Westinghouse

WORLD-WIDE VLF EFFECTIVE-CONDUCTIVITY MAP

Submitted to: Office of Naval Research
Department of the Navy
Washington, D. C. 20360
Under contract N00014-67-C-0274

15 January 1968

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WORLD-WIDE VLF EFFECTIVE-CONDUCTIVITY MAP

Westinghouse Electric Corporation
Environmental Science and Technology Department

ABSTRACT

A map showing effective electrical earth conductivity values for a propagating wave at VLF (10 kHz to 30 kHz) has been prepared for the major land areas of the world. Land area conductivity determinations were in most cases based upon known geological and climatological information. Actual conductivity data was collected where possible to aid in determining regional effective conductivity values, but the correlation between geology (and other known factors), and conductivity was used in estimating conductivity for the majority of the land areas.

The conductivity data are overprinted on seven 17 × 22 inch base maps. Effective conductivity values are designated by numbers from 1 to 10 referenced to a legend on each sheet. Separate page-size maps showing a confidence factor and a variability factor are included in the accompanying report.

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WORLD-WIDE VLF EFFECTIVE-CONDUCTIVITY MAP

1.0 INTRODUCTION

A map showing effective electrical conductivity of the earth at very low frequencies (10 kHz to 30 kHz) has been prepared to aid in radio propagation and navigational studies. Values of conductivity were determined for land areas whose boundaries are in most cases based upon climatological, pedological, physiographical, and geological information. Data was collected to aid in establishing regional effective-conductivity values. It was necessary, however, to rely on the correlation between geology and other known environmental factors and conductivity for the majority of the land areas [1].

It is noteworthy that there is considerable difference between effective-conductivity maps for use at broadcast frequencies (1 MHz) and the VLF maps; these differences are due primarily to the greater depth of penetration of the VLF energy. Earth materials to depths of over 50 meters must be considered for conductivities on the order of 10^{-2} mho/meter, and greater depths of penetration are involved for lower conductivities.

Because of the relationships between conductivity and phase velocity, and between conductivity and attenuation rate, it is much more important to accurately determine conductivities which are below 10^{-3} mho/meter than to accurately determine conductivities which are 10^{-2} mho/meter and greater, hence, the lack of detail on the maps for this latter conductivity range. Materials which fall into the lower, more

important range include geologically old, crystalline rocks. Areas where permafrost occurs, and areas with ice caps (Greenland and the Antarctic) are similarly important. Measurements were made in permafrost areas of the Canadian Shield during an earlier program which produced the conductivity map of North America to help define the effect of freezing on the in situ electrical properties of the rocks [2].

The author would like to acknowledge the assistance of Mr. Gary Aho, during the summer of 1967, who shared a large part of the responsibility for the project during that time. The author is indebted to the many scientists and research organizations who sent hundreds of replies to requests for electrical conductivity data. Of particular help in this data collection effort were the United States Embassies throughout the world. Plans are to publish additional material which can include a list of contributors. It is hoped that contributors will continue to send data as it becomes available, and that future editions of the map will therefore be of increased usefulness to the scientific community throughout the world.

2.0 DESCRIPTION AND USE OF MAP

The conductivity map is overprinted on seven 17 X 22 inch base maps supplied by Bonn Cartographic Corporation of Salt Lake City, Utah. The effective-conductivity values are designated by numbers 1 to 10, referenced to a legend on each sheet.

Since little appropriate VLF data exists on a world-wide basis, it is not possible to evaluate directly the accuracy of the entire map. As an alternative, two factors directly related to the reported values are presented. The Confidence Factor refers to the quality, quantity and type of information which determined the regional conductivity values. The Variability Factor indicates the amount by which local values of conductivity can be expected to vary from the regional average.

The above two factors are seen to be independent, and are presented separately for each sheet of the map in Figures 1 through 7. These factors are distinguished as follows:

Confidence Factor

Highest Confidence: Correlation based on sound geologic and conductivity data. These values are not expected to change appreciably from the reported values.

Moderate Confidence: Some data available. Geology-conductivity correlation believed to be reliable. These values will probably not need to be revised by more than one level (one half decade).

Limited Confidence: Geology-conductivity correlation not well known. Some data may be available, but it is limited in quantity or quality. These values may change as data becomes available.

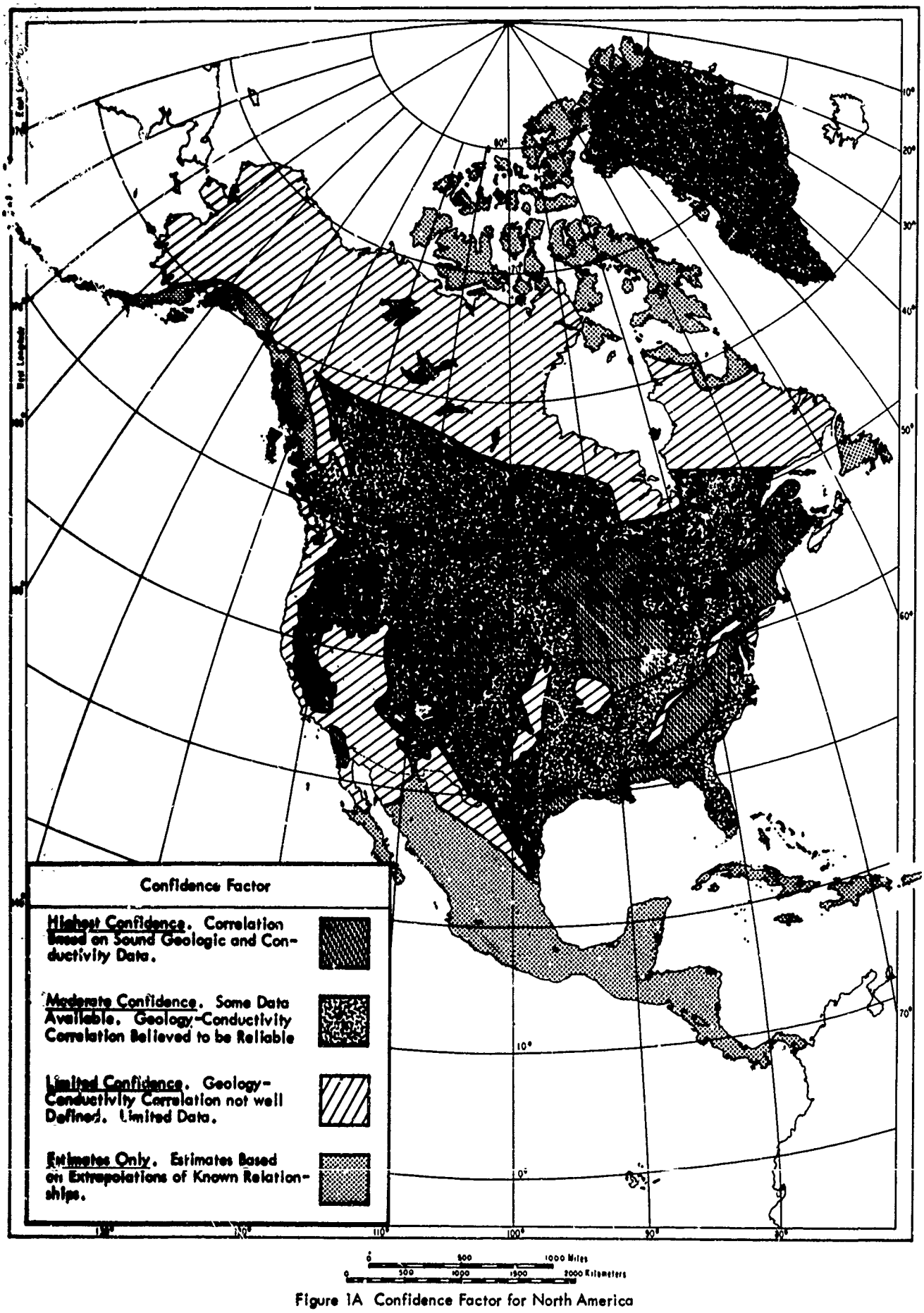

Figure 1A Confidence Factor for North America

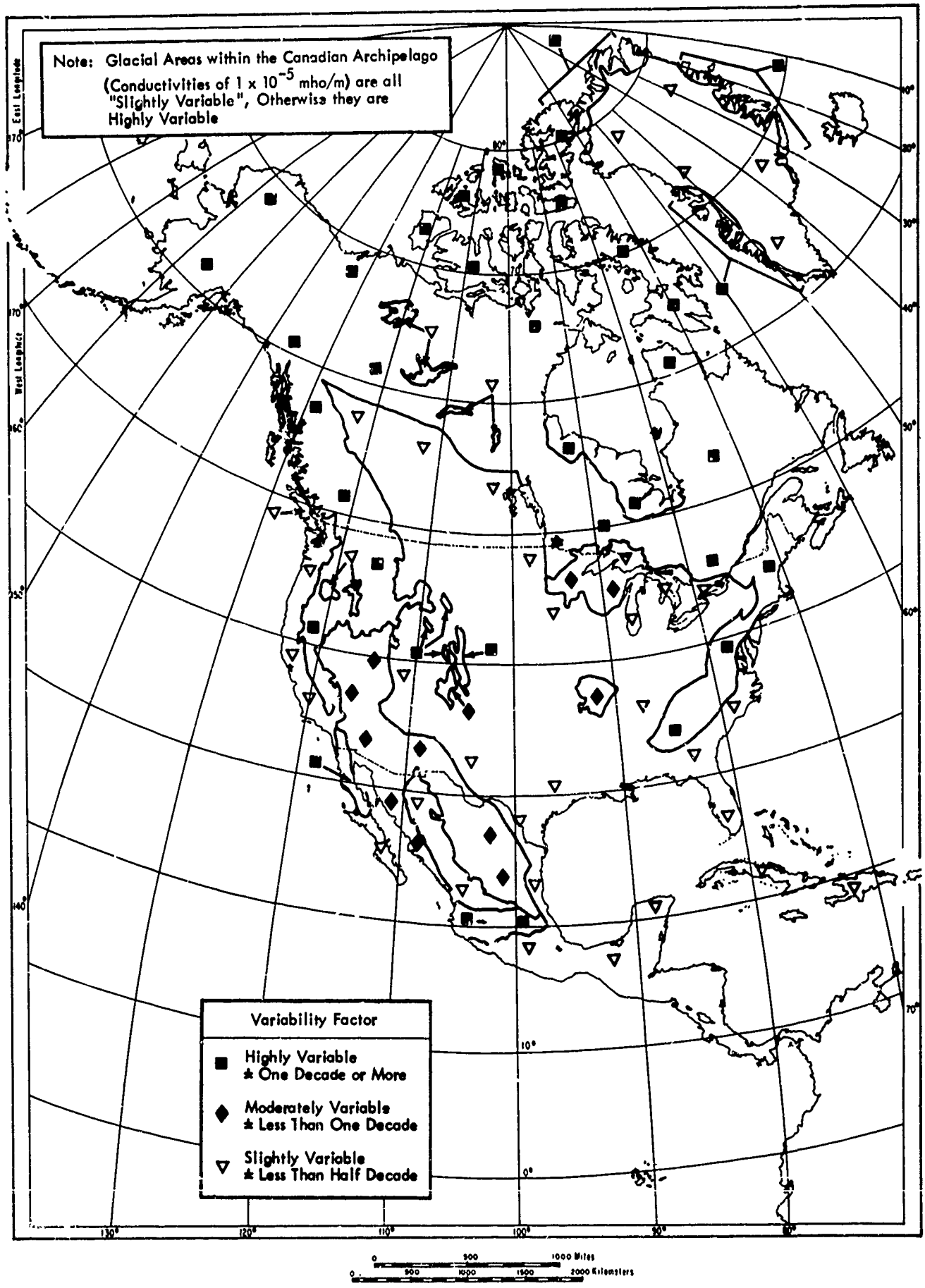

Figure 18 Variability Factor for North America

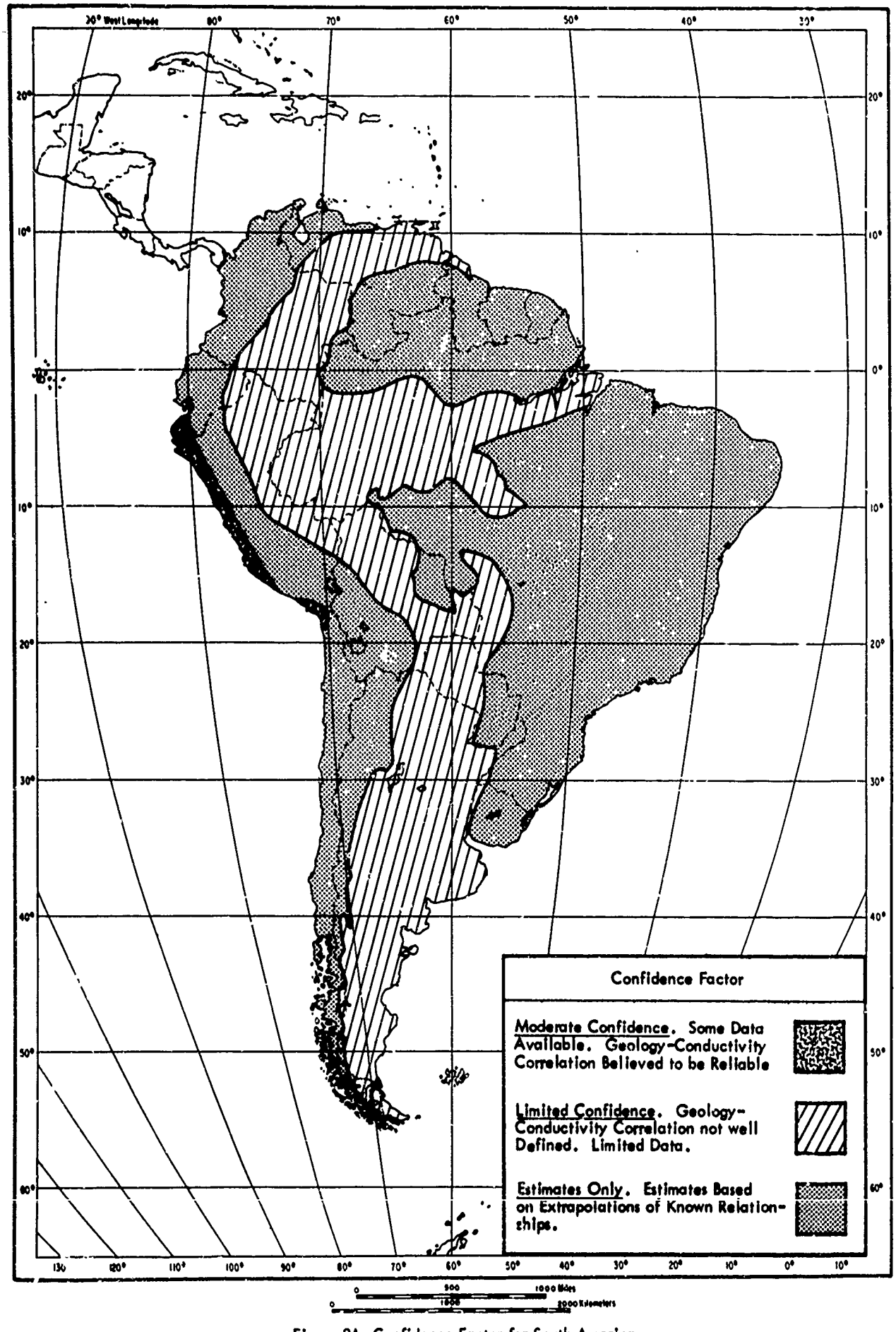

Figure 2A Confidence Factor for South America

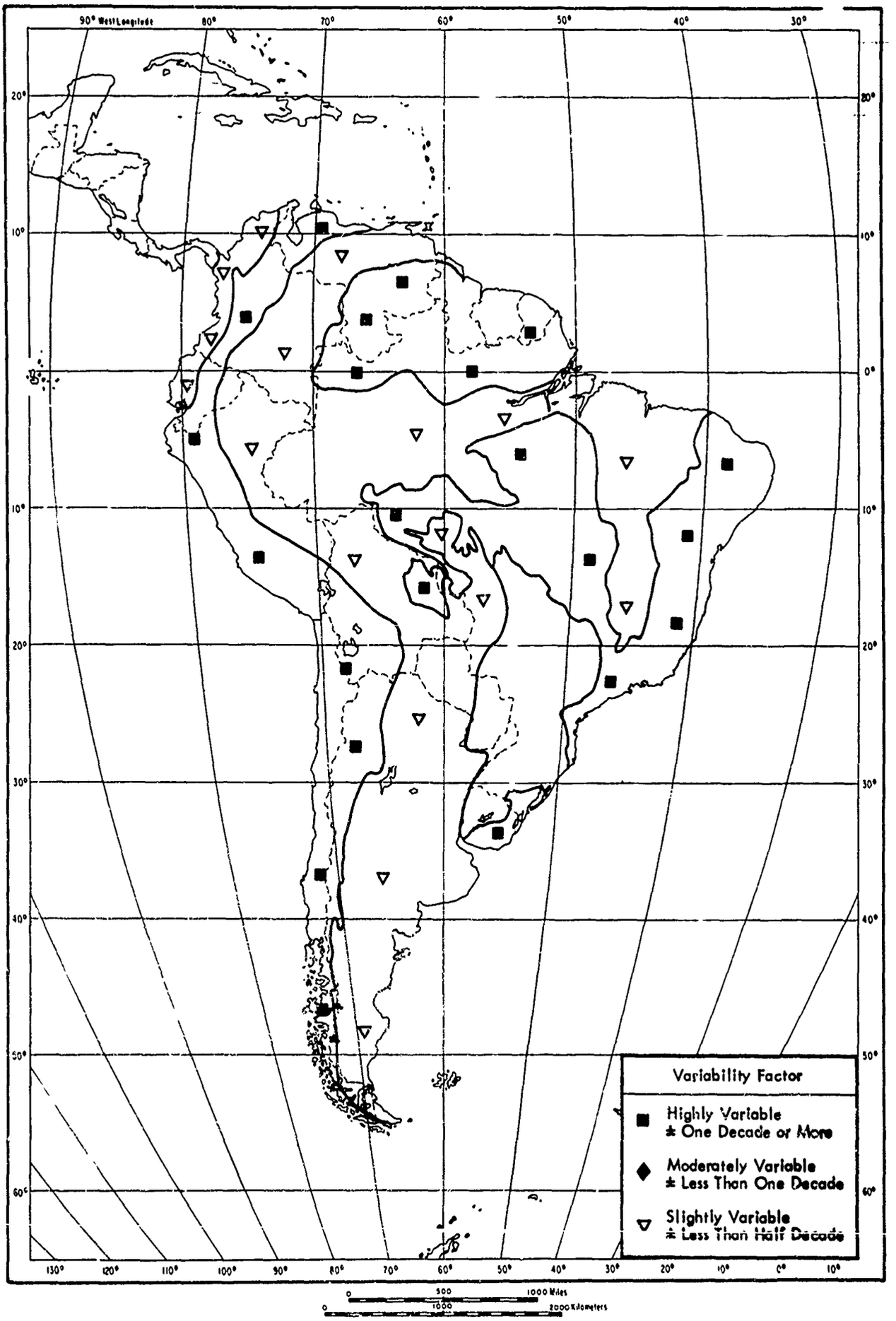

Figure 28 Variability Factor for South America

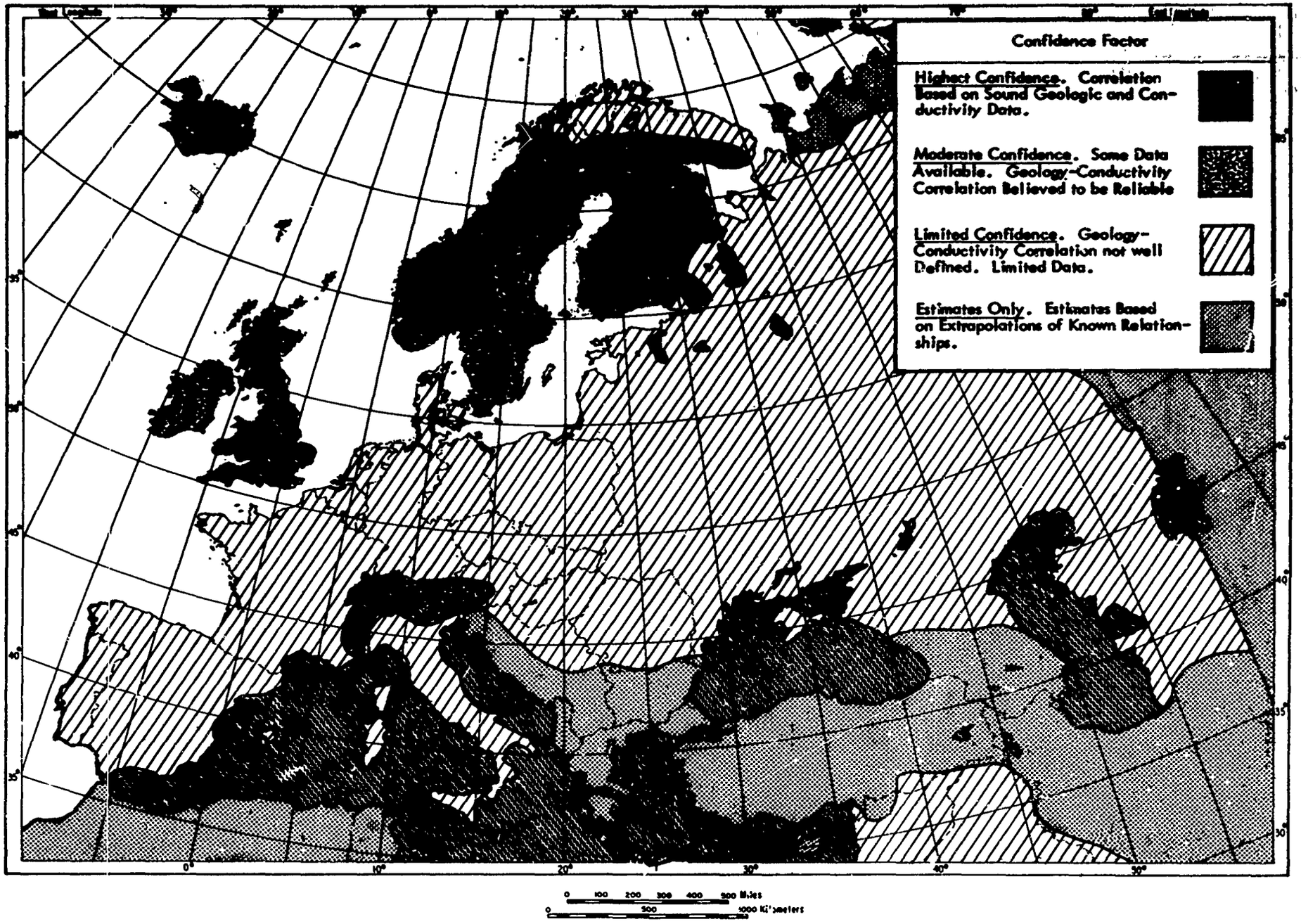

Figure 3A Confidence Factor for Europe

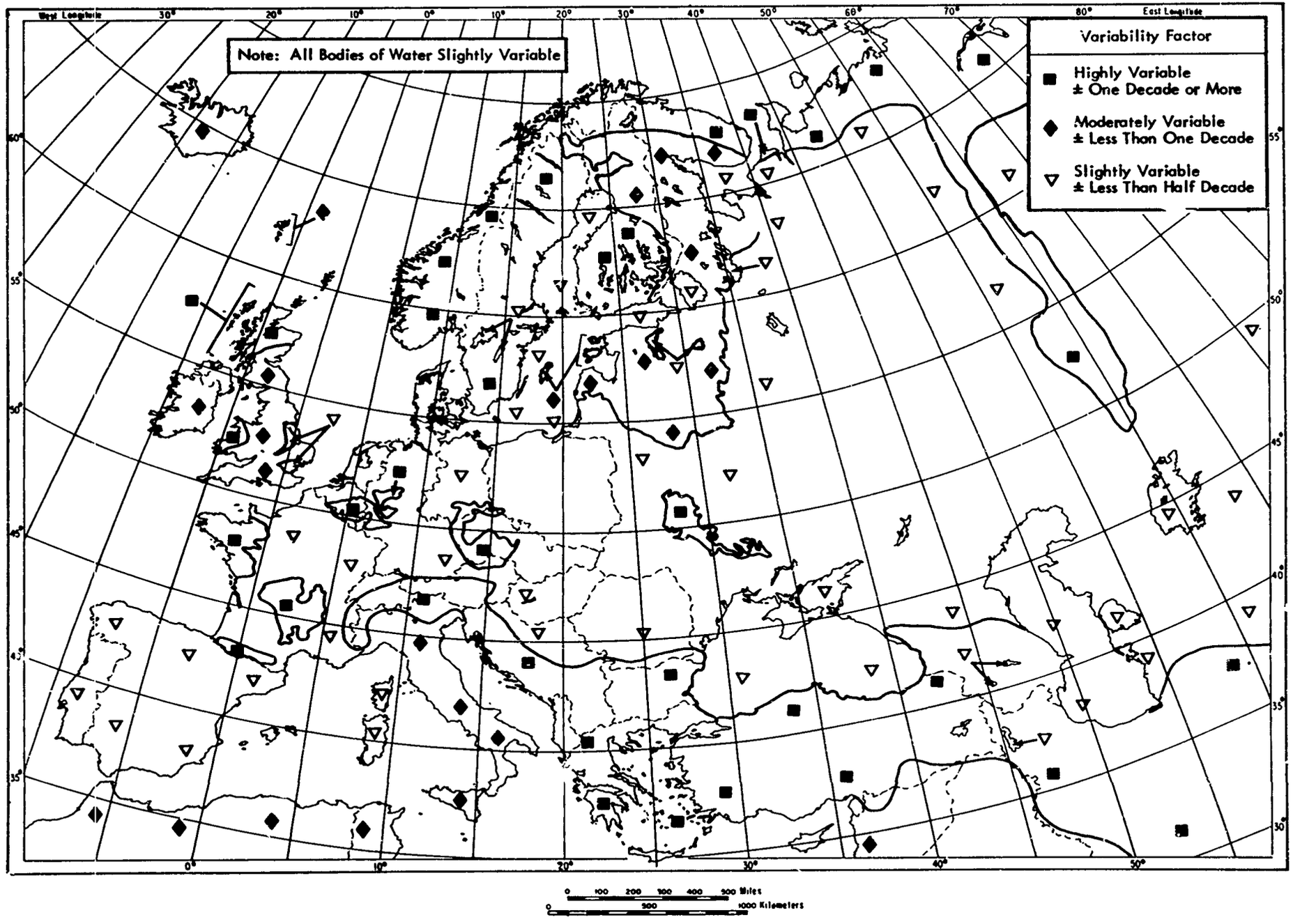

Figure 3B Variability Factor for Europe

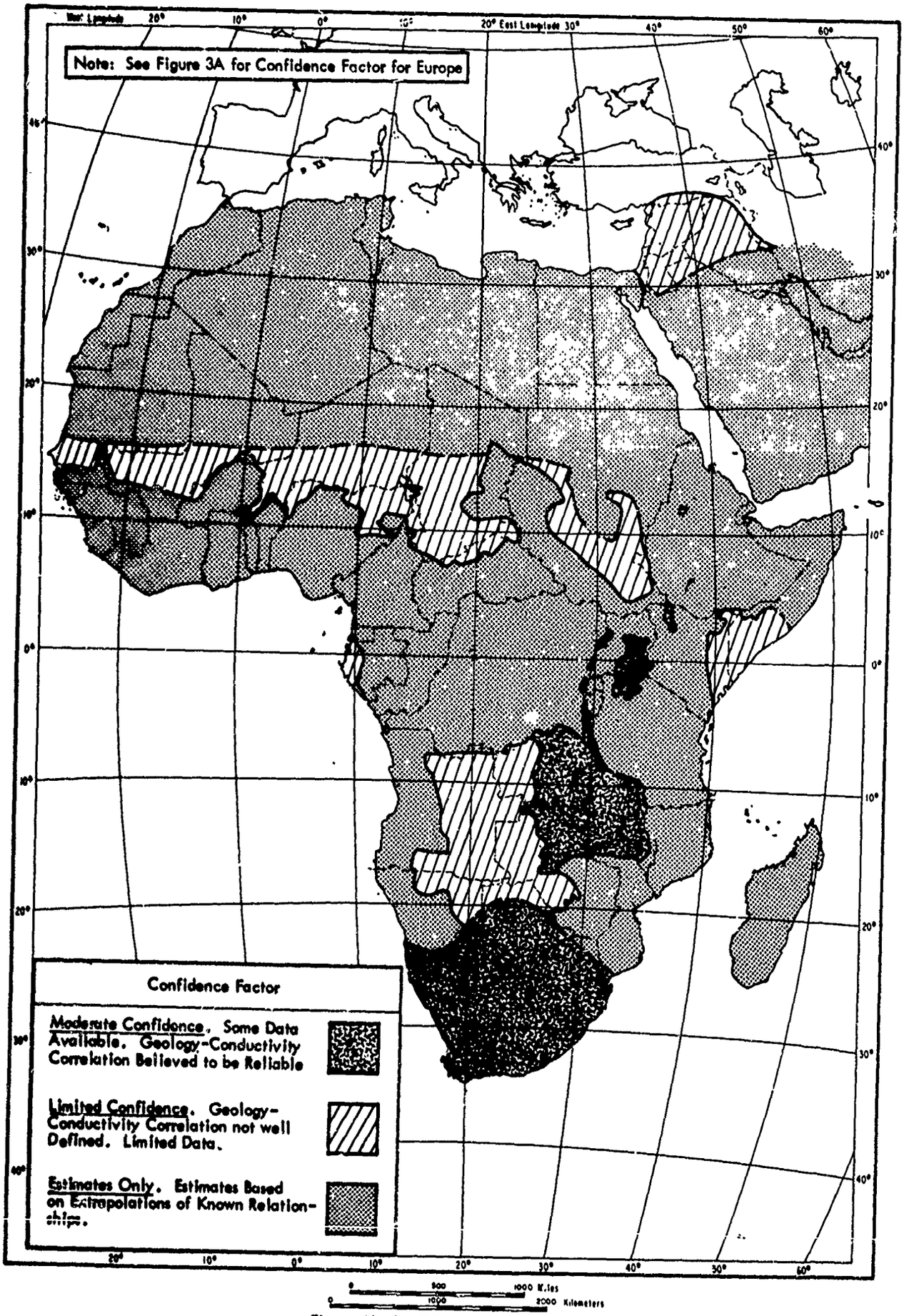

Figure 4A Confidence Factor for Africa

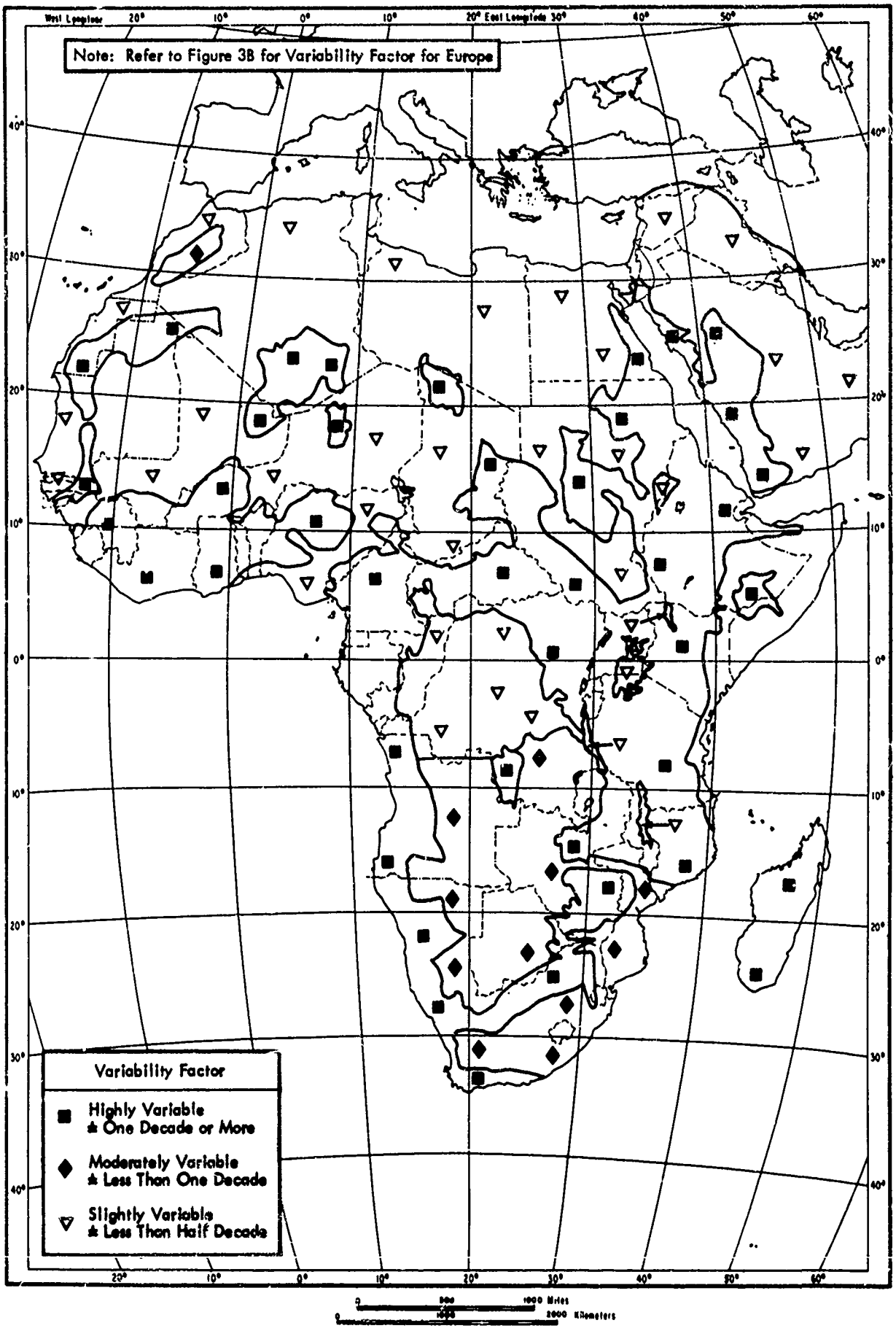

Figure 4B Variability Factor for Africa

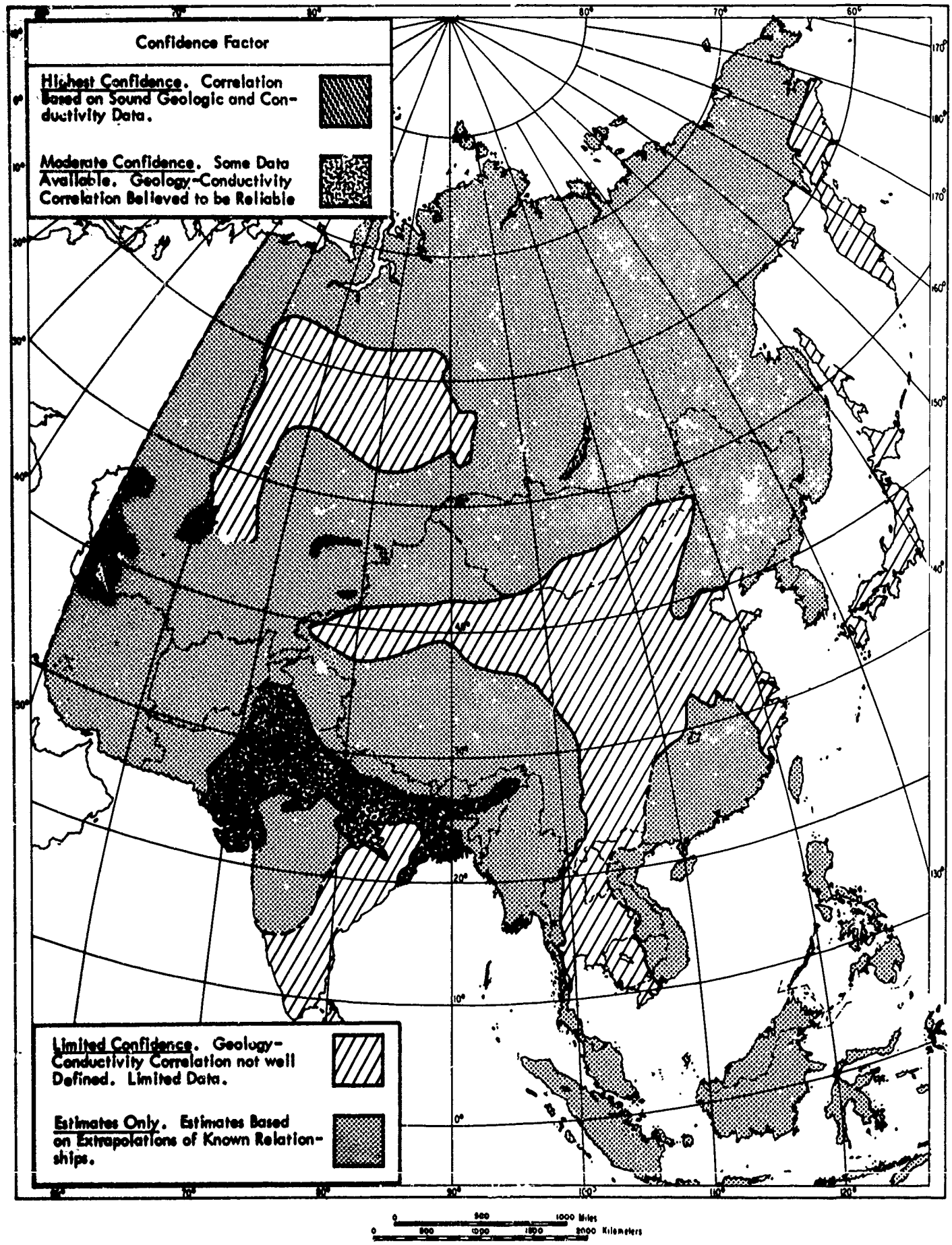

Figure 5A Confidence Factor for Asia

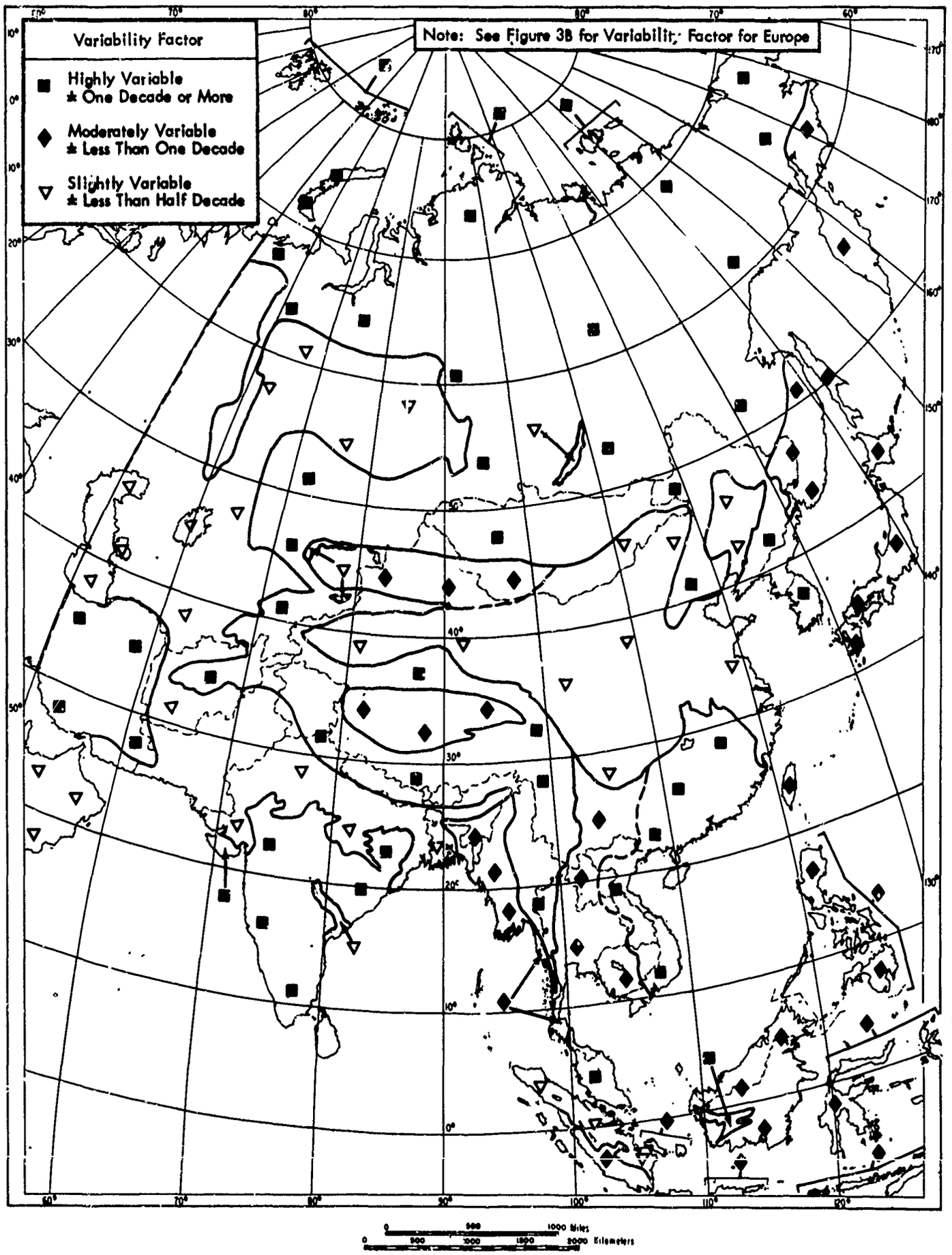

Figure 5B Variability Factor for Asia

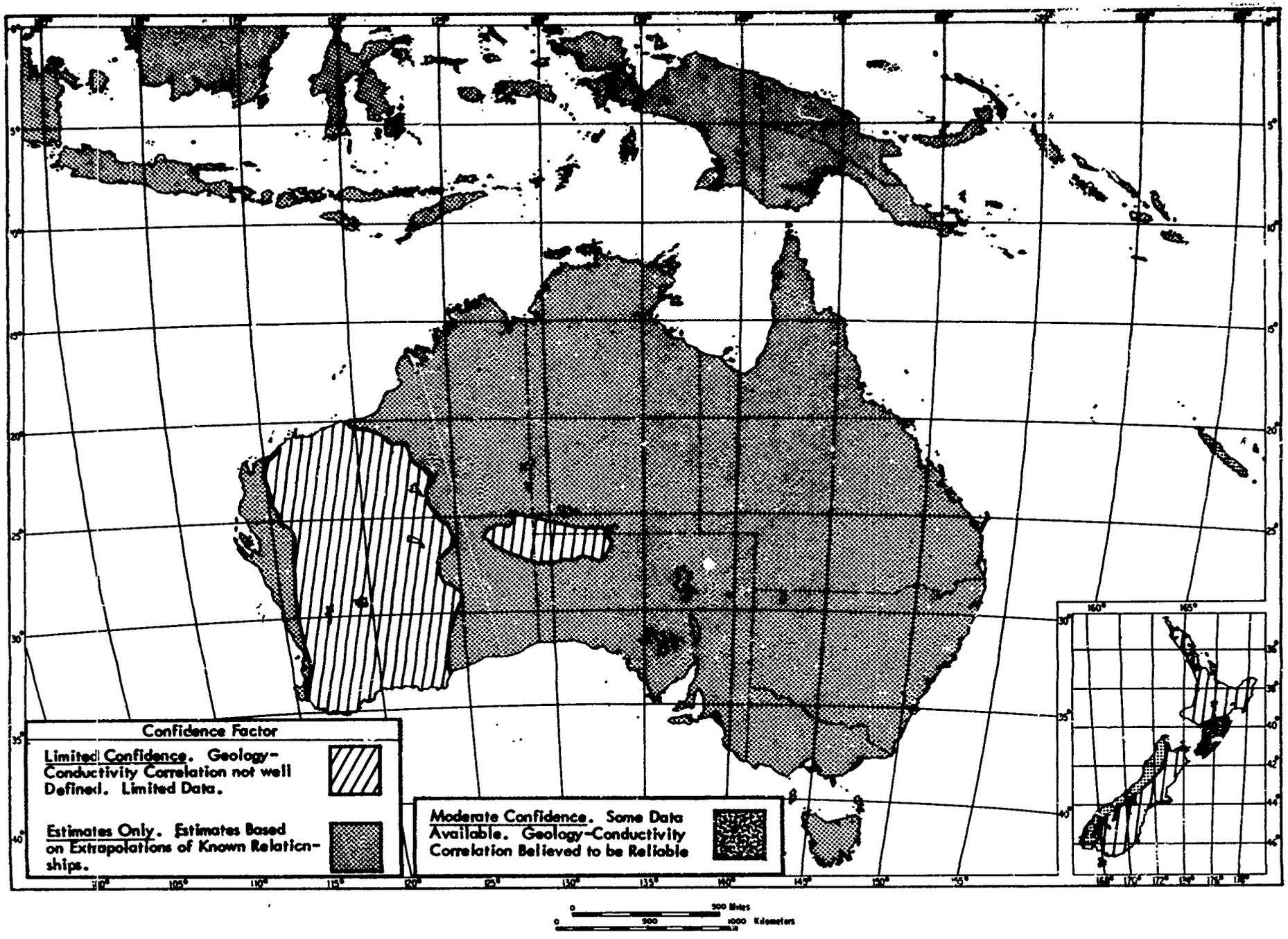

Figure 6A Confidence Factor for Australia

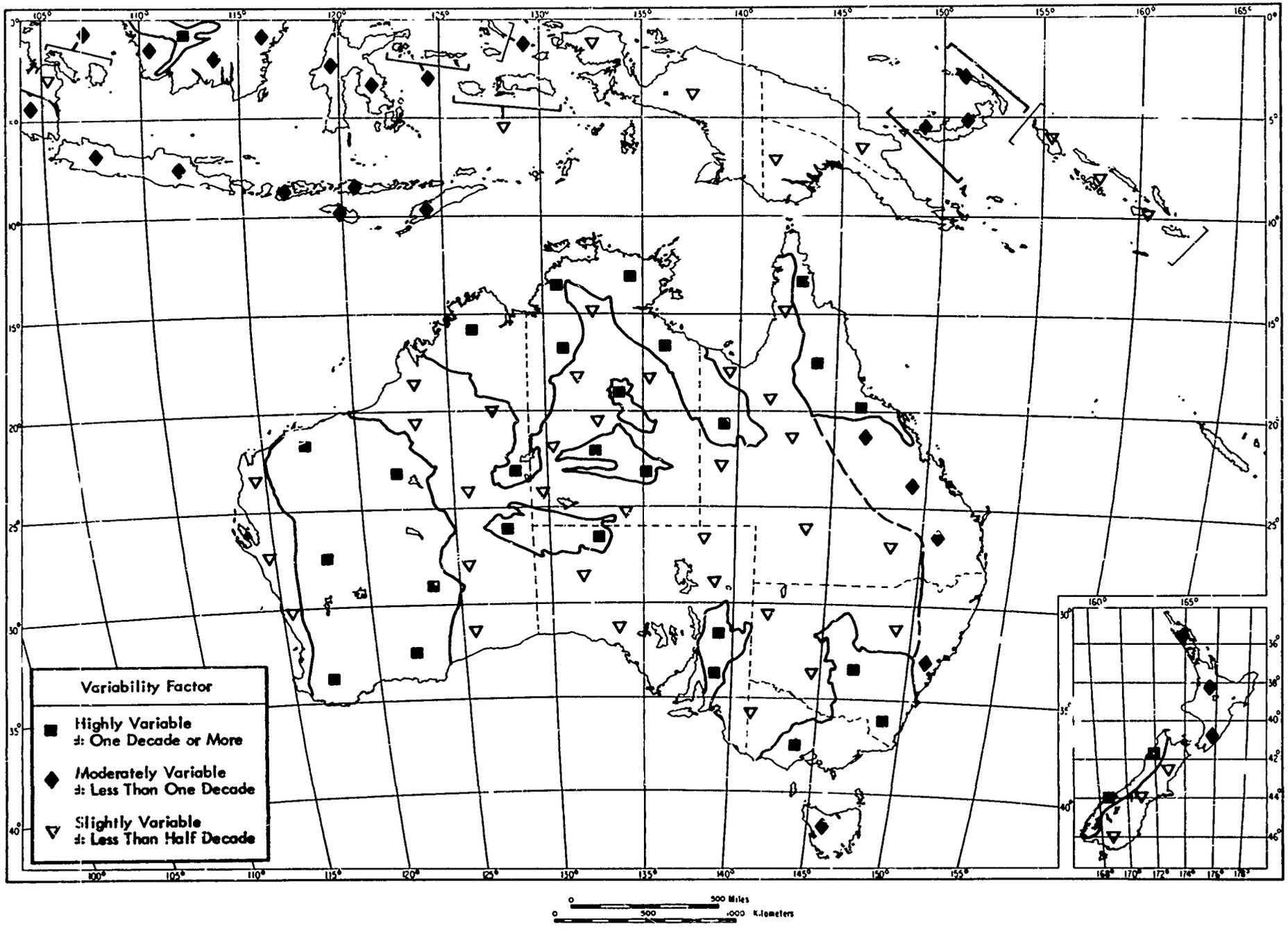

Figure 6B Variability Factor for Australia

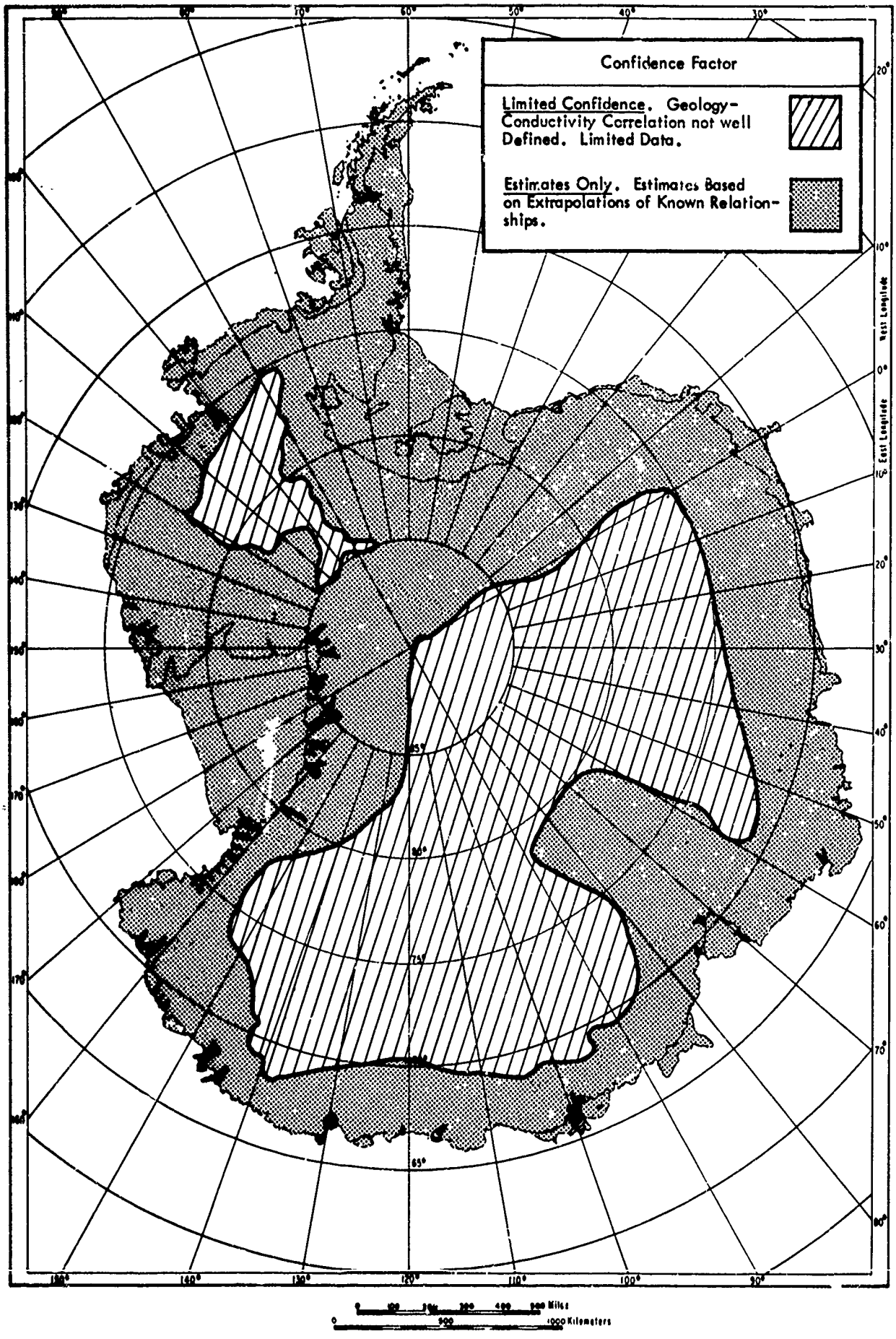

Figure 7A Confidence Factor for Antarctica

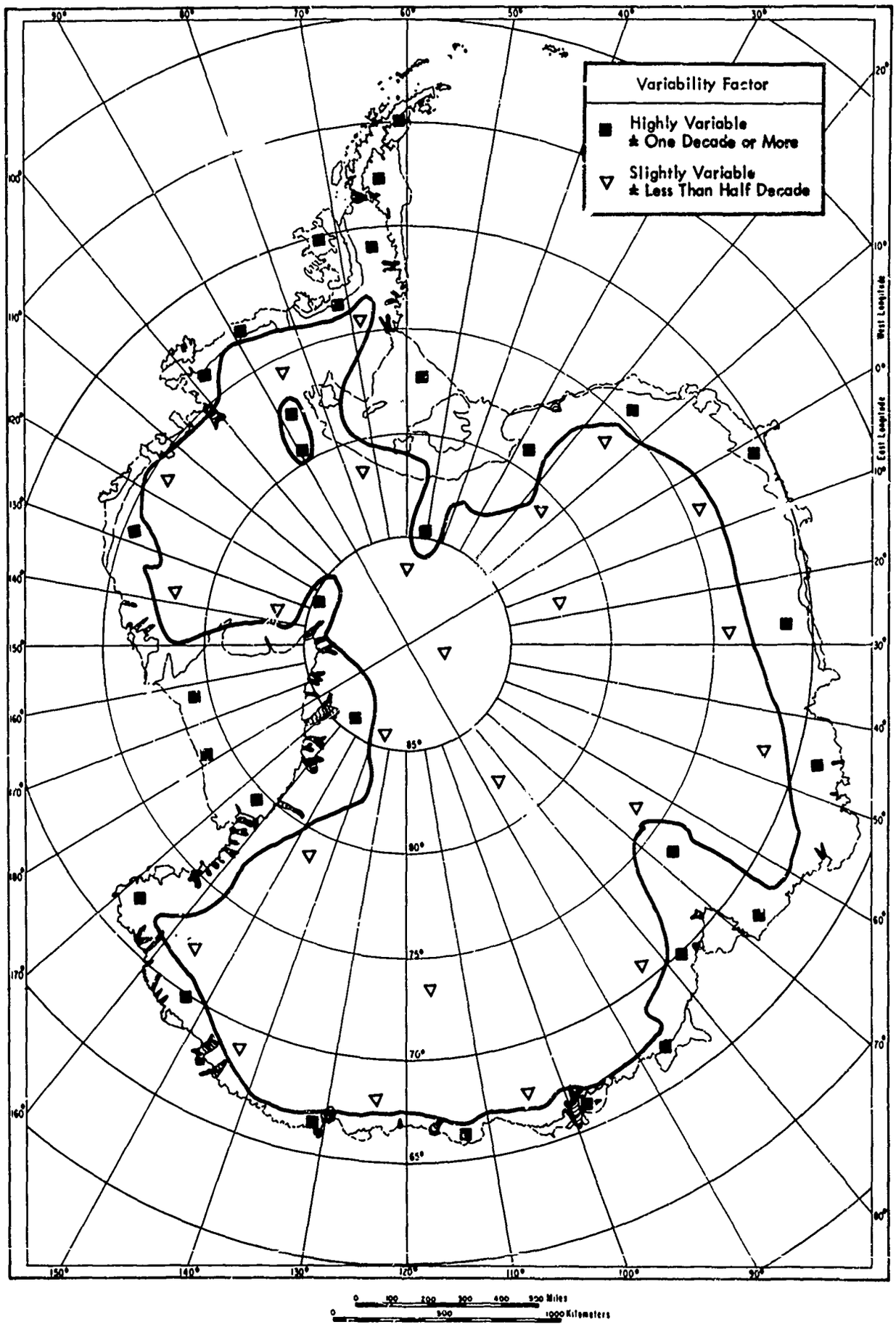

Figure 7B Variability Factor for Antarctica

Estimates Only: Estimates based on extrapolations of known correlations, or on knowledge of conduction mechanisms. These are areas where data is most needed.

Variability Factor

Highly Variable: Variations in local conductivity may be ± one decade or more from the average regional value.

Moderately Variable: less than ± one decade.

Slightly Variable: less than ± half decade.

Important factors relating to the use of the map include effects of "closed lines" where it is evident that energy spreading and defraction can result in less attenuation than would be obtained for a "straight" path between receiver and transmitter. Similarly, transmission across a narrow conductivity contrast which the energy may not circumvent may result in more attenuation than predicted because of energy conversion, reflection, and scattering. Similar effects may be experienced over high rugged mountains, and effects equivalent to one order of magnitude (smaller conductivity) than that attributed to the electrical properties of the materials have been observed for paths across the length of mountain chains. Users should consider the above items in light of the Fresnel spreading of the propagating energy, and the conductivity profile for a propagation path should be determined consistent with this concept, i.e., it is suggested that users consider values of earth conductivity over an area representing the width of the path rather than along a very narrow "line" (great circle) [3].

3.0 EFFECTIVE CONDUCTIVITY

Effective conductivity of a region is defined as the conductivity of a plane, uniform, homogeneous earth which would have the same effect on a propagating electromagnetic field as that of the region. Complications arise for instances where displacement currents in the earth become comparable in magnitude to conduction currents [4] and also for cases where lateral changes result in an anisotropic conductivity in the plane of the surface. These effects were not accounted for in this present work:

1. In most of the land areas of the world, the earth approximates a conductor. Limited data indicate that even for the Greenland Ice Cap, the conduction currents are probably dominant over displacement currents at 10 kHz [5].

2. Only in a few areas was there sufficient data to indicate a difference in conductivity with compass direction. The additional complication of the maps does not justify including this.

Where there was enough information, the magnitude of effective (complex) conductivity was computed for a horizontal layered case [2, Appendix A, also see reference 6].

4.0 ACCURACY OF MAP

Some estimation of the accuracy of the maps for VLF propagation studies may be gained from a comparison of Figures 8 and 9. Figure 8 is a portion of the map of North America, which was produced in 1965 [2]. This map is essentially identical to the northern portion of Sheet 1. Figure 9 shows a revised map based on VLF propagation measurements made in September 1959 and August 1961 (these maps were provided by the U.S. Naval Research Laboratory). Note two significant changes suggested by the NRL Map:

1. The boundary of the "3" region northwest of Hudson Bay should extend further north. This may indicate that the extent of continuous permafrost is further north than previously estimated, or that a thicker deposit of conducting overburden exists in this area.

2. There is an area of "2" conductivity, 3×10^{-5} mho/m, between Labrador and Hudson Bay. This is most likely due to a previously unrecognized occurrence of continuous permafrost. If this area had been so designated, it is noted that the conductivity would have been estimated as 1×10^{-4} mho/m rather than the 3×10^{-5} mho/m as indicated by the NRL Map. Measurements of earth conductivity in this area are therefore suggested.

Other areas can be expected to undergo similar revisions when more data is obtained. These revisions are not expected to be of significance for regions indicated as "highest confidence." Areas similar to the Canadian Shield region which are not well known geologically, and where there is only limited information on permafrost extent and thickness, can be expected to undergo the most extensive revisions.

Further discussion, a list of contributors, etc., may be found in the Appendices which accompany the larger report.

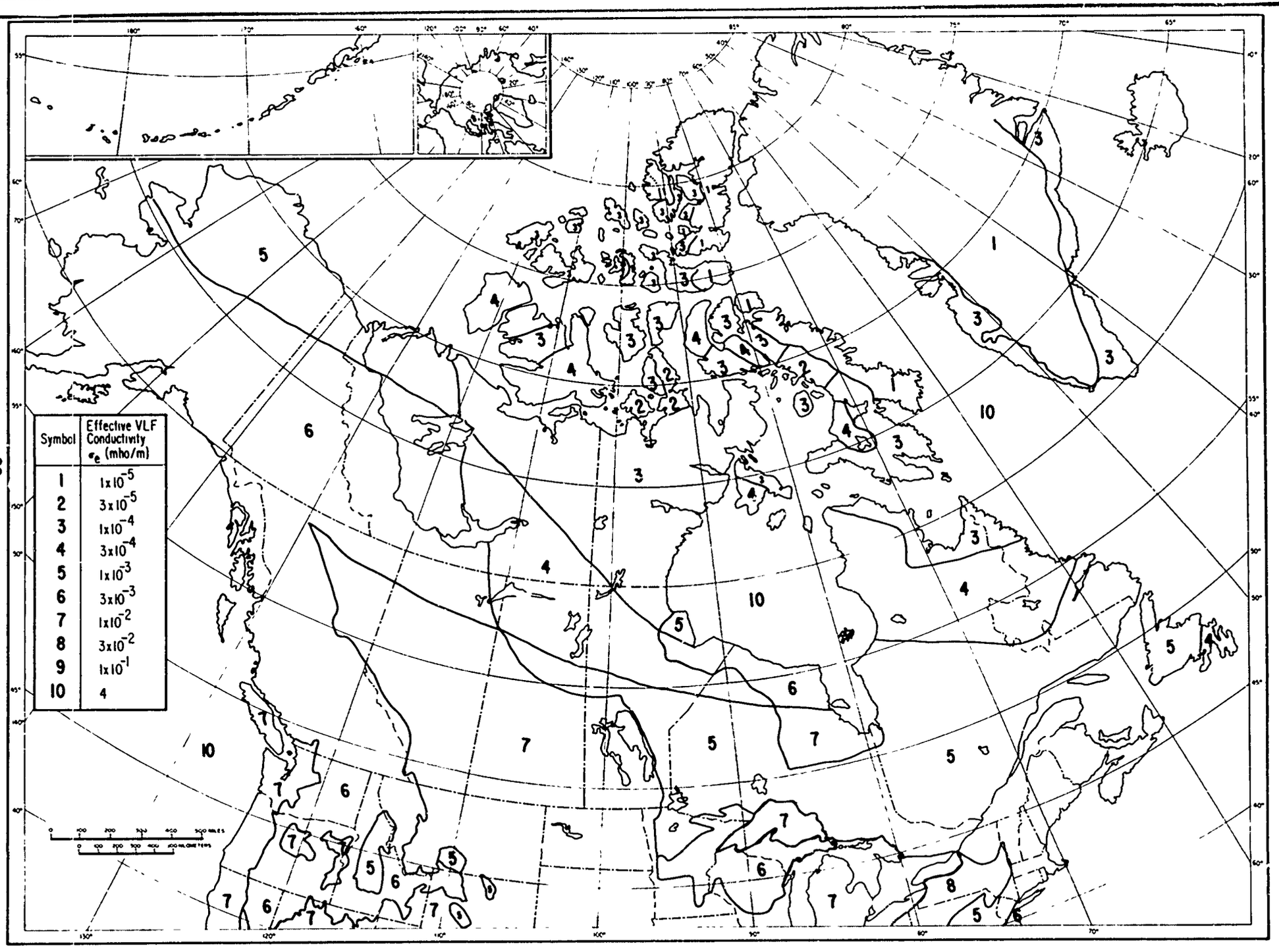

Figure 8 Conductivity Map of Canada.

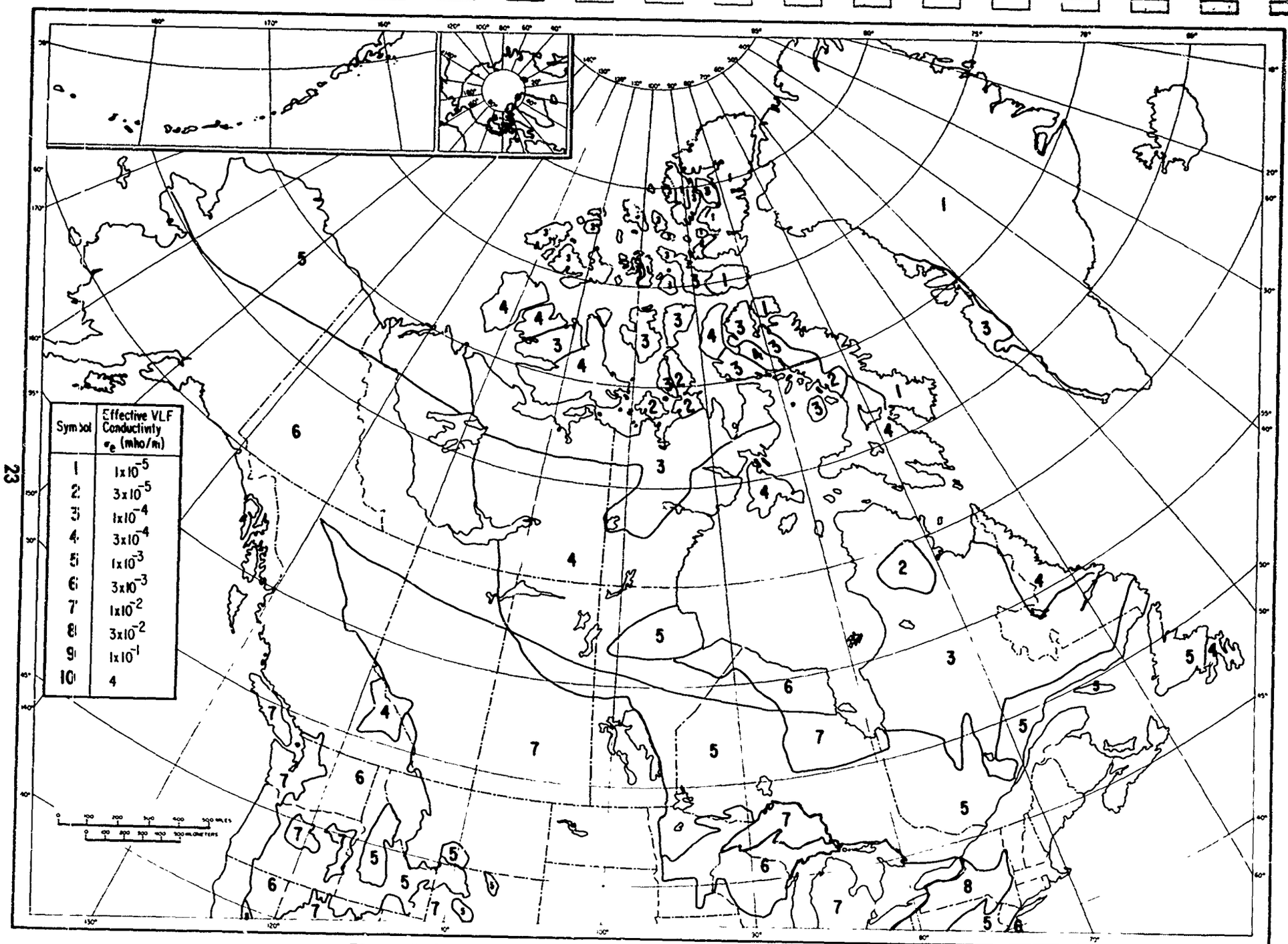

Figure 9 Revised Conductivity Map of Canada. Revision by NRL is Based on Propagation Measurements

REFERENCES

[1] Card, R. H., Correlation of Earth Resistivity with Geologic Structure, Trans. AIME, V 138, pp 380-398, 1940.

[2] Morgan, R. R. and E. L. Maxwell , Omega Navigational System Conductivity Map, DECO Report 54-F-1, December 1965, under contract NOnr 4107(00).

[3] Watt, A. D., VLF Radio Engineering, Pergamon Press, New York 1967.

[4] Wait, J. R., The Propagation of Electromagnetic Waves Along the Earth's Surface, appearing in Electromagnetic Waves, R.E. Langer, editor, University of Wisconsin Press, 1962.

[5] Watt, A. D. and E. L. Maxwell, Measured Electrical Properties of Snow and Glacial Ice, NBS Journal of Research, 64D, July-August 1960.

[6] Wait, J. R., Electromagnetic Waves in Stratified Media, Pergamon Press, London, 1962.

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Westinghouse Electric Corporation	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

World-wide VLF Effective-Conductivity Map

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical Report

5. AUTHOR(S) (Last name, first name, initial)

Morgan, Robert R.

6. REPORT DATE 15 January 1968	7a. TOTAL NO. OF PAGES 24	7b. NO. OF REFS 6
8a. CONTRACT OR GRANT NO. N0014-67-C-0274 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 80133F-1 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) None	

10. AVAILABILITY/LIMITATION NOTICES

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Office of Naval Research Department of the Navy

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Security Classification

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
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Effective Electrical Earth Conductivity Correlation Between Geology and Conductivity VLF Effective Conductivity Maps						

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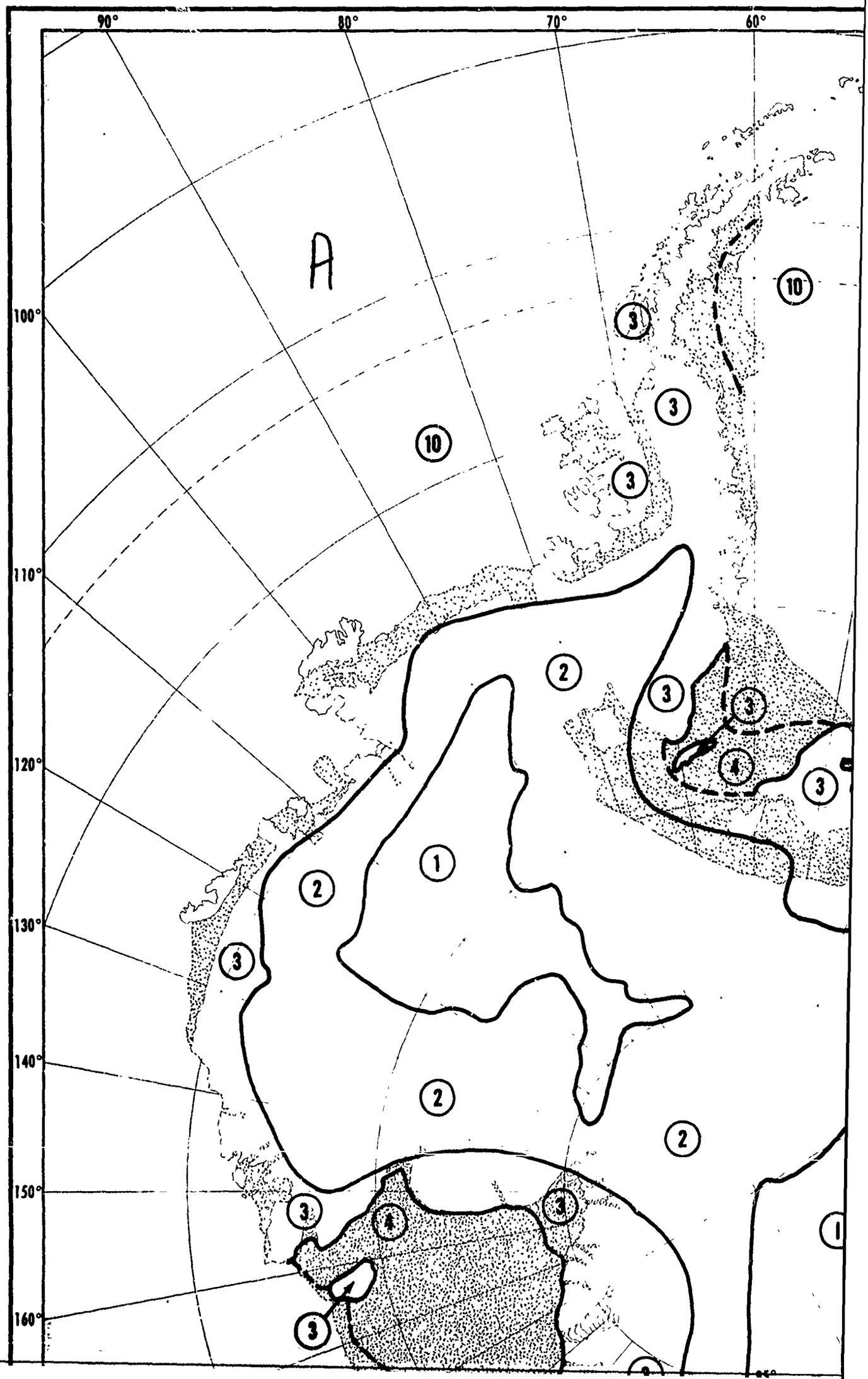
Security Classification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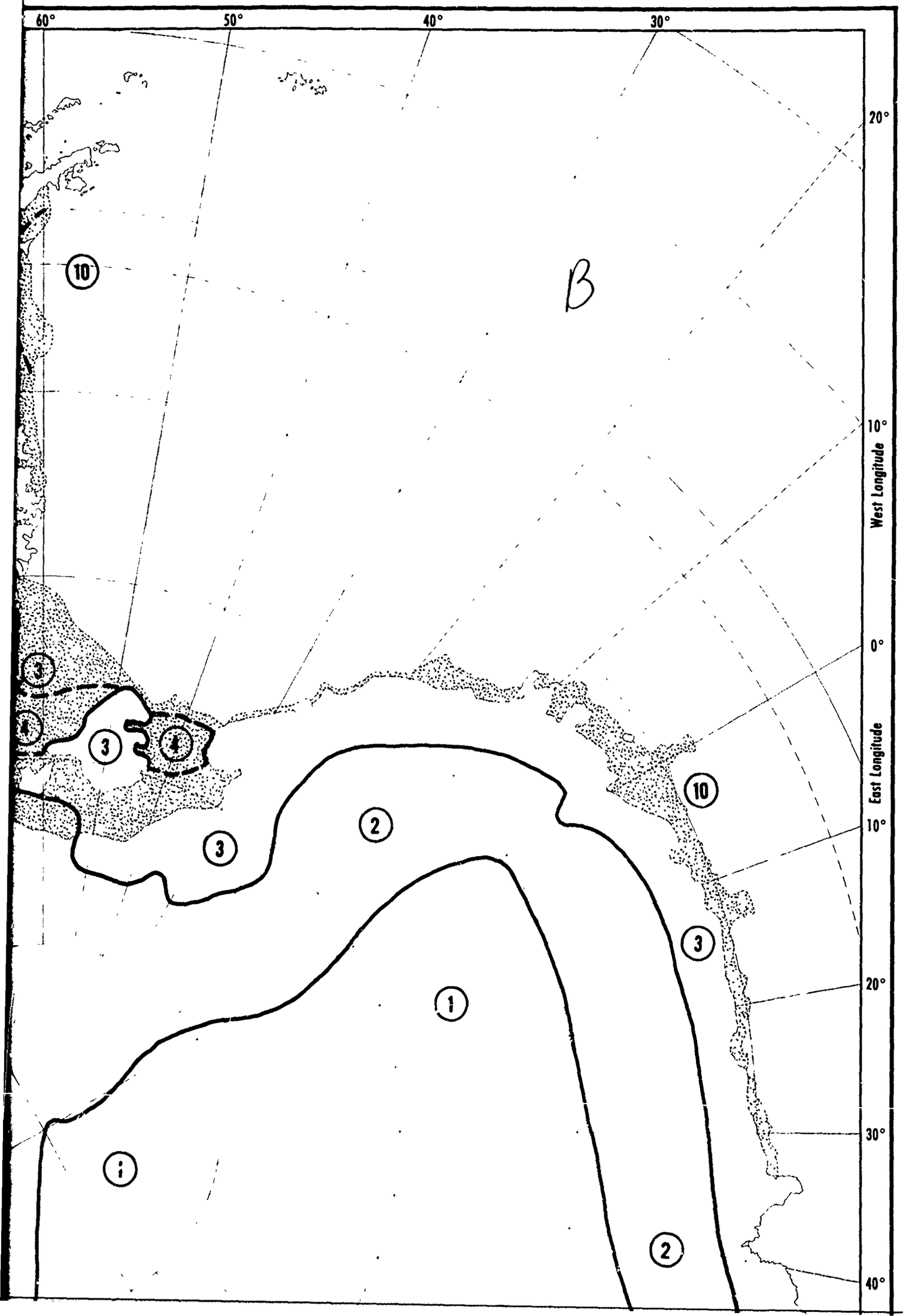
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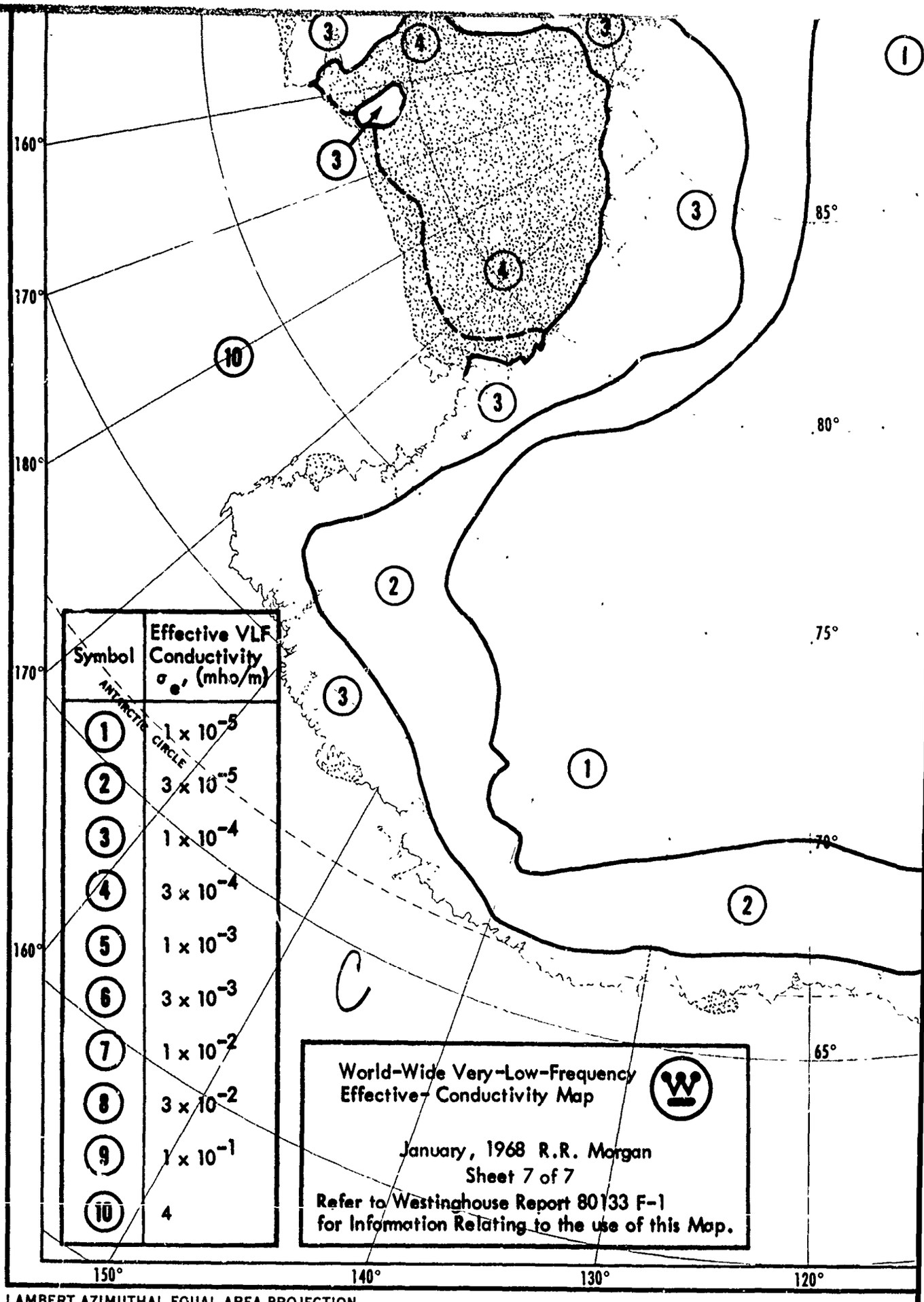

LAMBERT AZIMUTHAL EQUAL AREA PROJECTION

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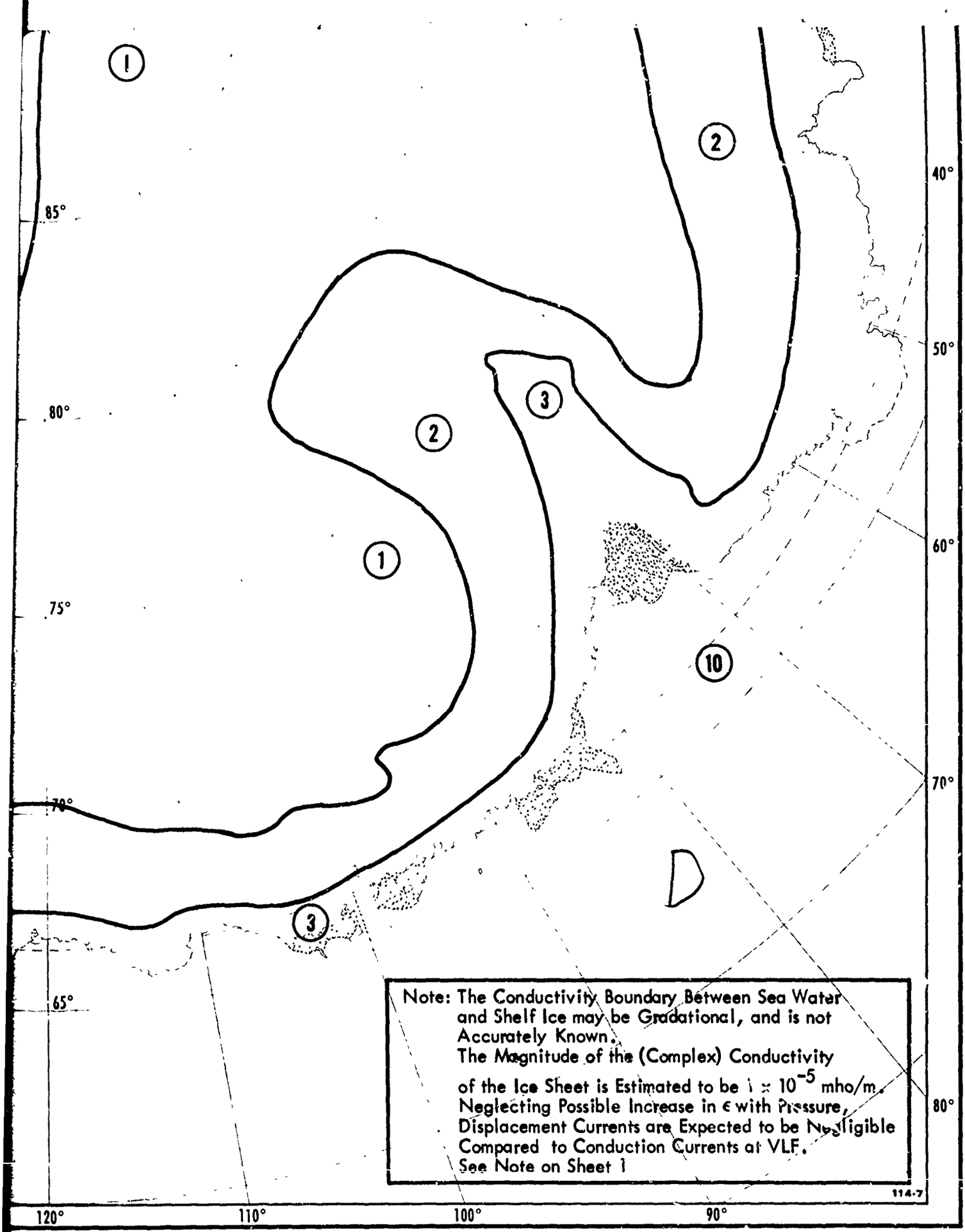

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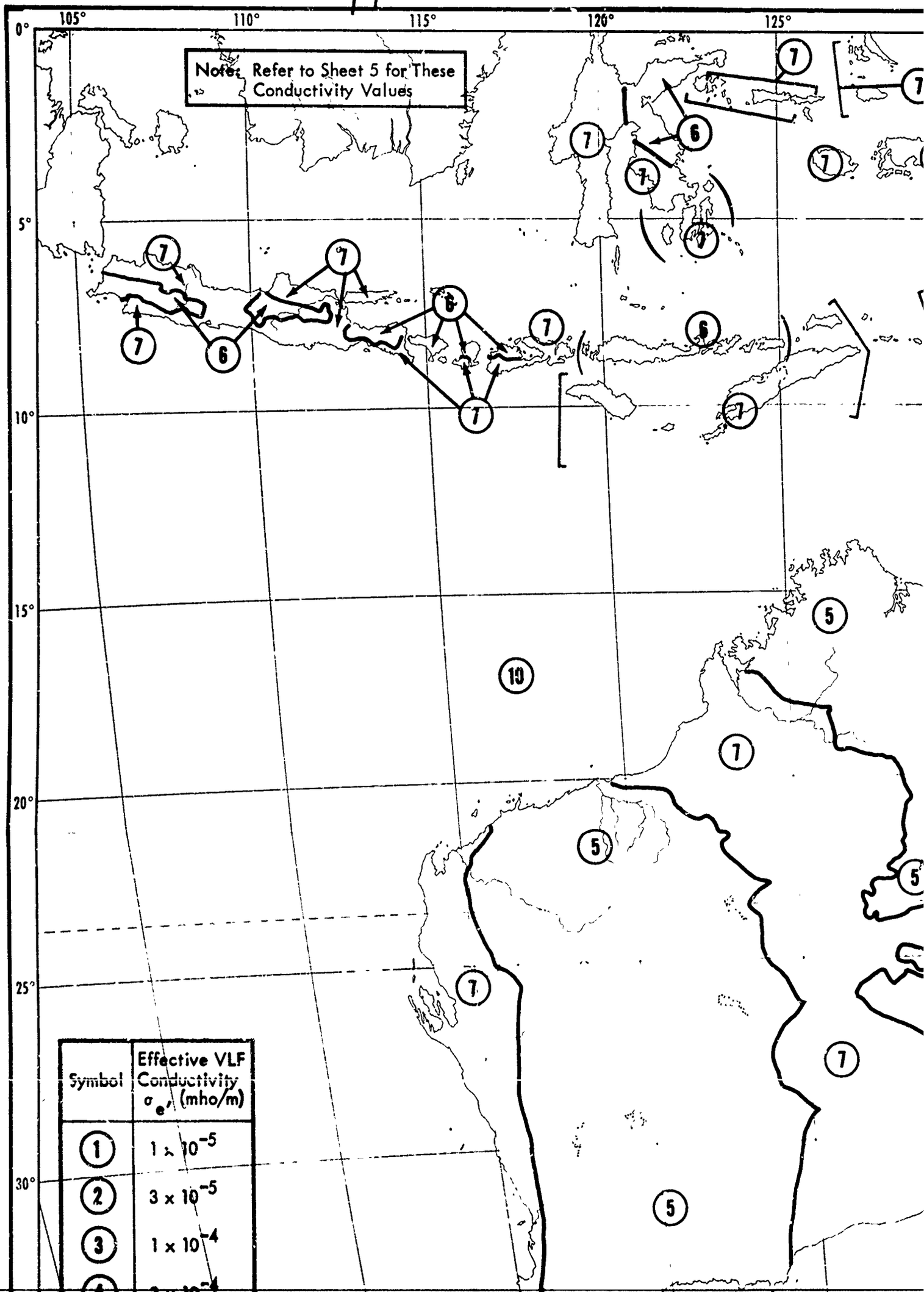
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Note: Refer to Sheet 5 for These Conductivity Values
Symbol
Effective VLF Conductivity σ_e (mho/m)
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2 3 x 10^{-5}
3 1 x 10^{-4}

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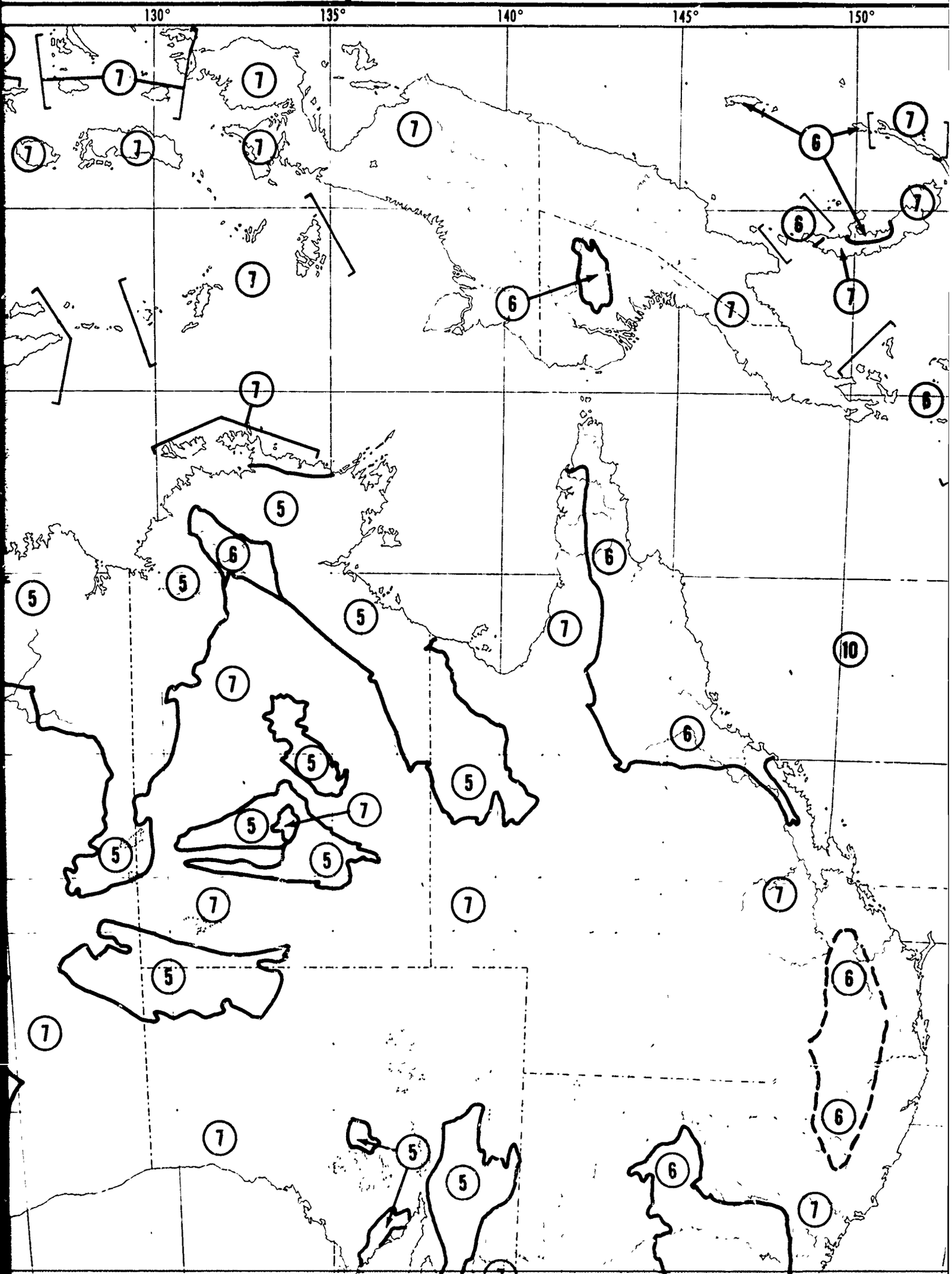

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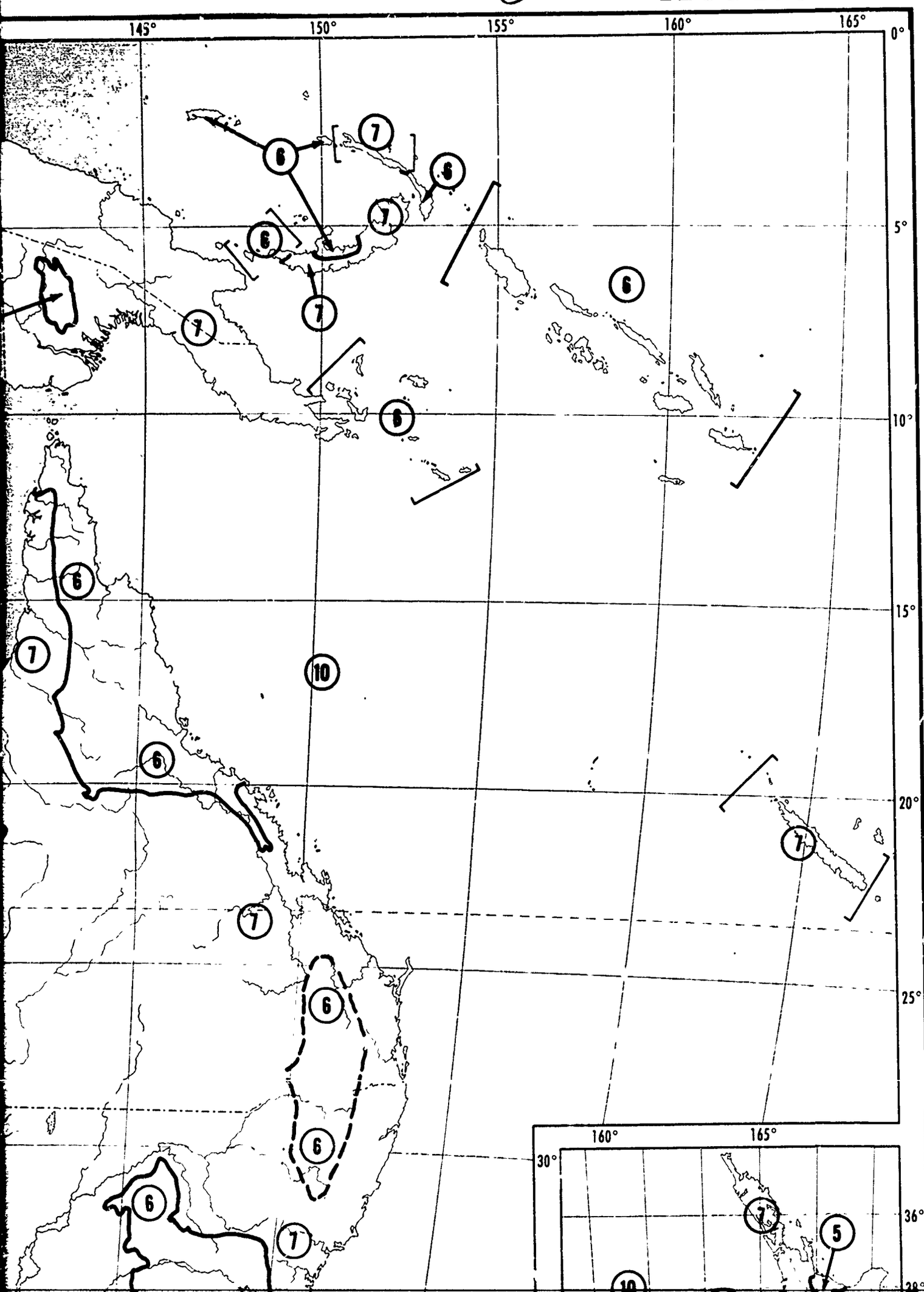
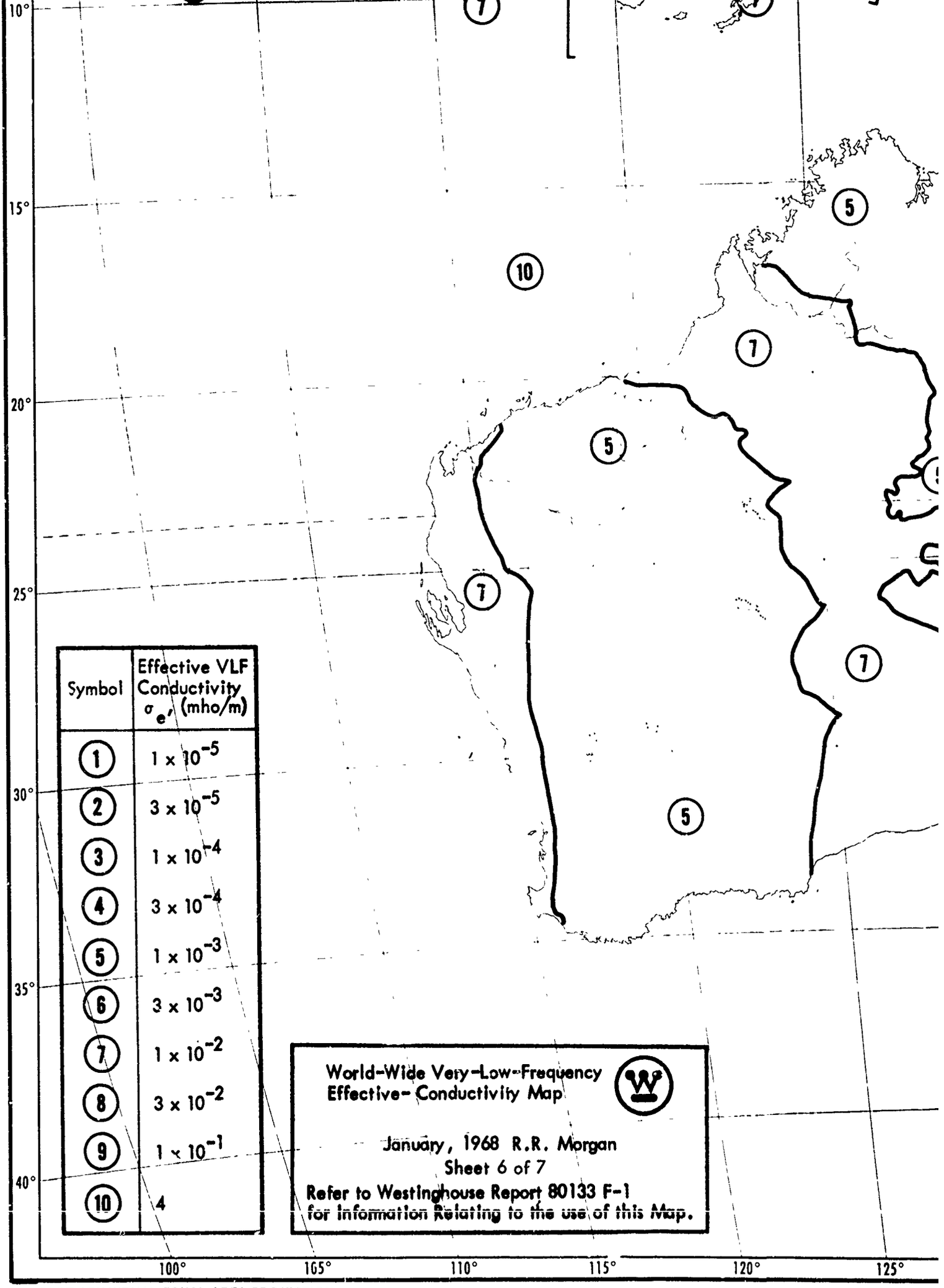




Symbol	Effective VLF Conductivity σ_e, (mho/m)
1	1×10^{-5}
2	3×10^{-5}
3	1×10^{-4}
4	3×10^{-4}
5	1×10^{-3}
6	3×10^{-3}
7	1×10^{-2}
8	3×10^{-2}
9	1×10^{-1}
10	4

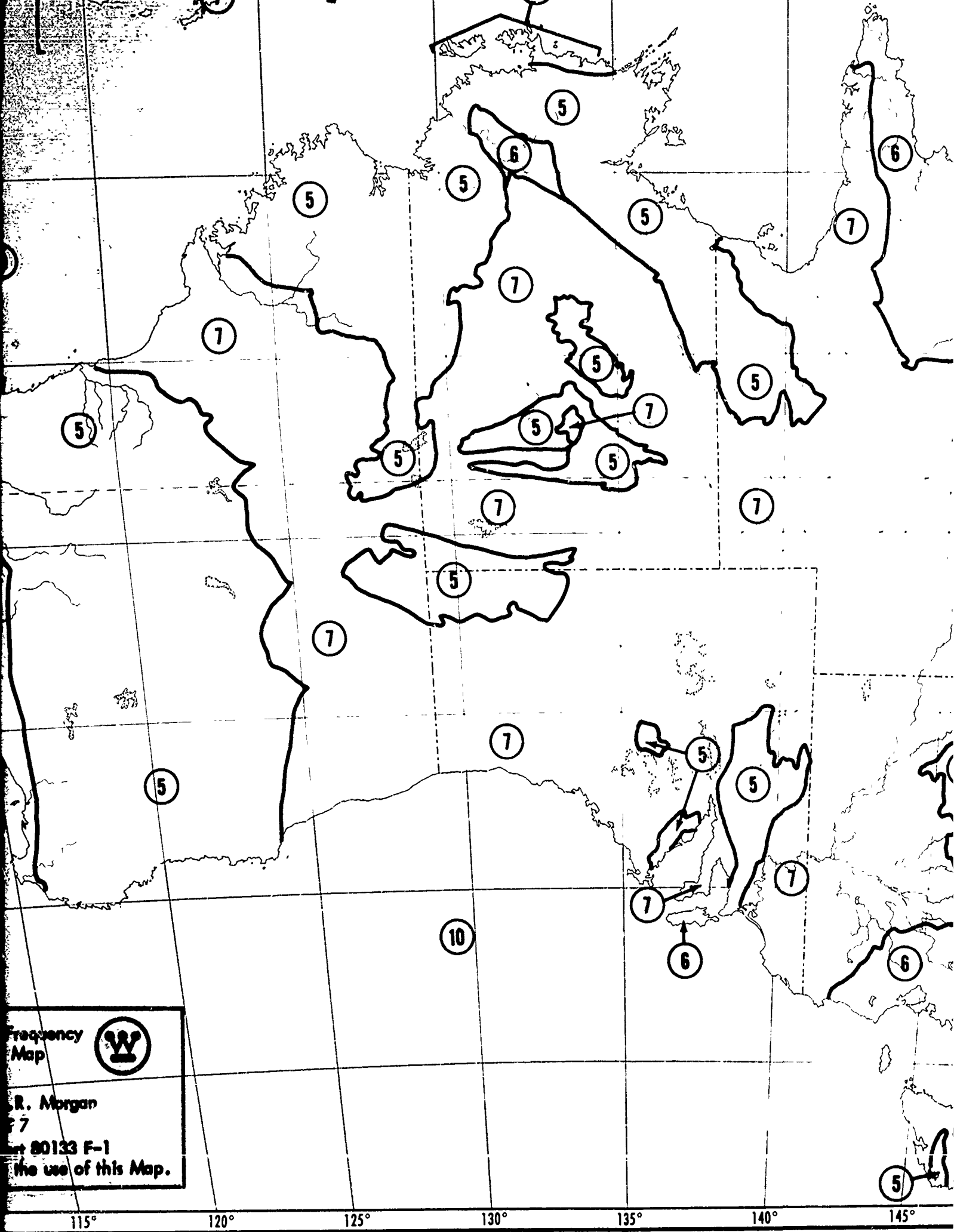
World-Wide Very-Low-Frequency Effective-Conductivity Map

January, 1968 R.R. Morgan
Sheet 6 of 7

Refer to Westinghouse Report 80133 F-1 for information relating to the use of this Map.

LAMBERT AZIMUTHAL EQUAL AREA PROJECTION

D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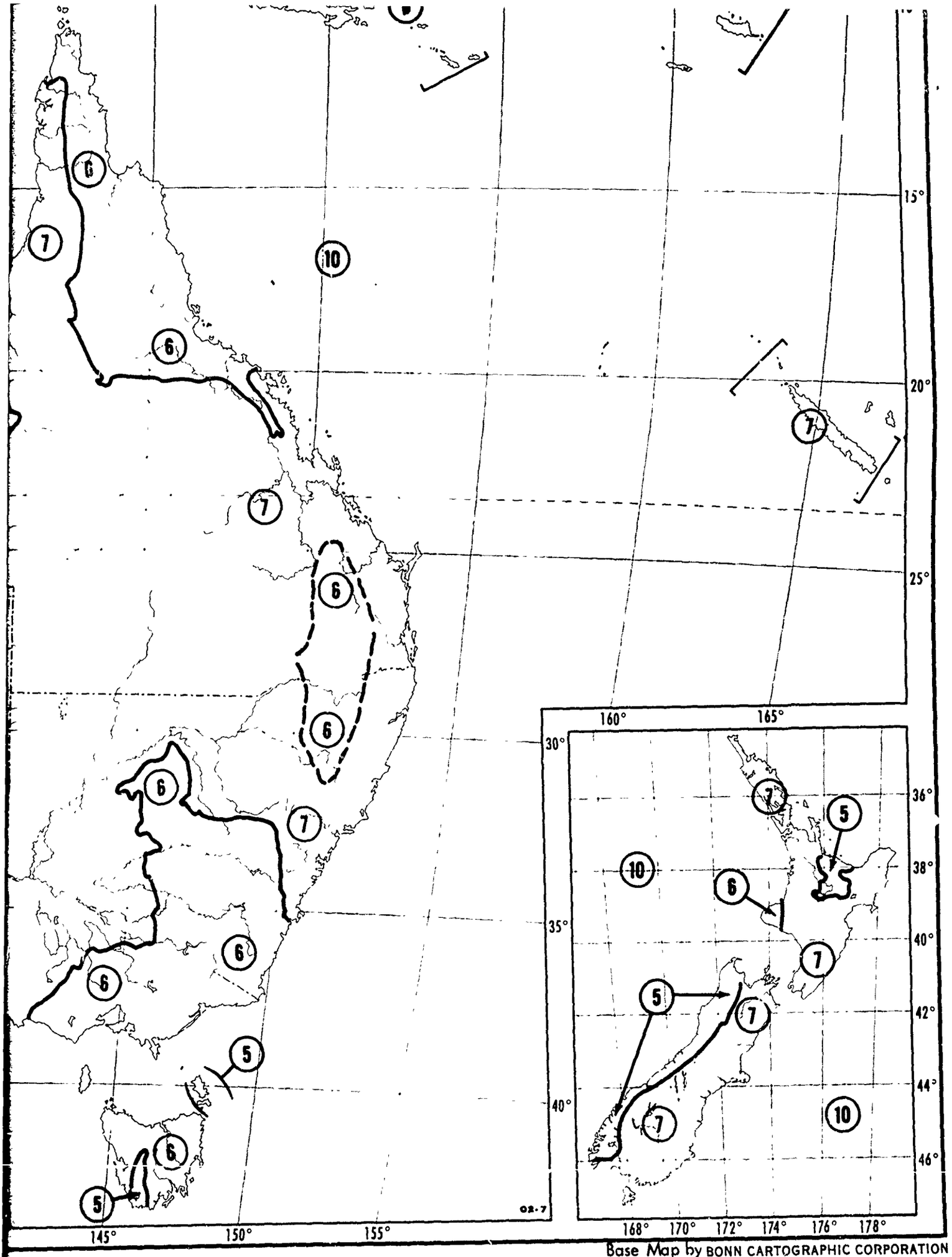

Base Map by BONN CARTOGRAPHIC CORPORATION

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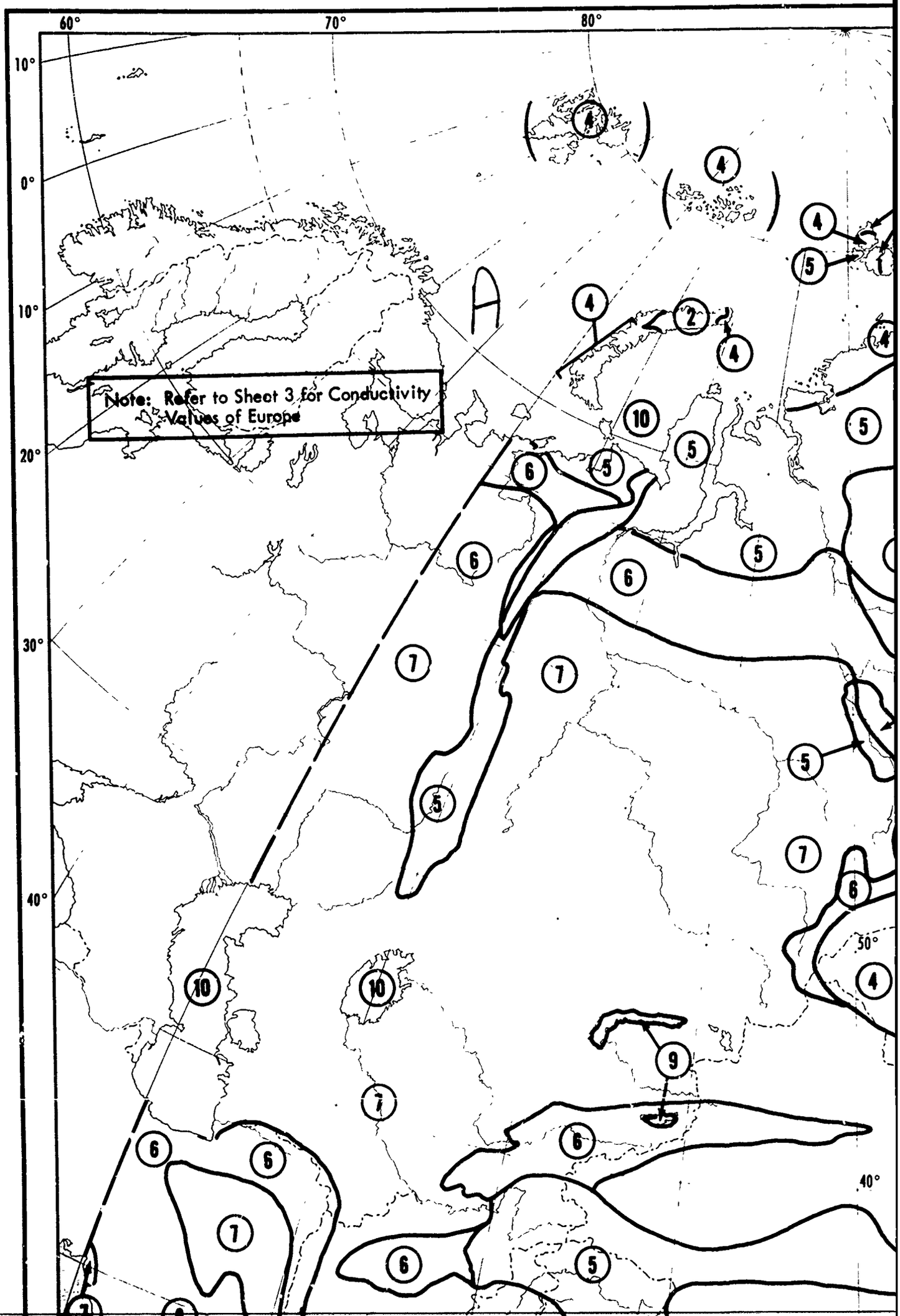
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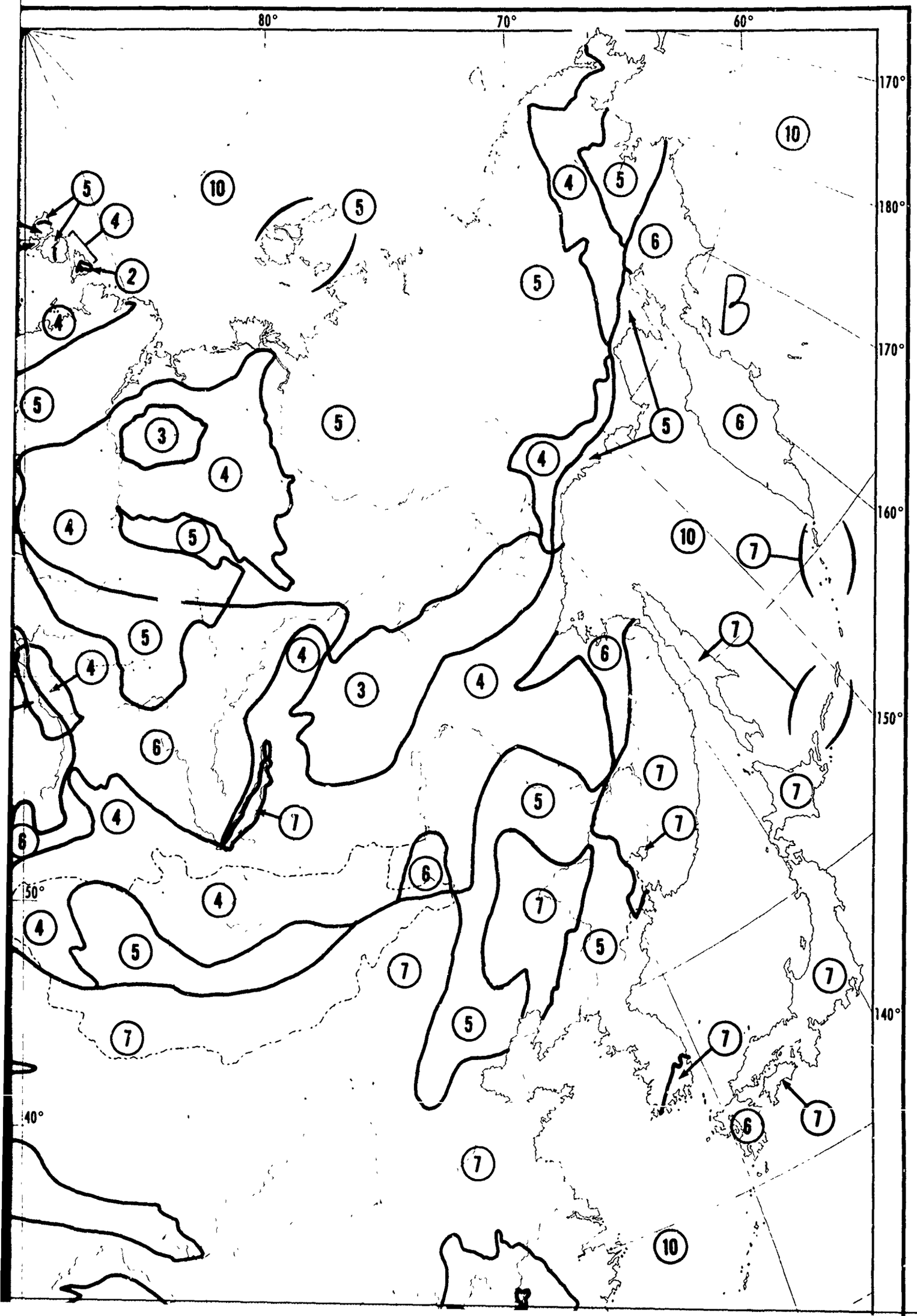
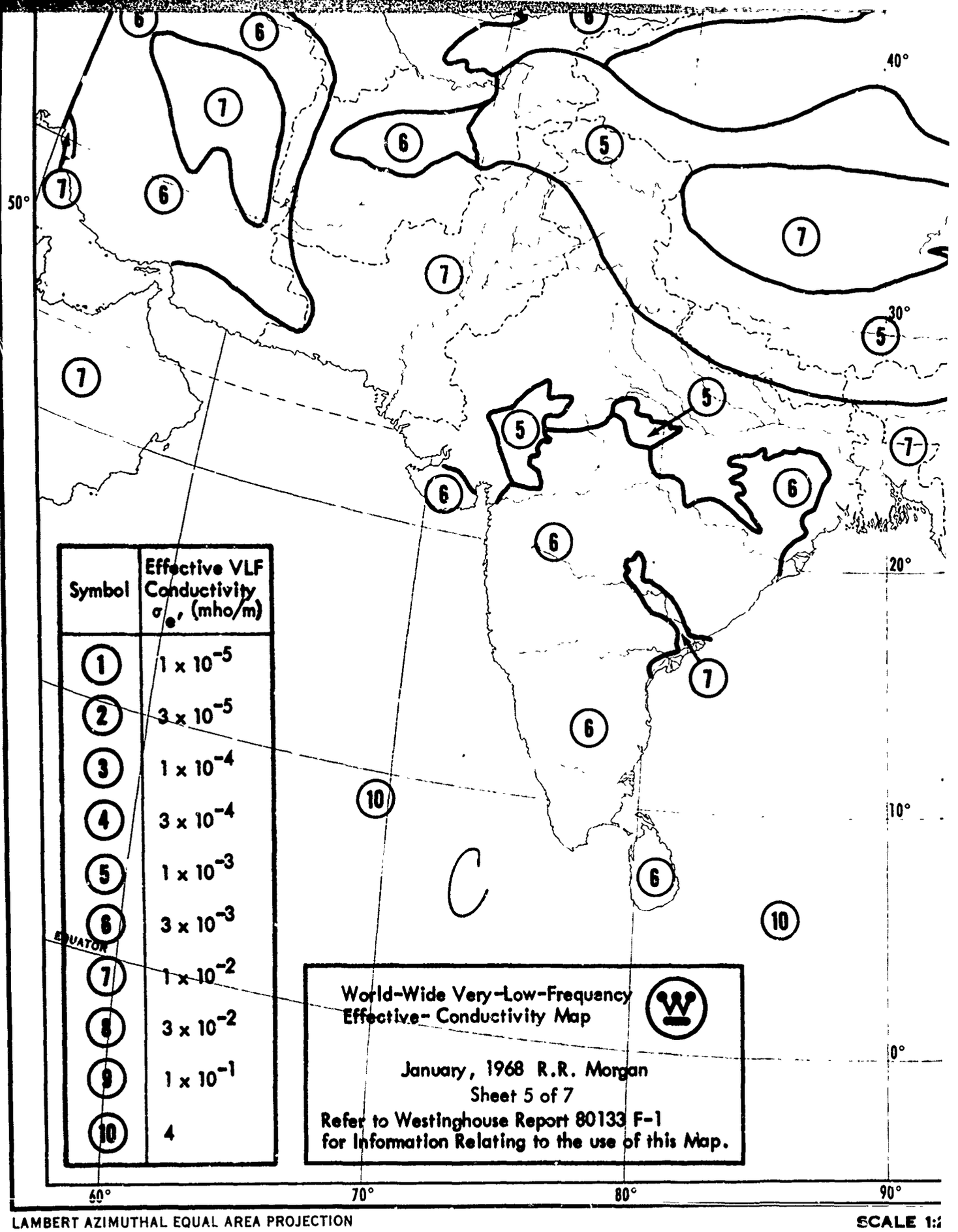
50°
40°
A
Note: Refer to Sheet 3 for Conductivity Values of Europe


80°
70°
60°
170°
180°
170°
160°
150°
140°
50°
40°
B



Symbol	Effective VLF Conductivity σ_e, (mho/m)
1	1×10^{-5}
2	3×10^{-5}
3	1×10^{-4}
4	3×10^{-4}
5	1×10^{-3}
6	3×10^{-3}
7	1×10^{-2}
8	3×10^{-2}
9	1×10^{-1}
10	4

World-Wide Very-Low-Frequency Effective- Conductivity Map

January, 1968 R.R. Morgan

Sheet 5 of 7

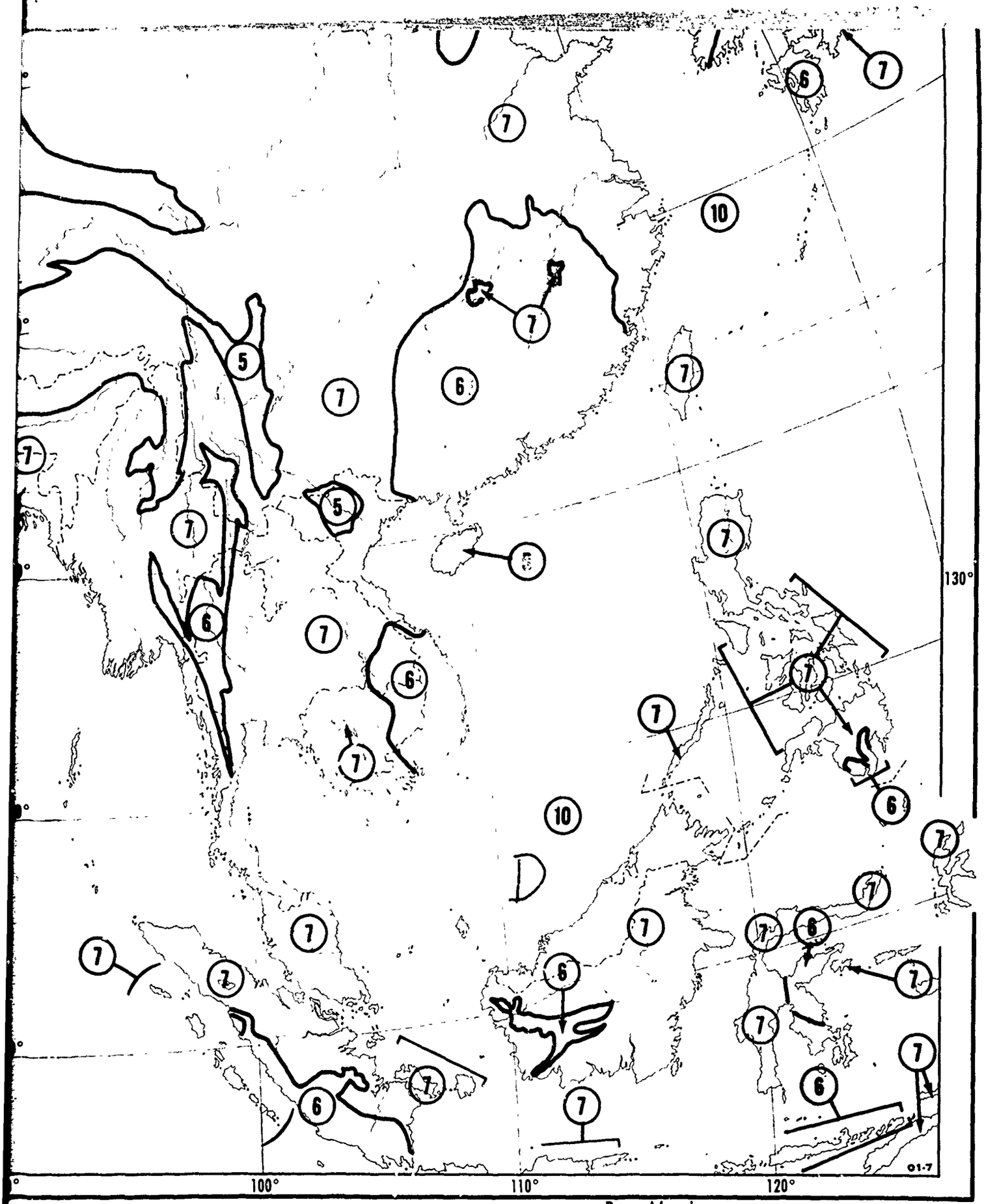
Refer to Westinghouse Report 80133 F-1 for Information Relating to the use of this Map.

LAMBERT AZIMUTHAL EQUAL AREA PROJECTION

SCALE 1:

0 5

0 500 1

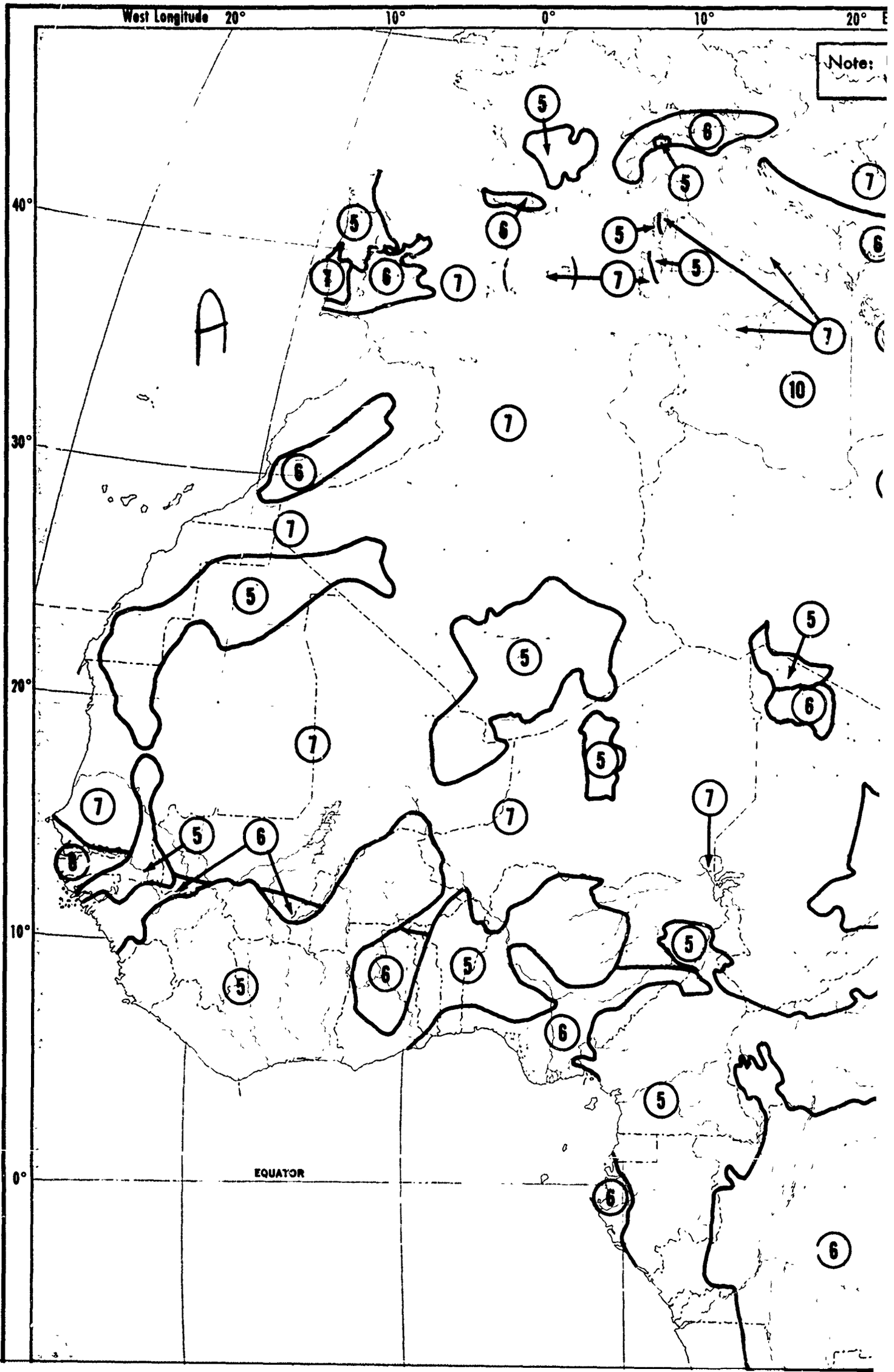


LE 1:22,000,000

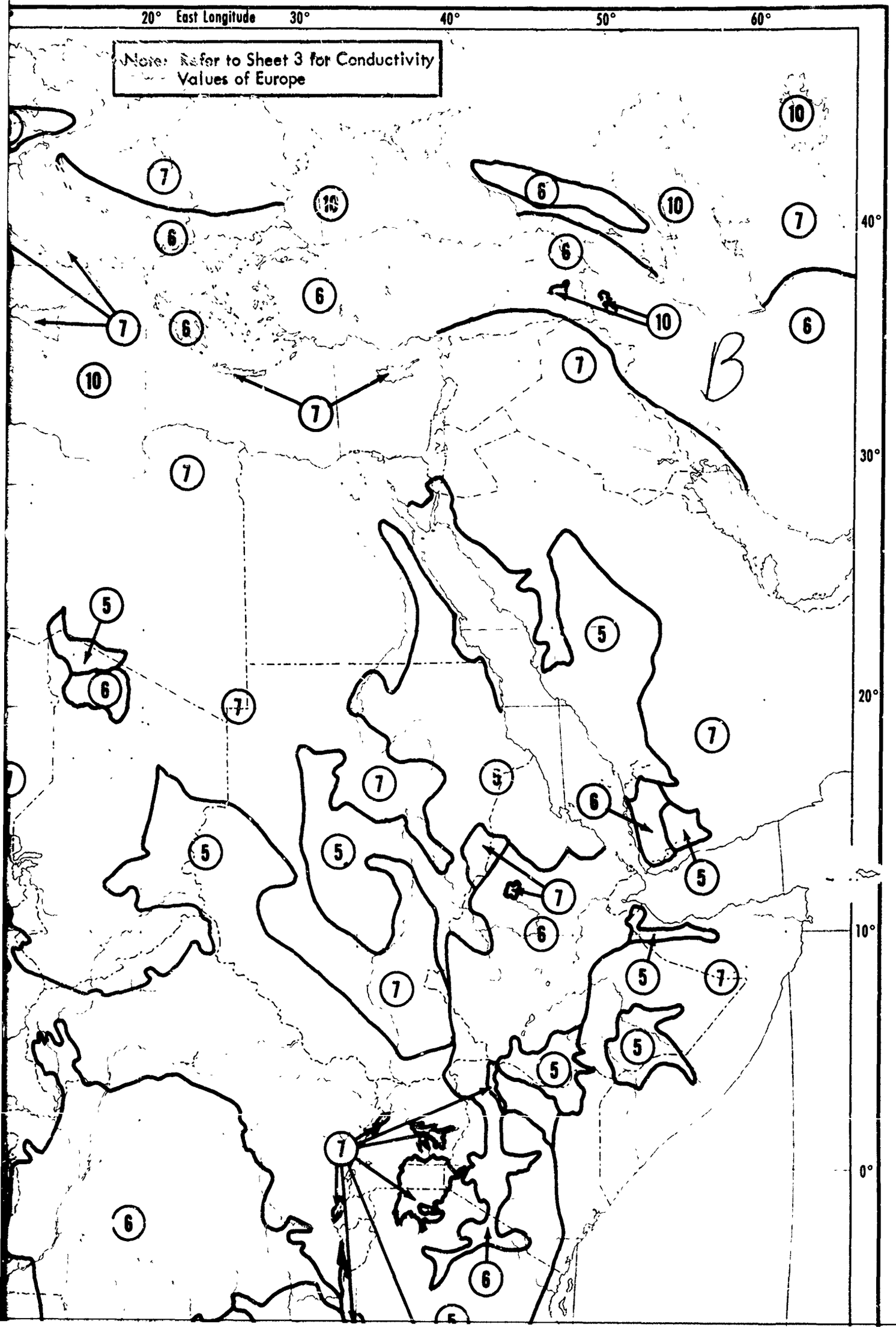
Base Map by BONN CARTOGRAPHIC CORPORATION

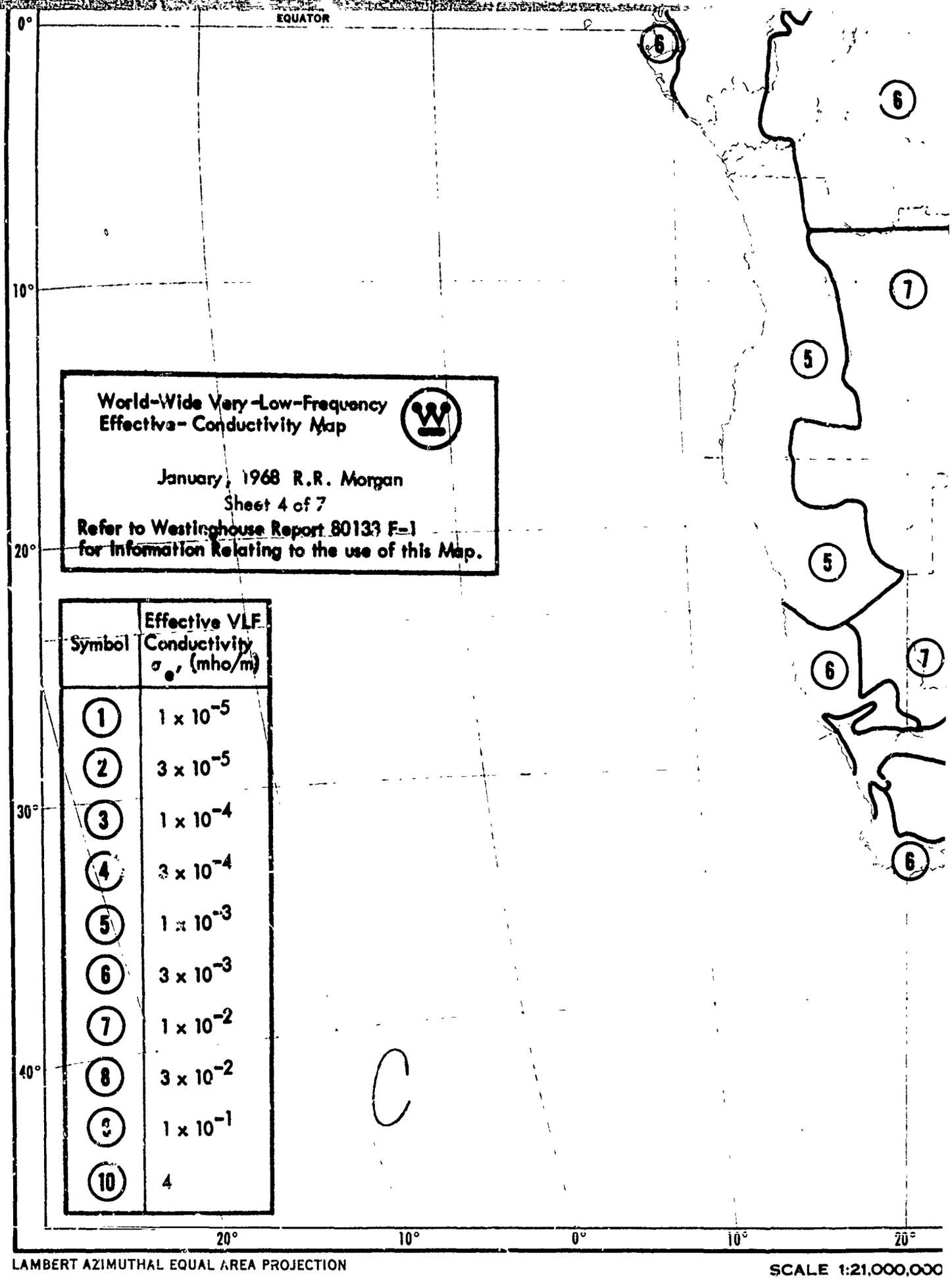
500 1000 MILES

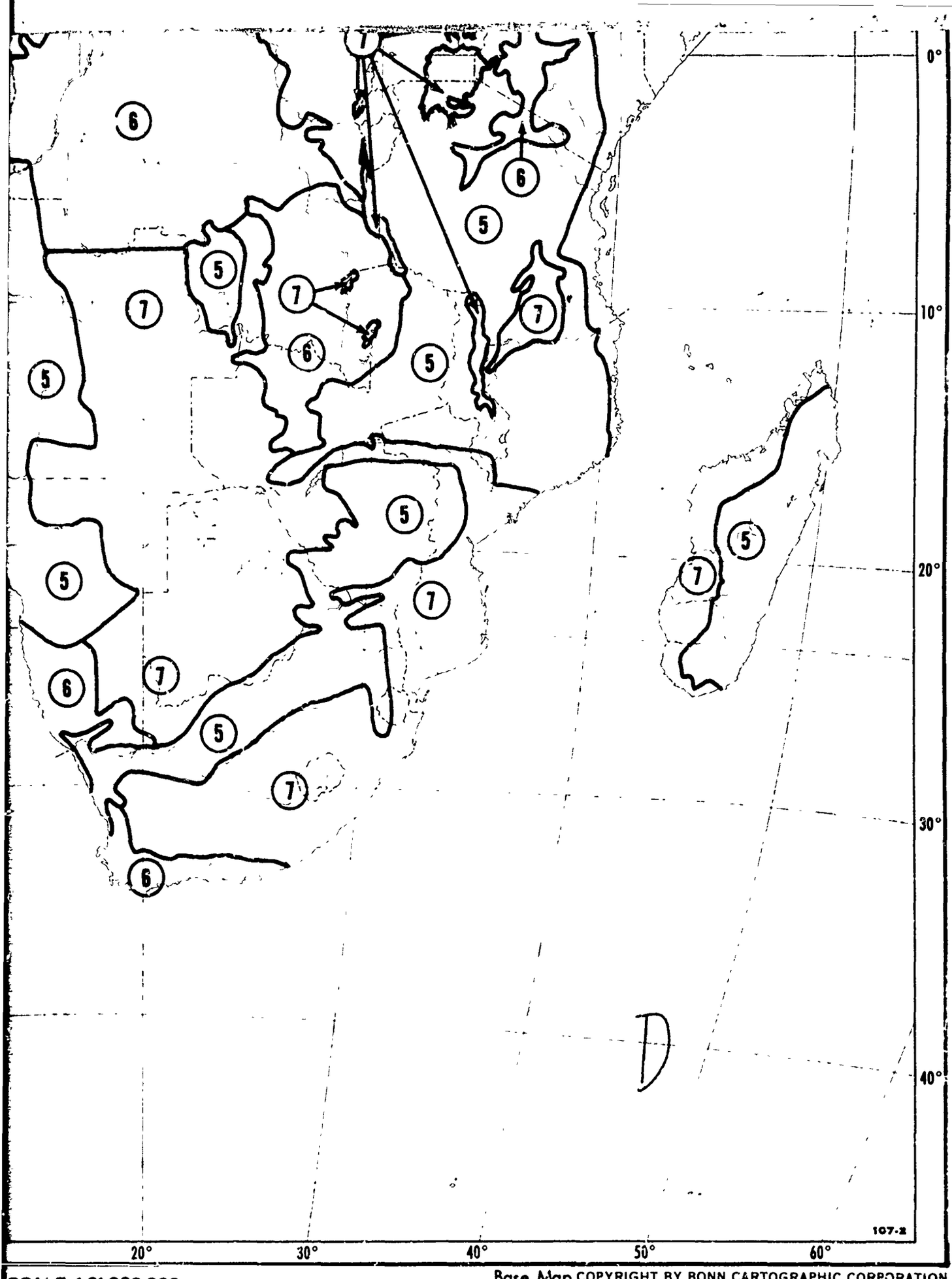
1000 1500 2000 KILOMETERS


West Longitude 20°
10°
0°
10°
20°
Note:
40°
30°
20°
10°
0°
EQUATOR
A

AFRICA


20° East Longitude
30°
40°
50°
60°
Note: Refer to Sheet 3 for Conductivity Values of Europe
40°
30°
20°
10°
0°
B

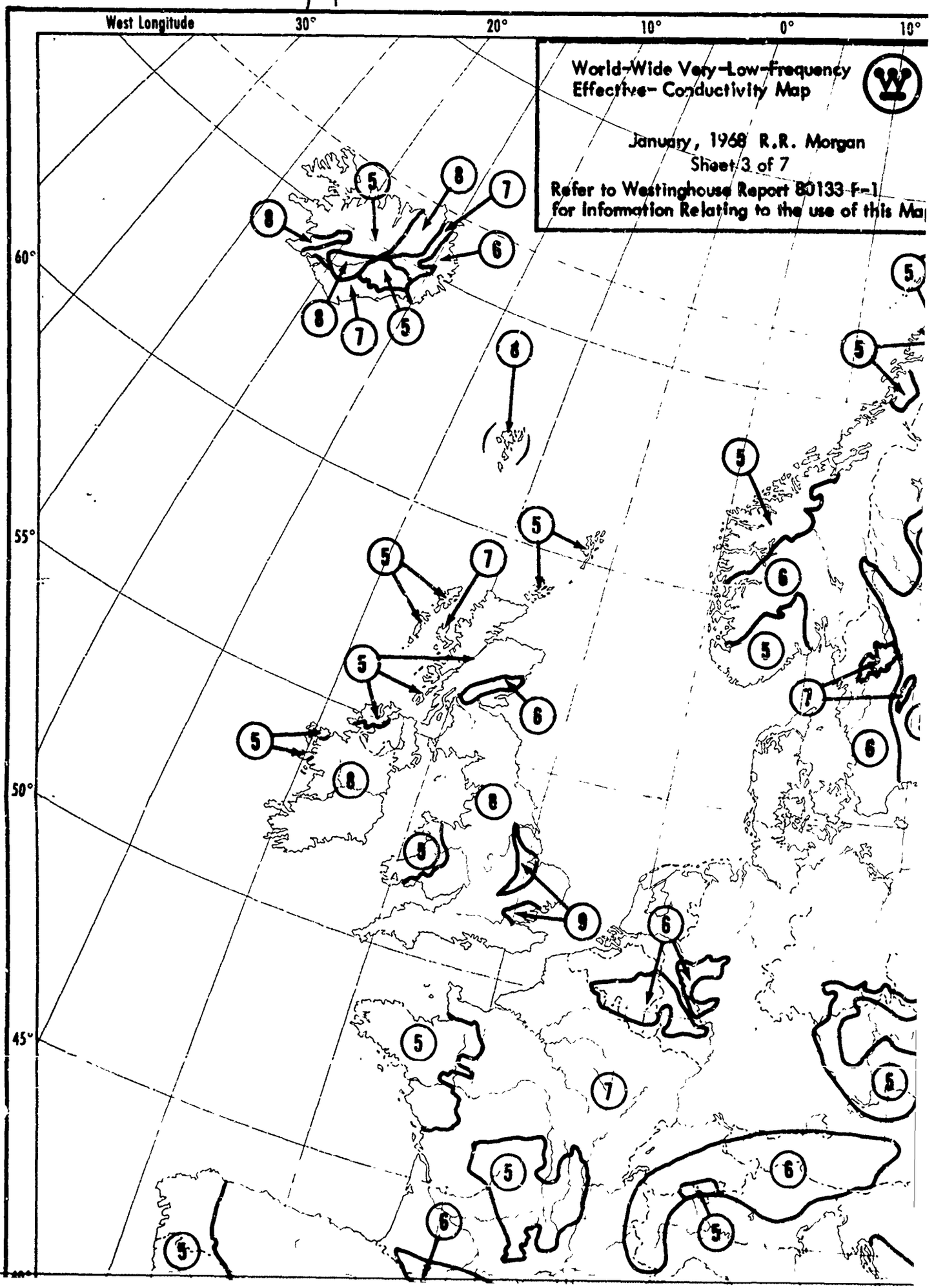

EQUATOR
0°
10°
20°
30°
40°
20°
10°
0°
10°
20°
World-Wide Very-Low-Frequency
Effective- Conductivity Map
January, 1968 R.R. Morgan
Sheet 4 of 7
Refer to Westinghouse Report 80133 F-1
for information Relating to the use of this Map.
Symbol
Effective VLF Conductivity σ_e, (mho/m)
1 1 x 10^-5
2 3 x 10^-5
3 1 x 10^-4
4 3 x 10^-4
5 1 x 10^-3
6 3 x 10^-3
7 1 x 10^-2
8 3 x 10^-2
9 1 x 10^-1
10 4
LAMBERT AZIMUTHAL EQUAL AREA PROJECTION
SCALE 1:21,000,000
0 500
0 1000



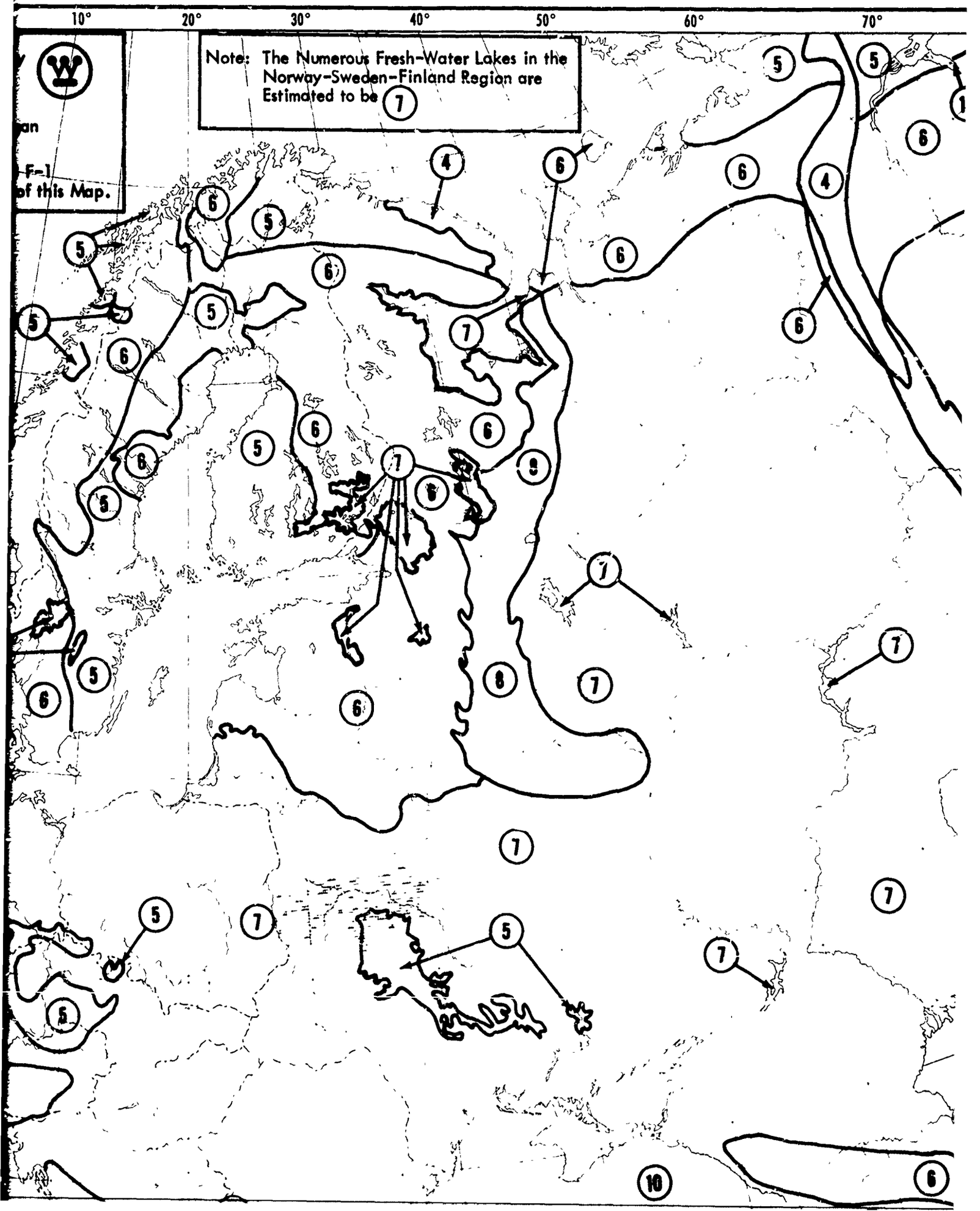
SCALE 1:21,000,000

500 1000 MILES

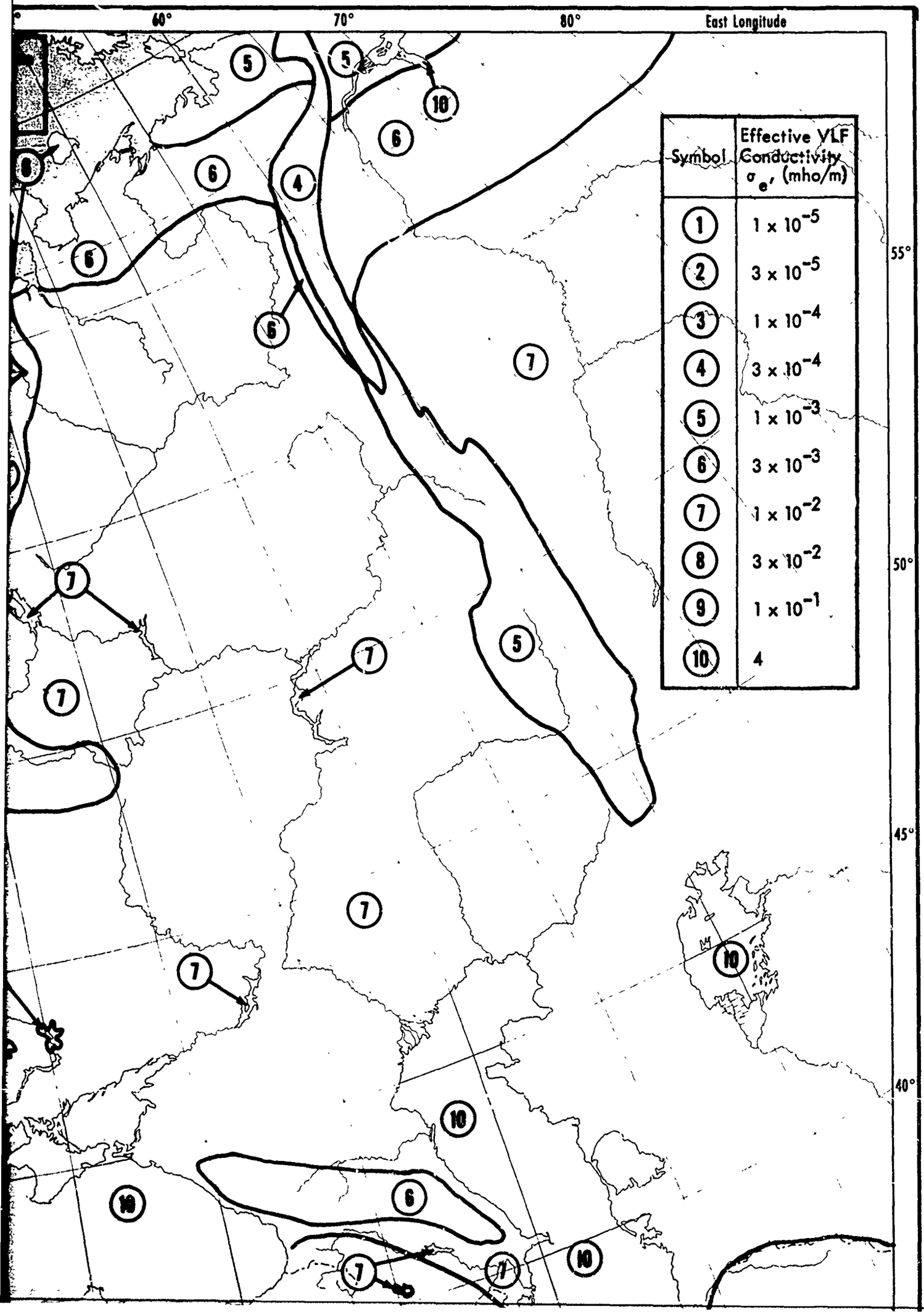
1000 2000 KILOMETERS

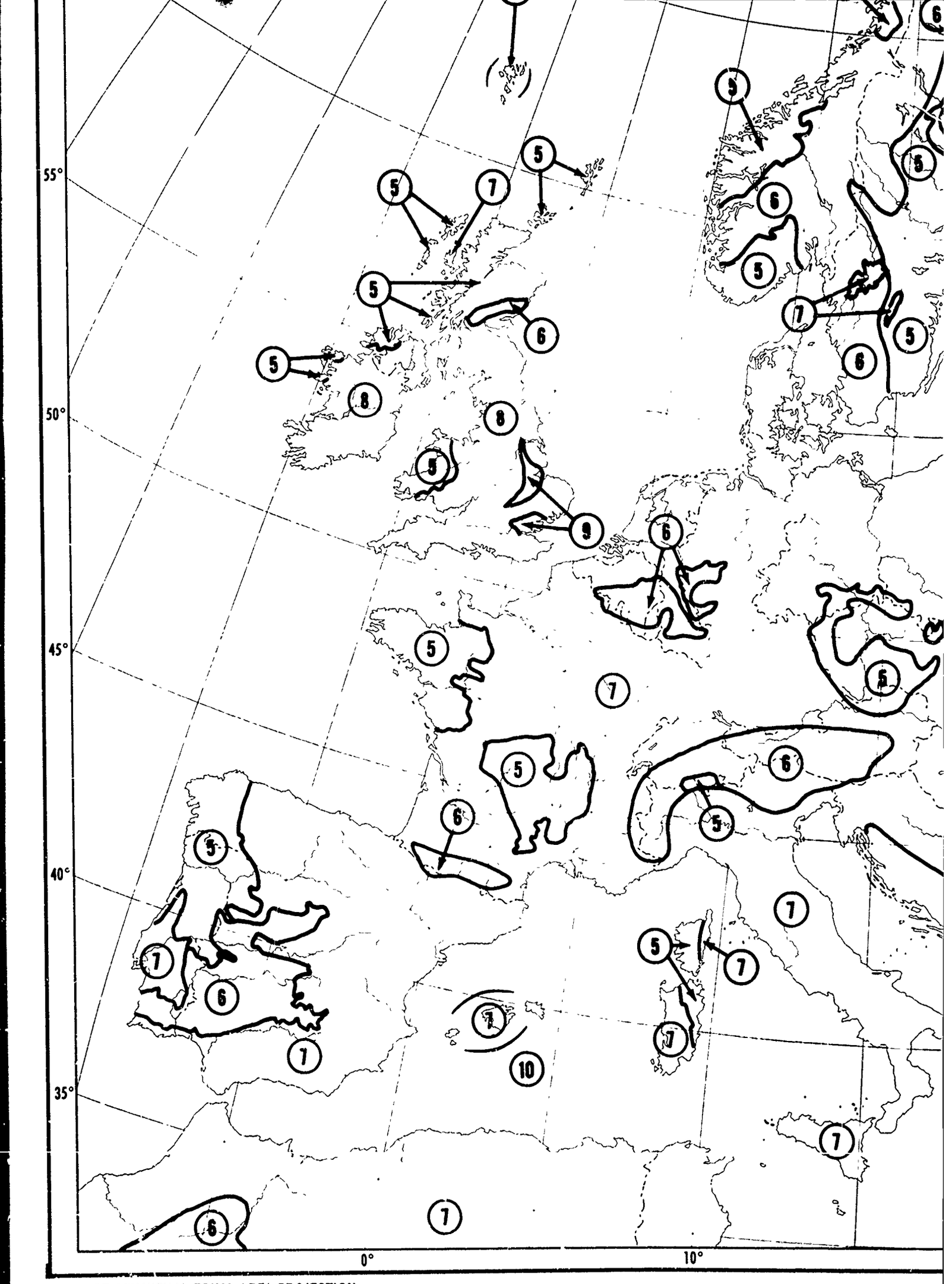

West Longitude
30°
20°
10°
0°
10°
60°
55°
50°
45°
World-Wide Very-Low-Frequency
Effective- Conductivity Map
January, 1968 R.R. Morgan
Sheet 3 of 7
Refer to Westinghouse Report 80133 F-1
for Information Relating to the use of this Ma

B


10°
20°
30°
40°
50°
60°
70°
Note: The Numerous Fresh-Water Lakes in the Norway-Sweden-Finland Region are Estimated to be 7
F-1
of this Map.

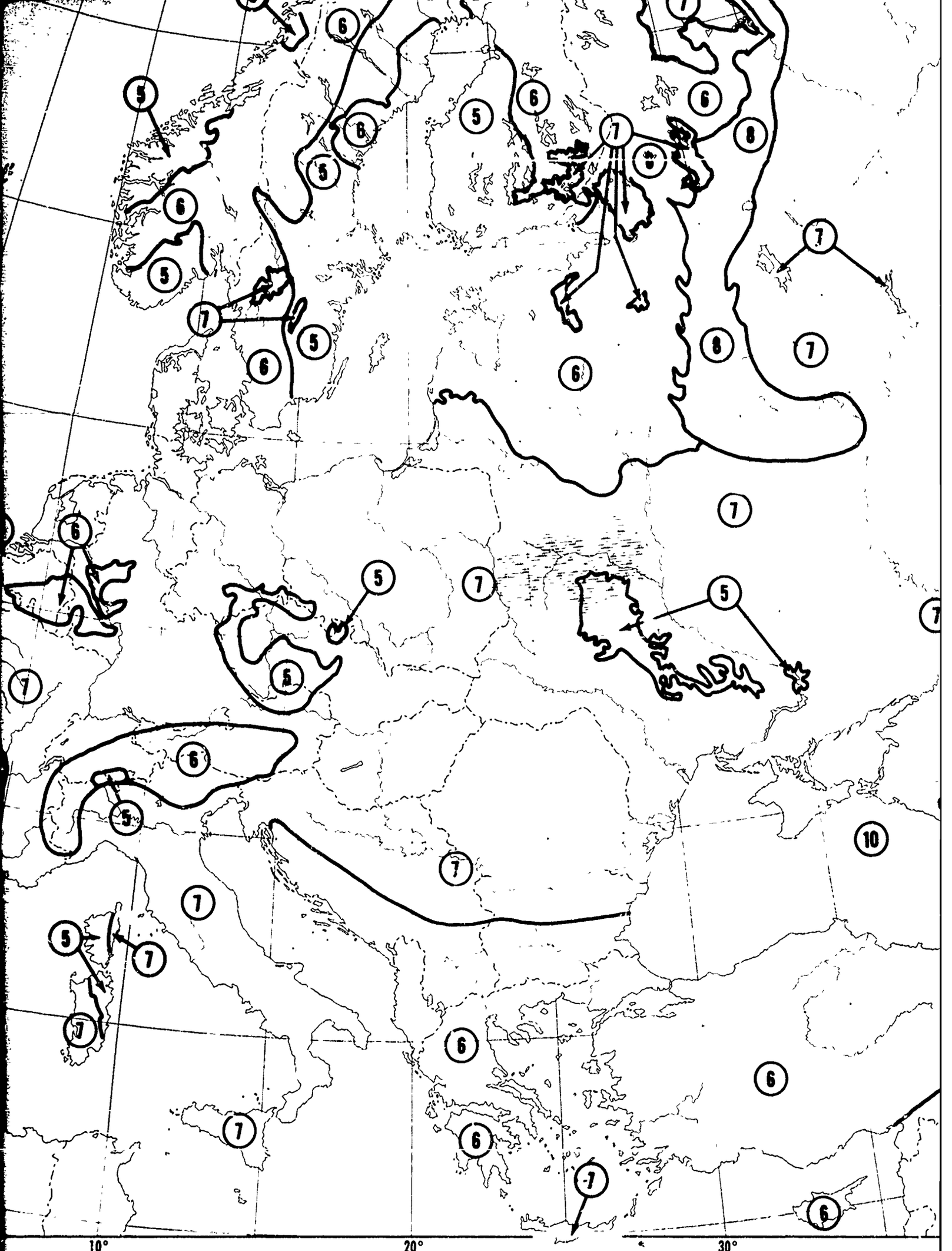
EUROPE


60°
70°
80°
East Longitude
55°
50°
45°
40°
Symbol
Effective VLF Conductivity σ_e, (mho/m)
1 1×10^{-5}
2 3×10^{-5}
3 1×10^{-4}
4 3×10^{-4}
5 1×10^{-3}
6 3×10^{-3}
7 1×10^{-2}
8 3×10^{-2}
9 1×10^{-1}
10 4



LAMBERT AZIMUTHAL EQUAL AREA PROJECTION

D

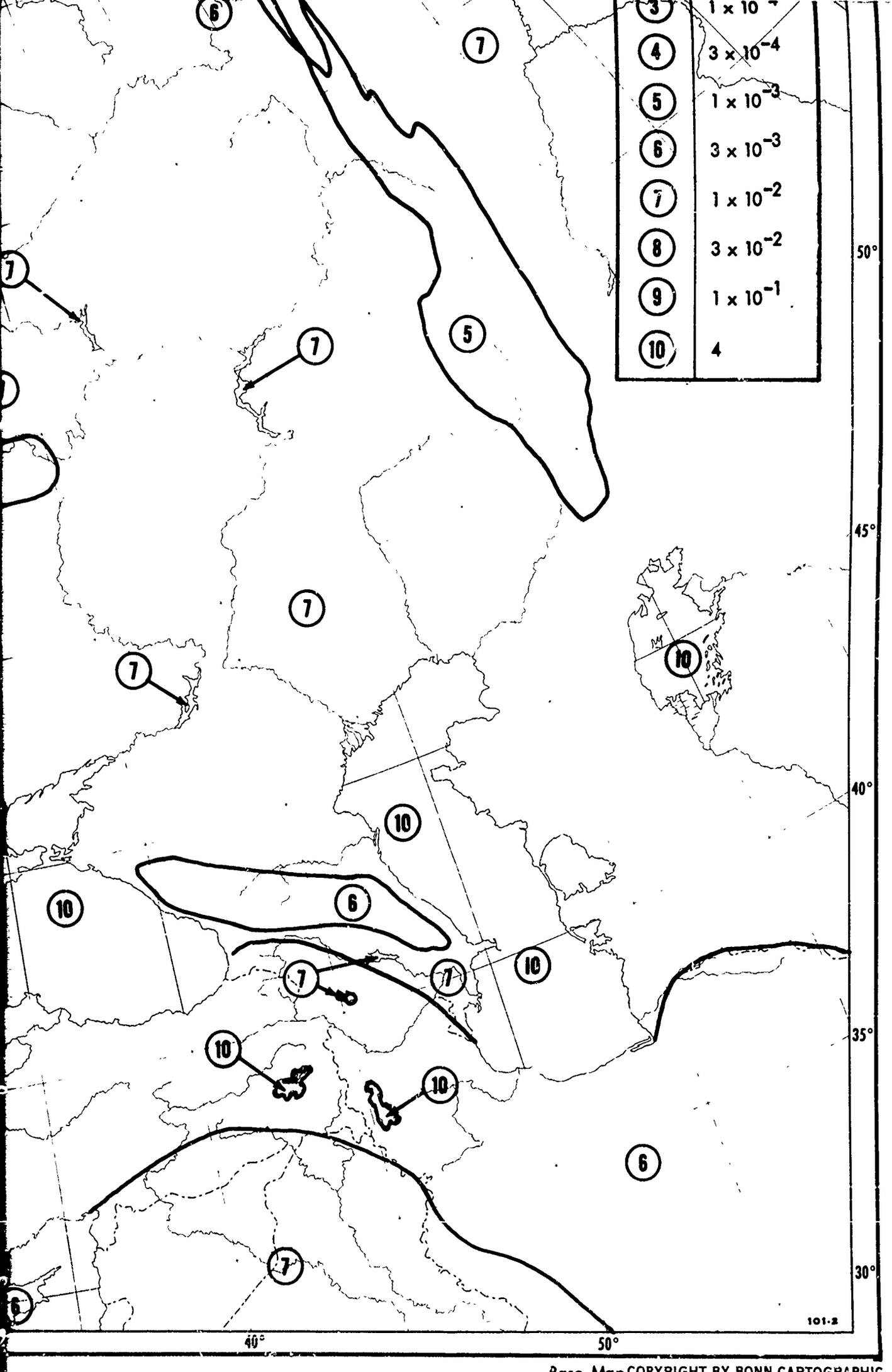


SCALE 1:12,500,000

0 100 200 300 400 500 MILES

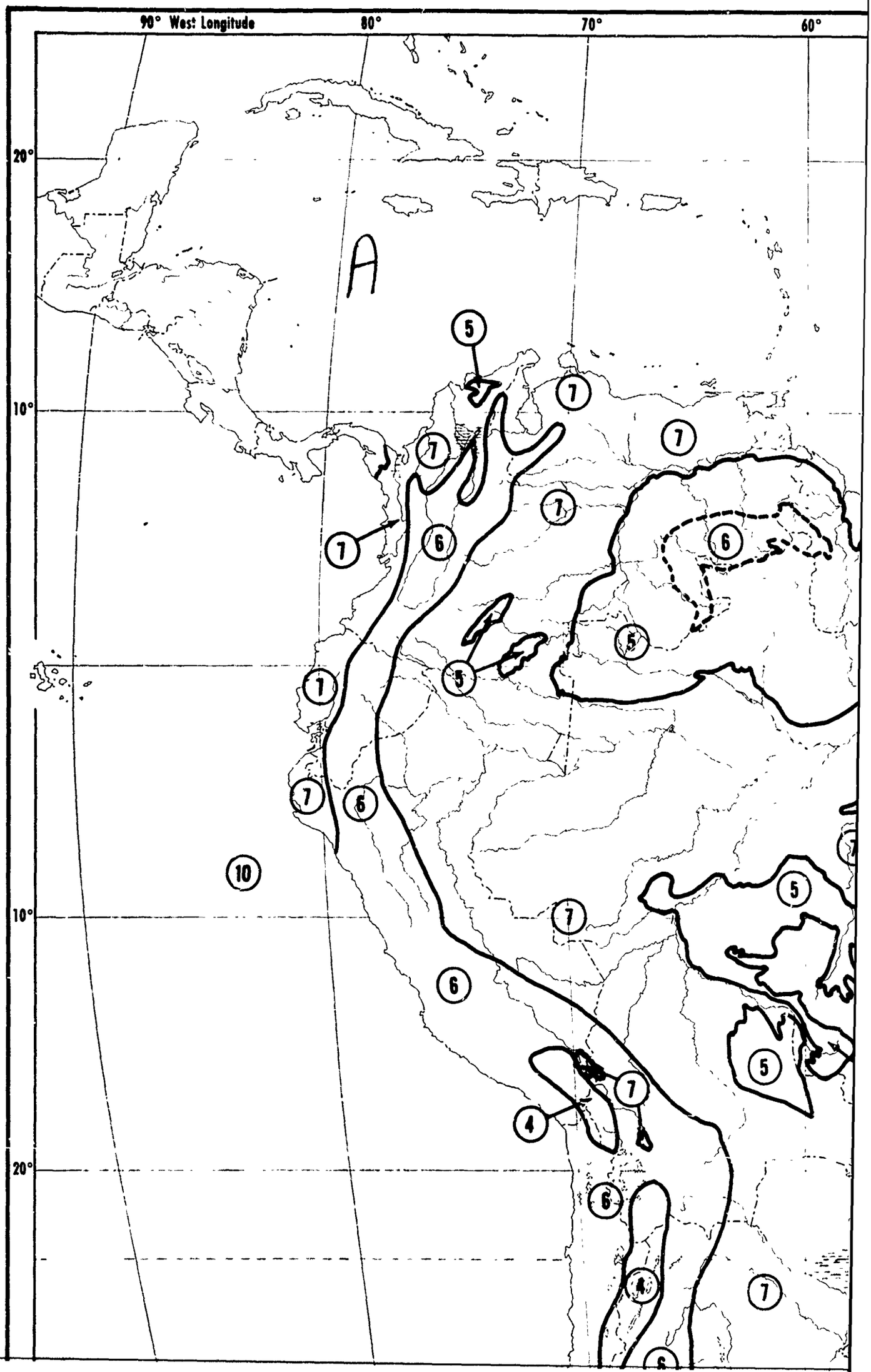
0 500 1000 KILOMETERS

E

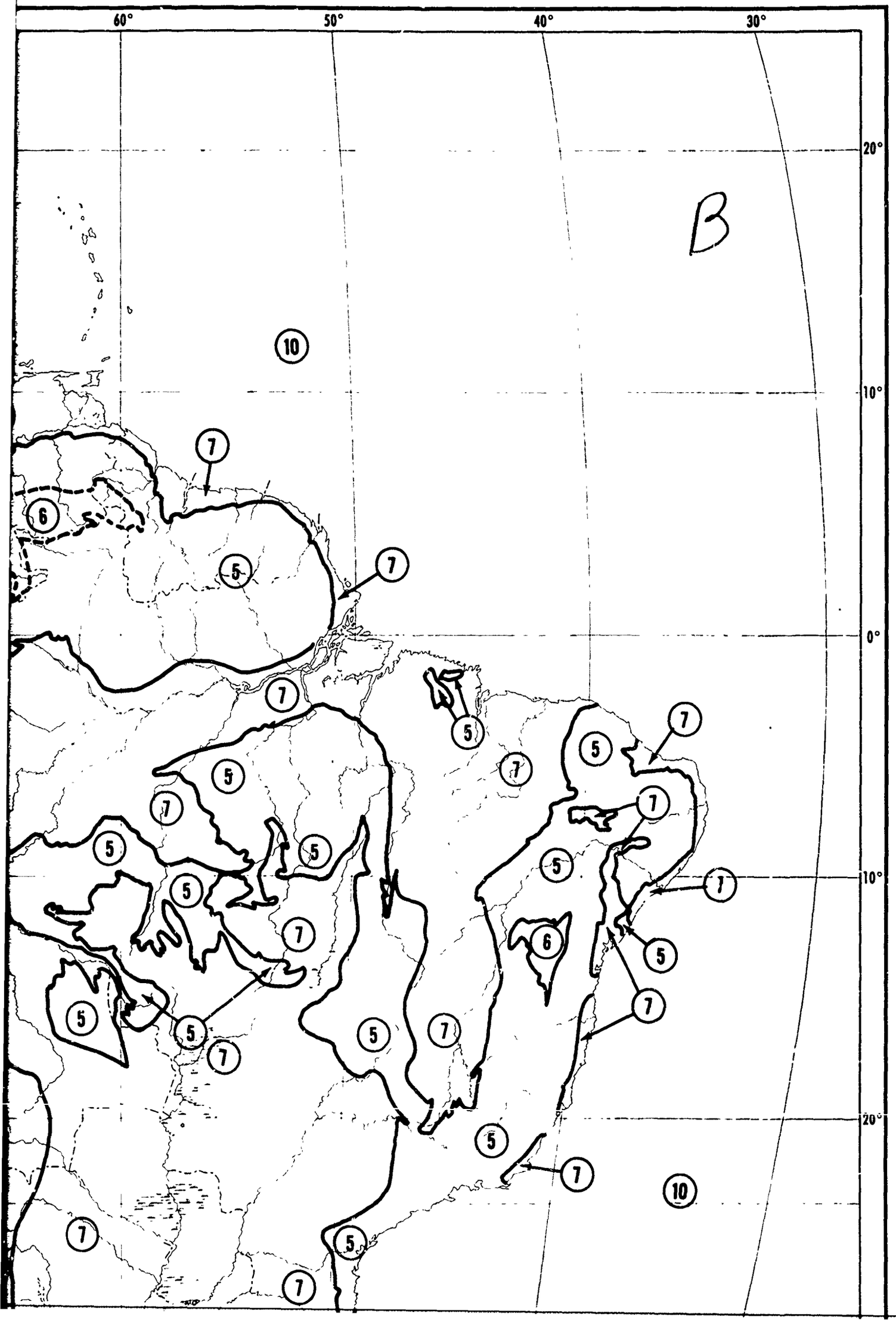


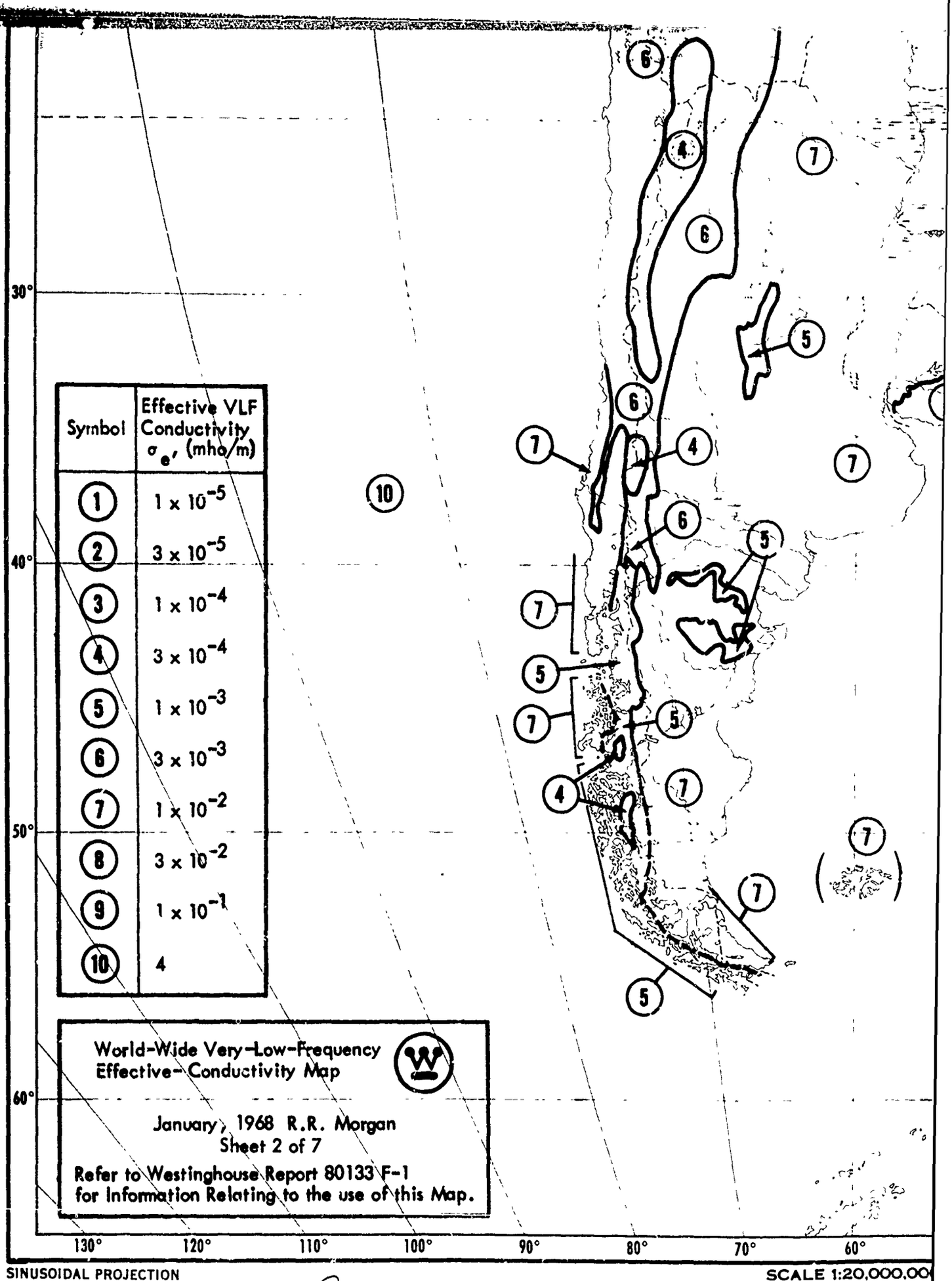
Base Map COPYRIGHT BY BONN CARTOGRAPHIC
SALT LAKE CITY

F


90° West Longitude
80°
70°
60°
20°
10°
10°
20°
A
5
7
7
7
7
7
6
6
7
5
5
7
7
6
10
7
6
5
5
7
4
6
4
7
6

SOUTH AMERICA





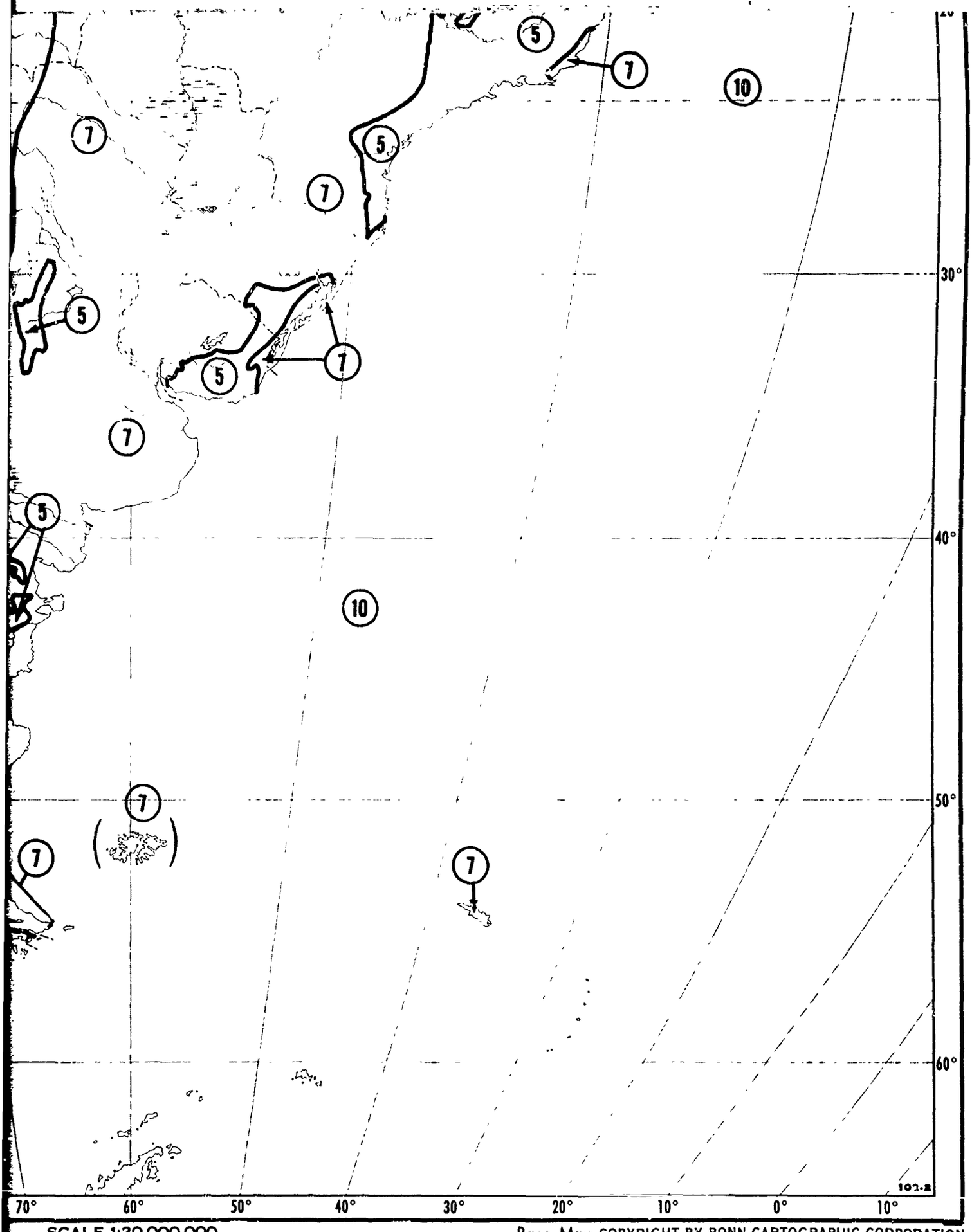
Symbol	Effective VLF Conductivity σ_e, (mho/m)
1	1×10^{-5}
2	3×10^{-5}
3	1×10^{-4}
4	3×10^{-4}
5	1×10^{-3}
6	3×10^{-3}
7	1×10^{-2}
8	3×10^{-2}
9	1×10^{-1}
10	4

World-Wide Very-Low-Frequency Effective-Conductivity Map

January, 1968 R.R. Morgan
Sheet 2 of 7

Refer to Westinghouse Report 80133 F-1 for Information Relating to the use of this Map.

C

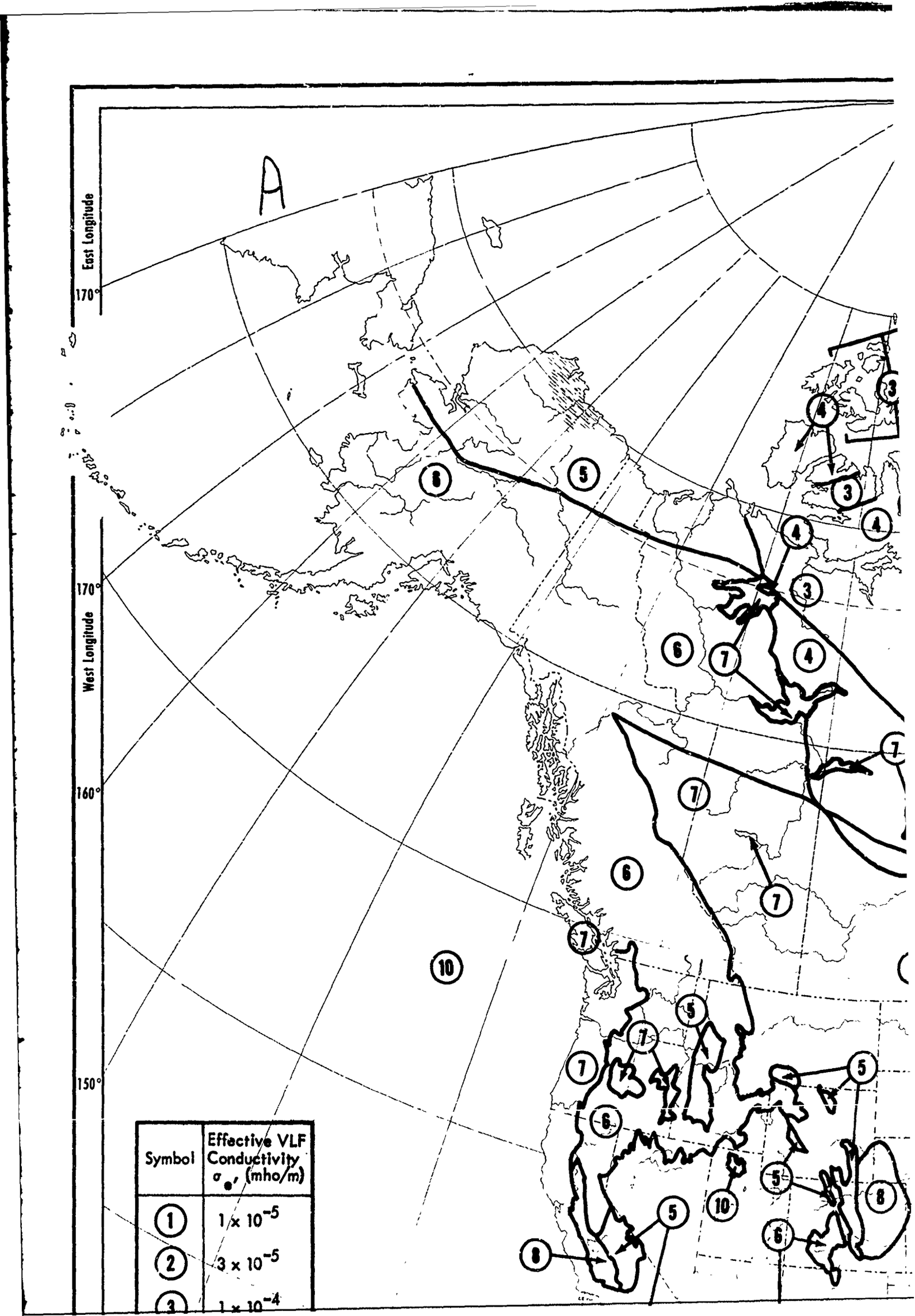


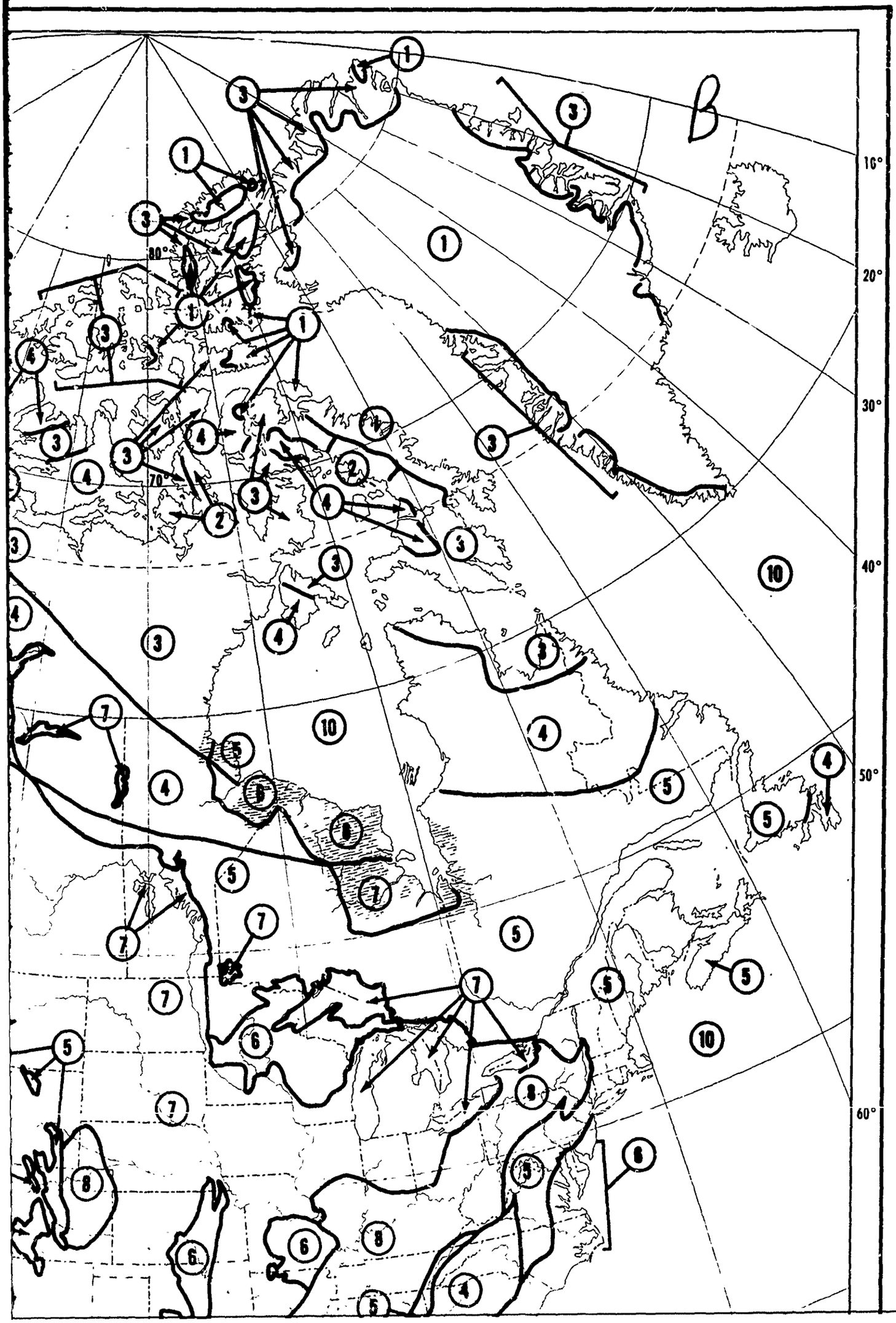
SCALE 1:20,000,000

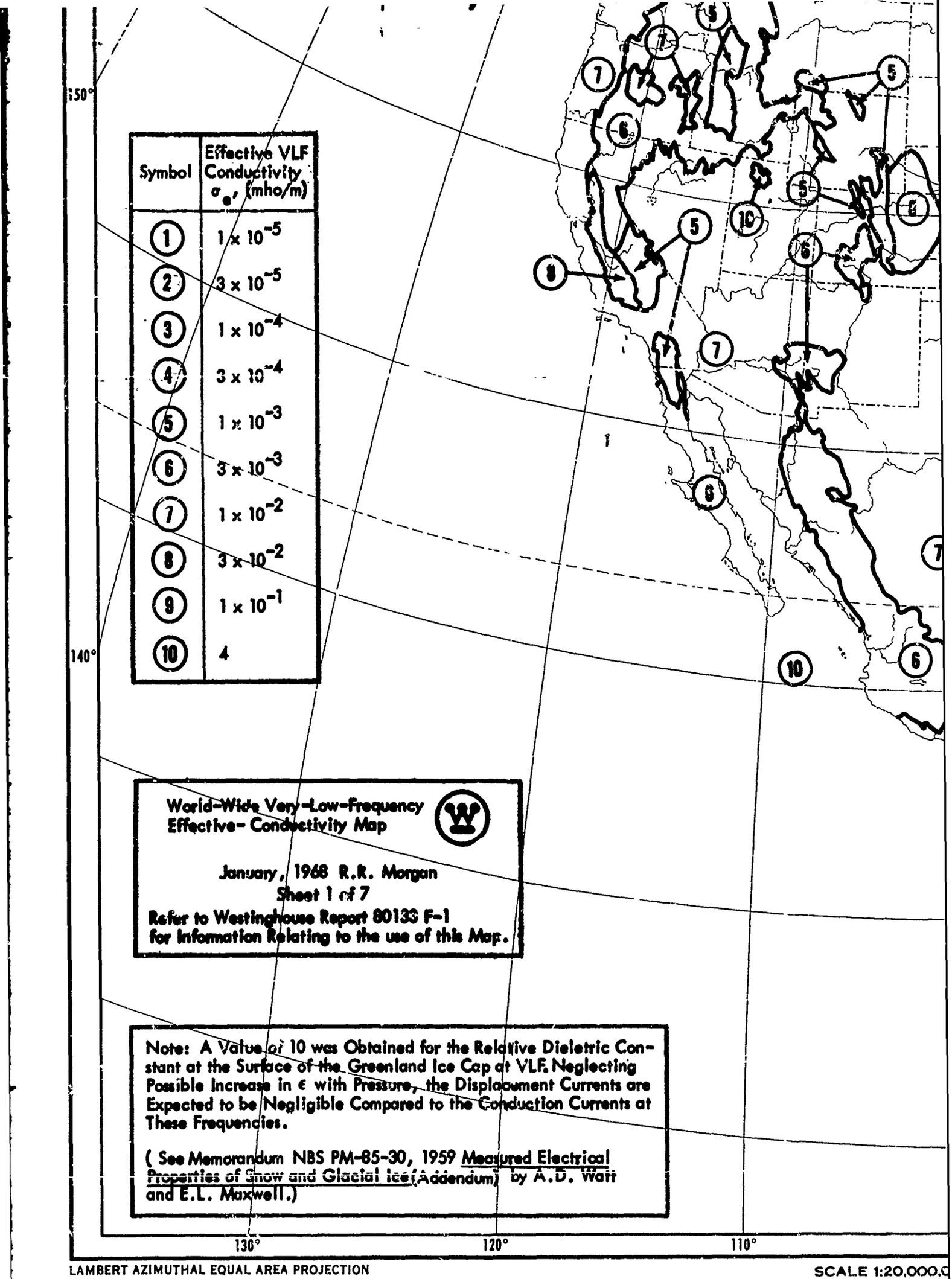
500 1000 MILES

1000 2000 KILOMETERS

D


A
East Longitude
170°
West Longitude
170°
160°
150°
Symbol
Effective VLF Conductivity σ_e, (mho/m)
1 1×10^{-5}
2 3×10^{-5}
3 1×10^{-4}


B
80°
70°
10°
20°
30°
40°
50°
60°



Symbol	Effective VLF Conductivity σ_e, (mho/m)
1	1×10^{-5}
2	3×10^{-5}
3	1×10^{-4}
4	3×10^{-4}
5	1×10^{-3}
6	3×10^{-3}
7	1×10^{-2}
8	3×10^{-2}
9	1×10^{-1}
10	4

World-Wide Very-Low-Frequency Effective-Conductivity Map

January, 1968 R.R. Morgan
Sheet 1 of 7

Refer to Westinghouse Report 80133 F-1 for Information Relating to the use of this Map.

Note: A Value of 10 was Obtained for the Relative Dielectric Constant at the Surface of the Greenland Ice Cap at VLF. Neglecting Possible Increase in ϵ with Pressure, the Displacement Currents are Expected to be Negligible Compared to the Conduction Currents at These Frequencies.

(See Memorandum NBS PM-85-30, 1959 Measured Electrical Properties of Snow and Glacial Ice (Addendum) by A.D. Watt and E.L. Maxwell.)

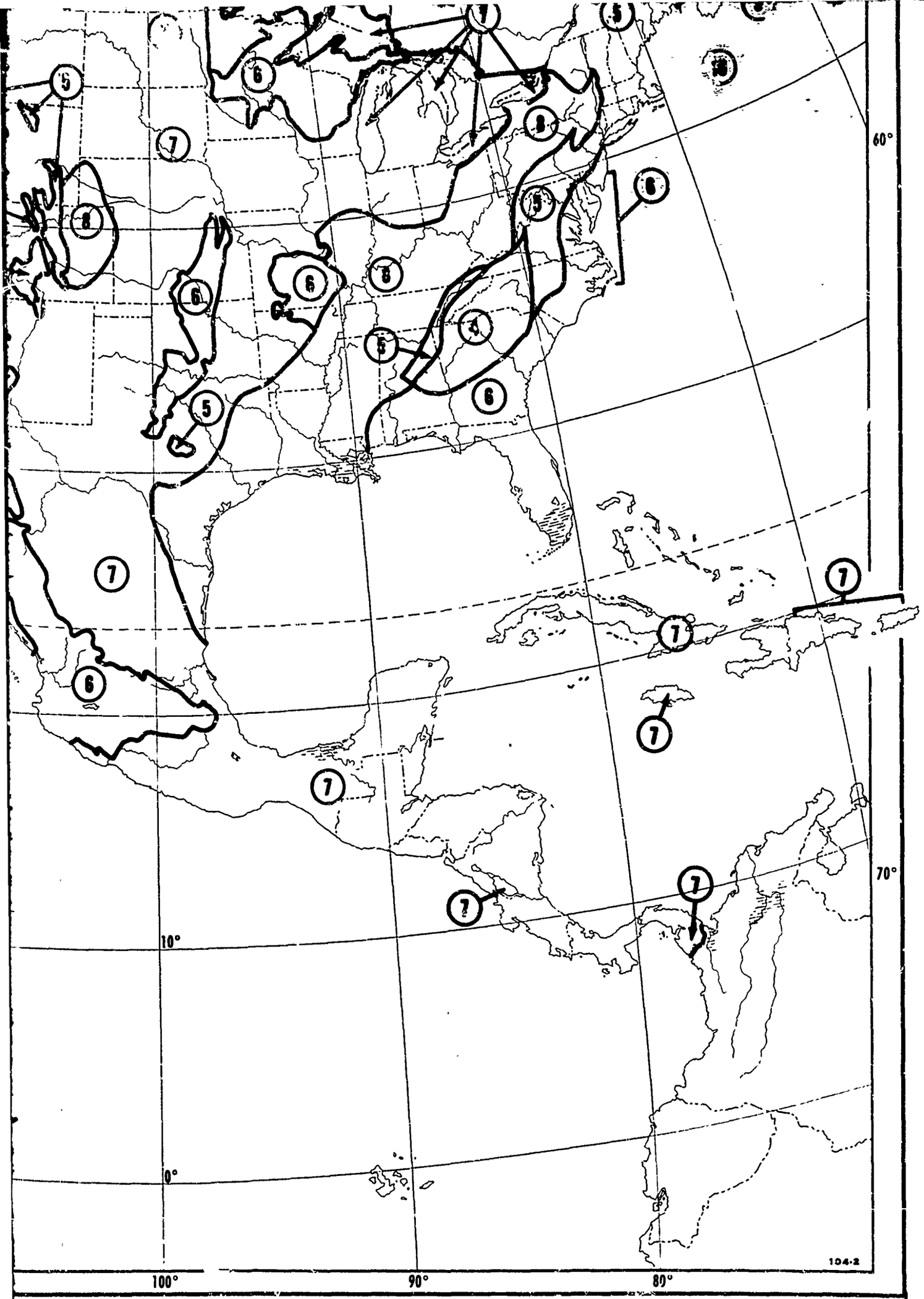
LAMBERT AZIMUTHAL EQUAL AREA PROJECTION

SCALE 1:20,000,0

0 500

0 500 1000

C



ALE 1:20,000,000

500 1000 MILES

1000 1500 2000 KILOMETERS

D