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POST-DOCTORAL PROGRAM IN SEISMOLOGY

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By

Department of Geology and Geophysics

Massachusetts Institute of Technoloby

Cambridge, Massachusetts 02139

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POST-DOCTORAL PROGRAM IN SEISMOLOGY

Annual Report

To

Air Force Office of Scientific Research

1 July 1966 - 30 June 1967

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Project Scientists - Frank Press 617/864-6900 Ext.3382
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(also: Keiiti Aki, Paul E. Green, Jr., and Edward J. Kelly, Jr.)

Short Title of Work - Post-Doctoral Program in Seismology

ABSTRACT

Seismic research projects undertaken by three Research Associates supported by this contract are described.

CONTENTS

INTRODUCTION

During the first year of this program 3 research associates (Dr. E. Husebye, M. Saito, and R. Turpening) have been appointed. They have been, either on individual basis or in cooperation with the other members of the Department of Geology and Geophysics, engaged in a variety of seismological research problems. These include both theoretical and data oriented studies and utilize data from LASA as well as single stations.

The Research projects that have been completed during the year or still in progress are : (1) Synthesis of dilatation and rotation seismograms, (2) Particle motion-mode filters, (3) Structure of the earth's core (4) Partial derivatives of phase velocity of surface waves with respect to anisotropy factors, (5) Application of array data processing techniques to a network of seismograph stations, and (6) Excitation of free oscillations and surface waves by a point source in a vertically heterogeneous earth.

These studies are briefly described in the following pages of this report.

REASEARCH PROJECTS

1. Synthesis of Dilatation and Rotation Seismograms (M. Saito)

From an array of identical 3-component stations it is possible to compute dilatation and rotation seismograms by carrying out the spatial differentiations numerically.

Let (x, y, z) be Cartesian coordinates with z axis positive upward, and let (u,v,w) be components of displacement in (x,y,z) direction. The purposes of this program is to compute

$$\theta_a = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$$

$$\varpi_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

from ovserved value of u and v. In these equations θ_a represents area dilatation and ϖ_z a component of rotation around the z axis. θ_a and ϖ_z are unaltered by a rotation of coordinates around a vertical axis. ϖ_z contains only SH type motions, but θ_a has P, SV and Rayleigh wave components. Besides θ_a and ϖ_z have different phase relationships to vertical, longitudinal and transverse displacements.

In a homogeneous infinite medium a plane P wave traveling in x-z plane can be written as

$$u \sim -ik \exp[i(\omega t - kx - \nu z)]$$
$$w \sim -i\nu \exp[i(\omega t - kx - \nu z)]$$
$$v = 0$$

in customary notations. Phase angles between θ_a and the longitudinal or vertical component can be computed from

$$\varpi_z = 0$$
$$\frac{\theta_a}{u} = -ik \qquad \text{(P-wave)}$$
$$\frac{\theta_a}{w} = -i\frac{k^2}{\nu}$$

Let us assume $\nu > 0$ so that seismic waves come from below. The phase angle between θ_a and w is always $-\pi/2$ and that of θ_a and u is $\pm\pi/2$ depending on the direction of propagation.

For SV waves in a homogeneous infinite medium we have

$$\varpi_z = 0$$
$$\frac{\theta_a}{u} = -ik$$
$$\frac{\theta_a}{w} = i\nu \qquad \text{(SV wave)}$$

Note that the phase angle between θ_a and w differs by π from that of P waves.

SH body waves and the Love waves have the same characteristics concerning θ_a and ϖ_z . The values of the phase angle are given in Table 3.

The relationship in Tables 1 and 3 holds even when the observation is made on a free surface. Table 2, on the other hand, does not hold true for an incident SV wave beyond the critical angle, for which $\arg(\theta_a/w)$ will assume either $\pm\pi$ or 0.

Rayleigh wave displacements at a free surface are given by

$$u \sim \epsilon \exp[i(\omega t - kx - \pi/2)]$$
$$w \sim \exp[i(\omega t - kx)]$$
$$v = 0$$

Where ϵ is the ellipticity of particle orbits at the surface and depends on the mode of propagation. Phase relationships for this case are

$$\varpi_z = 0$$
$$\frac{\theta_a}{u} = -ik \qquad \text{(Rayleigh Wave)}$$
$$\frac{\theta_a}{w} = -k\epsilon$$

Note that the phase angle $\arg(\theta_a/w)$ is $\pm\pi$ in contrast with that of body waves, and that it depends on whether the orbit is retrograde ($\epsilon < 0$) or prograde ($\epsilon > 0$) as well as the direction of propagation.

Since observations are made only at discrete points in space, differentiation of u and v must be done by interpolating observed values. Let u and v be interpolated by a set of functions $\phi_i(x,y)$:

$$u(x,y,t) \sim \bar{u}(x,y) = \sum_i a_i(t)\phi_i(x,y)$$

$$v(x,y,t) \sim \bar{v}(x,y,t) = \sum_i b_i(t)\phi_i(x,y)$$

Then dilatation and rotation are given by

$$\theta_a \sim \sum_i \left(a_i \frac{\partial \phi_i}{\partial x} + b_i \frac{\partial \phi_i}{\partial y} \right)$$

$$\omega_z \sim \sum_i \left(b_i \frac{\partial \phi_i}{\partial x} - a_i \frac{\partial \phi_i}{\partial y} \right)$$

A simplest estimate of coefficients $a_i(t)$ and $b_i(t)$ is given by the least square method. For this purpose it is convenient to adopt matrix formulation. Let $u_j = u(x_j, y_j, t)$ and $v_j = v(x_j, y_j, t)$ be observed values of u and v at j-th station, and let U and V be column matrices made from u_j and v_j, respectively. Then the least square estimate of a_i and b_i are given by

$$\begin{Bmatrix} A \\ B \end{Bmatrix} = \left[(\Phi \, \Phi^T)^{-1} \Phi \right] \begin{Bmatrix} U \\ V \end{Bmatrix}$$

where A and B are column matrices made of a_i and b_i.

The matrix Φ is defined by

$$\Phi = \begin{bmatrix} \phi_1(x_1, y_1) & \phi_1(x_2, y_2) & \cdots \\ \phi_2(x_1, y_1) & \phi_2(x_2, y_2) & \cdots \\ \vdots & \vdots & \end{bmatrix}$$

Substituting A and B we find that estimated value of u and v at each station are given by

$$\begin{Bmatrix} \bar{U} \\ \bar{V} \end{Bmatrix} = \left[\Phi^T (\Phi \Phi^T)^{-1} \Phi \right] \begin{Bmatrix} U \\ V \end{Bmatrix}$$

and that the residuals are given by

$$\begin{Bmatrix} E \\ F \end{Bmatrix} = \begin{Bmatrix} U - \bar{U} \\ V - \bar{V} \end{Bmatrix} = \left[1 - \Phi^T (\Phi \Phi^T)^{-1} \Phi \right] \begin{Bmatrix} U \\ V \end{Bmatrix}$$

Matrices for dilatation and rotation, whose components are dilatations and rotations estimated at stations, are given by

$$\begin{Bmatrix} [\theta_{a_j}] \\ [\varpi_{z_j}] \end{Bmatrix} = [\Phi_x^T (\Phi \Phi^T)^{-1} \Phi] \begin{Bmatrix} U \\ V \end{Bmatrix} \pm [\Phi_y^T (\Phi \Phi^T)^{-1} \Phi] \begin{Bmatrix} V \\ U \end{Bmatrix}$$

where Φ_x and Φ_y are derivatives of Φ defined by

$$\Phi_x = \begin{bmatrix} \frac{\partial \phi_1 (x_1, y_1)}{\partial x_1} & \frac{\partial \phi_1 (x_2, y_2)}{\partial x_2} & \cdots \\ \frac{\partial \phi_2 (x_1, y_1)}{\partial x_1} & \cdots & \\ \vdots & & \end{bmatrix}$$

Preliminary computations show remarkable difference between dilatation and rotation seismograms. As will be expected no distortional wave arrives at P arrival time, and both distortional and dilatational waves arrive at S arrival time. Comparing phase angles between strain seismograms and vertical, longitudinal and transverse component seismograms, one can identify several modes of propagation as well as the direction of propagation.

Table I. Phase angle for P wave

	direction of propagation	
	$+x$	$-x$
$\arg(\theta_a/u)$	$-\pi/2$	$\pi/2$
$\arg(\theta_a/w)$	$-\pi/2$	$-\pi/2$

Table 2. Phase angle for SV wave

	direction of propagation	
	$+x$	$-x$
$\arg(\theta_a/u)$	$-\pi/2$	$\pi/2$
$\arg(\theta_a/w)$	$\pi/2$	$\pi/2$

Table 3. Phase angle for SH (Love) wave

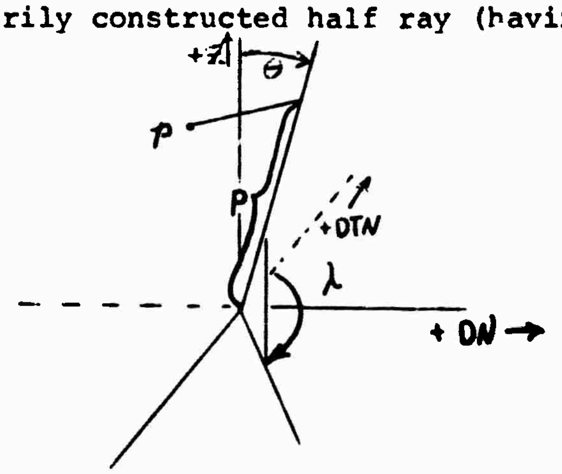
	$+x$	$-x$
$\arg(\tau_{wz}/v)$	$-\pi/2$	$\pi/2$

Table 4. Phase angle for Rayleigh wave

	retrograde ($\epsilon<0$)		prograde ($\epsilon>0$)	
	$+x$	$-x$	$+x$	$-x$
$\arg(\theta_a/u)$	$-\pi/2$	$\pi/2$	$-\pi/2$	$\pi/2$
$\arg(\theta_a/w)$	0	$\pm\pi$	$\pm\pi$	0

2. Particle Motion - Mode Filters (R. Turpening)

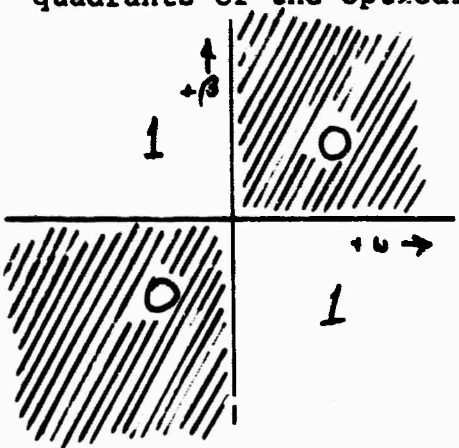
Analog - optical mode filtering schemes have been applied to seismic data to enhance rectilinear motion in the presence of retrograde elliptical motion (Turpening, 1966). The system involves projecting the instantaneous particle motion p(derived from three component information) onto an arbitrarily constructed half ray (having coordinates θ and λ).



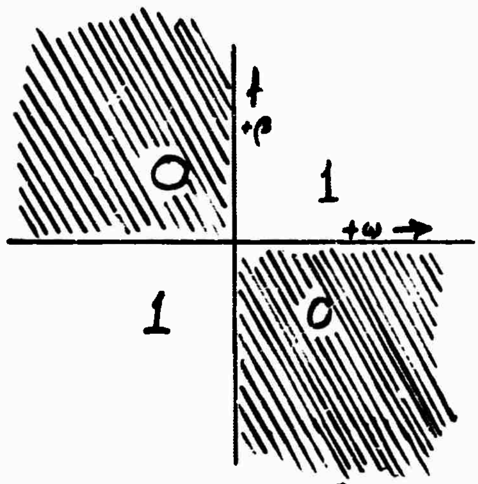
The projection P (t, θ, λ) that occurs along a certain finite number of these half rays is systematically ($\alpha = 2\pi\lambda + \theta$) placed on film in a variable density format. Such a film is then processed by optical diffraction. (Jackson, 1965).

Digital equivalent of above optical filter can be constructed. At the present, the algorithms are being programmed to apply these filters to digital data.

One such example, the one currently being studied, is merely the filter which is zero in quandrants one and three (or two and four) and unity in the remaining quadrants of the optical Fourier plane.



Filter 1



Filter 2

The analytical expressions representing the output of these two are:

$$\tilde{P}(\alpha,t) = \tfrac{1}{2}\{\cos\alpha\, Z(t) + \sin\alpha[\cos\lambda_s\, DTN(t) + \sin\lambda_s\, DN(t)]\}$$

$$\pm \tfrac{1}{\pi}A(\alpha)\left[\int_0^\infty \eta_c(f)\sin 2\pi f t\, df - \int_0^\infty \eta_s(f)\cos 2\pi f t\, df\right]$$

$$\mp \tfrac{1}{\pi}FC(\alpha)\left[\int_0^\infty d\tau_{n_c}(f)\sin 2\pi f t\, df - \int_0^\infty d\tau_{n_s}(f)\cos 2\pi f t\, df\right]$$

$$\mp \tfrac{1}{\pi}FS(\alpha)\left[\int_0^\infty dn_c(f)\sin 2\pi f t\, df - \int_0^\infty dn_s(f)\cos 2\pi f t\, df\right]$$

where: $\tilde{P}(\alpha,t)$ = filtered projection $P(\alpha,t)$

β = transform variable of α

$\alpha = 2\pi n + \theta_i$

$n = \lambda_i/\Delta\lambda$

$\bar{n} = [\alpha/2\pi]$

f = transform variable of t, ω frequency

$Z(t)$= time series representing vertical ground motion

$\eta_c(f), \eta_s(f)$= cosine and sine transforms, respectively of $Z(t)$

$DTN(t)$= time series representing ground motion in the direction transverse to the direction of noise propagation.

$dtn_c(f), dtn_s(f)$= cosine and sine transforms, respectively, of DTN(t)

$DN(t)$ = time series representing ground motion in the direction of noise propagation

$dn_c(f), dn_s(f)$= cosine and sine transforms, respectively of DN(t)

$$A(\alpha) = \cos\alpha\left[C_i(\alpha) - C_i(2\pi(\gamma+1)-\alpha)\right] + \sin\alpha\left[S_i(\alpha) + S_i(2\pi(\gamma+1)-\alpha)\right]$$

$$\begin{Bmatrix} FC(\alpha) \\ FS(\alpha) \end{Bmatrix} = \sum_{n=0} \begin{Bmatrix} \cos\lambda_n \\ \sin\lambda_n \end{Bmatrix} \left\{ \sin\alpha\left[C_i|\psi_1| - C_i|\psi_2|\right] - \cos\alpha\left[(-1)^{H(\psi_1)} S_i|\psi_1| - (-1)^{H(\psi_2)} S_i|\psi_2|\right] \right\}$$

$$\psi_1 = 2\pi(n+1) - \alpha$$

$$\psi_2 = 2\pi n - \alpha$$

$$C_i(a) = \int^{\infty} \frac{\cos x}{x}\,dx$$

$$S_i(a) = \int^{a} \frac{\sin x}{x}\,dx$$

$H(a)$ = unit step function at a = 0.

γ = number of incremental steps of λ

These expressions show that the above optical filters operate by adding certain input traces that have been shifted in phase by ninty degrees. The upper signs are taken when filter 1 is considered and the lower signs for filter 2 . Thus filter 1 will pass rectilinear motion. and prograde motion. Filter 2 will pass rectilinear and retrograde motion while attenuating prograde motion.

Other more complicated particle motion filters are also being constructed in the Fourier plane. If the filter exhibits no variation in the f- β direction than the filter will operate strictly on a "particle motion basis". However, those particle motion filters that operate by frequency filtering using judgements on particle motion may be constructed here by the appropriate variations in both the f and β directions.

3. Structures of the Earth's Core (E. Husebye)

A series of core models have been proposed by Jeffreys, Gutenberg, Bolt, Adams and Randall. These models agree fairly well with each other, except for a crucial transition zone between the liquid core and the inner core. Calculations of $dT/d\Delta$ and $d^2T/d\Delta^2$ from the velocity distribution of the above models, and comparison of these values with observed characteristics of core phases, indicate that none of the core models are quite satisfactory. For example, the precursors implied in Bolt's and Adams' and Randall's models have much smaller amplitudes relative to the PKIKP phase than should be expected.

Preliminary results of our studies includes observation of PKIKP down to about $\Delta \sim 105°$, some irregularities in $dT/d\Delta$ in the distance interval 110° - 140° with at least one caustic near $\Delta \sim 121°$. Precursors have been observed between $\Delta \sim 105° - 142°$, being most prominant between 105° - 120° and 130° - 142°. These precursors have usually no sharp onsets nor large amplitudes contrary to the normal behavior of core phases. An alternative explanation of these phases might be P wave leakage into the core from the diffracted P wave propagating in the mantle-core boundary.

In the crucial 140° - 150° distance interval, our observations favor a continuous wave velocity increase in the transition zone between the inner and outer core, roughly agreeing with that of Gutenberg. The amplitudes of waves traveling in the outer core are larger than those of the inner core, requiring a modification of the velocity gradient in this part of the core.

The data used in the above analysis come from North American WWSS and LRSM stations. At present we are combining this network of stations to a super array to compute $dT/d\Delta$ and $d^2T/d\Delta^2$ for the core phases.

4. Partial Derivatives of the Phase Velocity of Surface Waves with Respect to Anisotropy Factors.

(M. Saito)

Perturbations of phase velocities due to small changes in earth models are calculable from the partial derivative data of phase velocity. The same technique can be applied to compute dispersion curves for slightly anisotropic models.

A transversely isotropic medium which is symmetric around $x_3 = z$ axis is characteristized by five elastic constants, c_{11}, c_{33}, c_{44}, c_{12}, and c_{13}. In a cylindrical coordinate system (r, ϕ, z) with z axis positive upward the stress-strain relation is given by

$$p_{rr} = c_{11} e_{rr} + c_{12} e_{\phi\phi} + c_{13} e_{zz}$$

$$p_{\phi\phi} = c_{12} e_{rr} + c_{11} e_{\phi\phi} + c_{13} e_{zz}$$

$$p_{zz} = c_{13} e_{rr} + c_{13} e_{\phi\phi} + c_{33} e_{zz}$$

$$p_{r\phi} = \frac{c_{11} - c_{12}}{2} e_{r\phi}$$

$$p_{\phi z} = c_{44} e_{\phi z}$$

$$p_{zr} = c_{44} e_{zr}$$

In a homogeneous infinite medium three different types of plane wave solution exist. When the wave is propagating in a direction perpendicular to the z axis, three velocities are given by

$$P_H = \sqrt{\frac{c_{11}}{\rho}}$$

$$SV_H = \sqrt{\frac{c_{44}}{\rho}}$$

$$SH_H = \sqrt{\frac{c_{11} - c_{12}}{2\rho}}$$

For waves along the z axis, they are given by

$$P_V = \sqrt{\frac{c_{33}}{\rho}}$$

$$SV_V = SH_V = \sqrt{\frac{c_{44}}{\rho}}$$

It is convenient to use two elastic moduli λ and μ, and anisotropy factors ξ, φ and ζ defined by

$$\mu = c_{44}$$

$$\lambda + 2\mu = c_{11}$$

$$\xi = \frac{c_{11} - c_{12}}{2c_{44}}$$

$$\varphi = \frac{c_{33}}{c_{11}}$$

$$\zeta = \frac{c_{13}}{c_{11} - 2c_{44}}$$

In terms of the eigenfunction $\underset{\sim}{y}$, as defined in a previous paper (Saito, 1967), the partial derivative of the phase velocity of Love waves is given by

$$\frac{\xi}{c}\left[\frac{\partial c}{\partial \xi}\right] = \frac{1}{2\sigma^2 I_1}\left(\frac{c}{U}\right) k^2 \xi_1 - y_1^2$$

$$I_1 = \int \rho y_1^2 \, dz \tag{1}$$

For Rayleigh waves partial derivatives are given by

$$\frac{\varphi}{c}\left[\frac{\partial c}{\partial \varphi}\right] = \frac{1}{2\sigma^2 I_1}\left(\frac{c}{U}\right)\left\{\frac{1}{\varphi}\frac{1}{\lambda+2\mu}\left(y_2 + k\zeta\lambda y_3\right)^2\right\}$$

$$\frac{\zeta}{c}\left[\frac{\partial c}{\partial \zeta}\right] = \frac{1}{2\sigma^2 I_1}\left(\frac{c}{U}\right)\left\{-\frac{\zeta}{\varphi}\frac{2k\lambda}{\lambda+2\mu} y_3\left(y_2 + k\zeta\lambda y_3\right)\right\}$$

$$I_1 = \int \rho \left(y_1^2 + y_3^2\right) dz \tag{2}$$

From these data we calculate perturbation of c due to changes in ξ φ and ζ by

$$\Delta c = \int \left\{ \left[\frac{\partial c}{\partial \xi}\right]\Delta\xi + \left[\frac{\partial c}{\partial \varphi}\right]\Delta\varphi + \left[\frac{\partial c}{\partial \zeta}\right]\Delta\zeta \right\} dz \tag{3}$$

to the first order approximation. As an unperturbed model we may choose an isotropic model if the perturbations $\Delta\xi$, $\Delta\phi$ and $\Delta\eta$ are small enough.

As an example a Gutenberg-Bullen A model is perturbed to an anisotropic model, in which $\xi = \phi = 1.1$ and $\eta = 0.9$ between depths of 19 km and 100 km. The results are given in Table 1. In this table C is the phase velocity for isotropic model, ΔC_p the predicted value computed from (3), and ΔC is the exact value of perturbation. The accuracy of prediction is within 10%. It is interesting that the predicted value ΔC_p is always greater than the exact value.

Table 1

	Love Wave			Rayleigh Wave		
T(sec)	C(Km/sec)	ΔC	ΔC_p	C	ΔC	ΔC_p
10	3.69434	0.03007	0.03539	3.32953	0.01544	0.01722
20	3.91858	0.07224	0.07778	3.62059	0.06671	0.07382
30	4.12424	0.11357	0.11850	3.86213	0.05101	0.06141
40	4.24760	0.12252	0.12956	3.93965	0.03180	0.03895
50	4.31419	0.11223	0.12103	3.96395	0.02171	0.02126
60	4.35778	0.10288	0.11093	3.97672	0.01555	0.01832
70	4.39247	0.09596	0.10275	3.98919	0.01136	0.01303
80	4.42356	0.09071	0.09629	4.00466	0.00833	0.00936
90	4.45322	0.08649	0.09108	4.02403	0.00618	0.00678
100	4.48242	0.08291	0.08673	4.04753	0.00461	0.00499

5, Application of Array Data Processing Techniques to a Network of Seismograph Stations

Seismic Arrays have proved to be very effective and useful tools in seismology. With an array of instruments and appropriate data processing techniques significant gains in signal to noise ratio has been achieved. Furthermore, with Large Apperature Arrays quantities (such as $dT/d\Delta$) can be measured directly and interpreted in terms of structure.

Since the establishment of a very large aperature array is expensive, the possibility of the utilizing a net of single stations as a super large aperture seismic array was considered. For this purpose the Fennoscandia seismograph network was chosen. The network covers a large area with maximum dimension of 1800 km and crustal structures vary at different sites.

For the evaluation of such an array two separate studies were conducted. These are (1) Similarity of -wave signals frc station to station and (2) Signal-to-noise ratio improvement by simple processing. In the former, correlation of P-wave were computed between stations of varying distances. It is found that signal shapes remain the same although the amplitudes may vary. In the second,the array was phased by simple delay-and-sum operation and significant improvement in signal-to-noise ratio were observed both for earthquakes and explosions.

6. Excitation of Free Oscillations and Surface Waves by a Point Source in a Vertically Heterogeneous Earth

(M. Saito)

This work was described in a technical report and it will appear as an article in the J. Geophys. Res., within three months. The following is the abstract of the paper.

Radiation patterns of surface waves and free oscillations for vertically heterogeneous elastic media are derived for arbitrary sources using variational equations. The results are expressed in terms of normal mode solutions and source functions, and show that additional calculations other than normal mode solutions are unnecessary to construct radiation patterns. Source functions for a single force, a single couple, and double couple without torque, all in arbitrary directions, are derived.

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