AD/A-004 173

REGIONALIZATION OF THE ARCTIC REGION, SIBERIA, AND EURASIAN CONTINENTAL AREA

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Prepared for:

Air Force Office of Scientific Research
Advanced Research Projects Agency

September 1974

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AFOSR - TR - 75 - 0083 038C[illegible]9

Semi-Annual Technical Report

on the

REGIONALIZATION OF THE ARCTIC REGION, SIBERIA, AND EURASIAN CONTINENTAL AREA

Sponsored by
Advanced Research Projects Agency

ARPA Order No. 1827

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(Telephone No: 202-694-5456)

Contract Number: Air Force Contract F44620-73-C-0048, MOD.P00002

Amount of Contract: $114,986

Effective Dates of Contract: March 1, 1973 to May 31, 1975

Program Code: 4F10

Institute of Geophysics and Planetary Physics
University of California, Los Angeles

September 18, 1974

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59

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

1. REPORT NUMBER
AFOSR - TR - 75 - 0083

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
REGIONALIZATION OF THE ARCTIC REGION, SIBERIA, AND EURASIAN CONTINENTAL AREA

5. TYPE OF REPORT & PERIOD COVERED
Interim Jan - Jun 74

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
Professor Leon Knopoff

8. CONTRACT OR GRANT NUMBER(s)
F44620-73-C-0048

9. PERFORMING ORGANIZATION NAME AND ADDRESS
University of California, Los Angeles
Institute of Geophysics and Planetary Physics
Los Angeles, CA 90024

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
62701E 5F10
AO 1827-24

11. CONTROLLING OFFICE NAME AND ADDRESS
Advanced Research Projects Agency
1400 Wilson Boulevard
Arlington, VA 22209

12. REPORT DATE
September 1974

13. NUMBER OF PAGES
59

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)
Air Force Office of Scientific Research /NP
1400 Wilson Boulevard
Arlington, VA 22209

15. SECURITY CLASS (of this report)
UNCL/UNCL

15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of the regionalization of the Arctic region, Siberia and the Eurasian continental area is to determine the structural properties of the upper few hundred kilometers of the earth, and to determine the variation of these properties from one sub-region to another in the area under investigation. The first technical problem dealt with was the computation of experimental phase velocity curves for surface waves traversing all regions under investigation. We are now engaged in operation of the complete set of these 44 fundamental Rayleigh wave dispersion curves. The interpretation of these data will give us the regionalization of the area.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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TECHNICAL REPORT SUMMARY

In this investigation, we are regionalizing the Arctic region, Siberia and the Eurasian continental area using seismic surface waves. The purpose of this regionalization is to determine the structural properties of the upper few hundred kilometers of the earth, and to determine the variation of these properties from one subregion to another in the area under investigation. Once the structural properties in the various regions have been obtained, we will be able to apply our (existing) optimized computer techniques to the computation of accurate theoretical seismograms for any hypothetical type of source located anywhere within this continental area. These theoretical seismograms can be applied directly to the discrimination problem by comparing seismograms computed for both earthquakes and underground explosions with the actual recorded seismogram.

The first technical problem to be dealt with, which has recently been completed, is the computation of experimental phase velocity curves for surface waves traversing all of the regions under investigation. We are now engaged in the operation on the complete set of these 44 fundamental Rayleigh wave dispersion curves. The interpretation of these data will give us the regionalization of the area. This latter step is now being performed with existing computer programs; the data are obtained from analysis of seismograms taken by WWSSN instruments. The programs have already been used successfully in the regionalization of the Pacific Ocean area (Kausel, 1972; Leeds, 1973; Kausel, Leeds and Knopoff, 1974; Leeds, Knopoff and Kausel, 1974).

The phase velocity curves were obtained with the single-station phase velocity method, which is described in the main text of this report. Briefly, the method involves scanning our microfilm library of World Wide Standardized Seismographic Network (WWSSN) records for earthquakes which: (1) occurred within , or on the perimeter of, the area of interest, (2) produced good long-period surface wave records at WWSSN stations for which the epicenter-to-station lines lie within the regions being investigated, and (3) generated good, large recordings at a sufficient number of stations to ensure an accurate fault plane solution. When a suitable earthquake has been found, an extensive data processing and data reduction system is applied to transform the data into phase velocity curves for each of the selected epicenter-to-station lines through the area of interest.

The first two months of our work on this project were spent in detailed planning of our attack on the problem and in adapting our data processing and reduction system to the type of records to be used in the project. The main points of interest here are given at the end of the final section of the report.

In the remainder of the contract period, we have managed to complete all of the data analysis (for Rayleigh waves recorded by the WWSSN instruments) which will be required for the regionalization of the Arctic region, Siberia and the Eurasian continental area. We are currently involved in an intensive program of inversion of these data to obtain the desired lateral regionalization of these areas. In the final six months of the contract period, our primary goals are: first, to complete the regionalization of Siberia and the Eurasian continental area, using only the data for paths limited to these regions; second, to carry out the regionalization of the Arctic area, using only the data for paths limited to this region; and third, to perform a final regionalization of Siberia, the Eurasian continental area and also the Arctic region, using the entire set of data we have available, including many profiles which include both continental and oceanic segments between epicenter and station. Also, by the end of this contract period , we hope to have finished our tests of the records from the new high-gain wide-band instruments at CHG, MAT, EIL, TOL and KON. If these tests are satisfactory, the records from the new instruments should provide longer-period information, and hence, structural information to greater depths.

From our preliminary regionalization work on the continental areas, we can draw a few conclusions already. First, we note that the properties of much of the Asiatic upper mantle, averaged over long trans-Eurasian distances, are highly consistent with those of young stable regions observed elsewhere (Knopoff, 1972; Fouda, 1973; Knopoff and Fouda, 1974). Second, the Tibetan plateau has an extremely thick crust, perhaps as great as 100 km or more from surface to Moho. Third, the Alpine folded belt of Iran and Turkey has an extraordinarily well-developed low-velocity channel in the mantle, of remarkable contrast to the lid above. The principal problem in the inversion has been the construction of the boundaries to the geological provinces, for which only incomplete information is found in the literature.

TECHNICAL REPORT

I. Purpose of project

We are studying the localized properties of surface wave propagation in the Arctic region, Siberia and the Eurasian continental area using regionalization techniques recently developed at UCLA. The regionalization yields localized, long-period surface-wave dispersion data with the single-station method. The regions of high seismicity within and around the region to be investigated are quite favorably located for the application of the single-station technique. The dense set of WWSSN stations located around the perimeter of the region ensures that we can acquire sufficient data for the application of our regionalization methods. The new high-gain long-period installations in Norway, Spain, Israel, Thailand, and Japan are also well situated for the investigation. The long-period data from these latter stations may provide high structural resolution at depths significantly greater than were previously accessible in surface wave studies. Knowledge of the regionalized surface wave and structural properties will allow the seismograph response, to an arbitrary source within the region, to be synthesized at station locations on the perimeter.

II. Review of scientific background

Since the single-station surface wave method allows all stations to be located at the edge of the region under investigation, this technique is ideal for the proposed study.

Brune et al. (1960) were the first to describe the single-station method. Knopoff and Schwab (1968) corrected and extended this description to take into account the frequency dependence of the apparent initial phase of the source. Based on the Thomson (1950)-Haskell (1953) matrix formulation for surface wave propagation, Harkrider (1964) developed the theory for treating the surface wave response to buried point-source singlets. Ben-Menahem and Toksöz (1963) then developed the formalism, in terms of the singlet response, for representing the displacement field of an arbitary force system in a multilayered medium; and Ben-Menahem and Harkrider (1964) applied this formalism to obtain the surface wave response to point-source couples and double couples. Harkrider (1970) later made certain corrections and improvements in these last results. The far-field response to realistic, displacement-dislocation faulting was shown to be equivalent to the point-source, double-couple force replacement in an unfaulted medium (Maruyama, 1963; Burridge and Knopoff, 1964), and the single-station method was on firm theoretical ground for flat, multilayered media. By means of transformation techniques (Biswas and Knopoff, 1970; Schwab and Knopoff, 1972), it is possible to convert point-source programs for a flat structure, into those useful for treating sources in a spherical structure (Kausel and Schwab, 1973). These programs for the surface wave response to displacement dislocations in a radially heterogeneous sphere are now a part of our program library. We are using, improving, and optimizing these programs as part of the present project.

The initial, large scale, lateral regionalization of a portion of the earth by means of single-station surface wave studies was performed by Santô (1960a; 1960b; 1961a; 1961b) in an investigation of the Pacific Ocean basin. The bandwidth of his recordings and his data processing techniques limited almost all of his dispersion results to periods less than about 40 seconds; Santô's regionalization did not yield structural information below the crust and lid of the mantle. Our current data processing techniques (Biswas, 1971), and the availability of a nearly complete library of long-period seismograms from the WWSSN stations have made it possible to extend the lateral regionalization to a depth of about 250 km. The first application of our single-station regionalization techniques was an investigation of the upper mantle structure in the Pacific Ocean basin (Leeds, 1973).

The results of the work of Kausel (1972) showed an apparently continuous gradation of Rayleigh-wave phase velocities from low values observed on paths close to the East Pacific Rise to relatively high values on paths in the oldest parts of the lithosphere. Leeds (1973) increased the body of data and performed the first successful inversion of the data, assuming that regional variations in structure were correlated with lithospheric age; that study took into account bathymetry and available crustal information. The number of degrees of freedom in the data was found to be remarkably small, despite the large number of phase-velocity determinations. The inversion led to the conclusion that the data set did not permit obtaining detailed information concerning the bottom of the low-velocity channel. Furthermore, the lithosphere increased in thickness monotonically with age: at the ridge crest, the lithosphere has almost zero thickness; below the oldest parts of the oceanic lithosphere, the asthenosphere has almost zero thickness. This is thus the explanation for the observation that the phase velocities change systematically with distance from the ridge crest. The model of lithospheric thickness as a function of spreading age is consistent with a model wherein the lithosphere-asthenosphere interface is at the solidus for wet peridotite if the thickness of the slab moving laterally away from the ridge crest is relatively thick, of a thickness considerably greater than the depth to the bottom of the asthenosphere. Thus, on this model, there is negligible slip between the asthenosphere and the lithosphere. Other models are also possible. These single-station regionalization techniques are being refined for use in the present project.

The single-station, surface wave regionalization of an area is based on the assumption of great-circle propagation paths, and the assumption that the phase travel time from epicenter to station is just the sum of the travel times through the subdivisions of the laterally heterogeneous region (Knopoff, 1969). This permits the regionalization to be expressed at each frequency as a system of inhomogeneous equations; for each path, the total travel time is the inhomogeneous term, the distances through the subdivisions are the coefficients, and the slownesses in the subdivisions are the unknowns. Santô [equation (1), 1961b] applied this technique to the Pacific, using group travel times and group slownesses but, due to considerations involving uniqueness of inversion (Pilant and Knopoff, 1970), we prefer phase travel time and phase slownesses. The solution of this system of equations yields the experimental phase slownesses associated with each of the subdivisions, in principle; however, the above procedure represents a version of the computer program which is not pedagogically acceptable. Instead, we prefer to consider the model parameters as the primary unknowns in the inversion and to use the phase velocities therefrom.

Techniques for obtaining structural information from dispersion data were discussed by Knopoff (1961,1962), and the first programming of the inversion procedure appears to have been carried out by Dorman and Ewing (1962). In these papers, attempts were described to obtain the single best structure for fitting the experimental data. Subsequent efforts were mainly concerned with finding the set of structural models which fit the data to within the experimental accuracy (Keilis-Borok and Yanovskaya, 1967; Press, 1968,1969). This work led to the programming, under the direction of Knopoff and Keilis-Borok, of the Hedgehog inversion package (Biswas and Knopoff, 1974; Knopoff and Schlue, 1972). This technique involves seeking structures, which satisfy the data to within the experimental accuracy, by means of a pointwise search throughout a multidimensional parameter space. This package is efficient enough for routine application to surface wave dispersion data. We have now introduced variational parameters into the procedure, which has resulted in a significant increase in computational efficiency. A description of the ideas involved in this improvement is given by Jackson (1972); the technique takes into account the redundancy in the data as well as numerical instabilities in the solution.

Upper mantle studies in Eurasia appear to have suffered due to the Soviet seismologists' lack of efficient long-period instrumentation. Also, their extensive program in deep seismic sounding has undoubtedly served to focus interest upon crustal studies, to the detriment of sub-Moho investigations. The review by Arkhangel'skaya (1960) discusses the foreign and domestic surface wave studies performed in Eurasia prior to 1960. The early Soviet studies discussed in this review, as in the later studies to be mentioned here, were limited to short-period investigations--usually less than 40 seconds--and were concerned mainly with determining crustal properties. Of the early Soviet studies, which more or less paralleled the work in the west, the investigations of Savarensky and Ragimov (1958; 1959), Savarensky et al. (1959), and Savarensky and Sikharulidze (1959) clearly demonstrate this predominant interest in crustal features. The subsequent work by Popov (1960), Shechkov (1961), Savarensky and Shechkov (1961), Shechkov and Solov'eva (1961), and Shechkov (1964) indicated that the Soviet surface wave investigations would remain focused on crustal studies, and indeed, this has proven to be the case up through the most recent Soviet surface wave literature available to us (Savarensky and Peshkov, 1968; Sikharulidze and Makharadze, 1968; Savarensky et al., 1969; Shechkov, 1970).

All of these crustal studies, as well as Santo's (1962; 1965a; 1965b) short-period regionalization efforts, will be valuable in assisting to determine which shallow structures to combine with our trial parameterizations for the deep structures in the inversion portion of the present investigation.

III. Objectives, methods and results (of the first 18 months of the project)

To perform the regionalization of the area under investigation with the single-station method, we must know the orientation of the fault planes and the direction of displacement dislocation at the focus. These provide calculable corrections due to apparent initial phase of the Rayleigh wave signal. Our current interpretation procedures, for obtaining structural parameters as a function of depth, are based solely on the phase velocity dispersion of the isolated fundamental mode.

Our recent large-scale regionalization work (Biswas, 1971; Kausel, 1972; Leeds, 1973; Fouda, 1973; Kausel _et al_., 1974; Leeds _et al_., 1974; Knopoff and Fouda, 1974) has shown the value and ease of handling of seismic records of fundamental mode Rayleigh waves. Our initial efforts in the present study have therefore been focused on this well-tested approach.

Only the long-period records from the 47 WWSSN stations which border the region of interest have been used thus far in the study. The locations of these stations are shown in Figure 1.

In order to obtain the desired long-period information, it is necessary to use shocks of relatively large magnitude, yet small enough to be on-scale at the stations of the network. An example of the large-magnitude seismicity of the area is given in Figure 2. The epicenters are plotted for earthquakes having magnitudes between 5.9 and 6.6, which occurred during the interval from February, 1963 to February, 1967. The choice of this range of magnitudes is governed by two considerations. First, experience has shown that good long-period surface wave information requires events with magnitudes above a certain value and, of course, a shock which is so large as to send the instrument off scale is useless for our purposes. Second, the application of the single-station method requires knowledge of the focal mechanism. We must therefore use events large enough to allow us to obtain an accurate fault plane solution for each event we select for processing. In addition to the epicenters shown in Figure 2, there are regions of high seismicity along the eastern border of the Kamchatka peninsula and along the Aleutian arc, which may provide useful events for this study.

With such a dense set of stations around the area to be studied, and with the regions of high, large-magnitude seismicity located within and around the area, there has been no problem in obtaining sufficient data for the project. It is interesting to note that the area is almost completely encircled: There is only one significant gap -- between Japan and Alaska -- where stations do not exist. However, this gap is occupied by a region of high seismicity which, in the single-station sense, is equivalent to having a high station density in the region.

There are far too many epicenter-to-station paths to show individually, but the limits of the area which we hope to cover finally with a dense set of paths, are shown in Figure 3 by the solid lines. The solid regions are those of high, large-magnitude seismicity.

The first event processed has the following USCGS specification.

March 7, 1966 - 21:29:17.4 GMT, 37.3°N, 114.9°E,
$h=33$ km , $M=6.0$.

Our fault plane solution for this event is given in Figure 4. This first-motion information restricts the fault plane solution sufficient well so that only this information is required to determine the required focal specification. The location of the epicenter and the epicenter-to-station paths which were selected for processing, are given in Figure 5. For all of these recordings, we have digitized the event and impulse response from the seismogram, isolated the fundamental mode with frequency filtering-time windowing techniques, corrected for the instrument response, corrected for the apparent initial phase due to the source mechanism, and computed the final phase velocity dispersion curves. The dispersion data for these eight paths are in final form, ready to use in our inversion program.

The computation of the correction for the apparent initial phase requires the specification of the strike of the fault plane ϕ , its dip δ and the direction of slip λ , and the depth to the focus h . These parameters are shown in the fault-plane geometry given in Figure 6. For the above event, our fault-plane solution yields

$\phi = 122°$ east of north

$\delta = 82°$

$\lambda = 90°$

and inspection of the Rayleigh-wave amplitude spectra indicates a focal depth of

$h = 14.5$ km .

The second event selected for processing has the following USCGS specification.

August 25, 1964 - 13:47:20.6 GMT, 78.2°N, 126.6°E ,
$h=50$ km, $M=6.1$.

The location of the epicenter, and the epicenter-to-station paths which were selected for processing, are given in Figure 7. The fault-plane solution for this event was given by Sykes (1967) as

$\phi = 4°$ east of north
$\delta = 58°$ west

for one possible fault plane, and

$\phi = 22°$ west of north
$\delta = 54°$east

for the other.

Our result for this event is

$\phi = 155°$ east of north
$\delta = 58°$
$\lambda = 260°$
$h = 11.5$ km.

The angles ϕ and δ are well-constrained by the first-break fault-plane solution given in Figure 8; the additional information contained in the Rayleigh-wave amplitude radiation patterns, which are shown in Figure 9, is required to fix λ and h . The event recordings for these epicenter-to-station paths, and the corresponding impulse-response recordings, have been digitized; the fundamental mode has been isolated with filtering-windowing procedures, instrument-response and apparent-initial-phase effects have been removed, and final phase-velocity dispersion curves have been prepared.

The epicenter and propagation paths of the third event selected:

December 26, 1964 - 14:30:29.1 GMT, 51.8°N, 156.8°E,
h=136 km, M=5.7 (USCGS)

are shown in Figure 10, and the results of our first-motion fault plane analysis for this event are given in Figure 11. The reduced phase-velocity curves have been obtained for these paths.

The epicenter and propagation paths for the fourth event selected:

March 31, 1969 - 07:15:54.4 GMT, 27.7°N, 34.0°E,
h=33 km, M=6.0 - 6.8

are given in Figure 12.

Two events with approximately the same epicenter were also processed. These are

February 6, 1965 - 01:40:33.2 GMT, 53.2°N, 161.9°W,
h=33 km, M=6.4 - 6.7

and

February 6, 1965 - 16:50:29 GMT, 53.3°N, 161.8°W,
h=33 km, M=6.1 - 6.6

The paths are shown in Figure 13; the fault plane solutions are given in Figure 14.

Two events with approximately the same epicenter were the final ones processed. The USCGS specifications are:

February 5, 1965 - 09:32:09.3 GMT, 52.3°N, 174.3°E,
h=41 km, M=5.9 - 6.5

and

February 6, 1965 - 04:02:53 GMT, 52.1°N, 175.7°E,
h=35 km, M=5.9 - 6.0

These paths are shown in Figure 15; the fault plane solutions are given in Figure 16.

The combined Rayleigh wave propagation paths are shown in Figure 17, where the continental areas are emphasized, and in Figure 18, where the Arctic region is emphasized.

Sample phase velocity results are given in Figure 19, which illustrate the variation in dispersion for different propagation paths.

Two interesting points concerning the data-processing techniques have come to light during the present study. Both involve the accuracy of the digitizations of the recorded events. First, most of the event records we have used are about as large as they could be without going off scale. (See Figure 20 for an example.) This has necessitated a change in our data processing techniques which should be noted for the information of others involved in this type of work. In the past, our standard procedure, when working with smaller-amplitude recordings, has been to make copies of events from our 35mm microfilm records of the WWSSN seismograms. These copies are made with a standard microfilm reader-printer (Itek 18.24 Reader-Printer), and the events are then digitized from these copies. We followed this procedure during the initial phase of the present investigation, but later became concerned about the possibility of distortion in the copying process. Our tests comparing the phase velocity results obtained from full-size record copies provided by NOAA with the results obtained from our microfilm copies showed this concern to be valid. Our conclusion is that, when working with large-amplitude recordings such as those employed in the present study, one must use full-size record copies; one must not use a microfilm copier which forces the analysis to use several prints, spliced together to form the record copy from which the digitization is obtained.

The second point which arose, involving accuracy of digitization, concerns the fact that the direction of swing of the galvanometer may not be parallel to the axis of the recording drum (James and Linde, 1971). Although James and Linde (1971) term this phenomenon "a source of major error in digital analysis of WWSSN seismograms," our tests show the effect to be negligible on the phase velocities computed using the single-station method for epicenter-station separations of a few thousand kilometers. In the case of the poorest galvanometer alignment we encountered -- about triple the normal ramp slope of 0.3° -- we found only negligible differences between the phase velocity curve obtained with the correct digitization base line, and the curve obtained with the normal ramp as a base line.

Bibliography

Ben-Menahem, A. and M.N. Toksöz (1963). Source mechanism from spectra of long-period seismic surface waves. 2. The Kamchatka earthquake of November 4, 1952, J.Geophys.Res., 68, 5207-5222.

Ben-Menahem, A. and D.G. Harkrider (1964). Radiation patterns of seismic surface waves from buried dipolar point sources in a flat stratified earth, J.Geophys. Res., 69, 2605-2620.

Biswas, N.N. and L. Knopoff (1970). Exact earth-flattening calculation for Love Waves, Bull.Seismol.Soc.Amer., 60, 1123-1137.

Biswas, N.N. (1971). The upper mantle structure of the United States from the dispersion of surface waves, Ph.D. thesis, University of California, Los Angeles.

Biswas, N.N. and L. Knopoff (1974). Structure of the upper mantle under the United States from the dispersion of Rayleigh waves, Geophys.J.R.astr.Soc., 36, 515-539.

Boore, D.M. (1969). Effect of higher mode contamination on measured Love wave phase velocities, J. Geophys. Res. 74, 6612-6616.

Brune, J., J. Nafe, and J. Oliver (1960). A simplified method for the analysis and synthesis of dispersed wave trains, J. Geophys. Res. 65, 287-305.

Burridge, R. and L. Knopoff (1964). Body force equivalents for seismic dislocations, Bull. Seism. Soc. Am. 54, 1875-1888.

Dorman, J. and M. Ewing (1962). Numerical inversion of surface wave dispersion data and the crust-mantle structure in the New York-Pennsylvania area, J.Geophys.Res., 67, 5227-5241.

Fouda, A.A. (1973). The upper mantle structure under the stable regions, Ph.D. thesis, University of California, Los Angeles.

Haskell, N.A. (1953). The dispersion of surface waves on multilayered media, Bull. Seism. Soc. Am. 43, 17-34.

Harkrider, D.G. (1964). Surface waves in multilayered elastic media. Part II. Higher mode spectra and spectral ratios from point sources in plane layered earth models, Bull. Seism. Soc. Am. 60, 1937-1987.

Jackson, D.D. (1972). Interpretation of inaccurate, insufficient and inconsistent data, Geophys. J. 28, 97-109.

James, D.E. and A.T. Linde (1971). A source of major error in the digital analysis of World Wide Standard Station seismograms, Bull. Seism. Soc. Am. 61, 723-728.

Kausel, E., and F. Schwab (1973). Contributions to Love wave transformation theory: Earth-flattening transformation for Love waves from a point source in a sphere, Bull.Seism.Soc.Am., 63, 983-993.

Kausel, E.G.(1972). Regionalization of the lithosphere and asthenosphere of the Pacific Ocean, Ph.D. thesis, Columbia University, New York.

Kausel, E.G., A.R. Leeds and L. Knopoff (1974). Variation of Rayleigh wave phase velocities across the Pacific, Science, in press.

Keilis-Borok, V.I. and T.B. Yanovskaya (1967). Inverse seismic problems (structural review), Geophys.J., 13, 223-233.

Khain, V.E. and M.V. Muratov (1969). Crustal movements and tectonic structure of continents, in The Earth's Crust and Upper Mantle (Edited by P.J. Hart), Geophysical Monograph 13, American Geophysical Union, Washington, D.C.

Knopoff, L. (1961). Green's function for eigenvalue problems and the inversion of Love wave dispersion data, Geophys. J. 4, 161-173.

Knopoff, L. (1962). Higher order Born approximation for the inversion of Love wave dispersion, Geophys. J. 7, 149-157.

Knopoff, L. and F. Schwab (1968). Apparent initial phase of a source of Rayleigh waves, J. Geophys.Res. 73, 755-760.

Knopoff, L. (1969). Phase and group slownesses in inhomogeneous media, J. Geophys. Res. 74, 1701.

Knopoff, L. (1972). Observation and inversion of surface wave dispersion, Tectonophysics, 13, 497-519.

Knopoff, L. and J.W. Schlue (1972). Rayleigh wave phase velocities for the path Addis Ababa-Nairobi, Tectonophysics, 15, 157-163.

Knopoff, L., F. Schwab and E. Kausel (1973). Interpretation of Lg, Geophys.J.R.astr.Soc., 33, 389-404.

Knopoff, L. and A.A. Fouda (1974). Upper mantle structure under the Arabian Peninsula, submitted to Tectonophysics.

Kosminskaya, I.P. and Yu.V. Riznichenko (1964). Seismic studies in the earth's crust in Eurasia, in Research in Geophysics, Vol. 2 (H. Odishaw, ed.) MIT Press, Cambridge.

Kosminskaya, I.P., N.A. Belyaevsky and I.S. Volvovsky (1969). Explosion seismology in the USSR, in The Earth's Crust and Upper Mantle, (P.J. Hart, ed.), Geophysical Monograph 13, American Geophysical Union, Washington, DC.

Leeds, A.R.(1973). Rayleigh wave dispersion in the Pacific Basin, Ph.D. thesis, University of California, Los Angeles.

Leeds, A.R., L. Knopoff and E.G. Kausel (1974). Variations of upper mantle structure under the Pacific Ocean, Science, in press.

Lubimova, E.A. and B.G. Polyak (1969). Heat flow map of Eurasia , in The Earth's Crust and Upper Mantle (P.J. Hart, ed.), Geophys. Monog. 13, Amer. Geophys. Union, Washington, DC.

Maruyama, T. (1963), On the force equivalents of dynamical elastic dislocations with reference to the earthquake mechanism, Bull. Earthq. Res. Inst. 41, 467-486.

Molnar, P., J. Savino, L.R. Sykes, R.C. Liebermann, G. Hade, and P.W. Pomeroy (1969). Small earthquakes and explosions in Western North America recorded by new high gain, long period seismographs, Nature 224, 1268-1273.

Pilant, W.L. and L. Knopoff (1970). Inversion of phase and group slowness dispersion, J. Geophys. Res. 75, 2135-2136.

Pomeroy, P.W., G. Hade, J. Savino, and R. Chander (1969). Preliminary results from high-gain wide-band long-period electromagnetic seismograph systems, J. Geophys. Res. 74, 3295-3298.

Popov, I.I. (1960). Dispersion of long-period Love waves in the continental and oceanic crust along the path Indonesia-Crimea, Bull. (Izv.) Acad. Sci. USSR, Geophys. Ser. No. 10, 970-973.

Press, F. (1968). Earth models obtained by Monte Carlo inversion, J. Geophys. Res. 73, 5223-5233.

Press, F. (1969). The sub-oceanic mantle, Science 165, 174-176.

Rezanov, I.A. and V.M. Kochetkov (1962). Recent tectonics and seismic regionalization in the northeastern region of the USSR, Bull. (Izv.) Acad. Sci. USSR., Geophys. Ser. No. 12, 1045-1052.

Santô, T.A. (1960a). Observation of surface waves by Columbia-type seismograph installed at Tsukuba Station, Japan. (Part I) -- Rayleigh wave dispersions across the oceanic basin, Bull. Earthq. Res. Inst. 38, 219-240.

Santô, T.A. (1960b). Rayleigh wave dispersions across the oceanic basin around Japan (Part II), Bull. Earthq. Res. Inst. 38, 385-401.

Santô, T.A. (1961a). Rayleigh wave dispersions across the oceanic basin around Japan (Part III), Bull. Earthq. Res. Inst. 39, 1-22.

Santô, T.A. (1961b). Division of the Southwestern Pacific area into several regions in each of which Rayleigh waves have the same dispersion characters, Bull. Earthq. Res. Inst. 39, 603-630.

Santô, T. (1962). Dispersion of surface waves along various paths to Uppsala, Sweden. Part I: Continental Paths, Ann. Geofis. 15, 245.

Santô, T. (1965a). Lateral variation of Rayleigh wave dispersion chracter. Part I: Observational data, Pure and Appl. Geophys. 62, 49-66.

Santô, T. (1965b). Lateral variation of Rayleigh wave dispersion character. Part II: Eurasia, Pure and Appl. Geophys. 62, 67-80.

Savarensky, E.F. and Sh.S. Ragimov (1958). Determining the velocity of Rayleigh waves and direction to the epicenter by three nearby stations, *Bull. (Izv.) Acad. Sci. USSR, Geophys. Ser. No. 12*, 866-869.

Savarensky, E.F., O.N. Solov'eva, and B.N. Shechkov (1959). Love wave recording at seismological station Moscow and crustal structure, *Bull. (Izv.) Acad. Sci. USSR, Geophys. Ser. No. 5*.

Savarensky, E.F. and D.I. Sikharulidze (1959). Crustal thickness determinations from measured Love wave dispersion, *Bull. (Izv.) Acad. Sci. USSR, Geophys. Ser. No. 6.*

Savarensky, E.F. and Sh.S. Ragimov (1959). On the determination of the average thickness of the earth's crust from Rayleigh wave group velocity measurements, *Bull. (Izv.) Acad. Sci. USSR, Geophys. Ser. No. 9*, 969-971.

Savarensky, E.F. and B.N. Shechkov (1961). The structure of the earth's crust in Siberia and in the Far East from Love and Rayleigh wave dispersion data, *Bull. (Izv.) Acad. Sci. USSR, Geophys. Ser. No. 5*, 454-456.

Savarensky, E.F. and A.B. Peshkov (1968). On the use of surface wave velocities in choosing a model of crustal structure, *Akad. Nauk SSSR Izv. Fizika Zemli No. 10*, 79-87.

Savarensky, E.F., G.N. Bozhko, T.I. Kukhtikova, A.B. Peshkov, I.I. Popov, B.N. Sheshkov, O.I. Yurkevich, and L.M. Yudakova (1969). On the earth structure in some regions of the USSR from surface wave data, *Pure and Appl. Geophys. 73*, 99-119.

Savino, J., K. McCamy, and G. Hade (1972). Structures in earth noise beyond twenty seconds -- a window for earthquakes, Bull. Seism. Soc. Am. 62, 141-176.

Schwab, F. and L. Knopoff (1971). Surface waves on multi-layered anelastic media, Bull. Seism. Soc. Am. 61, 893-912.

Schwab, F. and L. Knopoff (1972). Fast surface wave and free mode computations, Chapter 3, Methods in Computational Physics, Volume 11 (Edited by B.A. Bolt), Academic Press, New York, 87-180.

Shechkov, B.N. (1961). Structure of the earth's crust in Eurasia from the dispersion of surface waves, Bull. (Izv.) Acad. Sci. USSR, Geophys. Ser. No. 5, 450-453.

Shechkov, B.N. and O.N. Solov'eva (1961). Group velocities of Rayleigh waves traveling along a mixed continental-oceanic path, Bull. (Izv.) Acad. Sci. USSR, Geophys. Ser. No. 8, 768-770.

Shechkov, B.N. (1964). Seismic surface wave dispersion and Eurasian crustal structure, Bull. (Izv.) Acad. Sci. USSR, Geophys. Ser. No. 3, 183-187.

Shechkov, B.N. (1970). Surface wave group velocities on Eurasian paths, Akad. Nauk SSR Izv. Fizika Zemli No. 8, 80-87.

Sikharulidze, D.I. and R.K. Makharadze (1968). The problem of using surface waves in seismic exploration, Akad. Nauk Gruzin. SSR Soobshch. 52, 335-340.

Sollogub, V.B. (1969). Seismic crustal studies in Southeastern Europe, in The Earth's Crust and Upper Mantle (Edited by P.J. Hart), Geophysical Monograph 13, American

Geophysical Union, Washington, D.C.

Sykes, L.R. (1967) Mechanism of earthquakes and nature of faulting on the mid-oceanic ridges, J.Geophys.Res., 72, 2131-2153.

Thatcher, W. and J.N. Brune (1969). Higher mode interference and observed anomalous apparent Love wave phase velocities, J. Geophys. Res. 74, 6603-6611.

Thomson, W.T. (1950). Transmission of elastic waves through a stratified solid medium, J. Appl. Phys. 21, 89-93.

Wiggins, R.A. (1972). The general linear inverse problem: Implication of surface waves and free oscillations for earth structure, Rev. of Geophys. and Space Phys. 10, 251-285.

FIGURE CAPTIONS

FIG. 1. Locations of WWSSN stations and new, high-gain installations to be used in the investigation.

FIG. 2. Example of the large-magnitude seismicity of the region we propose to study. The regions of high, large-magnitude seismicity along the eastern border of the Kamchatka peninsula and along the Aleutian arc may also provide useful events for the study.

FIG. 3. Limits (solid lines) of the region we propose to cover with a dense set of epicenter-to-station paths. Solid regions are those of high, large-magnitude seismicity.

FIG. 4. First-motion information and fault plane solution for event occurring at 21:29:17.4 GMT on March 7, 1966.

FIG. 5. Location of epicenter and epicenter-to-station paths selected for processing from event occurring at 21:29:17.4 GMT on March 7, 1966.

FIG. 6. Geometry and coordinate systems of fault plane, focus, and epicenter.

FIG. 7. Location of epicenter and epicenter-to-station paths selected for processing for event occurring at 13:47:20.6 GMT on August 25, 1964.

FIG. 8. First-motion information to be used for fault-plane solution for event occurring at 13:47:20.6 GMT on August 25, 1964.

FIG. 9. Rayleigh-wave amplitude information to be used for fault-plane solution for event occurring at 13:47:20.6 GMT on August 25, 1964. The central set of radiation patterns are the results of theoretical computations based on the fault plane solution given in the text. The other four radiation patterns depict the experimental results.

FIG. 10. Location of epicenter and epicenter-to-station paths selected for processing from event occurring at 14:30:29.1 GMT on December 26, 1964.

FIG. 11. Results from first-motion fault plane analysis for event occurring at 14:30:29.1 GMT on December 26, 1964.

FIG. 12. Location of epicenter and epicenter-to-station paths selected for processing for event occurring at 07:15:54.4 GMT on March 31, 1969.

FIG. 13. Location of epicenters and epicenter-to-station paths selected for processing for events occurring at 01:40:33.2 (dashed lines) and 16:50:29 GMT (solid lines) on February 6, 1965.

FIG. 14. Results from first-motion fault plane analysis for events occurring at 01:40:33.2 (Fig.14a) and 16:50:29 GMT (Fig.14b) on February 6, 1965.

FIG. 15. Location of epicenters and epicenter-to-station paths for events occurring at 09:32:09.3 GMT on February 5, 1965 (dashed line) and at 04:02:53 GMT on February 6, 1965 (solid line).

FIG. 16. Results from first-motion fault plane analysis for events occurring at 09:32:09.3 GMT on February 5, 1965 and at 04:02:53 GMT on February 6, 1965.

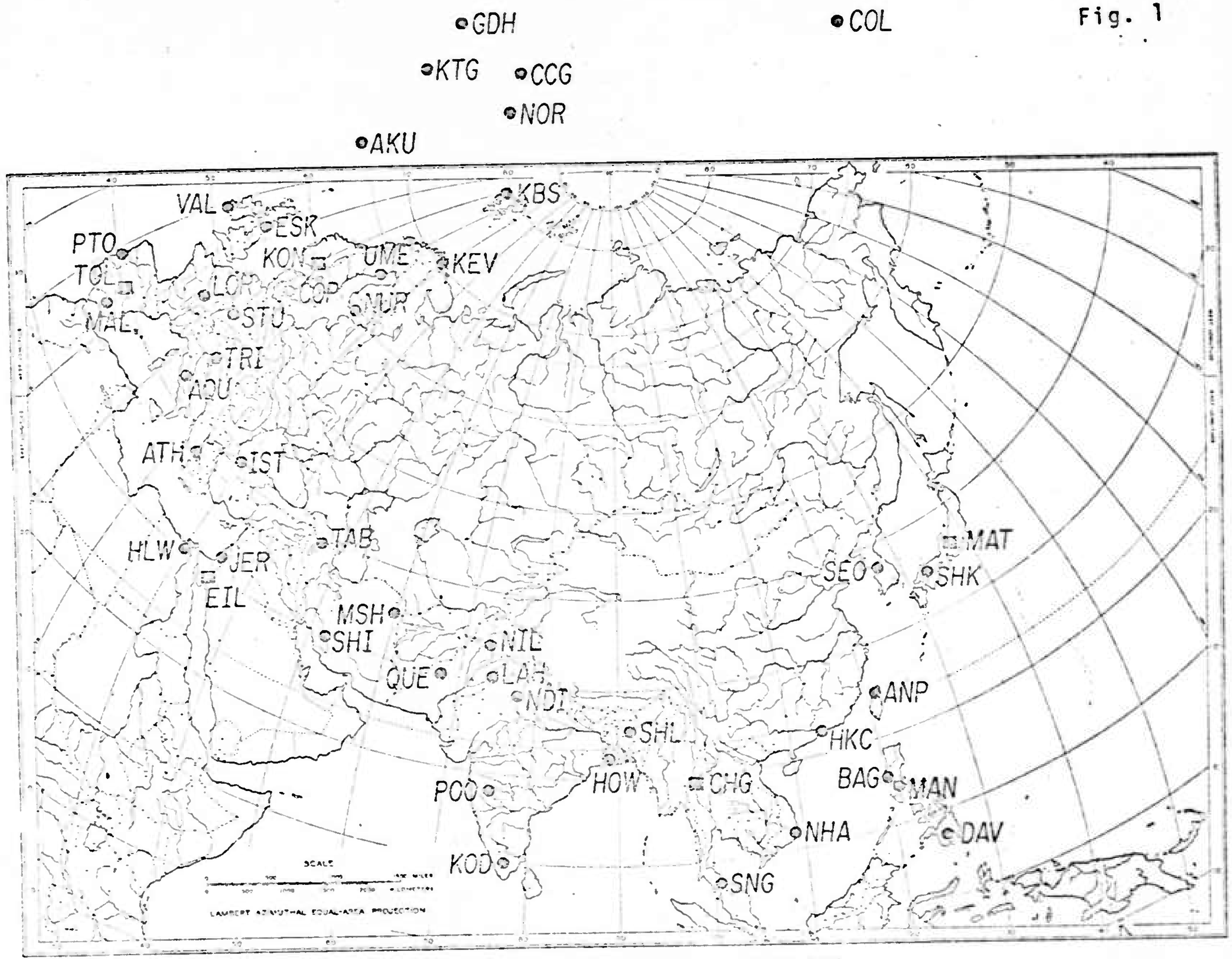
FIG. 17. Combined Rayleigh wave propagation paths. Continental results are emphasized here.

FIG. 18. Combined Rayleigh wave propagation paths. Arctic results are emphasized here.

FIG. 19. Sample phase velocity results for the paths noted. The paths are shown in Figures 5 and 7.

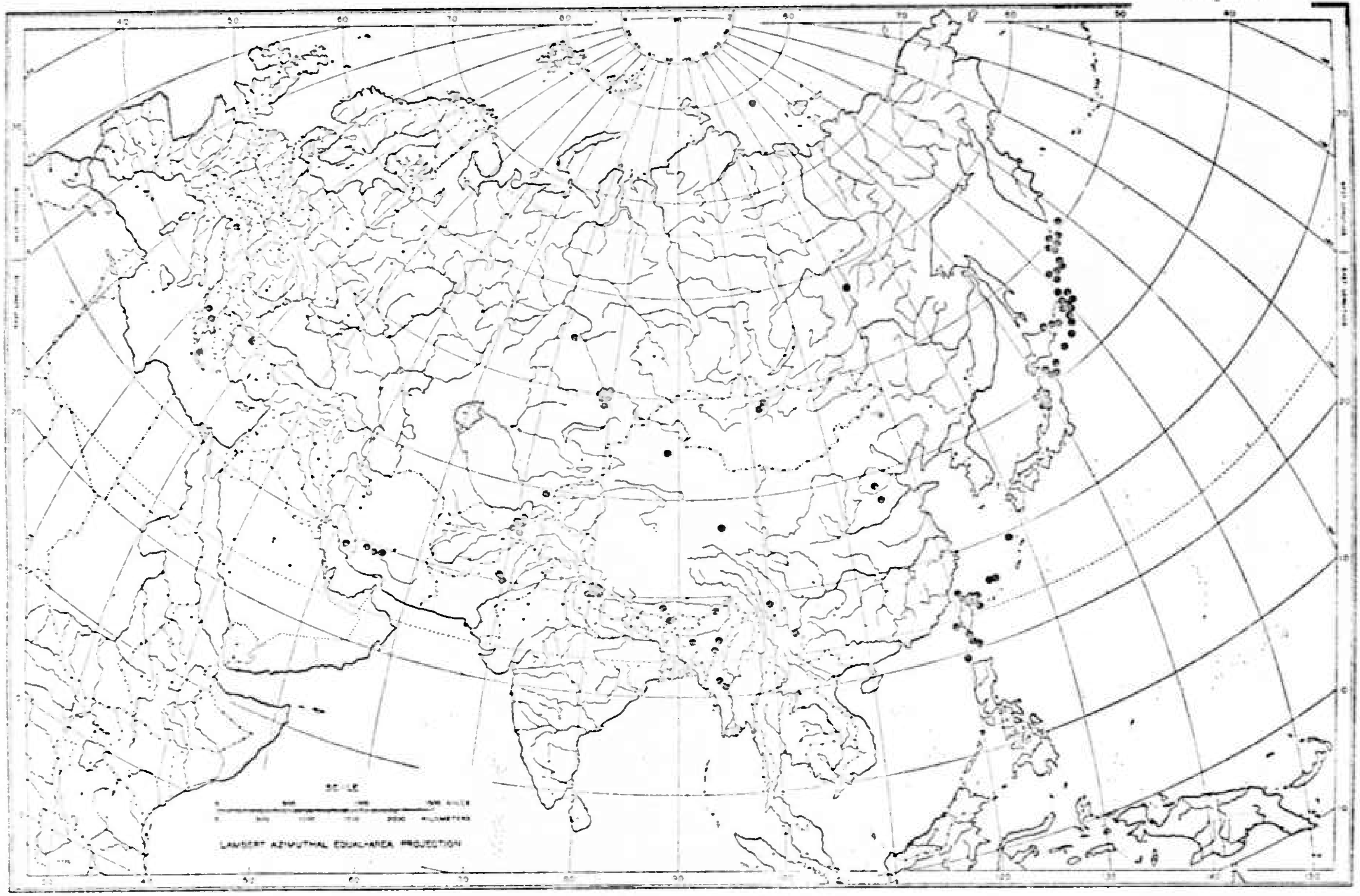
FIG. 20. Example of large-event recordings used in the present study. This is the recording at Kevo, Finland (KEV) from the event occurring at 21:29:17.4 GMT on March 7, 1966.

Fig. 1



○ WWSSN STATIONS
▣ HIGH-GAIN, LONG-PERIOD STATIONS

Fig. 2



USEFUL EPICENTERS
$5.9 \leq$ MAGNITUDE ≤ 6.6
FEB. 1963 - FEB. 1967

Fig. 3

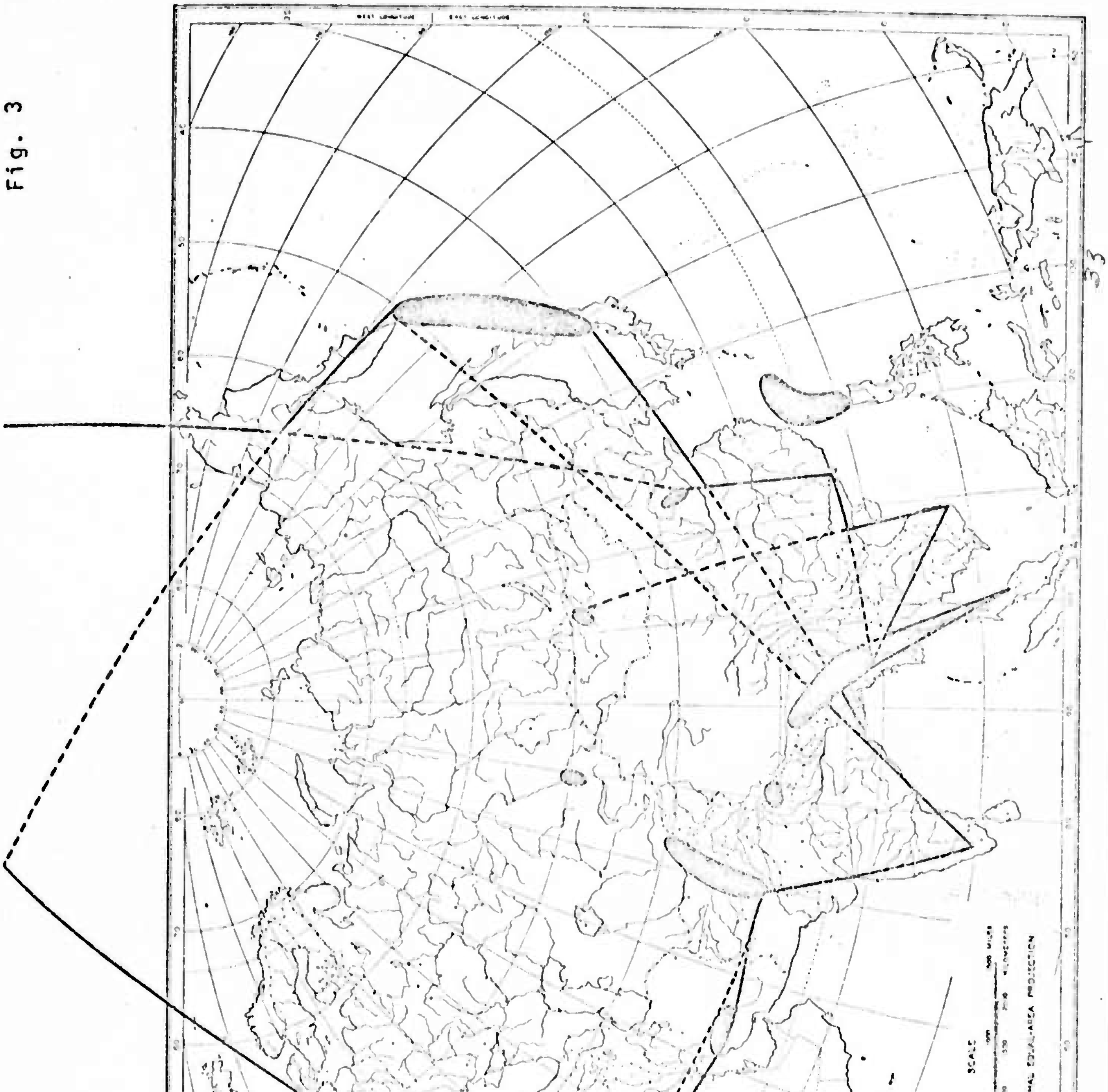
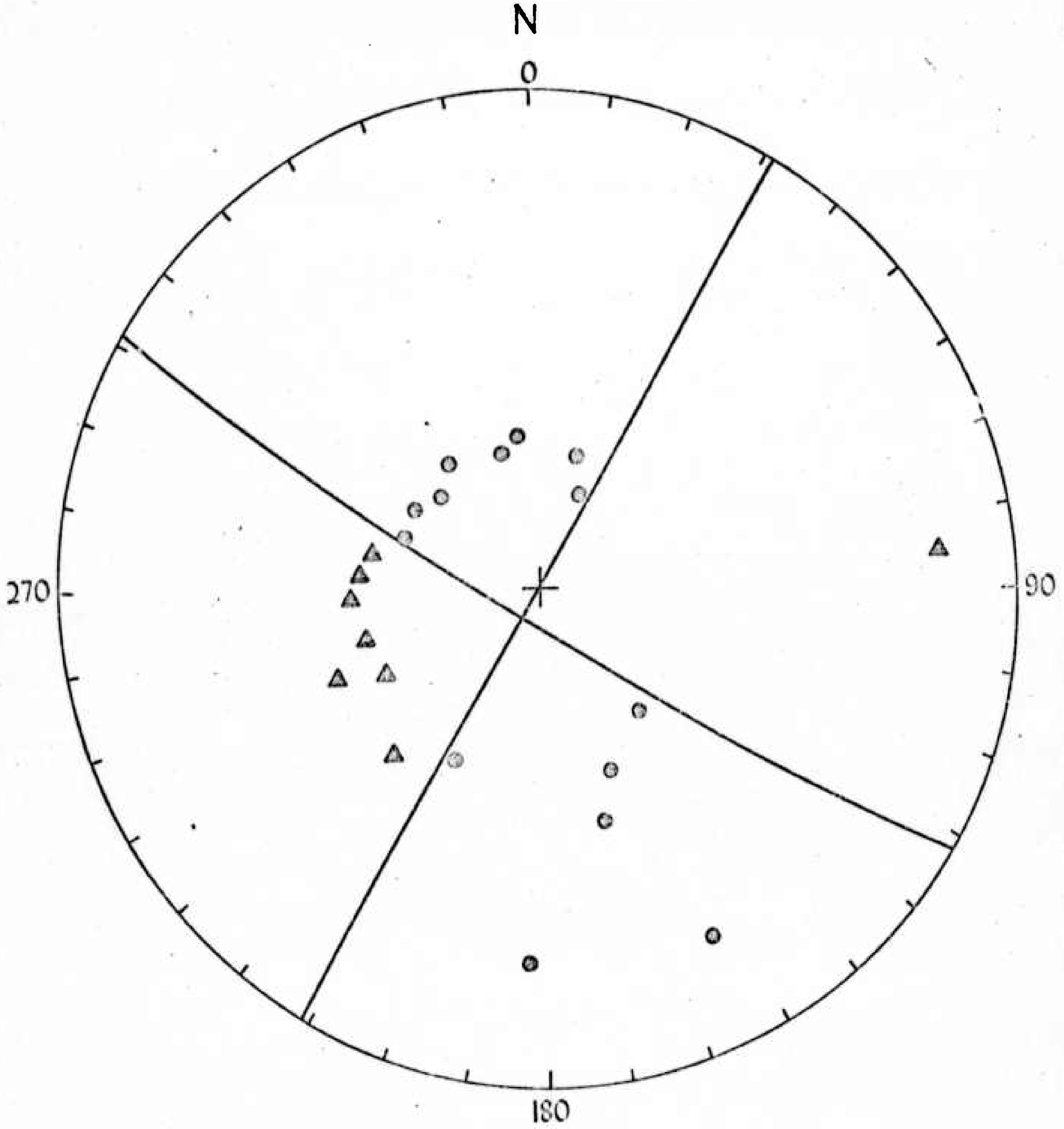

WEST LONGITUDE
EAST LONGITUDE
SCALE
LAMBERT AZIMUTHAL EQUAL-AREA PROJECTION

Fig. 4

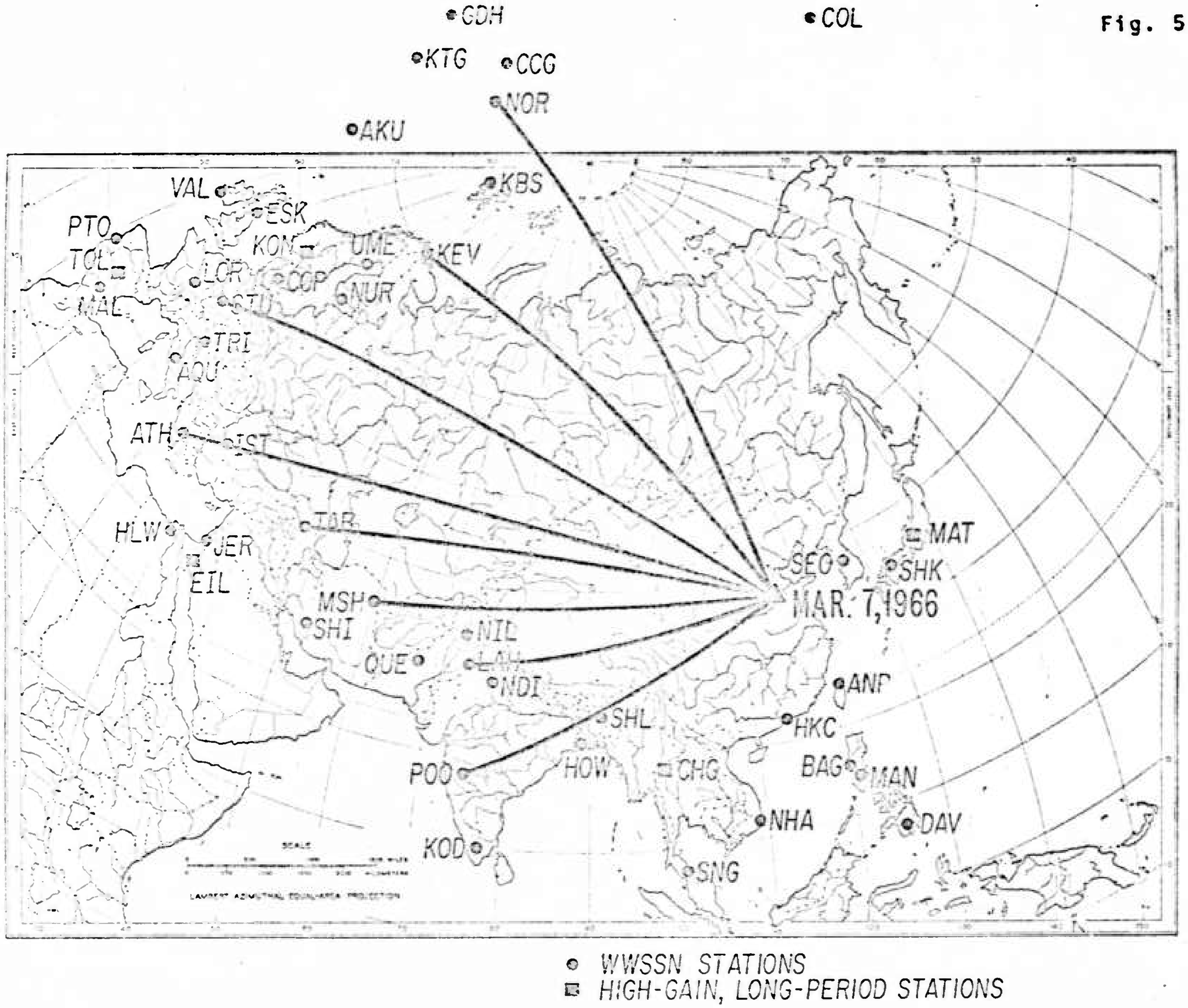


SOURCE DEPTH=15 KM

○ compression

▲ dilatation

Fig. 5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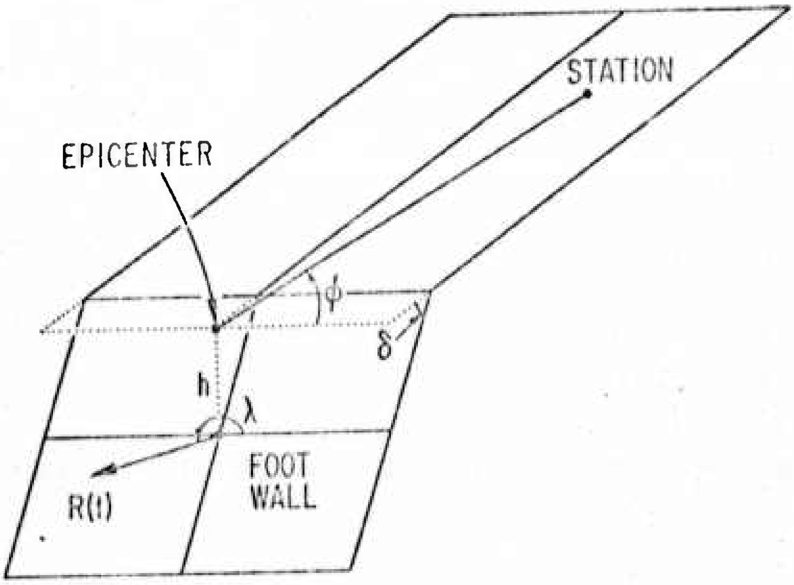
LAMBERT AZIMUTHAL EQUAL-AREA PROJECTION
WWSSN STATIONS
HIGH-GAIN, LONG-PERIOD STATIONS


STATION
EPICENTER
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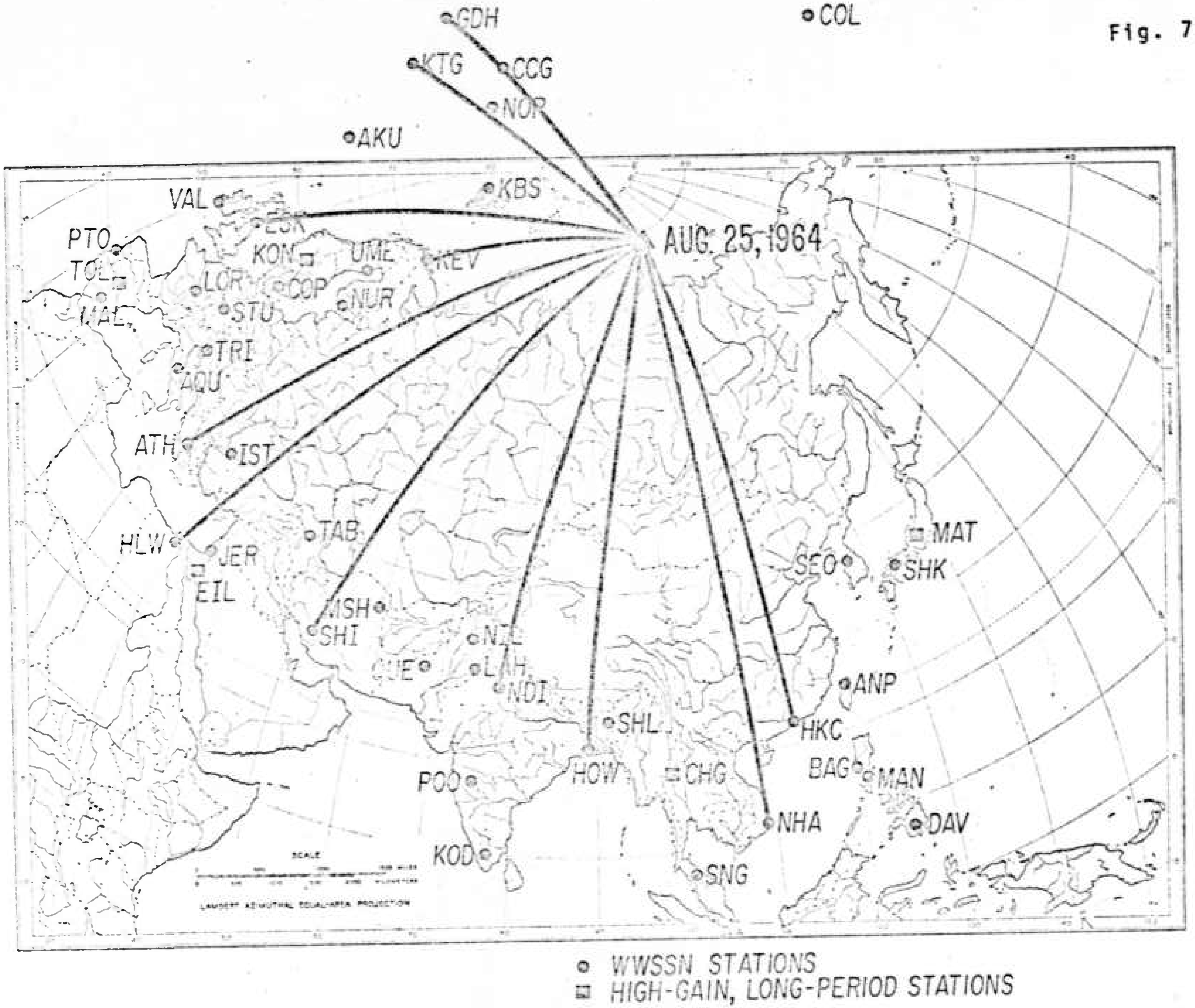
FOOT WALL

Fig. 7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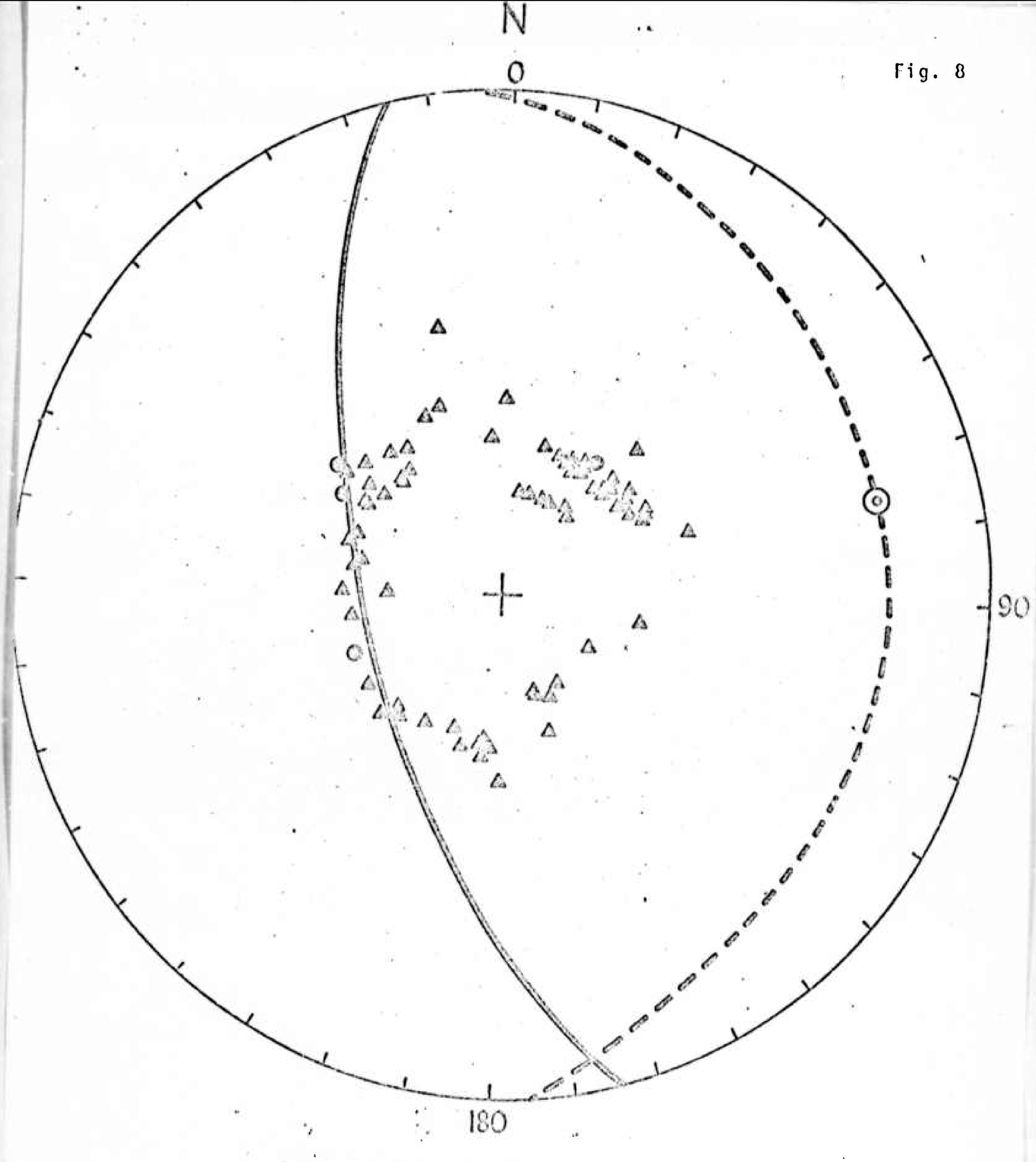
LAMBERT AZIMUTHAL EQUAL-AREA PROJECTION
○ WWSSN STATIONS
☐ HIGH-GAIN, LONG-PERIOD STATIONS

Fig. 8

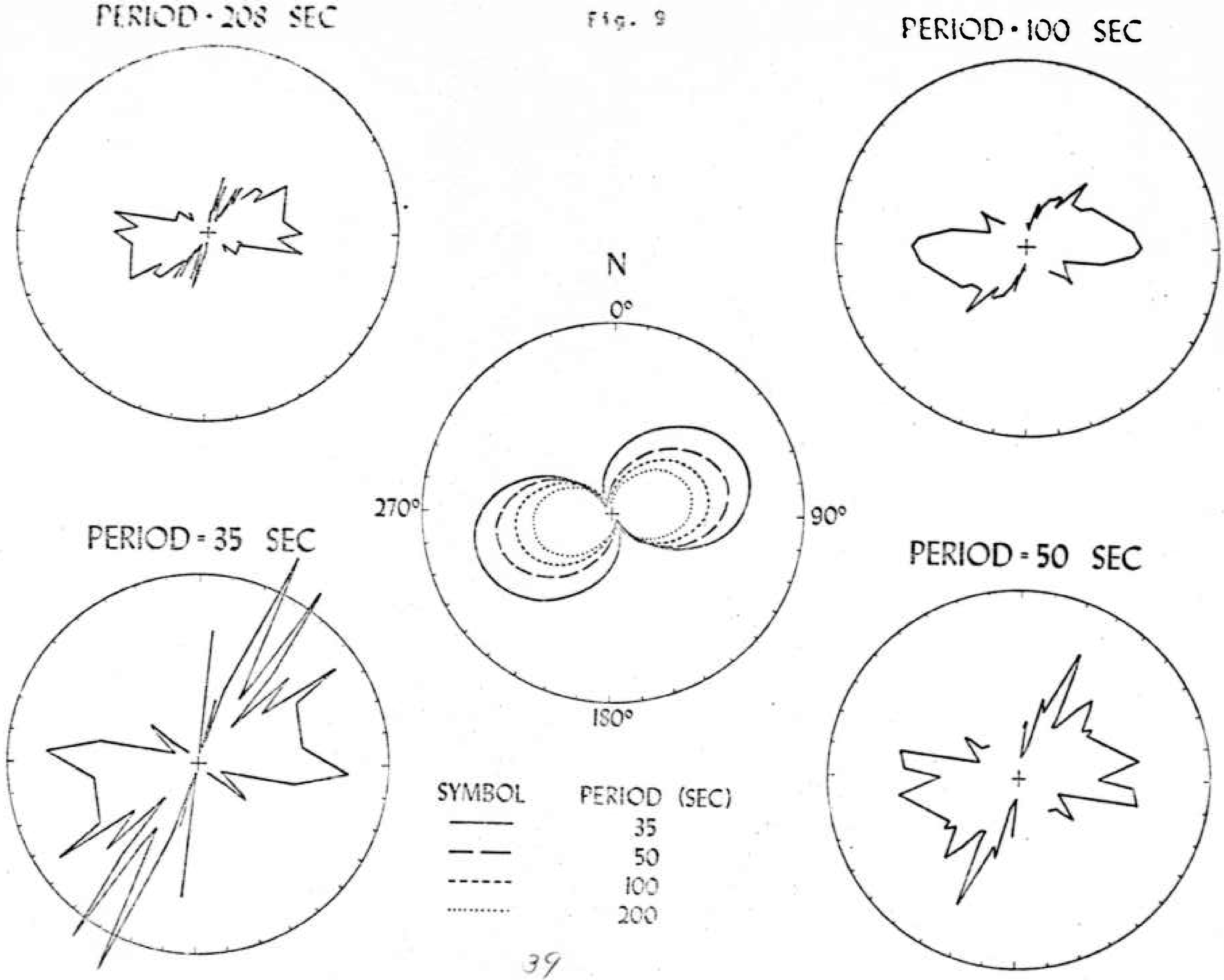


SOURCE DEPTH=11.5 KM

○ compression

△ dilatation

Fig. 9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PERIOD = 50 SEC
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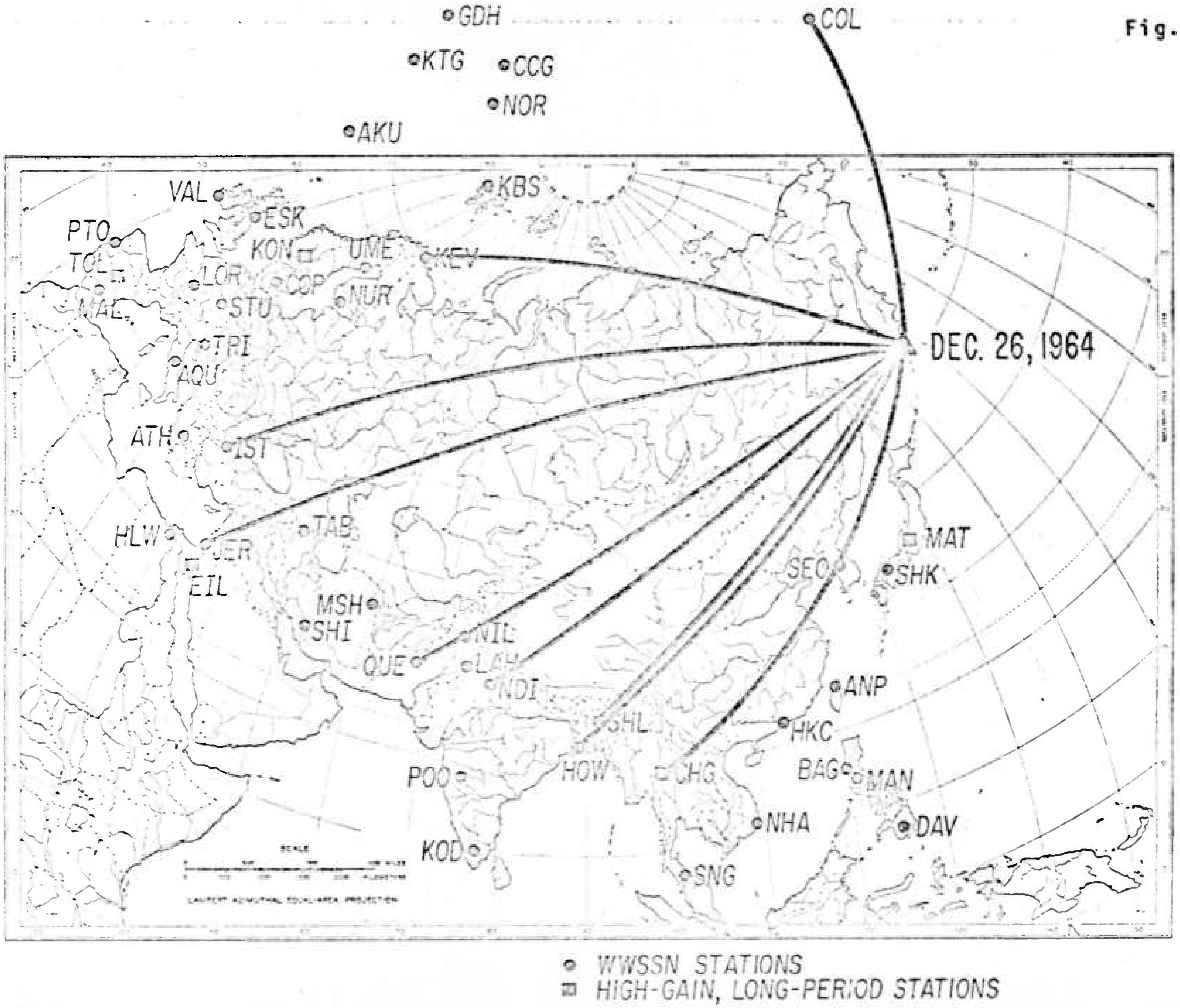
Fig. 10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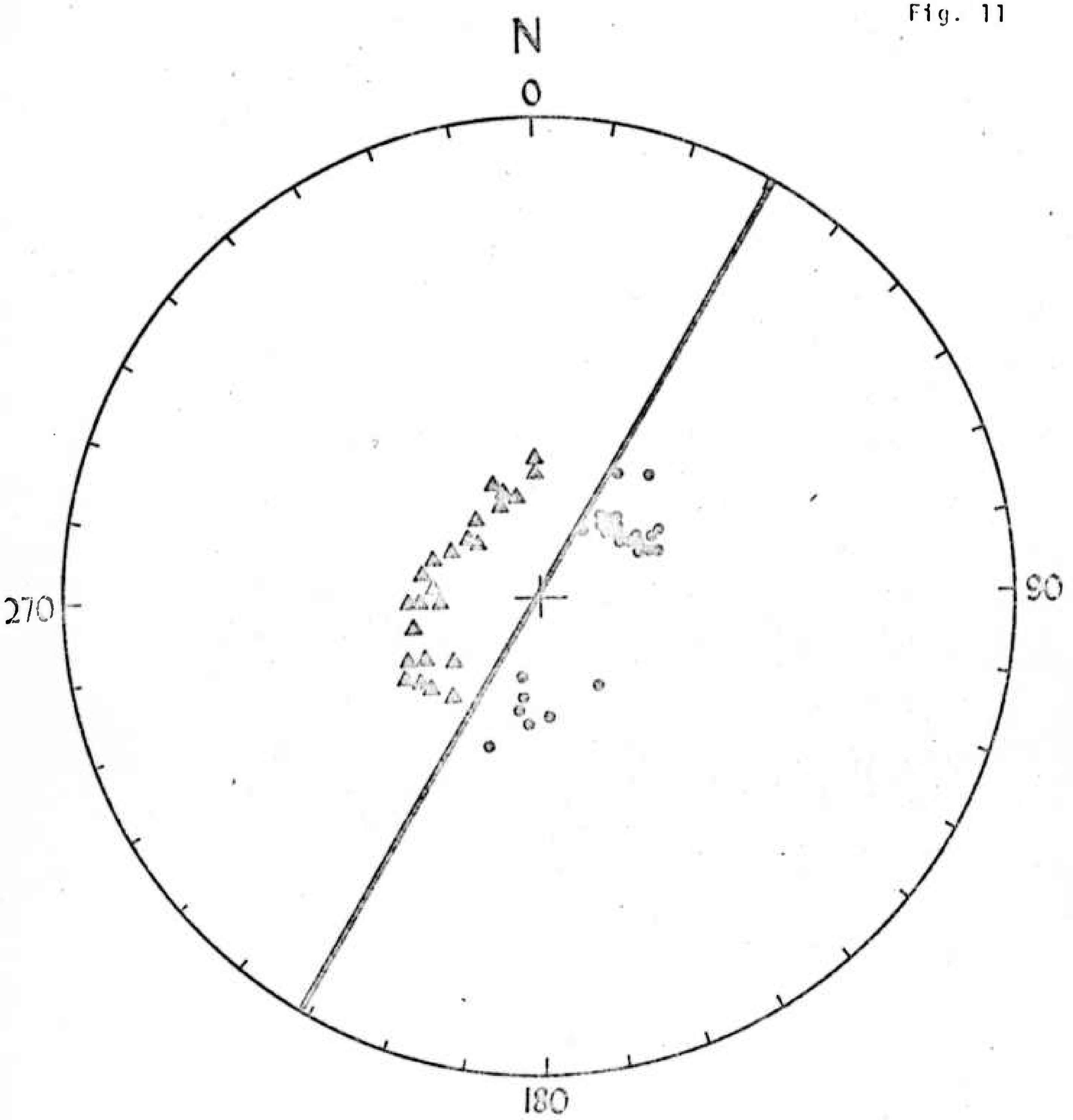
LAMBERT AZIMUTHAL EQUAL-AREA PROJECTION
WWSSN STATIONS
HIGH-GAIN, LONG-PERIOD STATIONS

Fig. 11

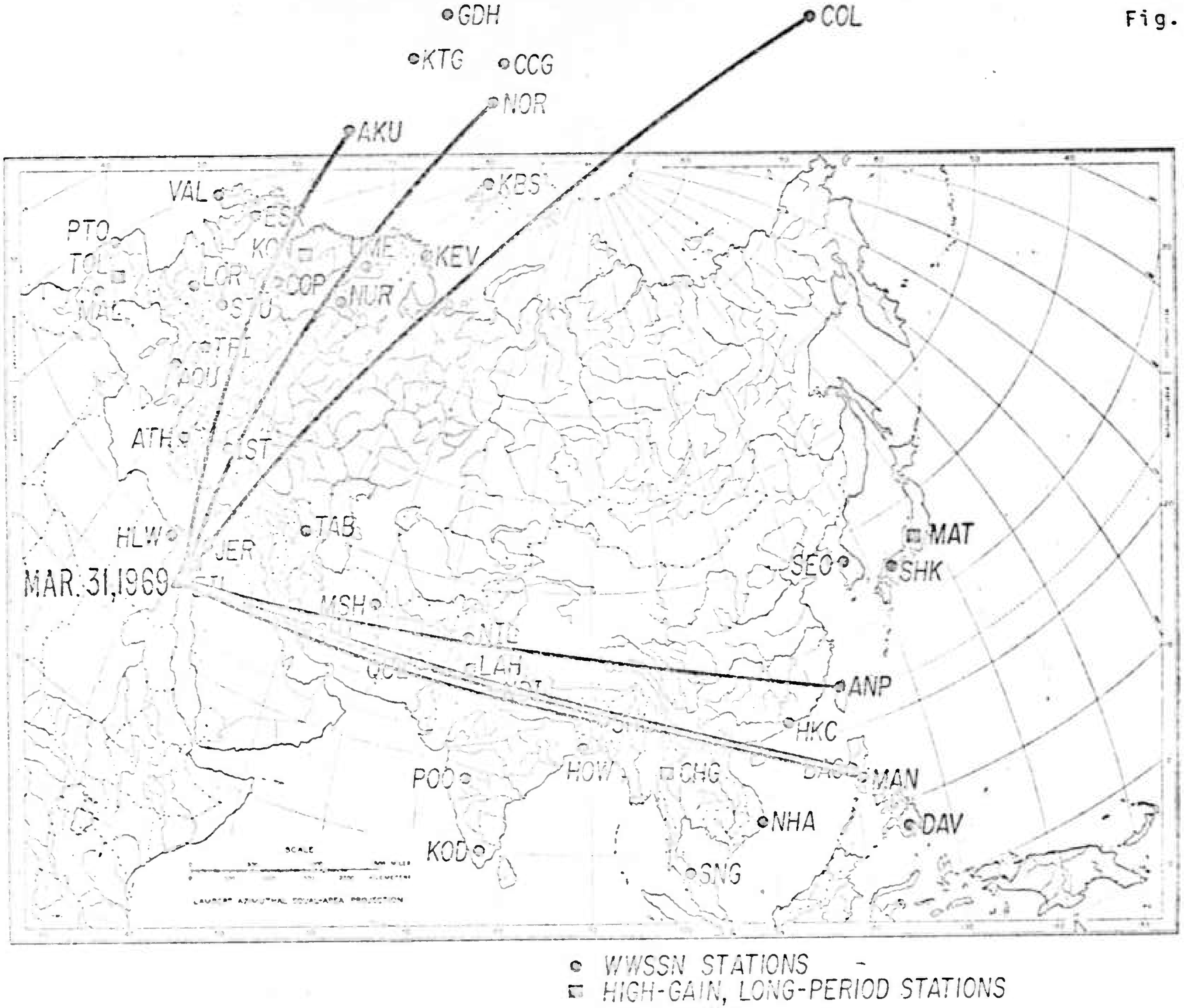


SOURCE DEPTH=136 KM

○ compression

△ dilation

Fig. 12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LAMBERT AZIMUTHAL EQUAL-AREA PROJECTION
WWSSN STATIONS
HIGH-GAIN, LONG-PERIOD STATIONS

Fig. 13

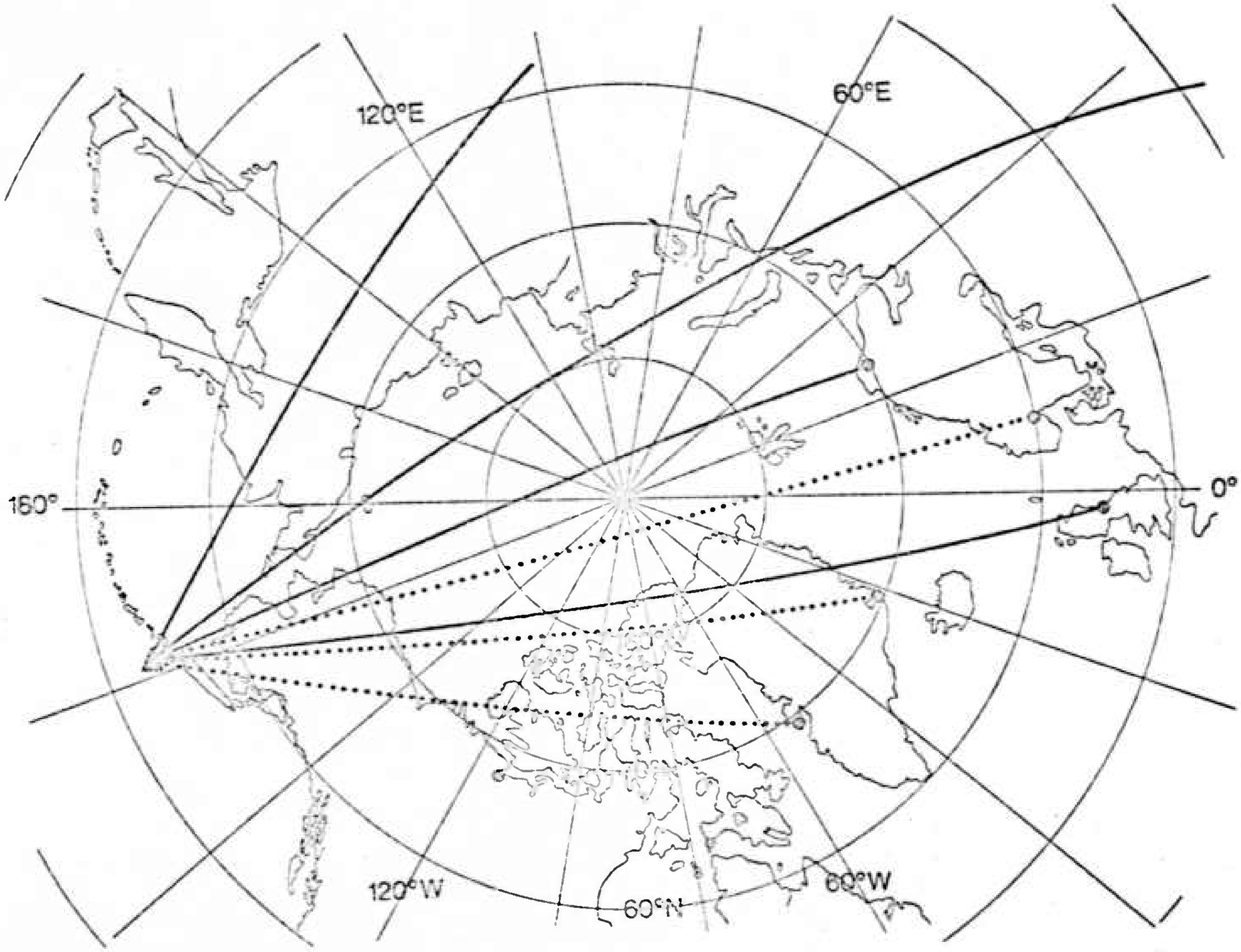
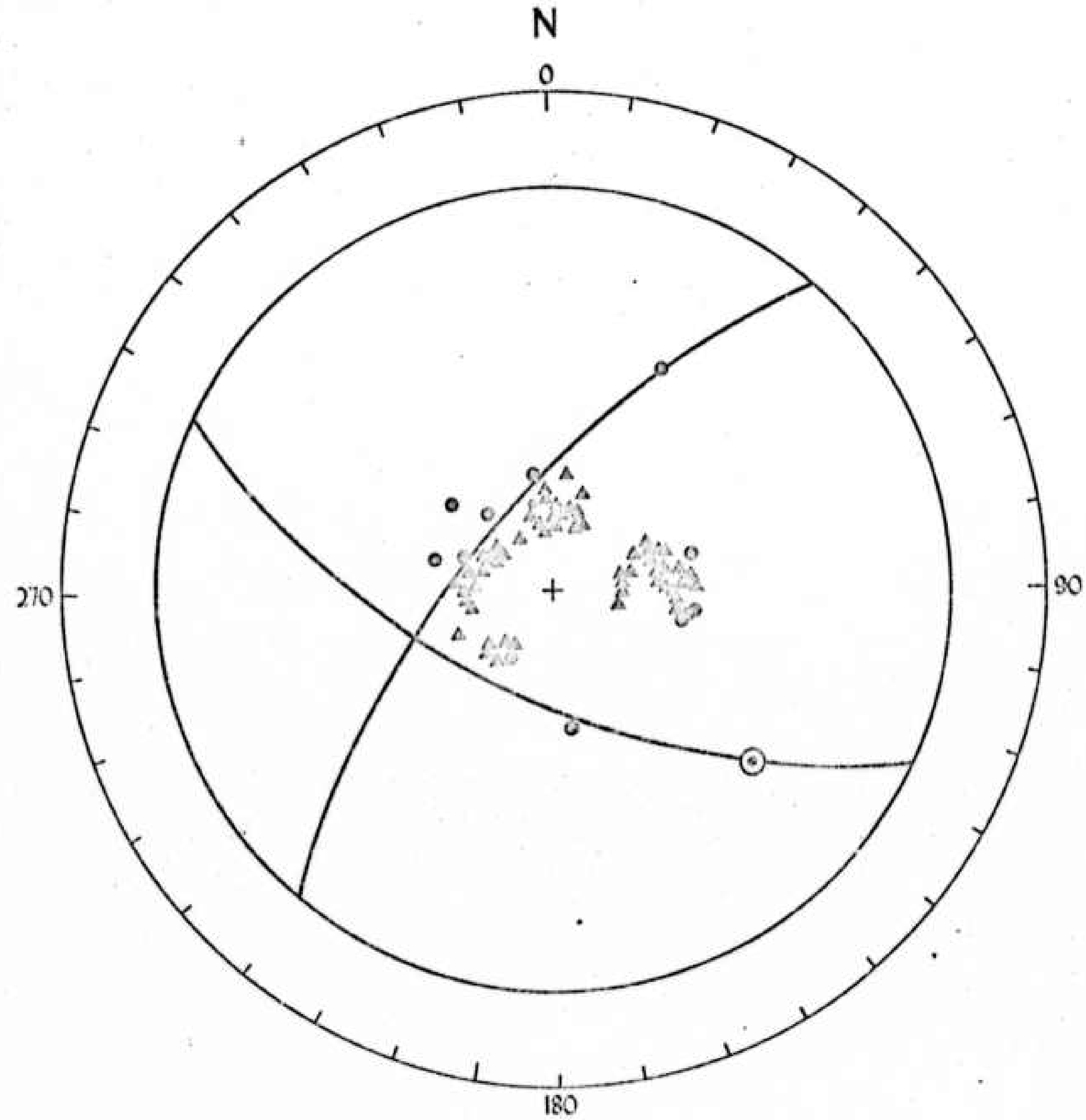


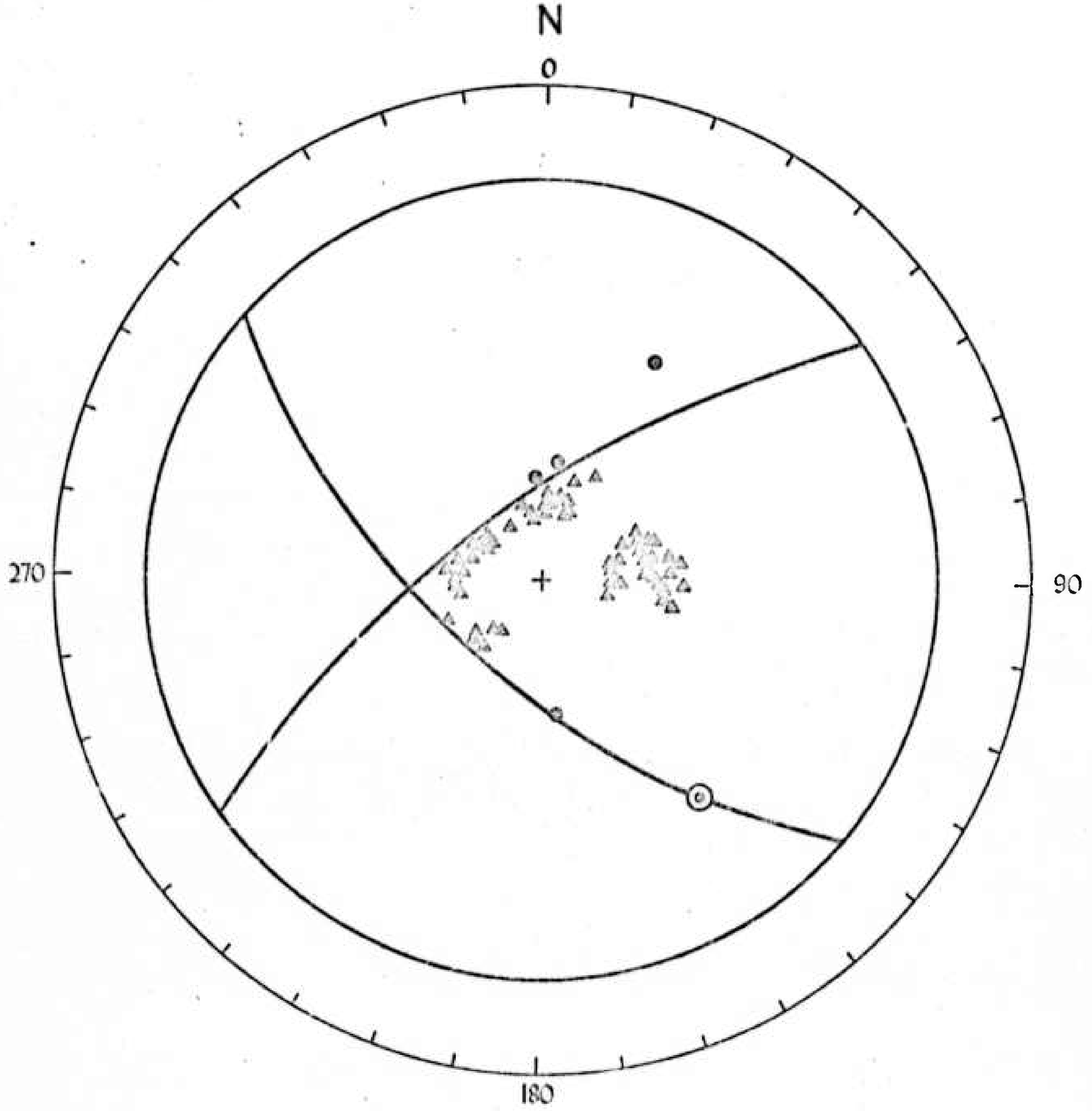
Fig. 14a



SOURCE DEPTH=33 KM

● compression
▲ dilatation

Fig. 14b



SOURCE DEPTH=33 KM

○ compression
△ dilatation

Fig. 15

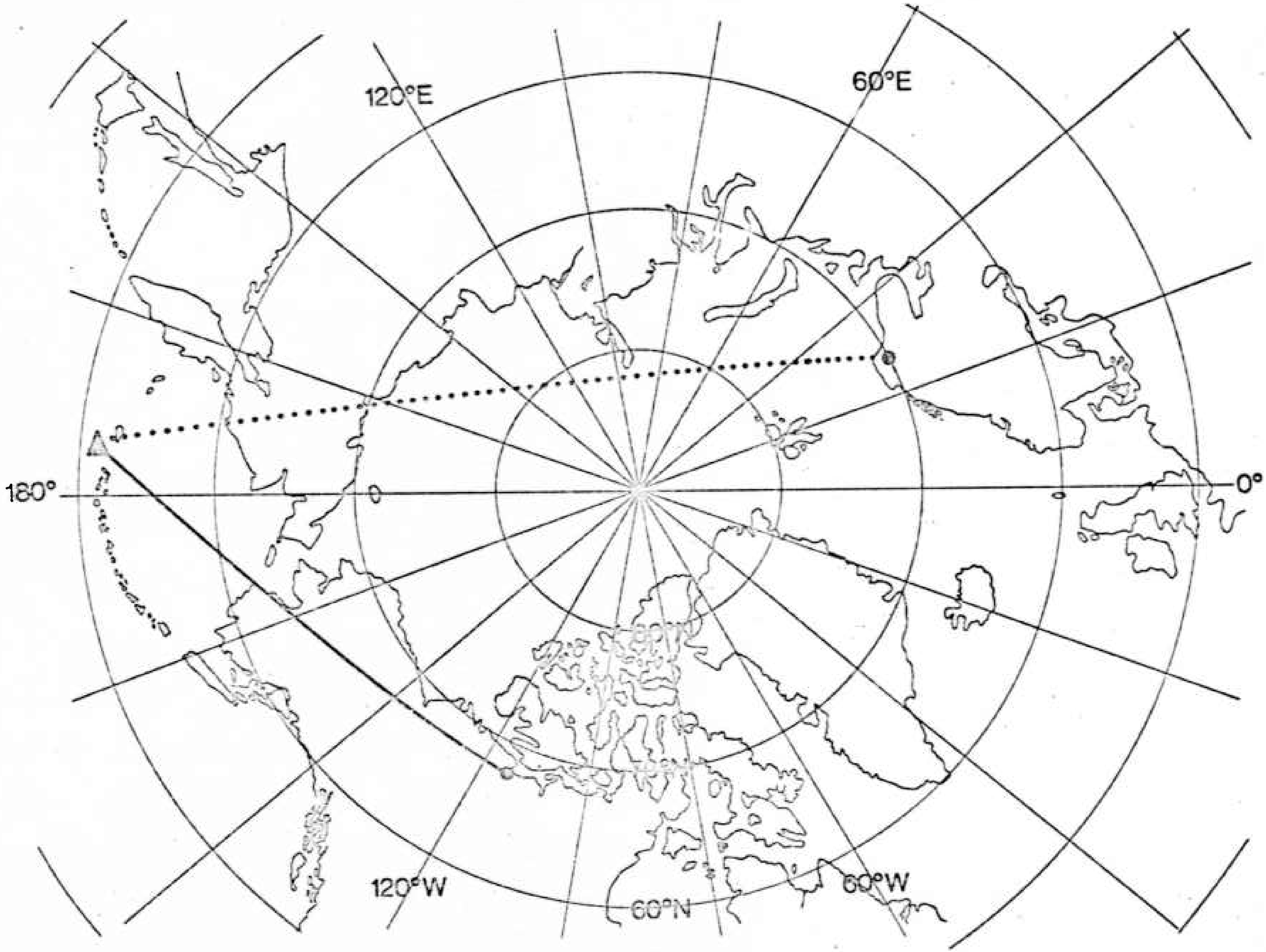
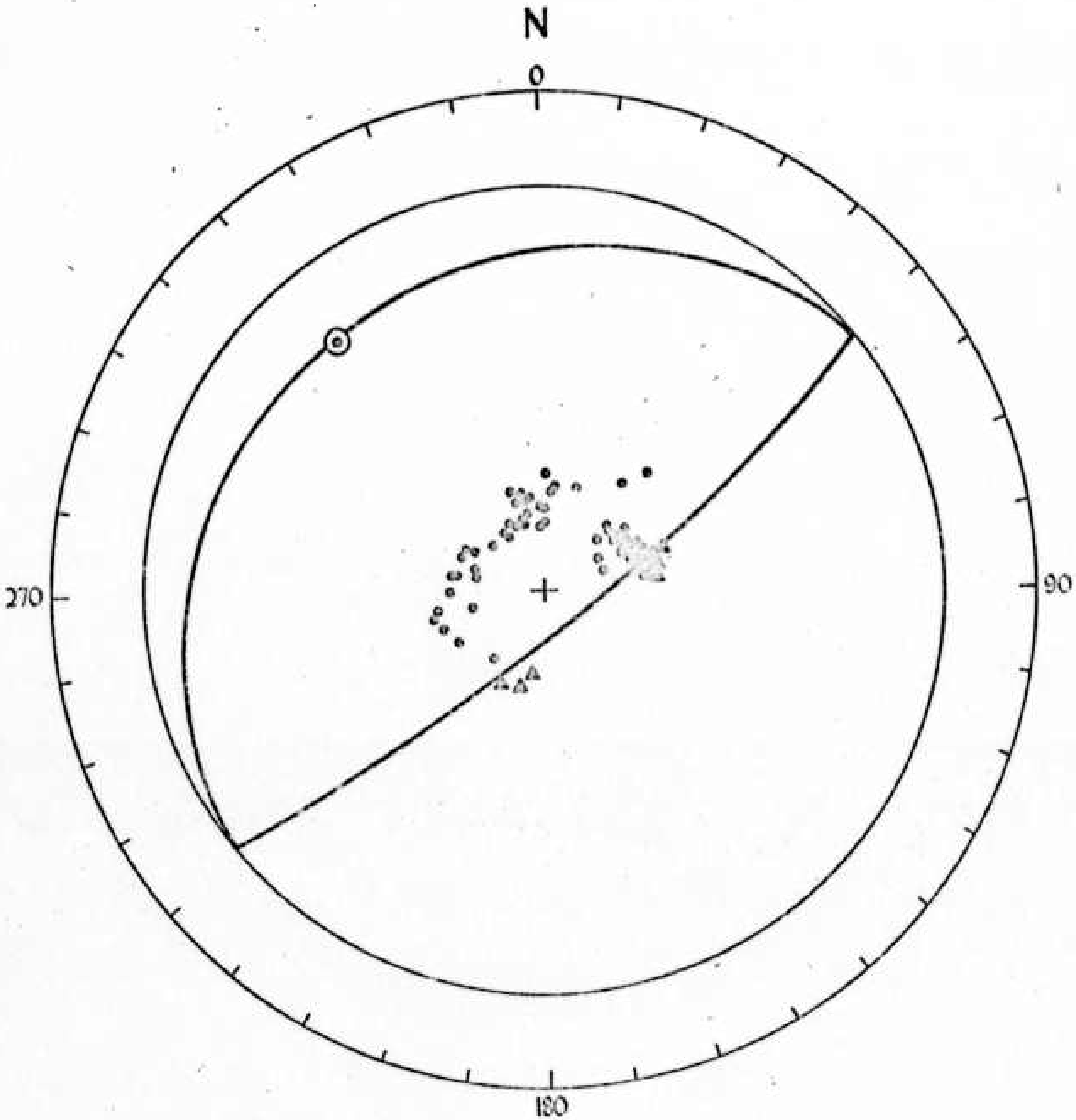


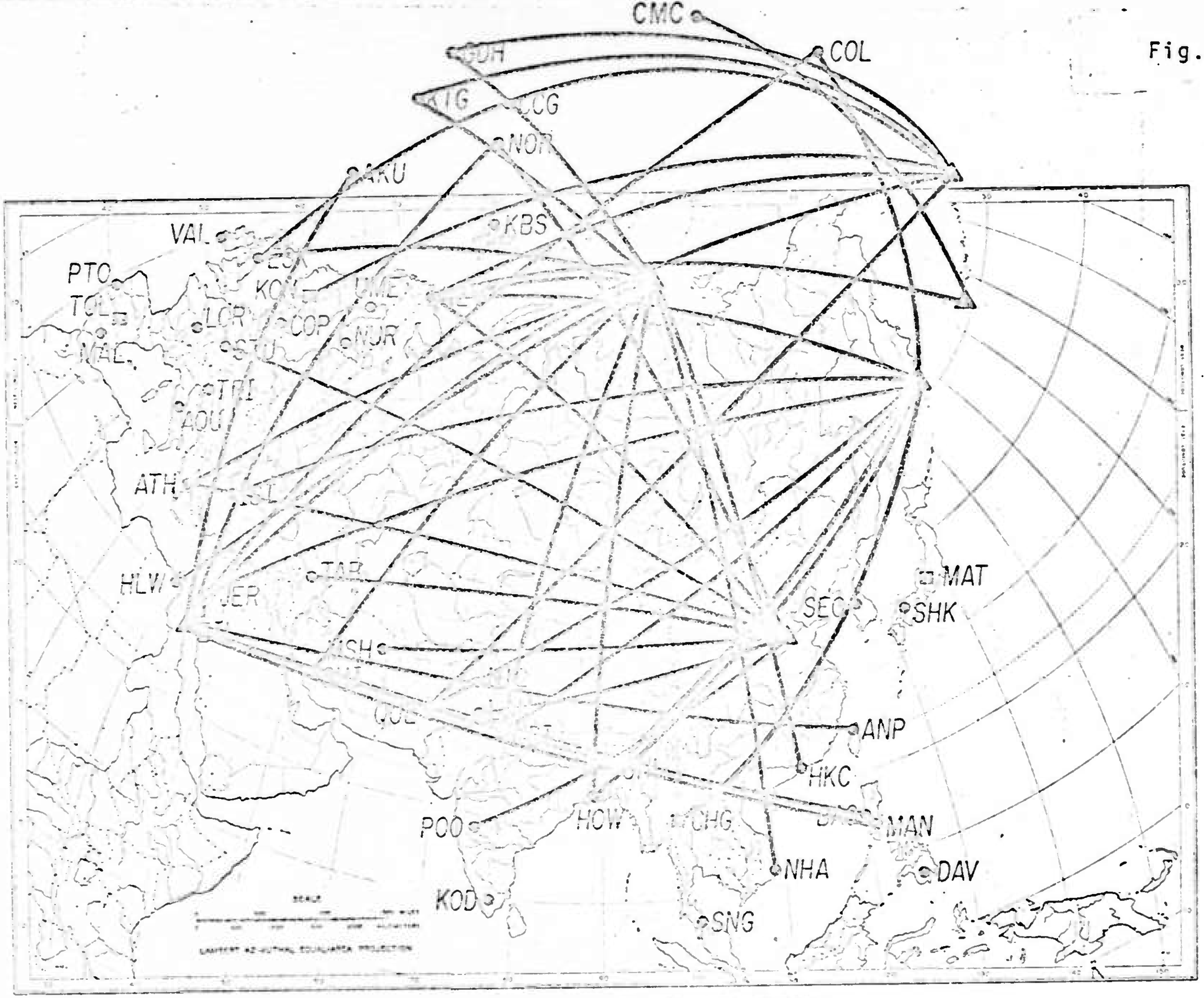
Fig. 16



SOURCE DEPTH=41 KM

- • compression
- ▲ dilatation

Fig. 17



○ WWSSN STATIONS
▫ HIGH-GAIN, LONG-PERIOD STATIONS

Fig. 18

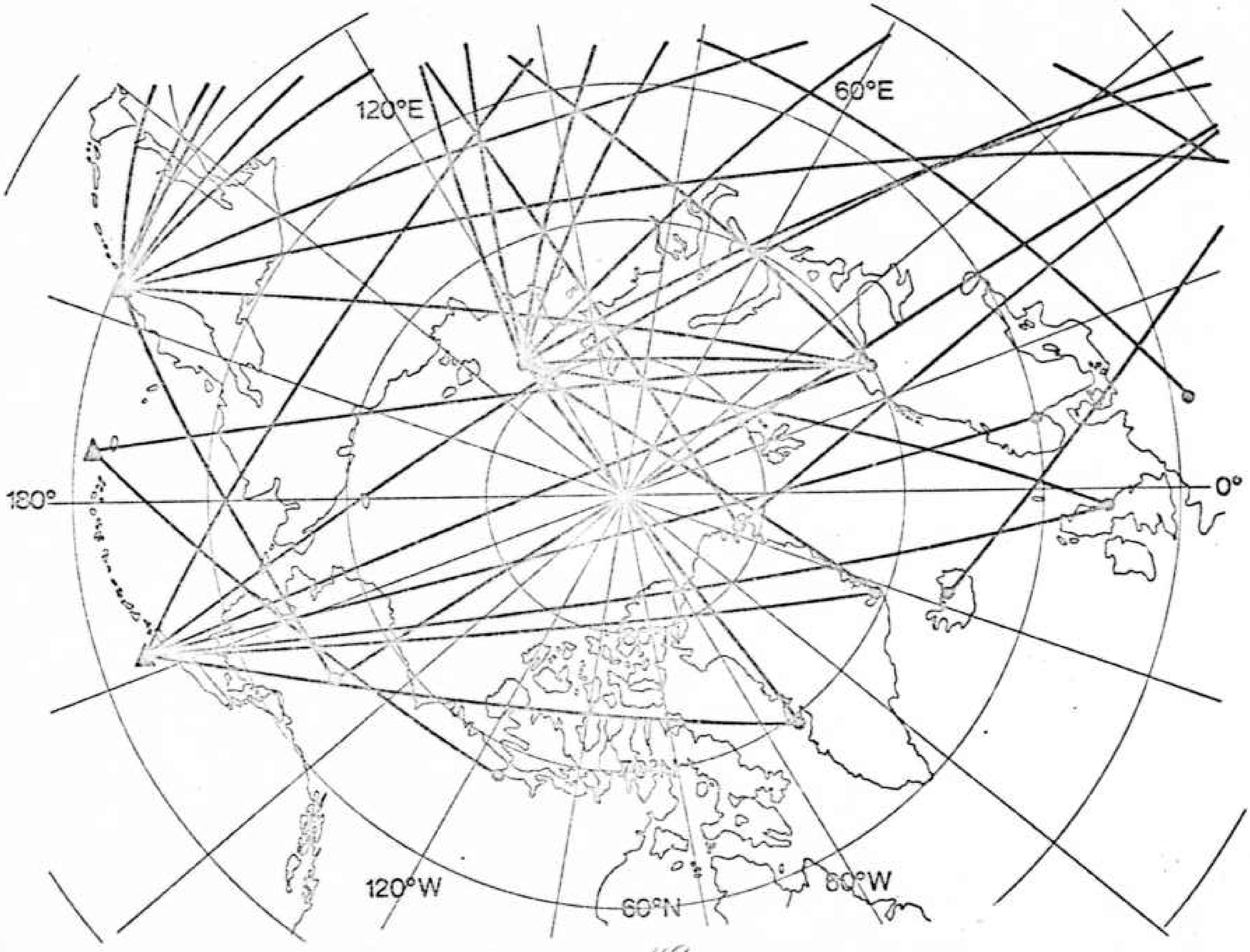
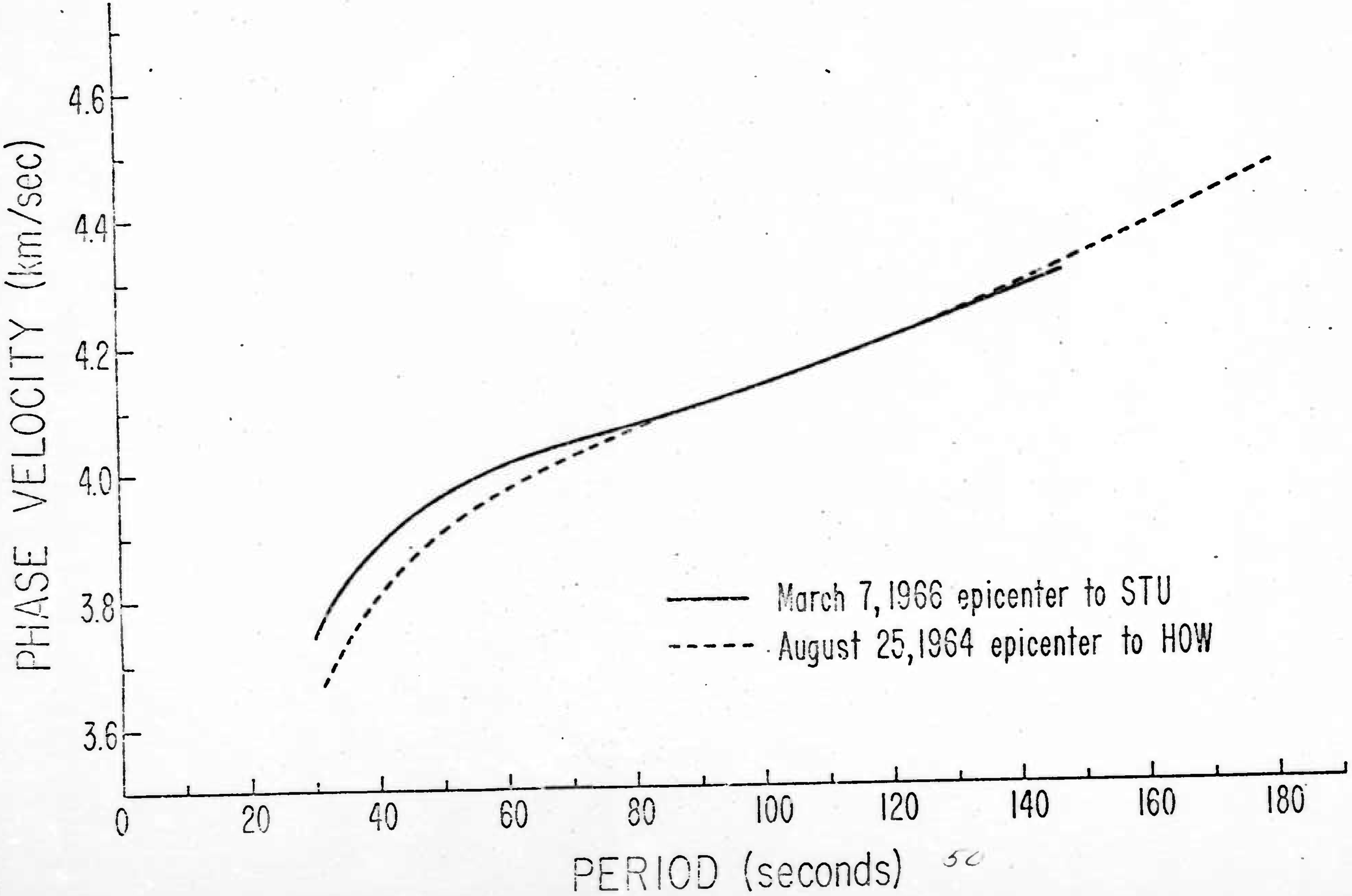


Fig. 19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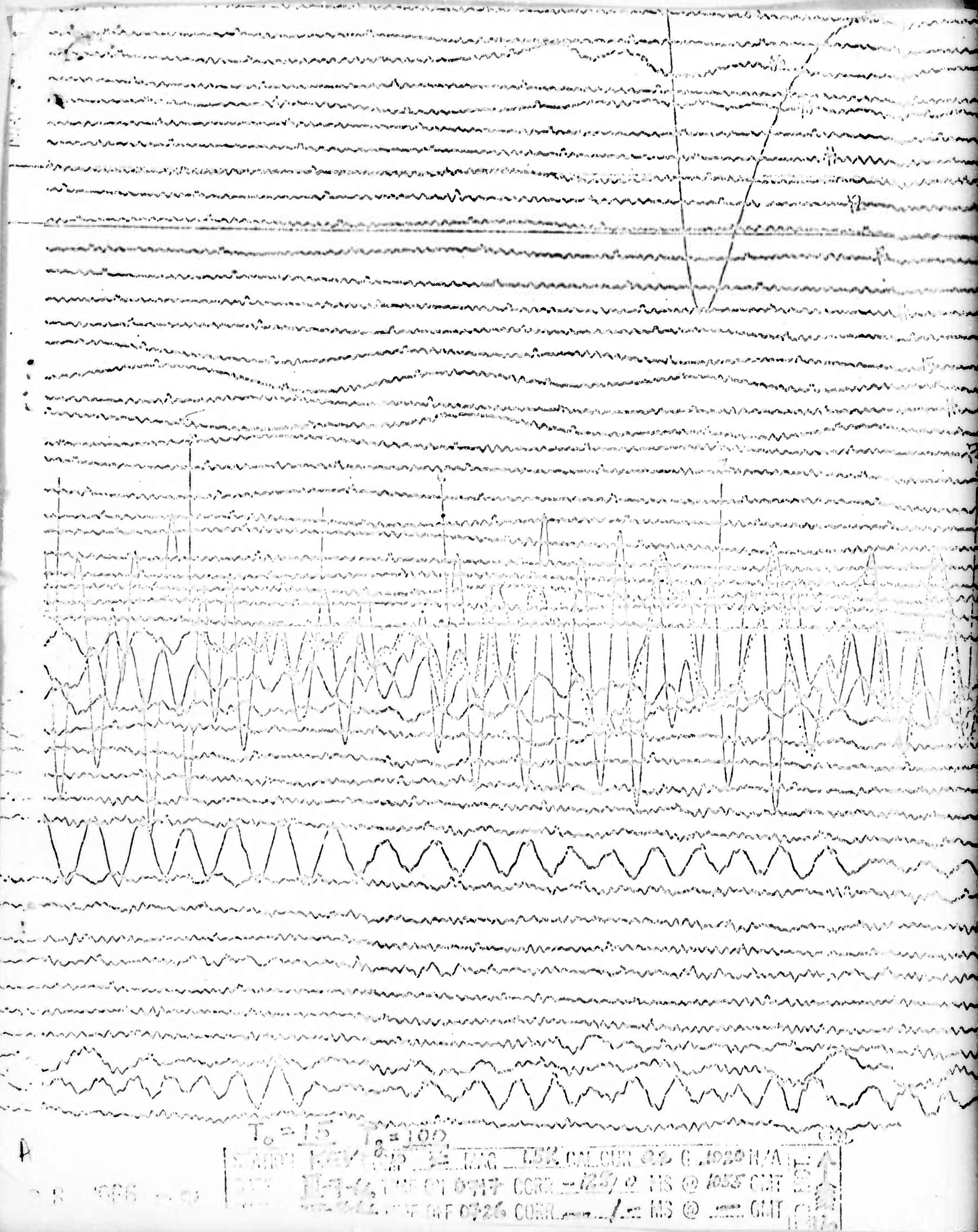
140
160
180
PERIOD (seconds)
March 7, 1966 epicenter to STU
August 25, 1964 epicenter to HOW

FISCAL STATUS

1.	Total amount of present award	$114,986
2.	Estimated expenditures and commitments to October 31, 1974	85,410
3.	Estimated funds required to complete proposed work	29,576

T₀ = 15 Tg = 100
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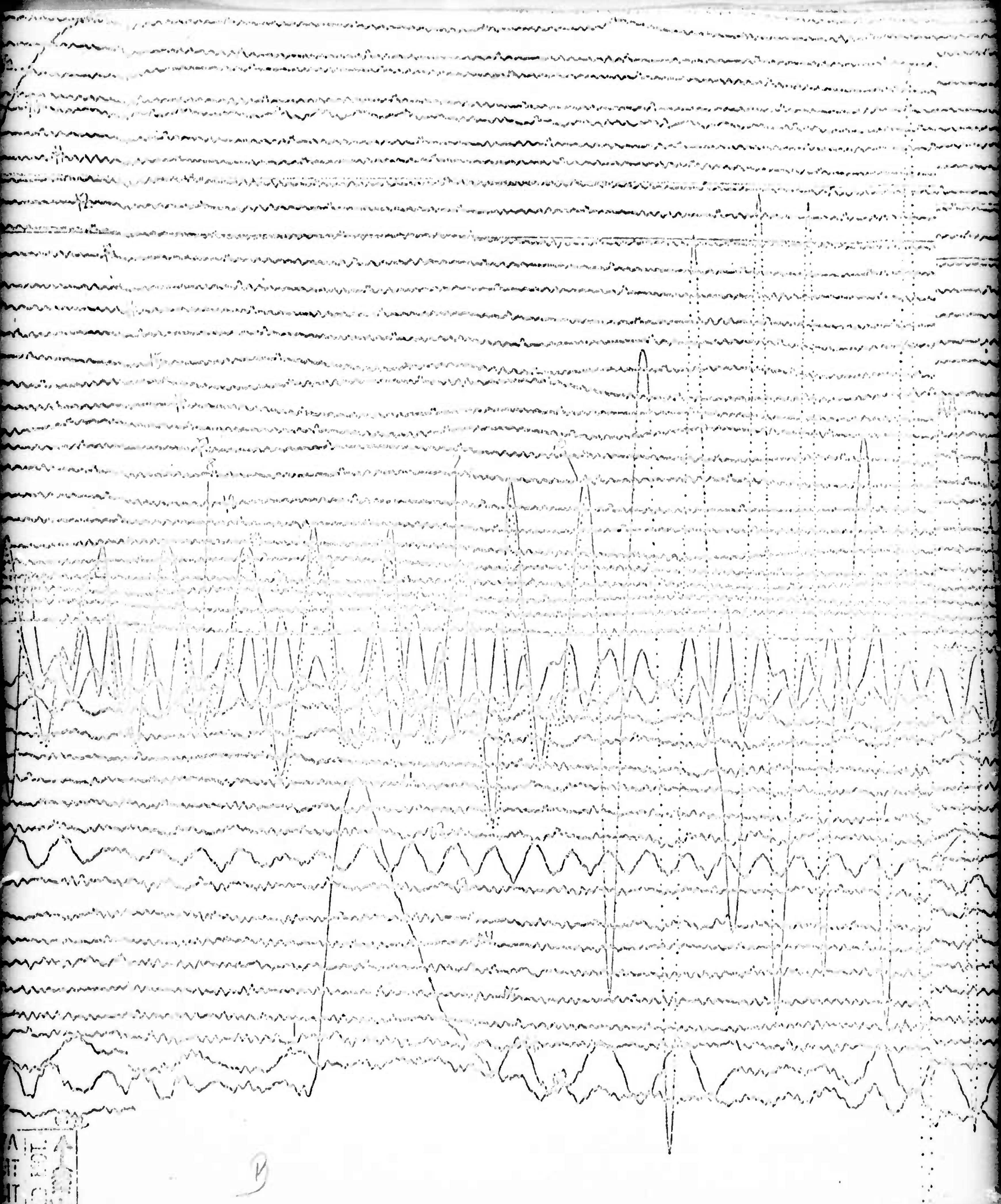
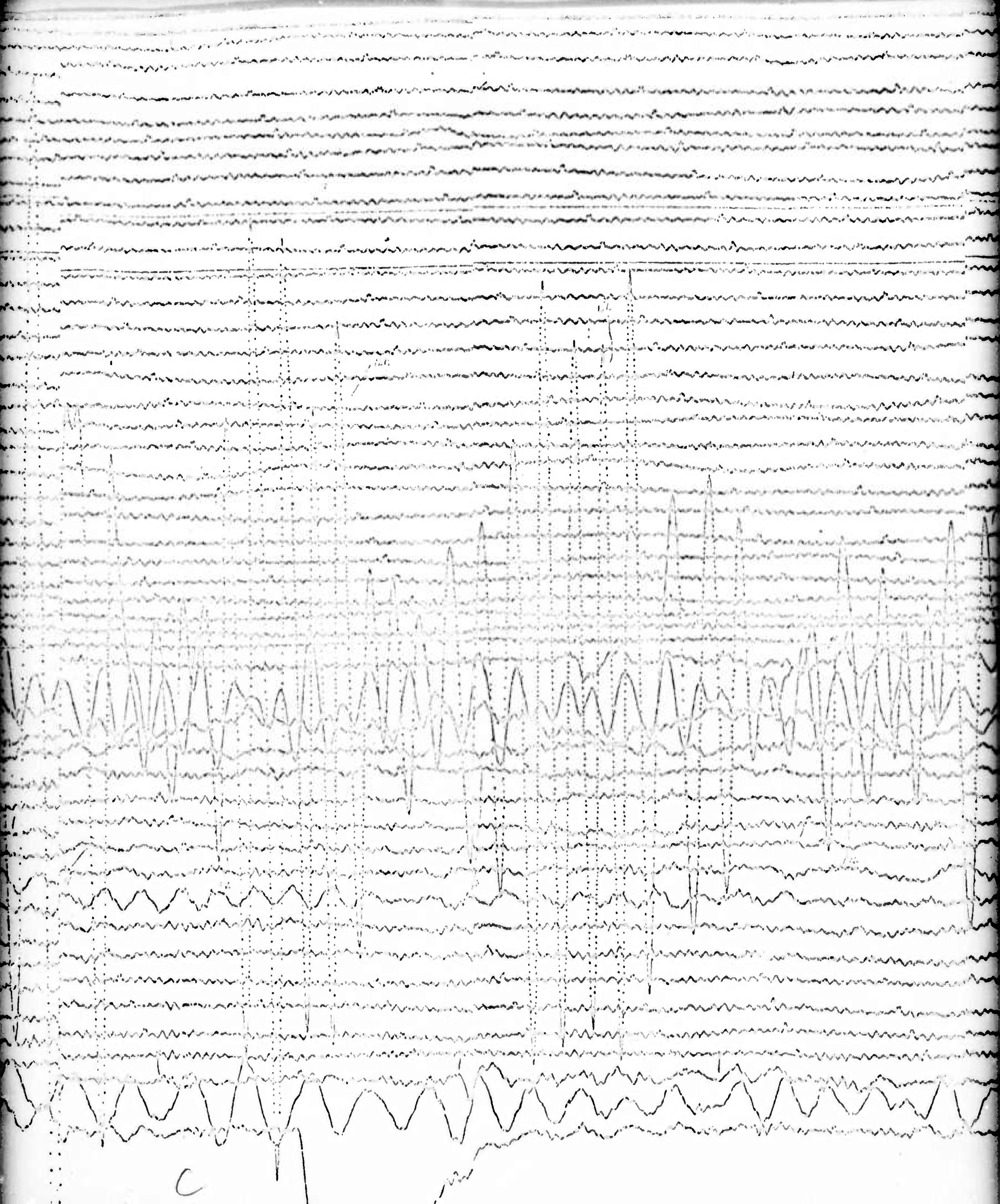
DATE II-7-66 TIME ON 0717 CORR -125/0 MS @ 1055 GMT
TIME OFF 0726 CORR MS @ GMT


B



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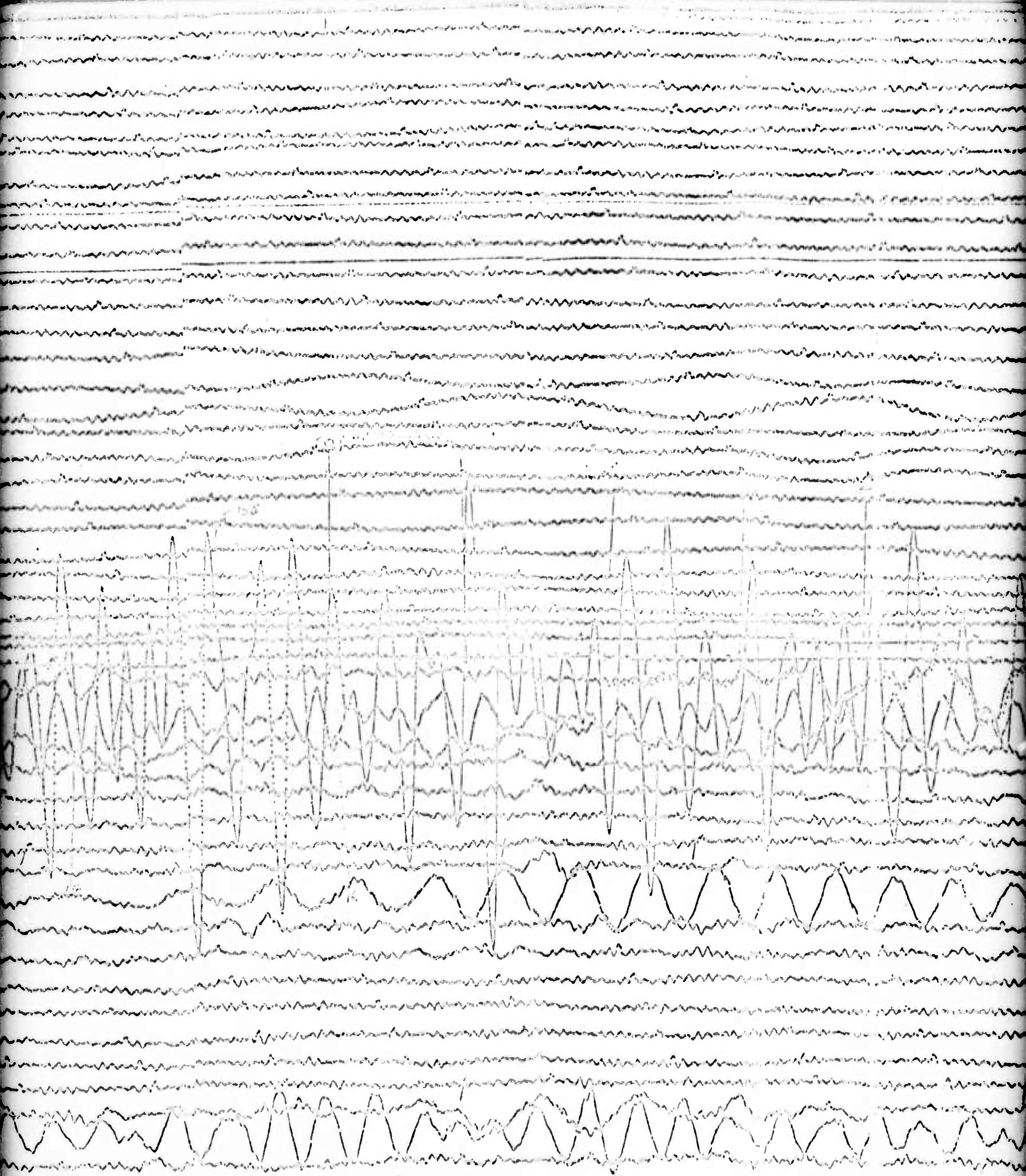

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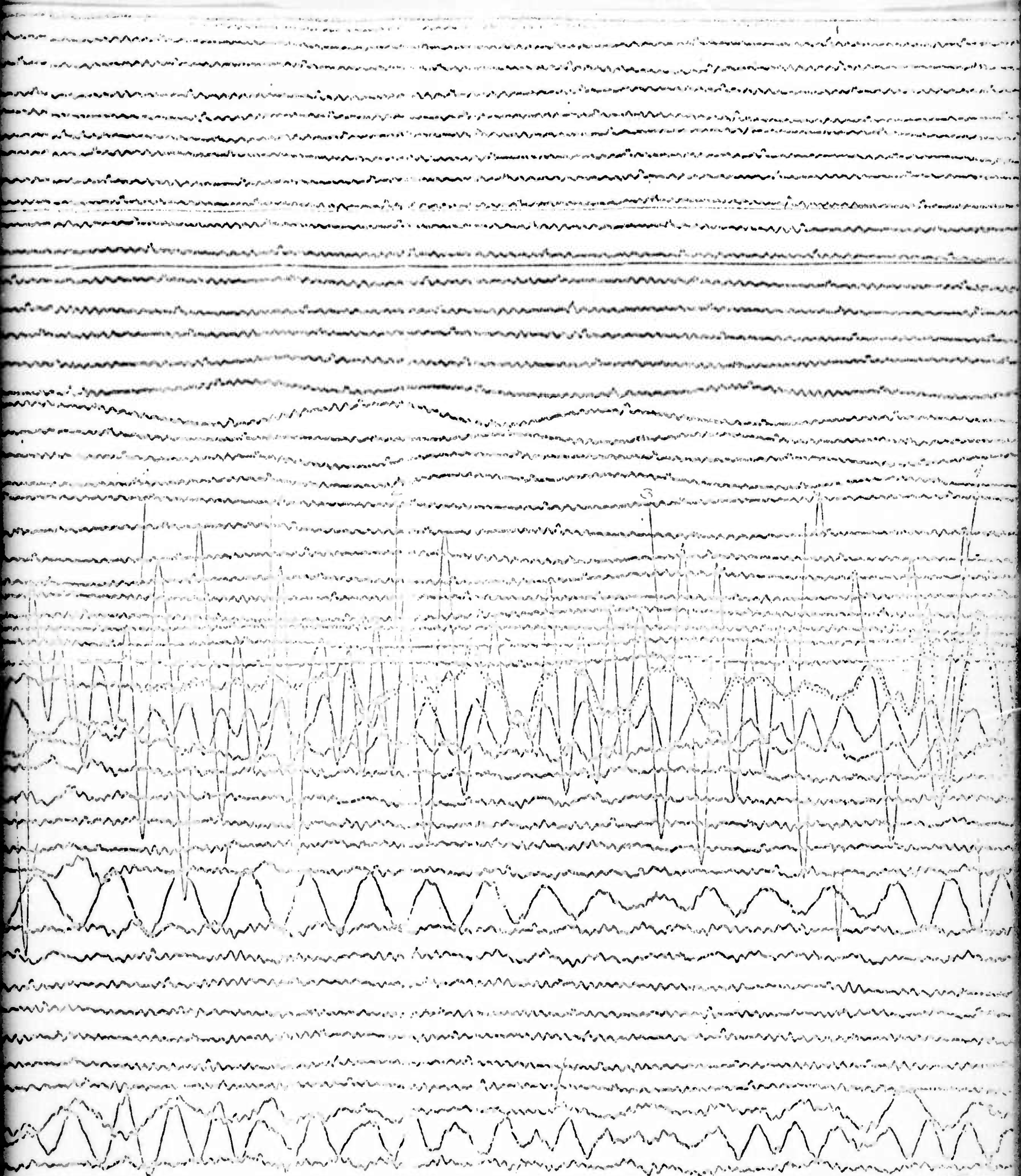

Fig. 20