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PRELIMINARY REPORT ON AND PROPOSAL FOR
FUTURE FOCAL MECHANISM STUDY OF NORTH
ATLANTIC EARTHQUAKES BY THE SURFACE
WAVE METHOD

K. Aki, et al

Royal Norwegian Council for Scientific and
Industrial Research

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Love dispersion, attenuation, focal depth, seismic moment and focal mechanism - would be useful quantities for discussing the tectonics of the North Atlantic.

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PROBLEMS AND HYPOTHESES

We are interested in the seismicity and earthquake mechanism of the Atlantic Ocean north of Iceland. Fig. 1 shows the map of epicenters determined for 528 earthquakes during the period 1955-1972, reproduced from Husebye et al (in press). They are shown in relation to major tectonic features such as the mid-ocean ridges, fracture zones and shelf edges. We are particularly interested in the mechanism of intra-plate earthquakes occurring in the Norwegian Sea between the Mohn's ridge and the Norwegian coast.

The mechanism of these intra-plate earthquakes was discussed by Husebye et al in relation to geological and geophysical data from the area within the context of plate tectonics. Their discussions suggest the following alternative hypotheses for their mechanism.

- 1) The post-opening marginal subsidence; in this case, we expect a normal faulting with fault strikes parallel to the coast.
- 2) The intra-plate stress which appears to have the horizontal compressive axis parallel to the direction of plate motion, as pointed out first by Mendiguren (1971) for the Nazca plate and later elaborated by Sykes and Sbar (1973). In this case, we expect a thrust faulting with fault strikes perpendicular to the direction of plate motion or a strike-slip faulting with the pressure axis parallel to the direction of plate motion.

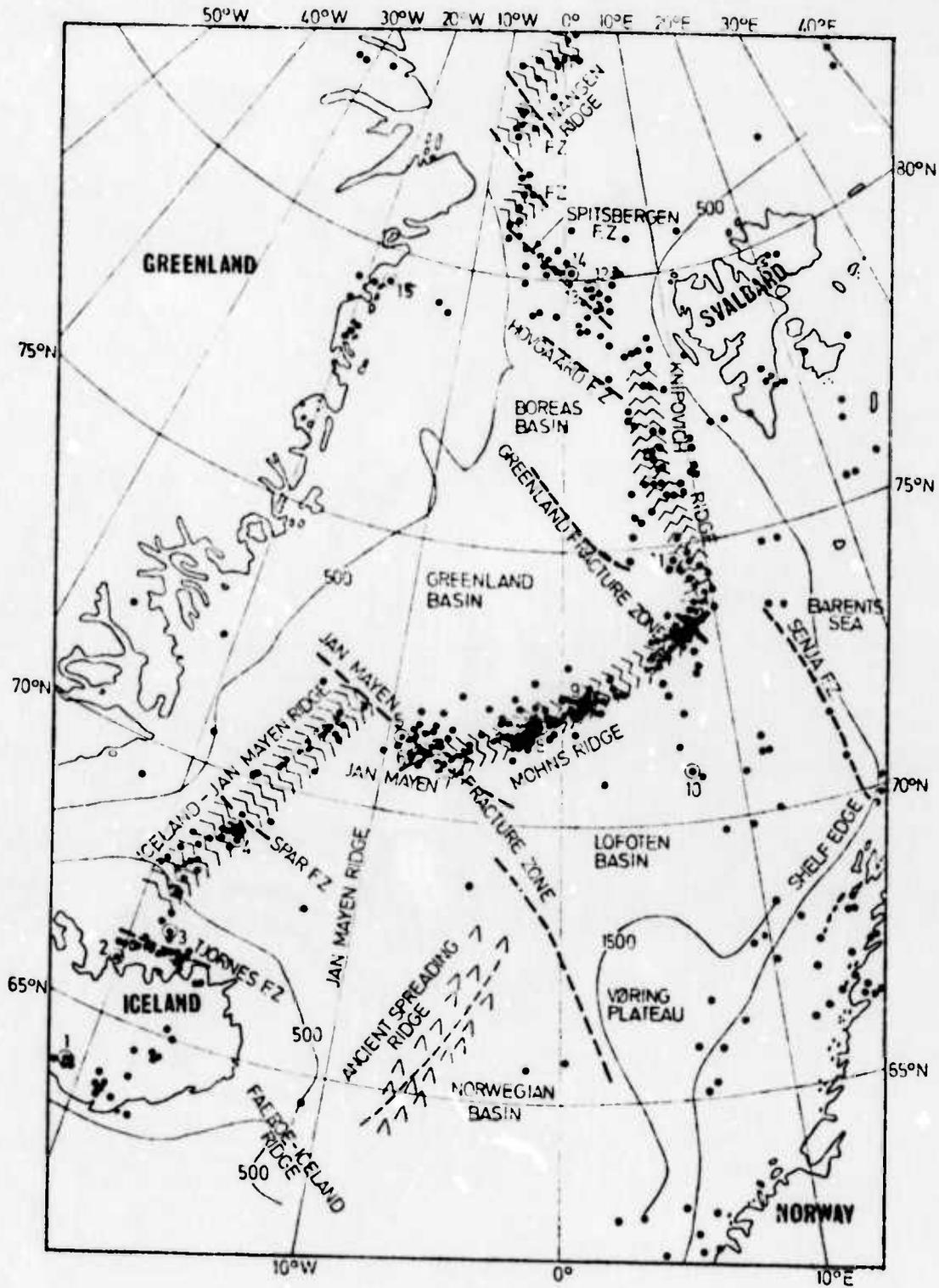


Fig. 1 Epicenter distribution (1955-1972) in the Norwegian-Greenland Sea and adjacent areas. Epicenters and selected sea bottom contours (in meters) are shown together with main structural features. Earthquakes for which focal mechanisms have been published are numbered from 1 to 15 (Husebye et al, in press). The two earthquakes used in analysis in this study are marked by crosses.

- 3) The seismic zone in the Norwegian Sea, especially the belt which continues southward as an apparent extension of the Knipovich ridge, may be a plate boundary. As shown schematically in Fig. 2, if the mid-Arctic ridge spreads faster than the Mohn's ridge, we expect right-lateral strike slip along the Knipovich ridge as well as along its extension into the Norwegian Sea. Two fault plane solutions published by Lazareva et al (1965) in this zone are right-lateral strike-slip along fault with the North-South strike, consistent with this hypothesis.
- 4) If the Mohn's ridge is spreading faster than the mid-Arctic ridge, we expect left-lateral strike-slip along the extension of the Knipovich ridge.

In order to examine these hypotheses, we shall determine the focal mechanism, focal depth and other source parameters as well as the surface wave dispersion and attenuation properties in various parts of the North Atlantic.

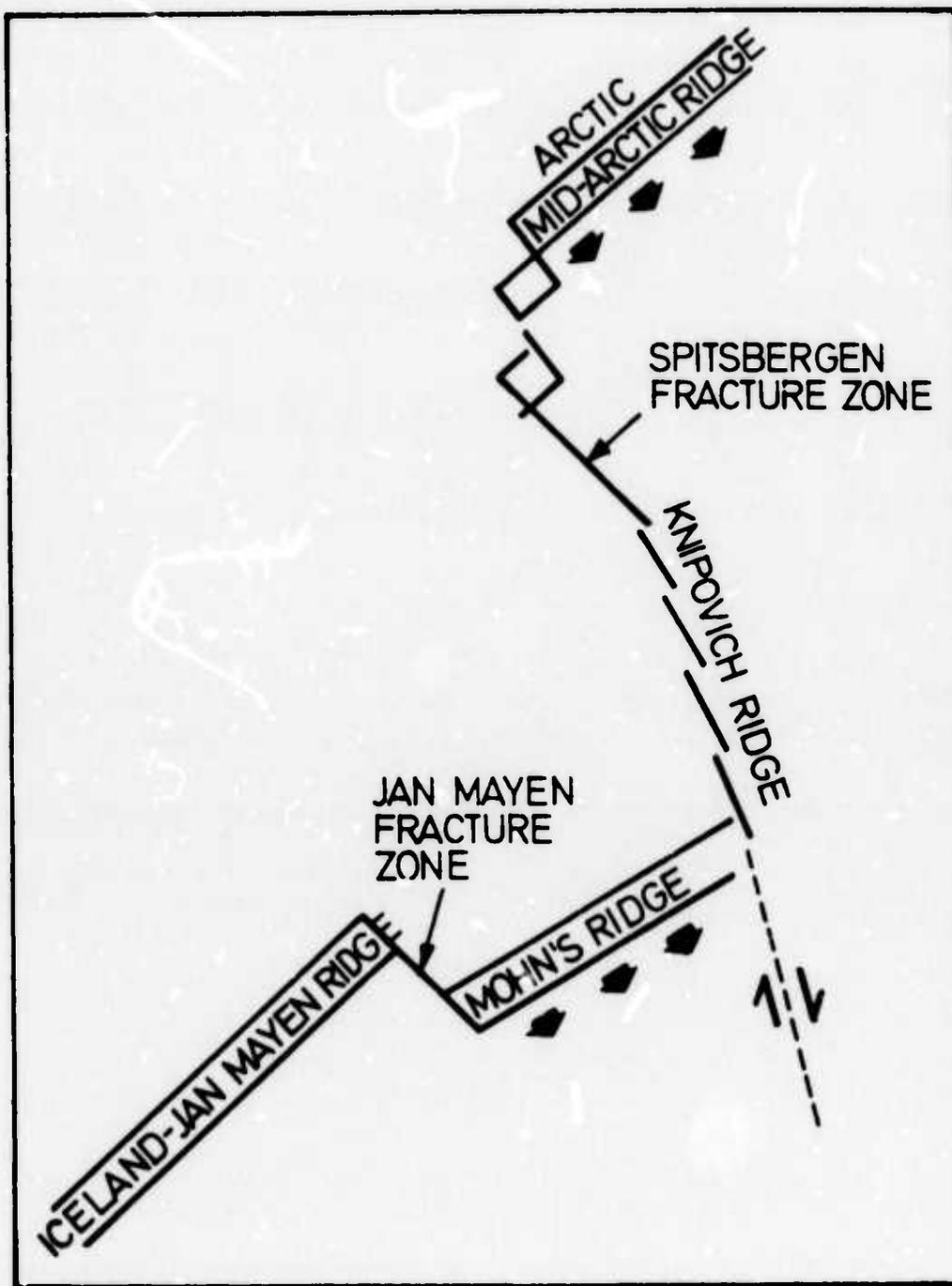


Fig. 2 Schematic view of principal spreading axis in the North Atlantic.

METHOD

As well known, reliable fault plane solutions can be obtained only for relatively large earthquakes (magnitude > 5.5) which give clear onset of P waves on WWSS LP records.

Our first step is to find as many as possible earthquakes with known fault plane solutions in the region of our interest. We shall use them as reference events when applying the surface wave method to smaller earthquakes.

The surface wave method can give us an accurate determination of focal depth of an earthquake if the fault plane solution is known (Weidner and Aki, 1973). We can also determine the phase velocity and attenuation of surface waves along the path from an epicenter to a station if the fault plane solution is known. Once the phase velocity and attenuation are known for various parts in the region of our interest, we can determine the source factor of amplitude and phase spectra for any earthquake in the area. If we have both Love and Rayleigh wave source spectra for a few different azimuths, we can probably make a reliable determination of the focal mechanism, seismic moment and focal depth. Additional data from body waves, such as the pP-P time difference and the sense of first P motion at crucial directions, would be helpful to increase the accuracy of the determinations. The outcome of the above studies - the dispersion, attenuation, focal depth, seismic moment and focal mechanism - are useful quantities for discussing the tectonics of the North Atlantic.

USE OF SURFACE WAVES

In analyzing surface waves, we shall assume that an earthquake is a slip-dislocation, and the earth is a laterally homogeneous elastic medium. For periods longer than 10

seconds and for earthquakes with $M \lesssim 6$, we shall further assume that the fault slip is a step-function in time and the effect of finite size of fault may be neglected (Tsai and Aki, 1970). We shall use a layered medium appropriate for the North Atlantic. The model used in calculations so far, denoted the Norwegian Deep Sea Basin model, is listed in Table 1

NORWEGIAN DEEP SEA BASIN MODEL				
Layer	Thickness (km)	Density (g/cm ³)	P-Velocity (km/sec)	S-Velocity (km/sec)
1	3.50	1.00	1.50	0.0
2	1.30	2.10	2.10	1.05
3	1.50	2.40	4.60	2.40
4	4.00	3.09	7.40	4.28
5	26.7	3.40	8.11	4.61
6	20.0	3.37	8.01	4.56
7	20.0	3.37	7.95	4.56
8	20.0	3.37	7.71	4.40
9	20.0	3.30	7.68	4.34

TABLE 1

Crust and upper mantle model for the Norwegian Sea used in this study. For Love wave calculations, the water layer is removed. The sedimentary and crustal layers are modeled after Hinz (1972) and Eldholm and Windish (in press). Note that the density and S-wave velocity of the sediments represent an intelligent guess. The upper mantle is typical for oceanic regions (Anderson, 1964).

Two computer programs have been written at Massachusetts Institute of Technology (M.I.T.) for calculating the amplitude and phase spectra of both Love and Rayleigh waves for the above models of source and medium. The first one is due to M. Saito, and computes the phase velocities and

eigenfunctions for an arbitrary layered medium. The second one is written by Y.B. Tsai, and computes the amplitude and phase spectra of Love and Rayleigh waves for an arbitrary dislocation source using the output of the Saito program. Tsai's program is based on the theory of Saito (1967), which is explained in detail in a class note by K. Aki. Both programs are working satisfactorily on the computer at NORSAR.

DATA

Husebye et al (in press) were able to collect only 15 fault plane solutions from about 15 years' earthquake data for the area. We are trying to obtain additional fault plane solutions by collecting and reading the WWSS and other records by ourselves. Reliable fault plane solutions are, however, expected only for relatively large magnitudes ($m_b \gtrsim 5.5$). On the other hand, the WWSS LP seismographs in Iceland, Greenland, Spitsbergen and Fennoscandia can register long-period Rayleigh and Love waves from earthquakes with M_s around 5. Further, the VLP seismograph at KON can record long period waves from earthquakes with M_s around 4. Thus, the surface wave method can be extended to earthquakes with magnitude one or two units lower than the P-wave fault plane method, thereby increasing the number of analyzable earthquakes by more than an order of magnitude. The increase in number of analyzable earthquakes is badly needed for the North Atlantic region, where the seismic activity is relatively low.

PRELIMINARY RESULTS

(1) The Mohn's Ridge Earthquake of 31 May 1971 - Event 1

According to Conant (1973), the fault plane solution of this earthquake consists of two nodal planes; one striking $N42^\circ E$ with dip angle 54° , the other striking $N52^\circ E$ with dip angle 64° . The focal parameters for this event are given

in Table 2. If the former is the fault plane, the fault is a normal fault with small right-lateral strike-slip. The Tsai program requires the slip angle ϕ , which is

EVENT	DATE (m/ d/ y)	O. TIME (h /m /sec)	LAT (deg)	LONG (deg)	DEPTH (km)	MAG (m_b) (M_s)	REGION
1	05/31/71	03.46.52.2	72.2N	1.2E	33	5.5 5.7	Mohn's Ridge
2	05/21/72	07.57.05.2	73.6N	7.6E	33	4.5 -	Mohn- Knipovich Ridge

TABLE 2

NOAA focal parameters for the two earthquakes used in analysis.

related to the difference $\Delta\psi$ between the strikes of two nodal planes and the dip angle δ of the auxiliary plane (when one of the nodal planes is called "fault plane", the other is called "auxiliary") by the following formula:

$$\cos \phi = \sin \Delta\psi \cdot \sin \delta \quad (1)$$

For Event 1, $\Delta\psi = 10^\circ$, $\delta = 64^\circ$, therefore $\cos \phi = 0.156$, $\phi = 81^\circ$.

The output of Tsai's program gives the amplitude and phase spectra at a certain azimuth measured counterclockwise from the strike of fault plane.

We choose the strike direction X as the positive X-axis, the upward vertical as the positive Z-axis. The positive Y-axis in the right-hand system, then, is fixed in the space. We define the dip angle as the angle between the fault-dip direction and the positive Y-axis. For the Mohn's ridge earthquake, taking the X-axis to $N42^\circ E$, the positive Y-axis is toward $N48^\circ W$. Since the fault plane is dipping to NW, the dip angle is 54° .

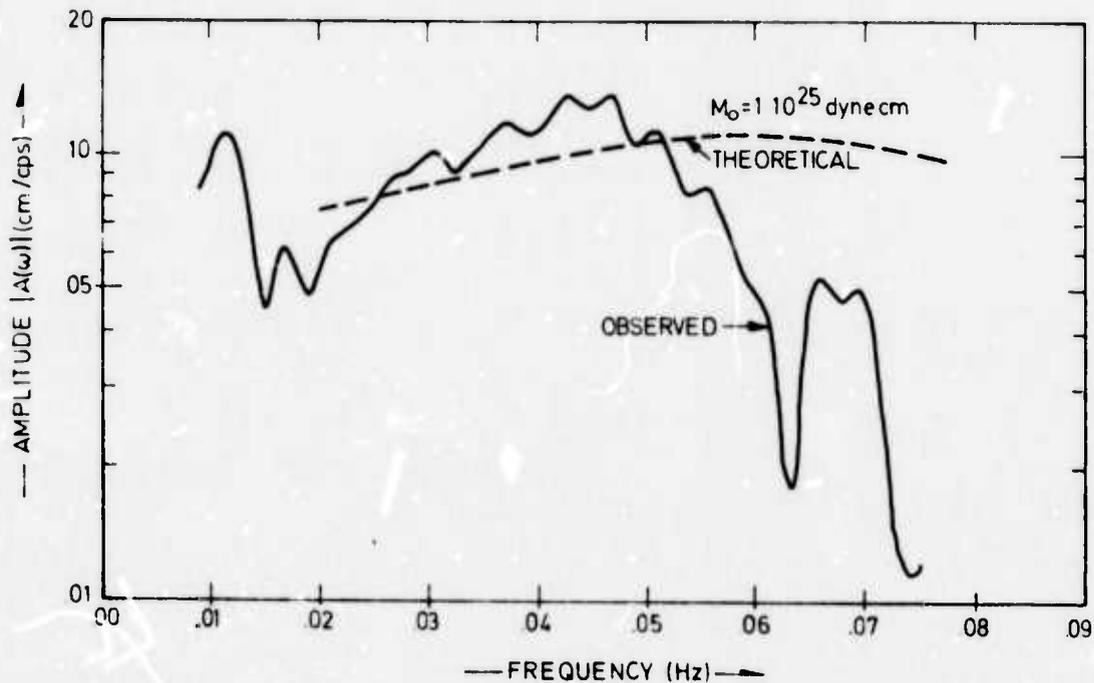


Fig. 3 Comparison of observed and theoretical Rayleigh wave spectra. The Rayleigh waves were recorded at KOM for the Mohn's ridge earthquake of 31 May 1971. The fault plane solution of Conant (1973) was used in the theoretical calculations, assuming a focal depth of 8 km. Fault plane strike is $N42^{\circ}E$ with dip angle 54° , auxiliary plane strike is $N52^{\circ}E$ with dip angle 64° .

The slip angle is the angle between the X-axis and the direction of slip of the body containing the positive Y-axis relative to the body containing the negative Y-axis. The angle is measured from the positive X-axis counterclockwise in the fault plane. The slip angle for the Mohn's ridge earthquake is 279° .

Tsai's program lists the amplitude $|A(\omega)|$ and source phase delay $\phi(\omega)$ under the heading of POINT AMP. and FOCAL PHASE respectively. For example, for Kongsberg $\Delta \approx 2000$ km and AZIMUTH $\approx 240^{\circ}$ from the Mohn's ridge earthquake which is taken at a focal depth of 5 km (below sea level),

$|A(\omega)| = 0.835 \times 10^{-26}$ cmsec/dynecm and $\phi(\omega) = 0.377$ at frequency 0.02 Hz. $|A(\omega)|$ is the displacement amplitude spectral density corresponding to a unit moment earthquake, $\phi(\omega)$ is measure in parts of a cycle. They are defined as

$$A(t) = \frac{1}{2\pi} \int |A(\omega)| \exp(i\omega t - i\frac{\omega\Delta}{C(\omega)} - i\phi(\omega)) d\omega \quad (2)$$

where $A(t)$ is the ground displacement in cm (already corrected for instrument response) and $C(\omega)$ is the phase velocity.

(2) Amplitude Spectrum of Rayleigh Waves

Fig. 4 shows the amplitude spectral density $|A(\omega)|$ for Rayleigh waves from the Mohn's ridge earthquake recorded

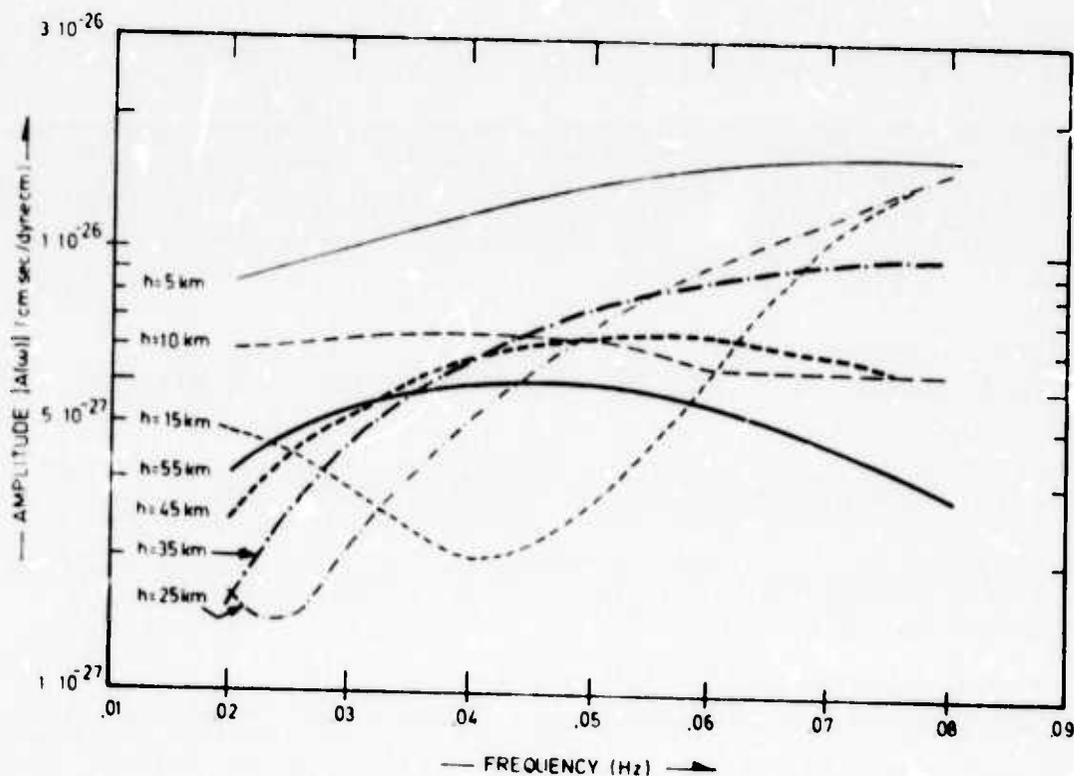


Fig. 4 Dependence of amplitude spectrum of Rayleigh waves on focal depth. The model is the Mohn's ridge earthquake recorded at Kongsberg (KON).

at KON. The seismogram trace $f(t)$ is digitized and $|A(\omega)|$ is obtained as

$$|A(\omega)| = \left| \int f(t)e^{i\omega t} dt \right| / |I(\omega)| \quad (3)$$

where $|I(\omega)|$ is the magnification of the seismograph at frequency ω , which is the ratio of record amplitude to ground displacement.

The observed spectrum is compared in Fig. 3 with the theoretical one calculated for the fault plane solution given above using the Tsai program. The theoretical curve is given for a source with the seismic moment 1×10^{25} dyne cm buried at a depth (below sea level) of 8 km.

The estimation of seismic moment depends on the assumption on (1) focal depth, (2) focal mechanism, especially the azimuth of fault strike, and (3) attenuation. The effect (3) may be neglected for periods longer than 20 sec for the epicentral distances we are interested in here. The effect (1) is very complicated as shown in Fig. 4. This effect requires a very careful examination. Fig. 4 suggests, for example, the best fit between theoretical and observed may be obtained for depths greater than 55 km. This was, as a matter of fact, a conclusion given in Tsai's thesis (1969) that the dip-slip earthquakes in the mid-ocean ridges are deep. Later, Weidner and Aki (1973) showed by the combined use of phase and amplitude spectra that these earthquakes must be shallow. The discrepancy at $T < 20$ sec between the observed and theoretical amplitude such as shown in Fig. 4 is attributed to the attenuation due to soft sediment by Weidner (1972).

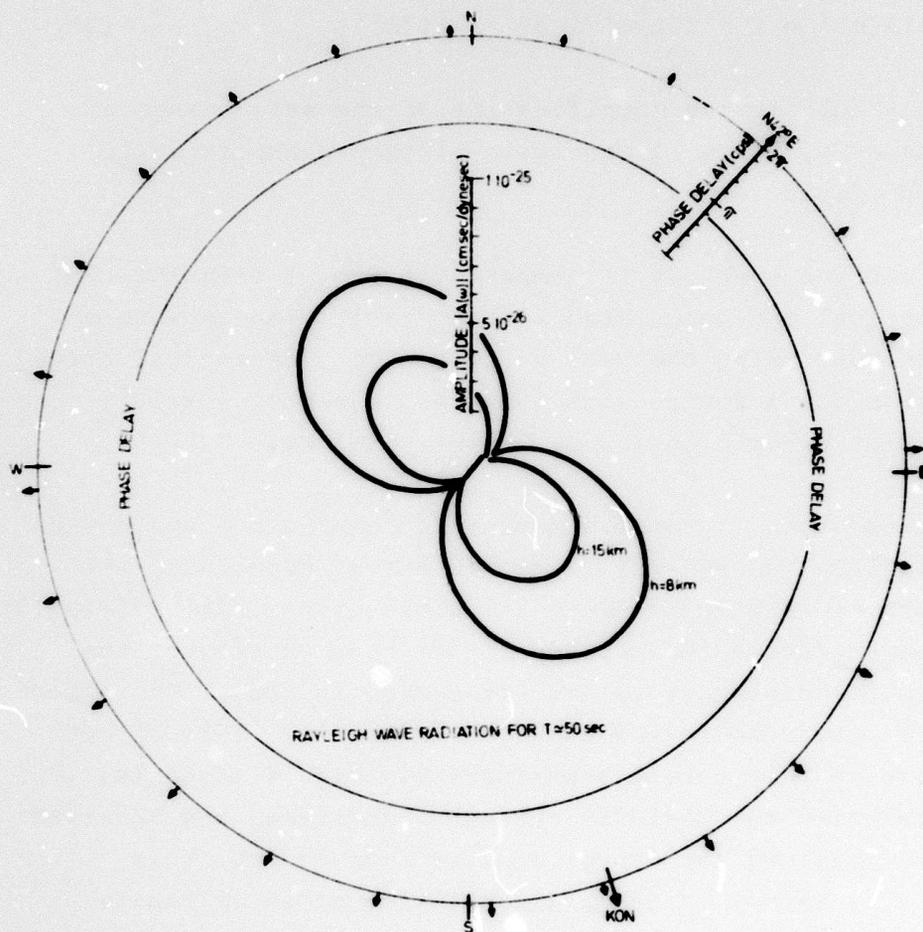


Fig. 5 Rayleigh wave radiation from the Mohn's ridge earthquake. For details on focal parameters see the caption of Fig. 3.

The effect (2) can be examined with the use of Fig. 5, which shows the radiation pattern of $|A(\omega)|$ for all azimuths. A small change in the strike of the fault which is not very well constrained for this earthquake can cause a large change in $|A(\omega)|$ near the nodal direction. To resolve the above ambiguities due to uncertain focal mechanism and focal depth, we must use additional information from

the phase spectra of Rayleigh waves as well as the amplitude and phase spectra of Love waves.

(3) Phase Spectrum of Rayleigh Waves

The phase spectrum of Rayleigh waves is a very powerful tool for determining the focal depth. For example, in the case of Mohn's ridge earthquake, the theoretical source phase at 50 seconds period is roughly 0.375 for all azimuth for depths $h < 25$ km, and changes to 0.7 ~ 0.8 for depths $h \geq 35$ km. This difference can be easily detected once reliable dispersion curve for Rayleigh waves is established for the area.

From the record $f(t)$ of Rayleigh waves (vertical component, upward positive) we find the phase delay $\phi(\omega)$, defined as

$$f(t) = \int |F(\omega)| e^{i\omega t - i\phi(\omega)} d\omega \quad (4)$$

where t is measured from the origin time of an earthquake.

For a single mode, we can write

$$\phi(\omega) = \omega \frac{x}{C(\omega)} + \phi_0(\omega) + \phi_{INST}(\omega) \pm 2N\pi \quad (5)$$

where x is the epicentral distance, $C(\omega)$ is the phase velocity, $\phi_{INST}(\omega)$ is the phase delay of record trace relative to ground displacement. For the WWSS LP record, $\phi_{INST}(\omega)$ approaches $\pi/2$ as $\omega \rightarrow \infty$. (This can be used to check the π error in phase calculations.)

In the output of Tsai's program, $\phi_0(\omega)$ is called the FOCAL PHASE. For simple fault geometrics, the values of $\phi_0(\omega)$ are shown in Figs. 6 and 7. They can be used to check blunders such as the π error.

SOURCE PHASES FOR SIMPLE FAULT GEOMETRICS

Vertical (upward positive) Rayleigh wave displacement

$$A_R(t) = \int |A_R(\omega)| \exp[i\omega t - i\omega\Delta/C_R(\omega) - \phi_R] d\omega$$

Transverse (counterclockwise positive) Love wave displacement

$$A_L(t) = \int |A_L(\omega)| \exp[i\omega t - i\omega\Delta/C_L(\omega) - \phi_L] d\omega$$

(1) Strike-slip on a vertical fault

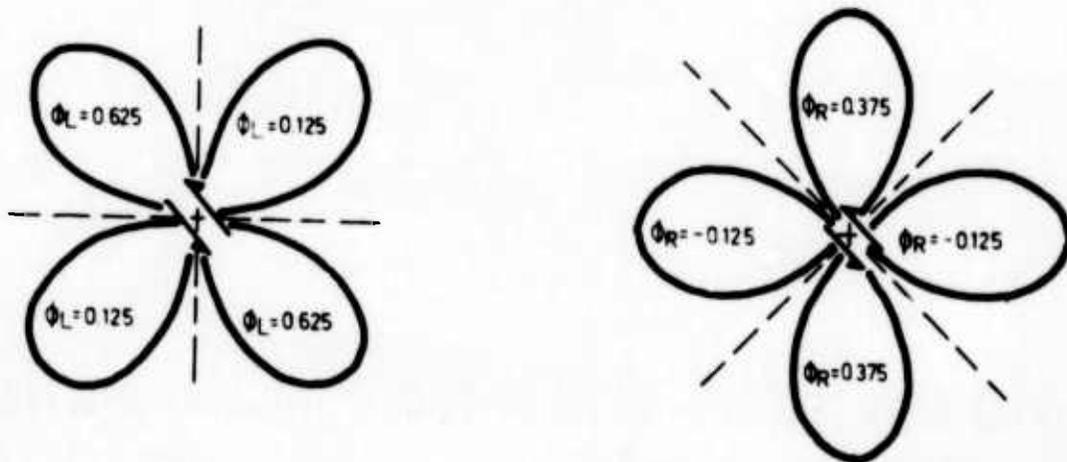


Fig. 6 Source phases for Love and Rayleigh waves for simple fault geometrics, i.e., strike-slip on a vertical fault. Δ is epicentral distance, $C(\omega)$ and ϕ are phase velocity and phase delay for respectively Rayleigh or Love waves.

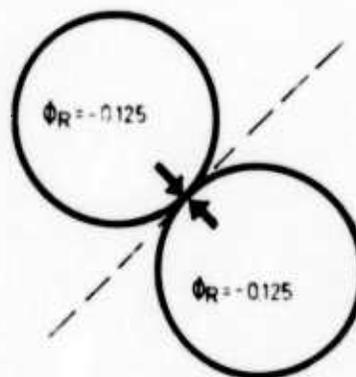
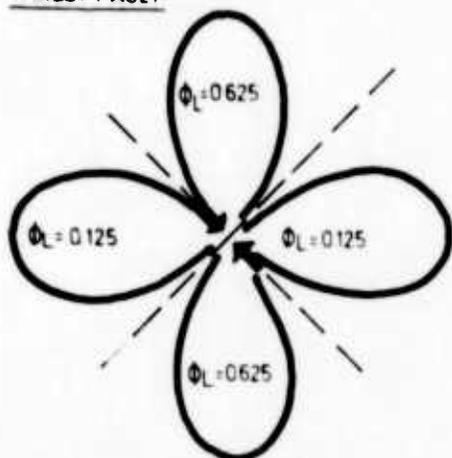
From the observed phase $\phi(\omega)$, one can obtain the phase velocity $C(\omega)$ if the source phase $\phi_0(\omega)$ is known. For Event 1, we assumed that the focal depth is less than 25 km and therefore $\phi_0(\omega) = 0.375$ at $T \approx 50$ sec. For different choices of integer N , one gets the values of $C(\omega)$ at $T=50$ sec., such as..., 3.51, 3.99, 4.62, Obviously, 3.51 km/sec is too low and 4.62 is too high. They are both definitely unacceptable. This fixes the integer N , and determines uniquely the entire phase-velocity curve as shown in Fig. 8.

The observed phase velocity curve is compared with the theoretical one used for the eigenfunction calculation by the Saito program. Clearly, the path from the Mohn's ridge to KON is a mixed one (e.g., see Talwani and Eldholm, 1972) and the observed curve departs from the theoretical one for the ocean considerably at short period.

SOURCE PHASES FOR SIMPLE FAULT GEOMETRICS

(2) Dip-slip on an inclined fault

THRUST FAULT



NORMAL FAULT

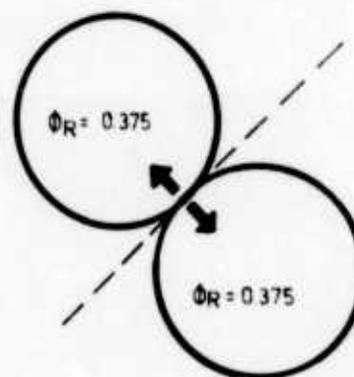
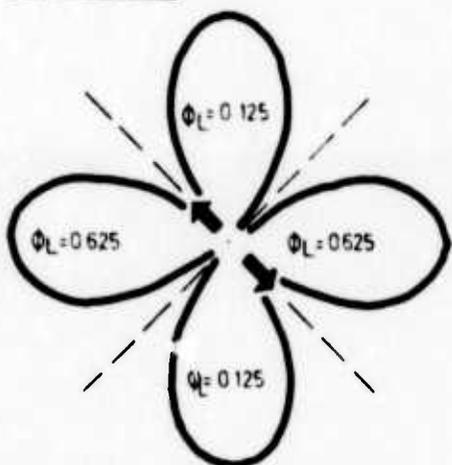


Fig. 7 Source phases for Love and Rayleigh waves for simple fault geometrics, i.e., dip-slip on an inclined fault.

Suppose that the focal depth was not less than 25 km but greater than 35 km. Then, the source phase changes by about π , giving alternative values of phase velocities 3.73 and 4.28 at $T \sim 50$ sec. These values seem to be rather too low or too high, but additional data will be needed to resolve this definitely.

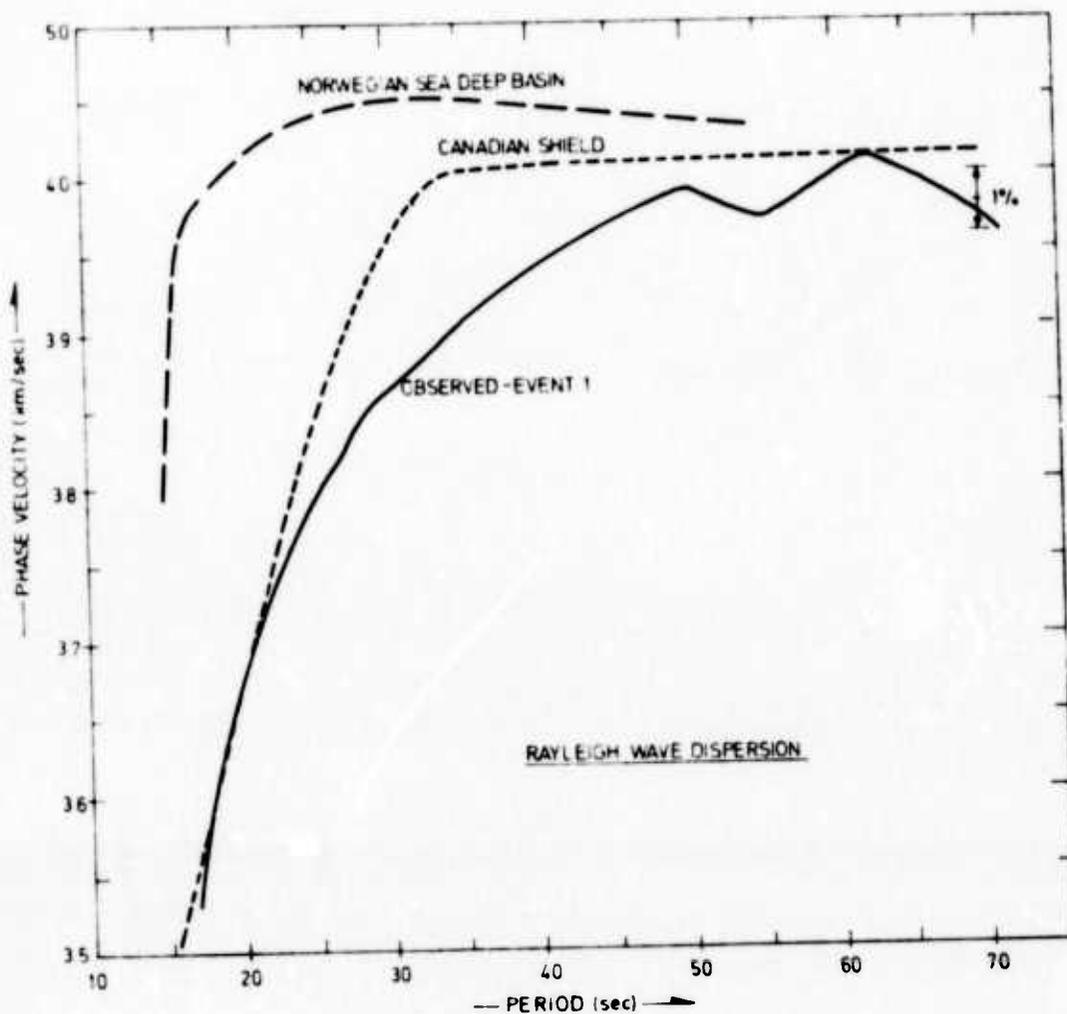


Fig. 8 Rayleigh wave phase velocity obtained by analysis of the John's ridge earthquake of 31 May 1971 (Event 1) using Kongsberg (KON) records. The Norwegian Sea Deep Basin dispersion curve is calculated from the model in Table 1, while the Canadian Shield curve is taken from Brune and Dorman (1963).

(4) Amplitude Spectrum of Love Waves

The amplitude spectrum of Love waves does not depend critically on the focal depth as Rayleigh waves do. Fig. 9 shows the dependence for the case of KON record for the Mohn's ridge earthquake.

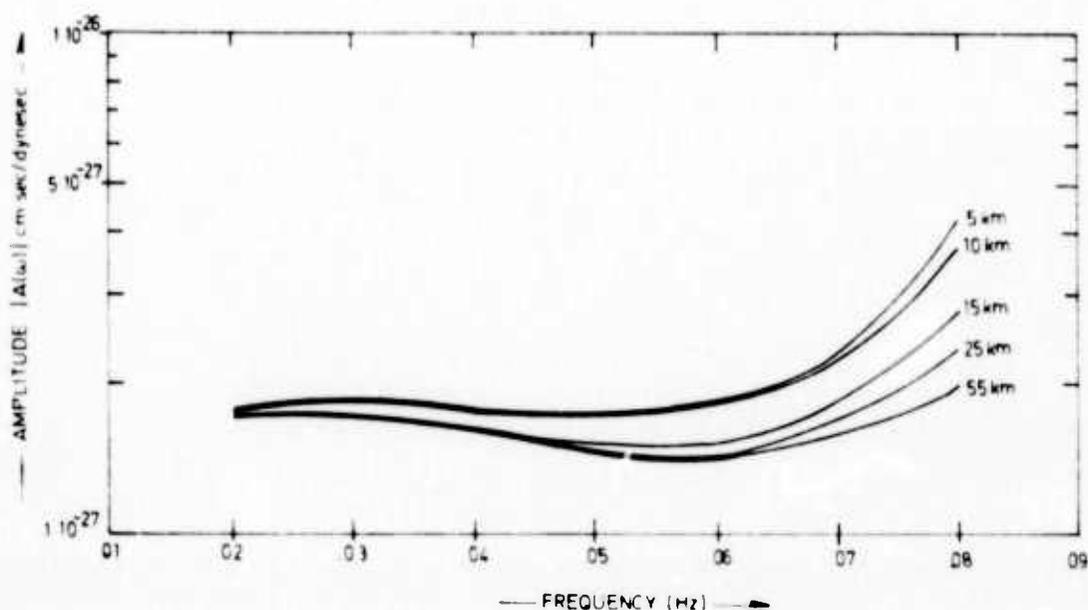


Fig. 9 Love wave amplitude dependence on focal depth for the Mohn's ridge earthquake recorded at Kongsberg.

The observed spectrum is compared with the theoretical in Fig. 10. A good fit of the amplitude spectral shape is obtained for $20 < T < 50$ sec. The observed spectral density at $T \doteq 50$ sec is around $0.35 \cdot 10^{-1}$ cm sec, and the theoretical density is $0.17 \cdot 10^{-26}$ cm sec/dyne cm. This gives a seismic moment of $\frac{0.35 \cdot 10^{-1}}{0.17 \cdot 10^{-26}} \approx 2 \cdot 10^{25}$ dyne cm. This is about a factor of 2 greater than the value previously estimated from Rayleigh waves.

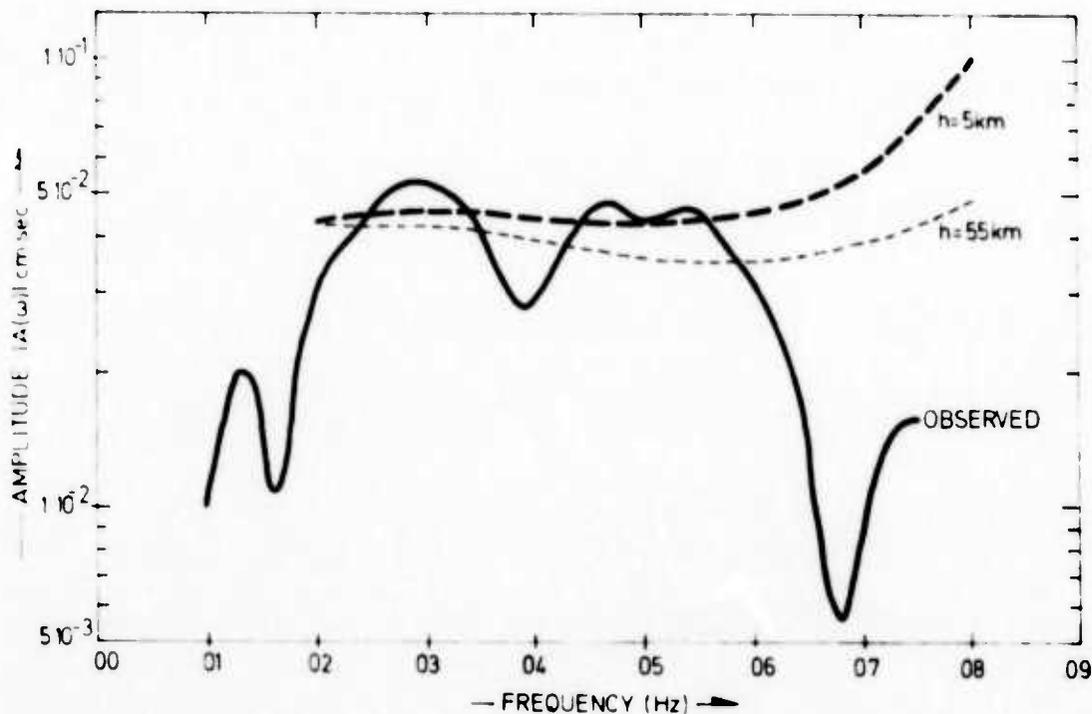


Fig. 10 Observed Love wave amplitude spectrum for the Mohn's ridge earthquake of 31 May 1971, using the Kongsberg station.

The above discrepancy may be resolved if we allow a small change in the fault plane solution. As shown in Fig. 11 and also in Fig. 5 both Love and Rayleigh wave amplitudes are sensitive to the change in the azimuth of fault strike. For example, if we rotate the fault clockwise by 20° or so, making the strike direction at $N20^\circ E$, then both Rayleigh and Love waves would give the same moment estimate, about $1.5 \cdot 10^{25}$ dyne cm. (Since the distance dependence of surface wave amplitude is inversely proportional to the square root of distance, and the theoretical value is calculated for $\Delta=2000$ km, but the actual distance is about 1500, the moment is overestimated by $\sqrt{\frac{1500}{2000}} = 1.15$.)

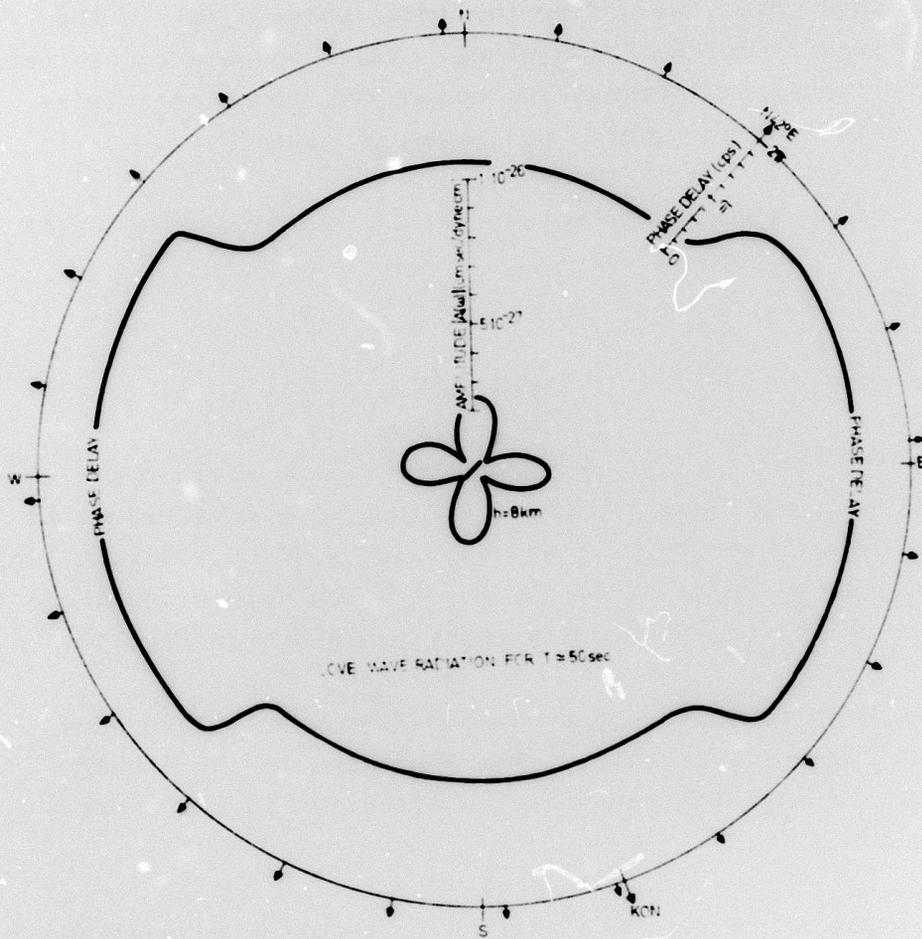


Fig. 11 Love wave radiation from the Mohn's ridge earthquake. For details on focal parameters, see the caption of Fig. 3.

(5) Phase Spectrum of Love Waves

For Love waves, we define the focal phase $\phi_0(\omega)$ in the same way as for Rayleigh waves. The Love wave displacement $f(t)$ (horizontal transverse component, counterclockwise as seen from the source positive) is given by

$$f(t) = \int |F(\omega)| \exp\{i\omega t - i\phi(\omega)\} d\omega \quad (6)$$

where

$$\phi(\omega) = \frac{\omega x}{C(\omega)} + \phi_0(\omega) + \phi_{\text{INST}}(\omega) + 2N\pi \quad (7)$$

For the Mohn's ridge earthquake, $\phi_0(\omega)$ is +0.13 cycle at $T \approx 50$ sec. Different choices of integer N give values of the phase velocity $C(\omega)$ as ..., 3.83, 4.40, 5.20, Only possible value is 4.40, and this choice determines the rest of the phase velocity curve, as shown in Fig. 12.

The phase velocities for periods less than 20 sec show some irregular behavior. The contamination by higher modes or Rayleigh waves may be effective in the short periods.

In addition to the Mohn's ridge earthquake, we analyzed the KON record of a shock at the intersection of Knipovich ridge and Mohn's ridge (Event 2) which occurred on 21 May 1972. The focal parameters of this event are given in Table 2. If we assume that the source mechanism of this earthquake is the same as the two nearby earthquakes given by Lazareva et al (1965), then we expect that the focal phase ϕ_0 of Love waves to be +.125 at KON.

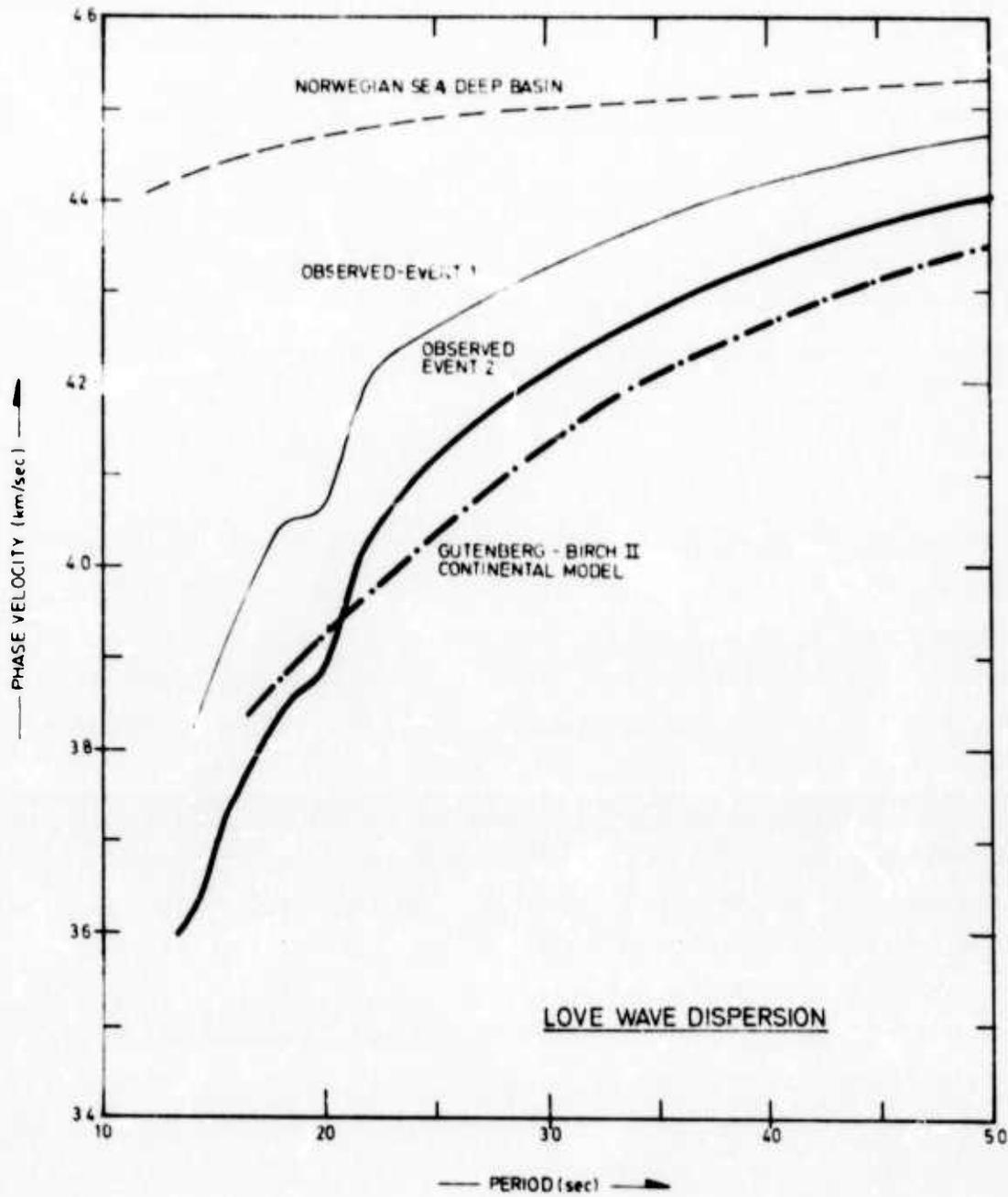


Fig. 12 Love wave phase velocity measurements using Kongsberg records for the Mohn's ridge earthquake of 31 May 1971 (event 1) and Mohn-Knipovich ridge earthquake of 21 May 1972 (event 2). The Norwegian Sea Deep Basin dispersion curve is calculated from the model in Table 1, while the Gutenberg-Birch II curve is taken from Anderson (1964).

The observed phase spectrum of Love waves from Event 2 gives the phase velocity of 4.47 km/sec at $T=50$ sec for $\phi_s = +.125$. The corresponding phase velocity curve is also shown in Fig. 12.

If we choose the hypothesis (4), and assume the strike-slip motion opposite to those given by Lazareva et al (1965) (and therefore $\phi_s = +.625$), we get the phase velocity values at $T \approx 50$ sec such as 4.10 and/or 4.82 km/sec. They seem to be too low or too high, not in favor of the hypothesis (4).

(6) Instrument Response for VLP Seismograph at KON

Unfortunately, the phase delay response of the VLP seismograph at KON (Locke, 1971) is not available at this moment. We tried to obtain it empirically by comparing the records of VLP seismographs with those of LP seismographs at the same station. We digitized and Fourier-analyzed both Love and Rayleigh waves from the Mohn-Knipovich ridge earthquake, and measured the amplitude spectral ratios and phase differences at various frequencies. Combining these measurements with the calculated response for the standard WWSS LP ($T_o=15$ sec, $\epsilon_o=1$, $T_g=100$ sec, $\epsilon_g=0.93$ and coupling coefficient $\sigma=0.047$ (Anonymous, 1966)), we obtained a reasonably stable estimate of amplification (Fig. 13) and phase delay curve (Fig. 14) for the VLP seismograph. These curves, however, should be considered as tentative.

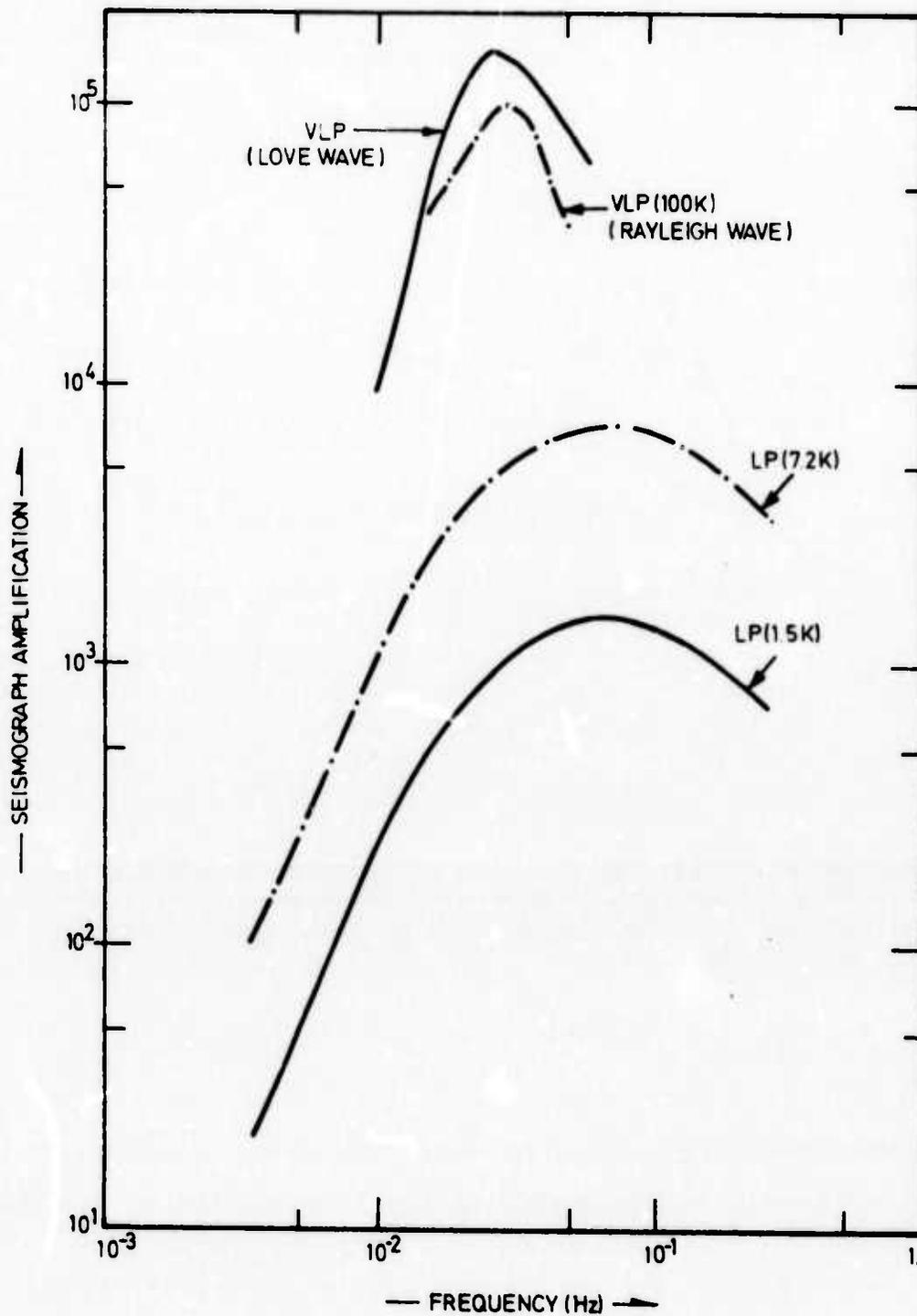


Fig. 13 Estimated amplification curves for the Very Long Period (VLP) seismograph at Kongsberg. For comparison similar curves for the ordinary, long period (LP) seismograph at the same location also are given.

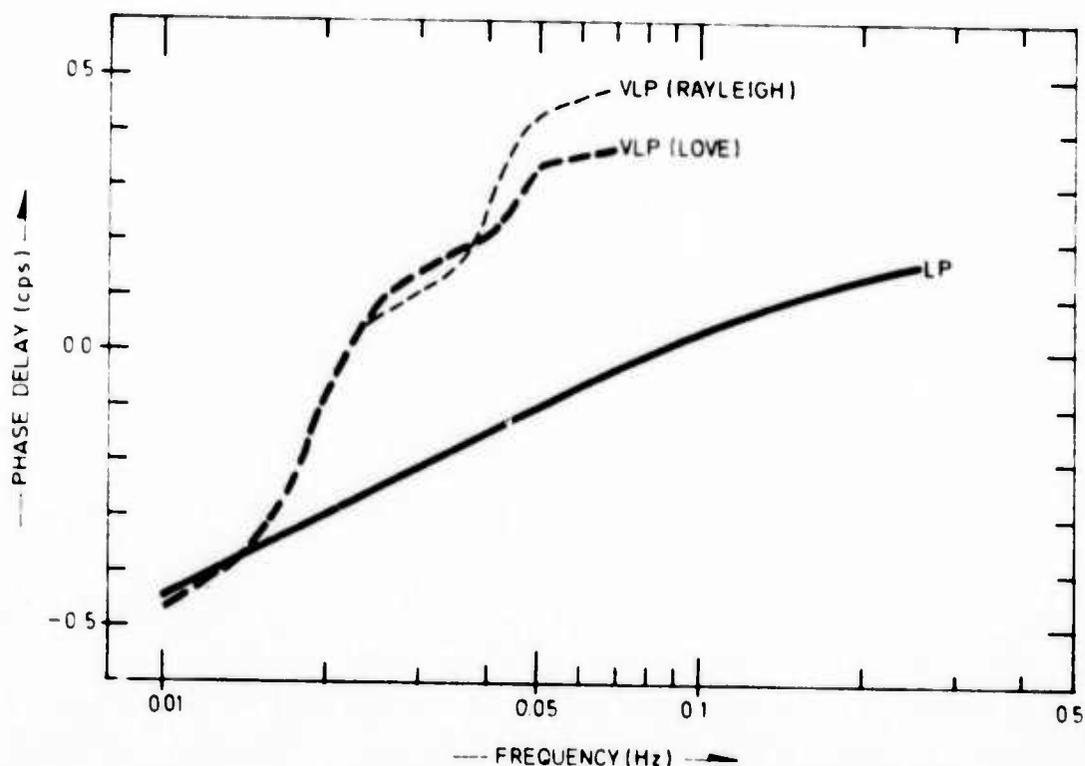


Fig. 14 Estimated phase delay curves for the Very Long Period (VLP) seismograph at Kongsberg. For comparison a similar curve for the ordinary long period (LP) station is also given.

FUTURE STUDIES

The above preliminary results offer the first approximations to the basic quantities involved in the analysis of surface waves from the North Atlantic ocean for the purpose of source mechanism studies. We made a thorough analysis of amplitude and phase spectra of Love and Rayleigh waves for the KON record of a Mohn's ridge earthquake with known fault plane solution. From this analysis, we obtained the first approximation to the phase velocity of Love and Rayleigh waves over the Norwegian Sea.

The next step will be the following:

- 1) A similar analysis of Rayleigh and Love waves from the same Mohn's ridge earthquake recorded at other stations.
- 2) A similar analysis of other North Atlantic earthquakes with known fault plane solution published by others or obtained by ourselves. Improve the phase velocity curves for various paths.
- 3) Determination of source mechanism of smaller earthquakes from the measurement of source phase using the first approximation phase velocity curves. Combine Love and Rayleigh waves for more reliable estimation.
- 4) Determination of seismic moment for smaller earthquakes using the source mechanism obtained from the source phase analysis. Combine Love and Rayleigh waves for more reliable estimation.

REMARK

The value of seismic moment obtained for Event 1 earthquake is comparable to the Parkfield, California, earthquake for which detailed source studies have been made by Aki (1972). We are somewhat bothered by this result, because M_s of Parkfield earthquake was determined to be 6.4 by Wu (1968) but M_s of this earthquake seems about 1 unit smaller than the Parkfield. We could not find, however, any blunder in the estimate of seismic moment.

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