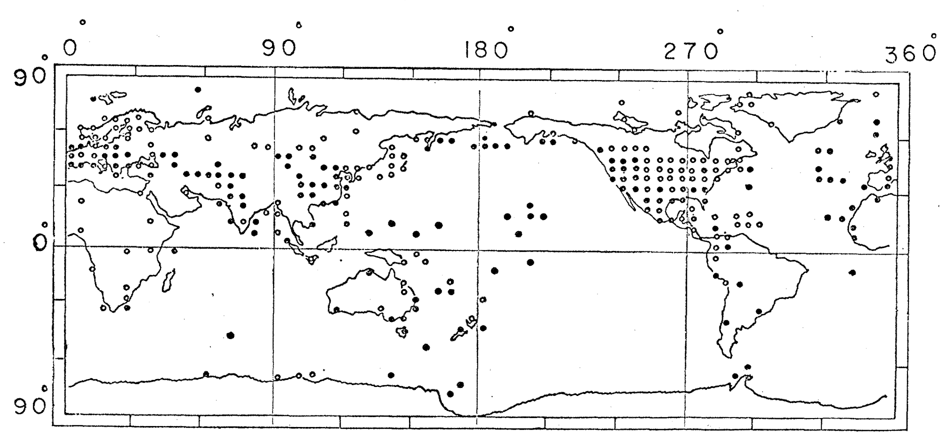

Fig. 1. Geographic distribution of data on seismic travel-time residuals after averaging over a 5° by 5° grid. Solid circles indicate positive residuals; open circles, negative.

uals represent delay along a path of normal incidence of seismic rays at any station. As well as at 260 primary stations, residuals were determined at 773 secondary stations by interpolation.

For spherical harmonic analysis the residuals R_i (R, $t_{obs} - t_{ref}$) are averaged over a 5° by 5° grid of latitudes and longitudes. The average residual R is obtained by use of

$$\bar{R} = \sum_{i=1}^{M} R\,(\theta_i,\phi_i)\,\sin\theta_i \Big/ \sum_{i=1}^{M} \sin\theta_i$$

where $R(\theta_i,\phi_i)$ is the value at a station located at colatitude θ_i and east longitude ϕ_i, and M is the number of stations inside a square limited by $\theta,\phi \leqslant \theta_i,\phi_i \leqslant \theta + 5°\text{–}\phi + 5°$. After averaging, the number of data points were reduced to 289. The geographical distribution of these points (Fig. 1) is uneven; most are on the continents as one would expect from distribution of the stations, North America and Europe having the best coverage.

Because of the relatively small number and the uneven distribution of the data, in the spherical harmonic expansion we computed coefficients only through the third degree, using

$$R = \sum_{n=0}^{3}\sum_{m=0}^{n} (C_{nm}\cos m\phi + S_{nm}\sin m\phi)\cdot P_{nm}(\cos\theta)$$

where θ and ϕ are colatitude and east longitude, respectively, and P_{nm} is the totally normalized associated Legendre polynomial. We obtained C_{nm} and S_{nm} (Table 1) by the least-squares method.

Table 2. Spherical harmonic expansion coefficients of gravitational potential (cgs), heat flow (μcal/sec cm^2), and "equivalent rock" surface topography (m).

M	$n = 0$		$n = 1$		$n = 2$		$n = 3$	
	C_{nm}	S_{nm}	C_{nm}	S_{nm}	C_{nm}	S_{nm}	C_{nm}	S_{nm}
				Gravitational potential, × 10^6				
0							0.960	0
1							1.940	0.150
2					2.430	−1.390	0.720	− .780
3							.550	1.240
				Heat flow				
0	1.475	0	0.118	0	−0.107	0	0.037	0
1			.064	−0.018	.107	0.085	− .162	−0.009
2					− .044	.133	.043	.089
3							.110	.219
				"Equivalent rock" surface topography				
0	− 1340	0	226	0	214	0	− 76	0
1			508	361	243	246	− 60	116
2					− 371	− 64	− 376	358
3							86	507

Table 3. Correlation coefficients. "Equivalent rock" topography, ERT.

	Seismic	Geoid	Heat flow	ERT
Seismic	1.00	−0.58	0.26	−0.39
Geoid		1.00	− .21	− .26
Heat flow			1.00	.52
ERT				1.00

The map of the P-wave travel-time residuals (Fig. 2), based on the computed coefficients C_{nm} and S_{nm}, is characterized by a very high positive peak in the Pacific Ocean. This peak may be artificial, since the distribution of data is extremely sparse and mainly in the islands. Arrivals at the island stations such as Hawaii are delayed more than those at the average continental stations. Relatively high delays in the circum-Pacific tectonic belt further contribute to this peak. Shield areas of Asia and North America are characterized by early arrivals.

The seismic residuals can be interpreted in terms of velocity variations in the crust or in the low-velocity zone or transition zone of the mantle. The magnitudes are such that the necessary variations in velocity can be distributed in a layer about 200 km thick without one exceeding the limits of accuracy of velocities determined by other seismic methods.

The correlation of seismic travel-time

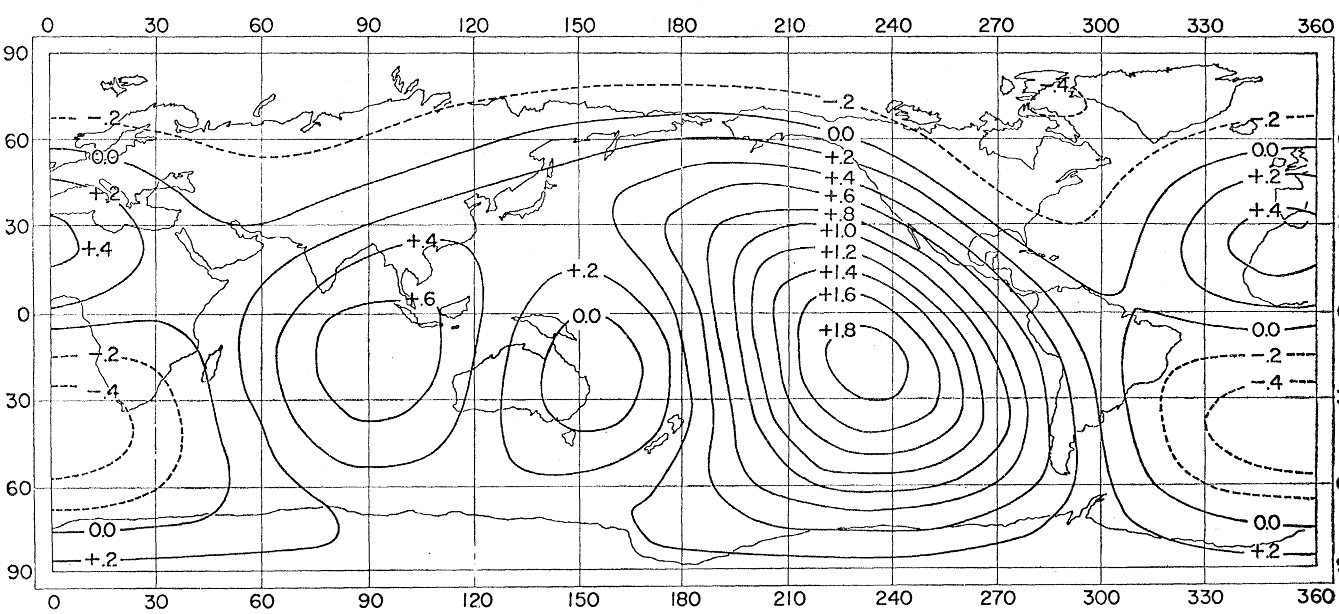

Fig. 2. Contours of P-wave travel-time residuals based on third-degree and third-order spherical harmonic expansion.

residuals with other geophysical data, such as heat flow, geopotential variations, and surface topography, may indicate the presence or absence of some relation between these quantities, and may point to some common explanation of lateral heterogeneities. The spherical harmonic coefficients for the geopotential variations (*2*), heat-flow values (*1*), and "equivalent rock" topography of Earth's surface (*5*) are listed in Table 2.

Correlation coefficients between two sets of data are computed by use of the spherical harmonic coefficients and the equation

$$\rho = \sum_{n=0}^{3}\sum_{m=0}^{n}(C_{nm}\cdot C'_{nm} + S_{nm}\cdot S'_{nm}) \Big/ \left\{\left[\sum_{n=0}^{3}\sum_{m=0}^{n}(C^2_{nm} + S^2_{nm})\right]^{1/2} \cdot \left[\sum_{n=0}^{3}\sum_{m=0}^{n}(C'^2_{nm} + S'^2_{nm})\right]^{1/2}\right\}$$

This analytic representation of correlation is used rather than individual points, because the data sets do not always have common locations on Earth's surface.

None of the computed correlation coefficients (Table 3, as a matrix) is very high. First of all, the very small correlation coefficients between surface topography and seismic travel-time residuals or the geopotential variations indicate that, at least on a broad scale, the surface topography does not control the lateral variations of seismic and geoid data; the causes must be sought somewhere deep in the crust or in the mantle. Correlation between heat flow and topography is relatively good; higher surface areas seem to be characterized by higher heat flow; tectonic regions of continents and oceanic ridges seem to contribute to such a correlation. Heat flow and seismic waves seem to have a positive correlation coefficient indicating that areas of high heat flow are characterized by slower seismic arrivals. The apparently poor correlation between heat flow and geopotential variations contradicts Wang's results (*5*) from earlier data.

The best correlation among the data sets that we have considered is between seismic travel-time residuals and the gravitational potential (ρ, -0.58). The negative correlation signifies that, where there is a deficiency of mass, seismic travel times are longer or seismic velocities are lower—not an unexpected result; a linear relation between seismic velocities and densities exists for rocks and minerals of similar composition (*6*). Lack of larger correlation coefficients may reflect lateral variations in composition of the upper mantle; partly, insufficient and poorly distributed seismic data.

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Stable Magnetic Remanence in Antiferromagnetic Goethite

Abstract. *Goethite, known to be antiferromagnetic, acquires thermoremanent magnetization at its Neel temperature of 120°C. This remanence, extremely stable, is due to the presence of unbalanced spins in the antiferromagnetic structure; the spins may result from grain size, imperfections, or impurities.*

In studying the magnetic properties of minerals one may usefully consider both antiferromagnetic and ferrimagnetic materials. Among the better-known magnetic minerals are magnetite and maghemite—both ferrimagnetic. On the other hand, minerals such as hematite are dominantly antiferromagnetic; its magnetic properties have always been difficult to understand. In large grain sizes it carries a strong spontaneous magnetization which is anisotropic; in small grains, about 1 μ or less, it has only a small spontaneous magnetization but does carry a weak isotropic remanence. This weak remanence probably results (*2*) from unbalanced spins due to grain-size effects,

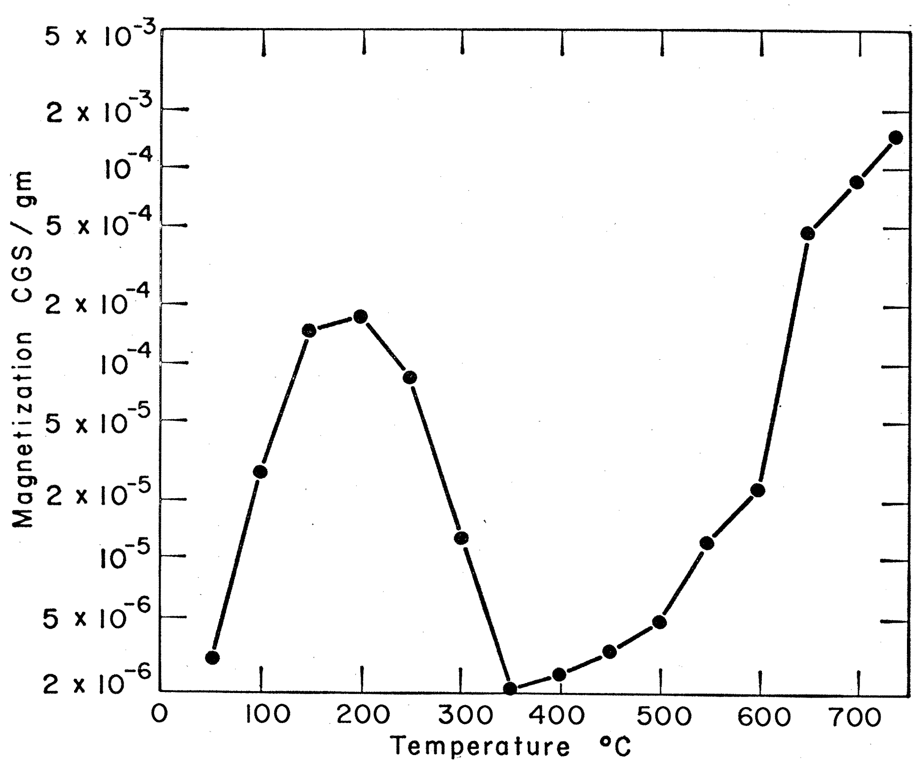

Fig. 1. Thermoremanent magnetism acquired during cooling, from temperatures shown, in Earth's magnetic field (sample No. 4A).