ENVIRONMENTAL IMPACT STATEMENT

DICKEY-LINCOLN SCHOOL LAKES

APPENDIX A

GEOLOGY AND SEISMOLOGY

DEPARTMENT OF THE ARMY
NEW ENGLAND DIVISION, CORPS OF ENGINEERS
WALTHAM, MASS.
02154

1977

MISCELLANEOUS PAPER S-77-2

EARTHQUAKE INVESTIGATIONS AT THE DICKEY-LINCOLN SCHOOL DAMSITES, MAINE

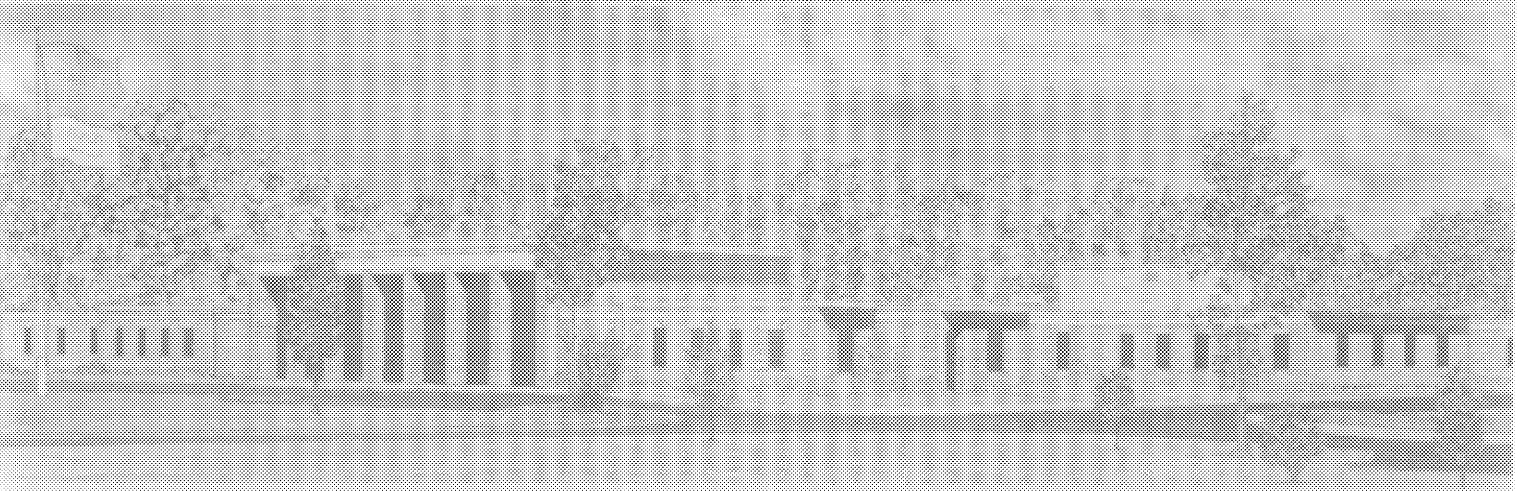
by

Ellis L. Krinitzsky, David M. Patrick

Soils and Pavements Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

January 1977

Final Report



Prepared for U. S. Army Engineer Division, New England
Waltham, Massachusetts 02154

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Miscellaneous Paper S-77-2	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) EARTHQUAKE INVESTIGATIONS AT THE DICKEY-LINCOLN SCHOOL DAMSITES, MAINE		5. TYPE OF REPORT & PERIOD COVERED Final report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Ellis L. Krinitzsky David M. Patrick		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Soils and Pavements Laboratory P. O. Box 631, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Engineer Division, New England 424 Trapelo Road Waltham, Mass. 02154		12. REPORT DATE January 1977 13. NUMBER OF PAGES 88
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 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)

Damsites
Dickey Dam
Earthquake hazards
Geological investigations
Lincoln School Dam
Seismic investigations
Site investigations

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

The Dickey-Lincoln School damsites are less than 50 miles from an area along the St. Lawrence River which has experienced some of the most severe earthquakes in North America. A geological and seismological investigation was made of the region in order to determine the hazards from earthquakes at the damsites. No active faults were found in the general area of the damsites. The source area of potentially severe earthquakes was found to be restricted to a narrow band that follows the St. Lawrence River. This band
(Continued)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (Continued).

was designated as Zone A. The boundary of Zone A is located 45 miles from the damsites. Zone B, with less seismic risk, borders Zone A and is 40 miles from the damsites. The damsites are situated in Zone C, which has the least seismic risk in the region. Zone D, with a level of seismic risk between that of Zones B and C, occurs 75 miles southeast of the damsites. The most severe ground motion at the damsites was interpreted to be from an earthquake in Zone A attenuated over a distance of 45 miles. Such movement is interpreted to have a peak acceleration of 0.35 g, a peak velocity of 65 cm/sec, and a peak displacement of 22 cm. The duration of shaking is estimated at 18 sec. Accelerographs are recommended for scaling in order to develop time histories of bedrock ground motion for dynamic analyses.

PREFACE

The U. S. Army Engineer Waterways Experiment Station (WES) was authorized to conduct this study by the U. S. Army Engineer Division, New England, on 14 April 1975 by appropriation order FY 75 IOA No. 75-C-51.

The work was done and the report written by Dr. E. L. Krinitzsky, Chief, Engineering Geology Research Facility, with the assistance of Dr. David M. Patrick. The interpretation of air imagery and the flights over the study area were coordinated with studies being made at the U. S. Army Cold Regions Research and Engineering Laboratory, under Dr. H. L. McKim at Hanover, New Hamphsire. Fieldwork was done with the assistance of Mr. Roy Gardner of Allagash, Maine, who served as guide. Consultants for this study were Dr. David B. Slemmons of the University of Nevada in Reno and Dr. Otto W. Nuttli of St. Louis University in St. Louis, Missouri. Helpful comments on the manuscript were furnished by Mr. S. J. Johnson, Special Assistant, Soils and Pavements Laboratory, WES.

The project was under the general direction of Mr. Don C. Banks, Chief of the Engineering Geology and Rock Mechanics Division, and Mr. J. P. Sale, Chief of the Soils and Pavements Laboratory. COL G. H. Hilt, CE, and COL J. L. Cannon, CE, were Directors of WES during the conduct of this study and preparation of this report. Mr. F. R. Brown was Technical Director.

CONTENTS

CONTENTS

LIST OF FIGURES

CONTENTS

CONTENTS

LIST OF TABLES

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
square miles	2.589988	square kilometres
degrees (angular)	0.01745329	radians

EARTHQUAKE INVESTIGATIONS AT THE DICKEY-LINCOLN SCHOOL DAMSITES, MAINE

PART I: INTRODUCTION

General

1. The Dickey-Lincoln School damsites in northeastern Maine are less than 50 miles* from an area of intense earthquakes along the St. Lawrence River. The historic record, which dates back to 1638, includes over 100 earthquakes, a number of which were of notable severity. Consequently, the sites needed to be evaluated carefully for seismic risk.

Objective

2. This study was undertaken to provide a review of the tectonism, faulting, present activity of faults, effects of glacial loading and unloading, and the significance of the seismic history in the region. These aspects were evaluated in terms of the levels of seismic risk that they imply. The latest practices were used to determine design earthquakes and their appropriate ground motions for the bedrock at the damsites.

---

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 6.

PART II: GENERAL GEOLOGY

Physiography

3. The Dickey and Lincoln School sites are in the New England Upland Subdivision of the New England Maritime Physiographic Province. The general relation of the sites to the St. Lawrence Valley, to the Canadian Shield, and to the structural grain of northern New England is shown in Figure 1.[1] The terrain in the general area of the sites is mantled with glacial drift and is gently rolling. Hilltops have approximate elevations of 1400 to 1700 ft msl and valley bottoms are 800 to 1000 ft msl. There are more highly elevated hills or mountains of which Hafey Mountain and Rocky Mountain are examples (see Figure 2).[2] Their elevations approach 2000 ft. These topographic highs are a result of greater resistance to erosion.

4. The major drainage system is the St. John River and its tributaries, the Black and Allagash Rivers. Generally, the overall character of the drainage is a result of continental glaciations with ponds, marshes, and misfit streams. Drainage alignment is irregular and may have been caused either by the disruption of drainage by glaciation or by structural controls in the bedrock.

5. The St. John, Black, and Allagash Rivers occupy valleys that contain deposits of glaciofluvial sand, gravel, and, occasionally, clay. The granular deposits along the St. John Valley appear to represent a valley train which resulted from the wasting of the last continental glacier. The largest streams have cut through the glaciofluvial deposits so that sand and gravel occur on the valley sides as high as 75 to 100 ft above the river level.

6. Stream terraces occur along the St. John River Valley and are developed at Lincoln School and farther downstream. In general, the terraces are irregularly developed. The occurrences of slump features and steep dips in these granular deposits suggest that the terrace material may have been in contact with glacial ice.

Stratigraphy

7. A schematic section of the rock sequences for the Dickey-Lincoln School sites is indicated by Section A-A' in Figure 3[3] (see location of section in Figure 1).

8. The knowledge of stratigraphy in this area is incomplete. Metamorphism, a lack of marker beds, faulting, glaciation, and thick forest cover have made the area difficult to interpret. This report has relied principally upon the work of Boudette et al.[2] for information on the geology. The discussion of the stratigraphy is here presented in terms of lithology as opposed to formational names because of a lack of detailed stratigraphic information.

9. Figure 3 illustrates the general geology of the area. The section consists of approximately 42,000 ft of metamorphosed sedimentary rocks including shale, slate, graywacke, metaquartzite, arkosic sandstone, and conglomerate. Shale and slate are the predominant rocks in the immediate vicinity of both sites. The geological ages range from Cambrian to Lower Devonian. The latter age is assigned to the shale and slate which outcrop at the proposed damsites. The fine-grained rocks are more highly metamorphosed than the coarser grained rocks; the highest metamorphism, excluding contact with igneous rocks, is that where chlorite has developed.

10. Igneous rocks include Devonian quartz monzonite and quartz latite, as well as greenstone and a metamorphosed andesite of Silurian age. The quartz latite is well exposed at Rocky Mountain. The andesite, greenstone, and quartz latite are exposed along the Rocky Mountain thrust fault (Figure 2).

11. Proceeding southeast from the St. Lawrence River toward the proposed damsites (approximately 50 miles) the sedimentary rocks become progressively younger. The rocks mapped in Quebec and northwest of the Dead Brook thrust are undifferentiated Cambrian and Ordovician slate, phyllite, graywacke, and metaquartzite. Some of the rocks exposed in the area northwest of the Dead Brook thrust are undifferentiated Paleozoic Rocks.

12. Ordovician slate, graywacke, feldspathic sandstone, and conglomerate occur on the northwest side (upper plate) of the Rocky Mountain thrust. These rocks have unconformable contacts with the older Cambro-Ordovician and younger Silurian rocks.

13. The Silurian system is represented by a sequence of slate, siltstone, graywacke, sandstone, and biostromal limestones. These rock units are of Upper Silurian age and generally exhibit gradational horizontal and vertical contacts. This sequence also contains the oldest igneous rocks: a metamorphosed andesite (greenstone) and quartz latite. These igneous rocks and the enclosing sedimentary types are exposed along the Rocky Mountain thrust. The igneous rocks are interpreted as extrusive lavas, although an intrusive interpretation could also be made.

14. Two sequences of rocks, separated by unconformity and both of Upper Silurian or Lower Devonian age, occur to the southeast of the Rocky Mountain thrust. These rock units consist of slate, phyllite, arkose, quartzite, and graywacke.

15. The youngest rock units are of Lower Devonian age and consist of slate, sandstone, graywacke, and metamorphosed basalt (greenstone) interpreted as extrusive. The sedimentary rocks are characterized by cyclical bedding and gradational horizontal and vertical bedding and gradational horizontal and vertical contacts. These rocks are exposed on the southeast side of the Rocky Mountain thrust and extend southeast of the Allagash River where they are mapped as undifferentiated Lower Devonian. The rocks underlying the proposed sites belong to this sequence.

Lithology

16. The sedimentary rocks have all been subjected to various degrees of metamorphism. The highest metamorphism near the sites is the chlorite which occurs west and north of the St. John and Little Black Rivers and in the drainage system near Dickey. Downstream and generally east of Dickey the rocks exhibit much less metamorphic alteration.

17. The fine-grained rocks exhibit well-developed foliation and cleavage and have been metamorphosed into slates and phyllites. The coarsest clastics are extremely hard and well indurated.

18. The rocks in the study area may be categorized as follows:

a. Shale, siltstone, slate, phyllite, argillite, and hornfels.

b. Arkose, graywacke, and conglomerate.

c. Sandstone, orthoquartzite, and quartzite (metaquartzite).

d. Quartz latite, andesite, and basalt.

e. Granodiorite and quartz monzonite.

Depositional History

19. The rocks at the sites resulted from deposition in a eugeosynclinal basin. This basin was probably very close to a source area to the southeast which was actively eroded and contributed fine and coarse clastic material. Some clastics were deposited as marine sediments; others were deposited in deltas and beaches. The poor sorting and heterogeneous composition of the rocks suggest tectonism and lack of stability in the source area. The organic population of the ancient sea was most likely sparse. Generally, coarse clastics do not present the most hospitable habitat for marine life; however, graptolites are preserved in the finer grained shales and slates.

PART III: TECTONIC HISTORY

Orogenies

20. Orogenic events have occurred as follows:

   a. Taconian. The earliest orogeny was the Taconian. This event occurred during late Ordovician or Silurian time and resulted in the development of large overthrust sheets which moved slices of geosynclinal sediments from the southeast toward the shield area to the northwest. This orogeny is marked by an unconformity between deformed Ordovician and older rocks, and the younger Silurian strata.

   b. Acadian. The Acadian orogeny occurred during middle and late Devonian time and resulted in faulting, folding, and extensive intrusive igneous activity, of which folding and faulting are the most characteristic in the study area. This orogeny was the last major tectonic event in the Northern Appalachian Deformed Belt. Although Upper Paleozoic rocks are absent in the study area, due either to nondeposition or erosion, they do occur in Gaspé (see Figure 1) where they exhibit only minor deformation.

   c Triassic events. After the Acadian orogeny and possibly after late Paleozoic deposition, the Northern Appalachian Deformed Belt was uplifted and experienced considerable erosion. During Triassic time, this region was subjected to tensional forces which resulted in normal faulting and the development of elongate grabens. These fault-bound structures received clastic sediments from the adjacent mountains which were then being eroded. Associated with the sedimentation in the grabens were basaltic intrusions and flows. Although the boundary faults along the graben margins predate the sediments, the sediments themselves have been affected by faulting and warping. The known Triassic grabens nearest the study area are in the Bay of Fundy and in the Gulf of Maine (Ballard and Uchupi[4]).

Structural Deformation

21. The type of structural deformation exhibited in the study area is one of both folding and faulting. The axes of the folds generally run from southwest to northeast as do the strikes of the major faults. The dips of the beds are quite steep and it is uncommon to

find bedding planes with dips less than 50 deg.

Folding

22. The study area lies between two broad fold axes: an anticlinal axis trending northeast-southwest in Quebec to the northwest and a synclinal axis of similar strike lying to the southeast. The folds occurring in the study area have been superimposed on the limbs of these larger folds.

Faulting

23. The faults mapped by Boudette et al.[2] (Figure 2) include two major overthrust faults, Rocky Mountain and Dead Brook; two reverse faults, Big Black River and Jones Brook; several small faults associated with the thrust faults; and a presumed fault, the Hunnewell, striking approximately parallel to the St. John River near both sites (see Figure 2). The data on the major faults are summarized in Table 1.

24. The faults listed above have been identified by Boudette et al. on an inferential basis. The criteria for classifying these structural features as faults are:

a. Photolinear offsets: Includes the discontinuity of lithologic units and displacement along strike as determined by aerial photographs.

b. Stratigraphic truncation: Based upon the truncation, disappearance, or apparent pinching out of significant thickness of a stratigraphic interval along a photolinear. Folding and/or unconformity may be offered as alternate explanations for the truncation, but Boudette et al. believe that faulting is the most realistic interpretation.

c. Stratigraphic juxtaposition: Related to stratigraphic truncation. Involves the juxtaposition of two lithologic units and the absence of an intermediate lithologic unit.

d. Lineaments: Photolinears, not related to topography, strike of bedding, or folding. Used for the mapping of the continuation of faults identified by other means. In the case of Hunnewell, was used for primary identification.

e. Ground evidence: Ground observation of faulted contacts. Best criterion. Generally, this means was not useful in the study area because of ground cover. Fault contacts are evident on Rocky and Hafey Mountains.

Table 1

Major Faults in the Project Area

Fault (See Figure 2)	Minimum Mapped Length, miles	Fault Type	Probable Stratigraphic Age Max	Probable Stratigraphic Age Min
1. Rocky Mountain	56	Major overthrust	Lower Devonian	Lower Devonian
2. Dead Brook	16	Major overthrust	Upper Silurian or Lower Devonian	Lower Devonian
3. Big Black River	14	Subsidiary reverse	Lower Devonian	Lower Devonian
4. Jones Brook	22	Subsidiary reverse	Upper Silurian or Lower Devonian	Lower Devonian
5. Hunnewell	29	Unknown	Lower Devonian	Lower Devonian

Rocky Mountain overthrust

25. This fault is the longest and one of the most significant structures in the study area. The length shown in Table 1 is only for the mapped segment in the western part of the study area, and it is possible that the fault continues into Canada where other faults have been mapped. The relative movement on the Rocky Mountain overthrust was northwest to southeast. The amount of lateral or strike-slip movement is unknown. The ages of the rocks cut by the Rocky Mountain overthrust range from Middle Ordovician to Lower Devonian.

Dead Brook overthrust

26. This fault exhibits a relative movement similar to the Rocky Mountain overthrust and cuts Cambro-Ordovician and Upper Silurian or Lower Devonian rocks.

Big Black River fault

27. This is a reverse fault associated with the Rocky Mountain overthrust in the southwestern part of the study area. The fault cuts Middle Ordovician and Lower Devonian rocks.

Jones Brook fault

28. This is a reverse fault associated with the Rocky Mountain overthrust in the northwestern portion of the study area. The fault cuts Middle Ordovician and Upper Silurian or Lower Devonian rocks.

Hunnewell lineament or fault

29. This structure is the largest inferred fault in the vicinity of both sites. The criterion for recognition was the lineament seen in aerial photographs. Boudette et al.[2] considered that the magnitude of the lineament and its truncation of bedding, folds, and topography were sufficient evidence to call the structure a fault. The location of the fault, within the Lower Devonian sequence, and ground cover have contributed to the absence of ground evidence for the existence of the fault.

PART IV: GLACIATION

30. During Pleistocene time the study area was covered by great thicknesses of glacial ice. The exact thickness of the ice sheet is unknown; however, Flint[5] (page 319) presents data indicating that the ice sheet may have been as much as 4700 ft thick in the Mt. Katahdin area to the south. The effects of the ice sheet were erosional, depositional, and tectonic.

31. The erosional effect of the ice, which moved from the northwest to southeast, was to temper the existing topography. There are no indications of deep glacial scouring although glacial striae are abundant on the harder rocks throughout the area. The absence of significant differential glacial erosion may be due to the fact that the direction of glacial movement was normal to the strike of the rocks.

32. The depositional features include a relatively thin veneer of ground moraine which covers most of the area. The ground moraine consists primarily of poorly sorted till and subordinate sand and gravel lenses. The till is usually quite thin and averages a few feet thick. Boudette et al.[2] indicate that the till may be locally quite deep and suspect that thicker deposits may occur on the northwest sides of hills facing the glacial advance. Glaciofluvial deposits resulting from the melting of the last ice sheet are also present throughout the area. These deposits include valley train or outwash along the St. John River and various other stratified deposits thought to be either kames, lacustrian deposits, or crevasse fillings.

33. The presence of such great thicknesses of glacial ice also resulted in a regional tectonic effect. This effect was crustal warping under the load of ice. The evidence for the amount of crustal warping has been derived from tide gage records and from elevations of Pleistocene tidal strandlines (Flint,[5] pages 249-255). Data indicate that northern Maine is rising or rebounding at the rate of approximately 30 cm/100 yr. The highest Pleistocene strandline in Maine is approximately 450 ft above present-day sea level, indicating that at the strandline the surface has rebounded 450 ft.

PART V: EARTHQUAKE ACTIVITY

Historic Earthquakes

34. Historic earthquakes in northern New England and adjacent parts of Canada are listed in Table 2. Corresponding locations are shown in Figure 4. The data were tabulated from publications of the Dominion Observatory (see Smith[6,7]) in Ottawa, Canada (now the Department of Energy, Mines and Resources); the Earthquake History of the United States through 1970 (Coffman and von Hake);[8] United States Earthquakes 1971 (Coffman and von Hake[9]); listings of the National Earthquake Information Service (NEIS) to 1975; and Hadley and Devine.[10] The Hadley and Devine earthquakes are those which occur on their seismotectonic map where they are credited to the Dominion Observatory and to the National Oceanic and Atmospheric Administration (NOAA). The accreditation was found to be erroneous when discrepancies were seen in comparing the Hadley and Devine events with those of a computer printout furnished by the NOAA Environmental Data Service. Carl von Hake* of NOAA advised us that the questioned events were not known to NOAA and are probably from USGS noninstrumental data belonging to Hadley and Devine. The questioned events are denoted by a special symbol in Figure 4 and are credited to Hadley and Devine.[10] They are not listed in Table 2 since, at the time of this writing, no further information had been received from the USGS.

35. The questioned earthquakes might be important as one of them lies only 20 miles from Dickey damsite. Two others are a little over 30 miles away. Yet, since they are probably not instrumental records and they are very small events reported from a sparsely populated region, their locations may be very inaccurate. The locations are not likely to represent epicenters and there is the possibility that they are errors altogether.

36. The earthquakes are expressed as intensities according to the

---

* Personal communication, 5 June 1975.

Table 2

Historic Earthquakes in Northern New England and Adjacent Parts of Canada (1638 to 1975)

Year	Date	Time EST	Locality	Coordinates N. Lat. Deg.	Coordinates W. Long. Deg.	Intensity MM	Source Data DO	Source Data NEIS	Source Data EHUS
1638	6 Jun	1900	St. Lawrence Valley	46.5	72.5	IX	x	x	
1661	10 Feb	1900	St. Lawrence Watershed	45.5	73.0	VII	x		
1663	5 Feb	1730	St. Lawrence River Valley region	47.6	70.1	X	x		x
1665	24 Feb	--	La Malbaie, Quebec	47.8	70.0	VIII	x		
1668	13 Apr	0800	Near Isle-aux-Grues	47.1	70.5	VI	x		
1732	16 Sep	1600	Montreal, Quebec	45.5	73.6	IX	x	x	
1791	6 Dec	2000	St. Lawrence River Valley	47.4	70.5	VIII	x		
1810	10 Nov	0215	--	43.0	70.9	VI		x	
1817	22 May	2000	Central Maine	46.0	69.0	VI		x	
1824	9 Jul	--	Providence of New Brunswick, Canada	46.5	66.5	V	x		
1831	May 7-8	Night	St. Lawrence River Valley	47.3	70.5	VII	x		
1831	14 Jul	--	St. Lawrence River Valley	47.6	70.1	VII	x		
1842	9 Nov	--	St. Lawrence River Valley	46.0	73.2	VI	x		
1847	8 Jan	1500	Felt near Grafton Harbour, Ontario	44.0	70.0	III	x		
1848	1 Feb	--	Felt at Yarmouth and Shelburne	43.5	65.5	III	x		
1848	6 Nov	0515	Felt at Grand Is-St. Lawrence River	47.6	69.9	II	x		
1853	Jul	--	Province of Quebec	47.5	70.0	III	x		
1855	4 Feb	--	Bay of Fundy	44.8	66.2	VI	x		
1855	8 Feb	0630	Near Moncton, N. B.	46.0	64.5	VII	x		
1855	Jun	--	SE of Granville Mountains N.S.	44.7	65.5	IV	x		
1858	17 May	1500	Richmond, Compton, Sherbrooke, Quebec	45.5	72.1	IV	x		
1860	17 Oct	0600	Canada, St. Lawrence River Valley	47.5	70.0	VIII-IX	x	x	x
1861	Oct	0900	Ile Jesus, Quebec	45.6	73.7	V	x		
1867	18 Dec	0800	W. Vermont	44.0	73.0	V	x	x	
1869	22 Oct	1100	Bay of Fundy	45.0	66.2	VIII	x	x	x
1870	8 Feb	--	Bay of Fundy	44.1	67.1	VI	x		
1870	20 Oct	1625	Baie-St. Paul, Quebec	47.4	70.5	IX	x	x	x
1871	9 Jan	--	Kamouraska, Quebec	47.5	70.1	V	x		
1872	10 Jan	0054	Canada and to the south	47.5	70.5	VII	x	x	x
1872	18 Nov	1900	--	43.2	71.6	V	x		
1873	30 Sep	0650	Felt at Montreal, Quebec	45.5	73.2	IV	x		
1874	28 Feb	0340	SE Maine	44.8	68.7	V		x	x
1877	4 Nov	0656	NE New York state	44.5	74.0	VII	x	x	
1879	11 Jun	--	Felt at Montreal	45.6	73.6	IV	x		
1880	6 Sep	0030	Felt at Montreal	45.2	73.8	IV	x		
1881	21 Jan	0240	Bath, Maine	44.0	70.0	V		x	x
1881	31 May	0330	Felt in Quebec	47.1	70.4	II	x		
1881	1 Oct	0140	Felt in Quebec	47.6	70.2	IV	x		
1882	19 Dec	2220	New Hampshire	43.2	71.4	V		x	x
1882	31 Dec	2200	New Brunswick coast	45.0	67.0	VI	x		x
1882	23 Nov	0030	South New Hampshire	43.2	71.7	V-VI			x
1883	1 Jan	0030	--	45.0	67.0	V		x	
1884	23 Nov	0530	--	43.2	71.7	VI		x	
1885	6 Apr	0900	Felt in Quebec	47.5	70.2	III	x		
1885	Jun	1000	Felt in Southern Head, N. B.	45.1	66.1	IV	x		
1886	12 Aug	a.m.	Felt in Quebec	46.0	74.0	IV	x		
1888	7 Dec	0925	Felt in Quebec	48.5	68.7	IV	x		
1891	2 May	0010	South New Hampshire	43.2	71.6	V		x	x
1893	27 Nov	1150	Felt over Quebec, New England	45.5	73.3	VII	x		
1894	17 Apr	1115	Felt at Montreal	45.6	73.3	IV	x		
1896	23 Mar	0056	Maine and New Brunswick	45.2	67.2	IV-V	x	x	x
1897	26 Jan	a.m.	Felt at Deer Islands, N. B.	44.9	66.9	III	x		
1897	28 Jan	2100	Felt at Southern Head, N. B.	44.5	66.8	IV	x		
1897	14 Feb	2100	Felt at Grand Manan Is, N. B.	44.7	66.8	III	x		
1897	23 Mar	1830	Near Montreal	45.5	73.6	VII	x		
1897	27 May	2000	Near Lake Champlain	44.5	73.5	VI	x		
1898	11 Jan	0200	Felt at Grand Manan Is, N. B.	44.7	66.8	IV	x		
1898	17 Sep	1550	--	44.3	69.1	V		x	
1904	21 Mar	0600	SE Maine	45.0	67.2	VII		x	x
1905	15 Jul	1000	Maine and New Hampshire	44.3	69.8	V		x	x
1905	30 Aug	1040	--	43.0	71.0	V		x	
1906	31 Dec	--	Charlevoix Co., Quebec	47.7	70.8	III	x		
1908	13 May	2400	Felt in 3 Co.'s N-S	44.0	65.8	V	x		
1908	8 Aug	0700	Hartland, N. B.	46.3	67.6	VI	x		
1909	14 Apr	Night	St. John, N. B.	45.4	66.4	III	x		
1910	23 Jan	0115	--	43.8	70.4	V		x	
1910	Feb	--	St. Lawrence Valley	48.0	70.0	VI	x		
1910	25 Oct	0430	Kamouraska Co., Quebec	47.6	69.8	V	x		
1912	11 Dec	1015	West of Eastport, Maine	45.0	68.0	VI	x	x	x

(Continued)

Note: Source Data:
1. DO - Dominion Observatory, Ottawa.[6,7]
2. NEIS - National Earthquake Info. Service, USGS, 1975.
3. EHUS - "Earthquake History of the United States," Pub. 41-1, NOAA, 1970, 1971.[8]

Table 2 (Continued)

Year	Date	Time EST	Locality	Coordinates N. Lat. Deg.	Coordinates W. Long. Deg.	Intensity MM	Source Data DO	Source Data NEIS	Source Data EHUS
1913	10 Aug	0515	Lake Placid, New York	44.0	74.0	V		x	x
1914	13 Jan	0800	Calais, Maine and N. B.	45.1	67.2	V	x	x	
1914	14 Feb	0430	N. of Ste. Emélie, Quebec	46.4	73.6	V	x		
1914	22 Feb	0015	--	45.0	70.5	V		x	x
1916	5 Jan	1355	--	43.7	73.7	V		x	
1916	3 Feb	0426	--	43.0	74.0	V		x	
1916	29 Feb	0015	Quebec City, Quebec	46.8	70.9	IV	x		
1916	2 Nov	0232	--	43.3	73.7	V		x	
1917	11 Jun	2100	S. shore of the St. Lawrence River	49.0	68.0	V	x		
1918	21 Aug	0412	S. Maine	44.2	70.6	VII		x	x
1919	26 Oct	0528	N. shore of the St. Lawrence River	47.6	70.0	IV	x		
1921	10 Oct	0800	Eastport, Maine	44.8	67.0	IV	x		
1922	2 Jul	1725	Central New Brunswick	46.5	66.6	VI	x		
1924	4 Mar	1415	N. of La Malbaie, Quebec	47.8	70.2	V	x		
1924	30 Sep	0852	W. of La Malbaie, Quebec	47.6	69.7	VII+-VIII	x		x
1925	28 Feb	2119	St. Lawrence River Valley	47.6	70.1	IX	x		
1925	1 Mar	0219	--	48.3	70.8	VIII		x	
1925	6 May	0414	Felt at Quebec City, Quebec	46.9	71.6	III	x		
1925	20 Jul	early	N. and NW of Quebec City	46.9	71.3	III	x		
1925	9 Oct	1355	SE New Hampshire and Maine	43.7	70.7	VI	x	x	x
1925	19 Oct	0705	Felt at Montreal	47.0	73.0	V	x		
1926	19 Feb	1520	St. Lawrence Valley	47.7	71.0	IV	x		
1926	21 Feb	1655	St. Lawrence Valley	47.6	70.9	IV	x		
1926	28 Aug	2100	W. Maine	44.7	70.0	V		x	x
1926	21 Sep	0630	Felt at St. Simeon, Quebec	48.0	70.5	IV	x		
1926	24 Nov	1430	Felt at Eastport, Maine	45.0	67.5	IV	x		
1927	24 Jul	1756	St. Lawrence Valley	47.3	71.0	V	x		
1927	9 Aug	0408	--	43.3	71.4	V		x	
1928	27 Jan	--	N. of La Malbaie, Quebec	48.0	70.2	IV	x		
1928	19 Mar	1907	Champlain Co., Quebec	46.6	72.5	II	x		
1928	25 Apr	2338	Berlin, N. H.	44.5	71.2	VI		x	x
1928	20 Nov	0230	NW of Eastport, Maine	45.0	67.2	IV	x	x	
1928	25 Dec	0200	--	46.2	67.9	--		x	
1929	29 Mar	--	--	45.2	67.3	--		x	
1929	11 May	0930	W. Sherbrooke, Quebec	45.2	71.5	IV	x		
1930	4 Jan	1430	Blackville, N. B.	46.7	65.8	(V)	x		
1930	19 Jun	1207	NE of Sherbrooke, Quebec	45.7	71.2	(IV)	x		
1930	13 Jul	0453	Near Kamouraska, Quebec	47.5	69.9	(III)	x		
1930	8 Oct	0109	Felt at Riviere Bersimis	48.9	68.7	(IV)	x		
1930	16 Oct	0035	Felt at Millerton, N. B.	46.9	65.6	II	x		
1930	13 Nov	0600	--	45.0	69.2	--		x	
1930	13 Dec	2318	Felt at Murray Bay, Quebec	47.6	70.2	(IV)	x		
1930	25 Dec	2208	Near La Malbaie, Quebec	47.6	70.2	(V)	x		
1931	8 Jan	0014	Near La Malbaie, Quebec	47.6	70.2	(VII)	x		
1931	24 Jan	1220	Near La Malbaie, Quebec	47.5	70.6	(IV)	x		
1931	9 Apr	--	Deer Is, N. B.	45.0	67.0	III	x		
1931	20 Apr	1956	--	43.4	73.7	VII		x	
1931	7 Aug	--	Digby	44.6	65.7	IV	x		
1931	14 Nov	1402	E. of Baie-St. Paul, Quebec	47.2	70.1	(IV)	x		
1932	27 Jul	0030	Felt at Baie-St. Paul, Quebec	47.5	70.5	I-II	x		
1932	2 Aug	0738	Felt at Baie-St. Paul, Quebec	47.5	70.5	(III)	x		
1932	26 Nov	0502	NW of Baie-St. Paul, Quebec	47.6	70.6	(III)	x		
1933	11 Jan	2332	Felt at Baie-St. Paul, Quebec	47.5	70.5	III	x		
1933	25 Feb	0943	Near St. Pacome, Quebec	47.5	70.0	(IV)	x		
1934	15 Mar	--	Southern Nova Scotia	43.5	65.5	III-IV	x		
1934	17 Mar	0258	Adirondack Mountains, NY	44.5	73.9	VI	x	x	

(Continued)

Note: Intensity: () indicates interpolated.
+ Indicates by NOAA as V.

Table 2 (Continued)

Year	Date	Time EST	Locality	Coordinates N. Lat. Deg.	Coordinates W. Long. Deg.	Intensity MM	Source Data DO	Source Data NEIS	Source Data EHUS
1936	29 Mar	0049	St. Lawrence River Valley	47.3	70.2	(V)	x		
1936	9 Nov	0246	--	43.6	71.4	V		x	
1937	19 Jan	2058	Felt at Baie-St. Paul, Quebec	47.5	70.5	(II)	x		
1937	24 Sep	0646	Felt in Montreal, Quebec	45.6	73.6	(II)	x		
1937	30 Sep	0758	NE of Rothesay, N. B.	45.5	65.9	(VI)	x		
1938	15 Jun	0508	NE of Napadogan, N. B.	46.5	66.8	III-IV	x		
1938	22 Aug	0748	Vicinity of Bangor, Maine	44.7	68.8	V			x
1939	24 Jun	1720	N. Seven Falls, Quebec	47.9	70.9	(VI)	x		
1939	19 Oct	1154	NE of La Malbaie, Quebec	47.8	70.0	VI		x	x
1939	27 Oct	0136	--	48.0	70.4	--		x	
1939	8 Dec	0118	Near Chicoutimi R., Quebec	47.9	71.5	(IV)	x		
1939	25 Dec	1029	NW of La Malbaie, Quebec	48.0	70.5	(V)	x		
1940	13 Apr	0813	NW of Baie-St. Paul, Quebec	47.7	70.7	(IV)	x		
1940	16 May	1400	W. of L'Assomption, Quebec	45.8	73.1	(IV)	x		
1940	11 Sep	0107	NE of Quebec City, Quebec	47.0	71.1	(IV)	x		
1940	13 Oct	1950	NW of Clermont, Quebec	48.0	70.5	(VI)	x		
1940	12 Dec	0727	Lake Ossipee, N. H.	43.7	71.5	VII	x	x	x
1940	24 Dec	1343	--	43.8	71.3	VII		x	
1941	6 Sep	1704	Felt at Baie-St. Paul, Quebec	47.5	70.5	(IV)	x		
1941	6 Oct	1634	NW of Baie-St. Paul, Quebec	47.6	70.7	(V)	x		
1942	5 Sep	1430	NW of Quebec City, Quebec	47.0	71.5	(III)	x		
1943	14 Jan	2132	Dover, Foxcroft area, Maine	45.3	69.6	V		x	
1943	8 Jun	early	Yarmouth Co., N.S.	43.7	65.7	III	x		
1943	25 Sep	0553	NW of Baie-St. Paul, Quebec	47.5	70.6	(IV)	x		
1943	28 Sep	1630	St. Lawrence River Valley, Quebec	47.2	70.4	(IV)	x		
1943	6 Nov	0006	St. Lawrence River Valley, Quebec	47.4	70.0	(IV)	x		
1944	5 Feb	1238	Baie-St. Paul, Quebec	47.4	70.5	(V)	x		
1944	6 Jun	0600	Bathurst, N. B.	47.5	65.6	III	x		
1944	9 Jun	1519	St. Lawrence River Valley	47.2	70.2	(IV)	x		
1944	14 Oct	1326	St. Lawrence River	48.5	67.0	(V)	x		
1945	18 Jun	1520	NE of Quebec City, Quebec	47.1	71.0	(VI)	x		
1945	9 Oct	1318	NW of Baie-des-Rochers, Quebec	48.0	70.0	(VI)	x		
1946	17 Jan	0805	NW of Baie-Comeau, Quebec	49.0	68.1	(V)	x		
1946	21 Apr	0506	NE of Montreal, Quebec	45.7	73.3	(IV)	x		
1946	1 Sep	0439	Jacques Cartier River, Quebec	47.3	71.5	(IV)	x		
1946	26 Sep	2119	S. of Deschaillons, Quebec	46.5	72.1	(IV)	x		
1947	2 Jan	1815	Ste. Anne de Beaupre, Quebec	47.0	70.9	III	x		
1947	2 Feb	1650	W. of Malbaie, Quebec	47.6	70.5	(V)	x		
1947	29 Mar	1229	St. Lawrence River	47.4	70.1	(V)	x		
1947	22 Oct	0937	NW of Baie-St. Paul, Quebec	47.5	70.8	(IV)	x		
1947	28 Dec	1958	Dover-Foxcroft, Maine	45.2	69.2	V		x	x
1948	1 Jan	1834	SE of Seven Falls, Quebec	47.3	70.5	(VI)	x		
1948	7 May	1202	NNE of Montreal, Quebec	45.8	73.6	(V)	x		
1948	9 Jun	0304	SSW of Montreal, Quebec	45.3	73.9	(IV)	x		
1948	13 Nov	1650	St. Paul-de-Montminy, Quebec	46.4	70.3	(IV)	x		
1949	5 Oct	0234	SW Maine	44.8	70.5	V		x	x
1949	30 Oct	2051	Near Parisville, Quebec	46.5	72.1	(IV)	x		
1950	4 Aug	0645	St. Lawrence River	47.3	70.2	(III)	x		
1951	25 Jul	0023	Jacques Cartier River, Quebec	47.1	71.3	(IV)	x		
1951	6 Nov	1755	U. S. - Canada Border	45.00	73.5	(IV)	x		
1952	3 Feb	0233	E. of Quebec City, Quebec	46.9	70.5	(III)	x		
1952	26 Feb	0057	Ste. Apolline, Quebec	46.7	70.2	(IV)	x		
1952	30 Mar	1311	St. Lawrence River	47.8	69.9	(V)	x		
1952	19 Apr	0251	W. of Baie-St. Paul, Quebec	47.5	70.5	(IV)	x		
1952	14 Oct	2204	South Central Canada, Quebec	47.9	69.8	V	x	x	x
1953	28 Nov	1547	St. Maurice River Valley	45.9	73.1	(III)	x		
1954	7 Feb	2024	Pointe-au-Pic, Quebec	47.7	70.2	(IV)	x		
1954	21 Feb	0900	NNW of St. Urbain, Quebec	47.6	70.6	(IV)	x		
1954	30 Jun	0741	St. Cyrille-Ste. Félicité, Quebec	47.0	70.1	(IV)	x		
1955	1 Feb	1240	N. of Baie-St. Paul, Quebec	47.6	70.5	(V)	x		
1955	7 Oct	1810	SW of Montreal	45.2	73.9	(IV)	x		
1955	20 Oct	2058	Portneuf R., Quebec	48.9	70.2	(III)	x		
1955	26 Nov	0650	Close to St. Gabriel, Quebec	46.3	73.3	(II)	x		
1956	30 Jan	0943	Felt N. of Quebec City, Quebec	47.0	71.1	(IV)	x		
1956	12 May	0040	SW of Kiskisink, Quebec	47.9	72.3	(II)	x		
1956	10 Oct	0551	St. Lawrence River	47.3	70.3	(III)	x		
1956	27 Oct	1440	St. Lawrence River Valley	48.2	69.0	(IV)	x		
1957	19 Feb	1833	NW of Tadoussac, Quebec	48.4	69.9	(IV)	x		
1957	4 Apr	1140	Near Coast of Maine	43.6	69.8	VI		x	x
1957	4 Aug	1241	E. of Juniper, N. B.	46.5	67.1	(IV)	x		

(Continued)

Table 2 (Concluded)

Year	Date	Time EST	Locality	Coordinates N. Lat. Deg.	Coordinates W. Long. Deg.	Intensity MM	Source Data DO	Source Data NEIS	Source Data EHUS
1957	6 Aug	2350	Near Baie-St. Paul, Quebec	47.3	70.4	(V)	x		
1957	17 Aug	0130	NW of Lac-Frontiere, Quebec	46.7	70.1	(IV)	x		
1957	9 Oct	1417	NW of Tadoussac, Quebec	48.4	69.9	(III)	x		
1957	13 Nov	2049	NW of Sault-au-Moulton, Quebec	48.7	69.6	(IV)	x		
1958	23 Mar	2204	SE of McAdam, N. B.	45.5	67.1	(IV)	x		
1958	18 Jul	2356	St. Lawrence River Valley	46.6	71.4	(III)	x		
1958	27 Jul	0858	St. Lawrence River Valley	47.3	70.3	(III)	x		
1958	8 Aug	2215	Riviere Malbaie, Quebec	47.9	70.3	(V)	x		
1958	12 Aug	0322	NW of Sault-au-Mouton, Quebec	48.6	69.3	(IV)	x		
1958	11 Sep	1750	W. of Sault-au-Mouton, Quebec	48.6	69.7	(IV)	x		
1958	29 Sep	1045	St. Lawrence River	48.3	69.2	(IV)	x		
1958	30 Sep	0014	E. of Beauharnois, Quebec	45.1	73.7	(IV)	x		
1958	23 Dec	2314	NE of Ste. Félicité, Quebec	46.9	69.8	(IV)	x		
1959	16 Apr	1636	SE of Bonsecours, Quebec	47.1	70.3	(IV)	x		
1959	14 May	1424	S. of Bonsecours, Quebec	47.0	70.3	(II)	x		
1959	22 Aug	0352	St. Lawrence River	46.9	70.8	(III)	x		
1962	10 Apr	1430	Vermont	44.1	73.1	V		x	x
1963	4 Dec	2132	--	43.6	71.5	V		x	
1964	26 Jun	1204	Near Warner, N. H.	43.3	71.9	VI		x	x
1966	24 Jul	2100	--	44.5	67.6	V		x	
1966	23 Oct	2305	--	43.0	71.8	V		x	
1967	1 Jul	1409	Kennebec Co., Maine	44.9	69.9	V		x	x
1967	1 Jul	1556	--	44.4	69.9	V		x	
1968	19 Oct	1037	--	45.4	74.0	V		x	
1973	15 Jun	0109	--	45.3	70.9	V		x	

Modified Mercalli (MM) scale of 1931. An abbreviated form of the scale is shown in Figure 5.

Distribution of Earthquakes

37. The geographic distribution of historic earthquakes can be observed in Figure 4.

38. In the Dickey-Lincoln School area, there are no historic earthquakes for a radius of 20 miles. Within a radius of 20 to 40 miles, there are four events. All are of MM intensity of II to IV. Three of the four are questionable events, attributed to Hadley and Devine.[10]

39. The most important concentrations of earthquake activity occur in the St. Lawrence Valley. There is a trend which follows the St. Lawrence River but it is discontinuous. The greatest concentration is immediately west of Rivière du Loup. An MM intensity X has occurred there, as have three intensity IX's, three VIII's, and nearly a hundred events altogether. The abundance of earthquakes, from large to small, defines this area as one of very high seismic risk.

Relation to Contemporary Intraplate Tectonics

40. The St. Lawrence seismic belt occurs approximately along a portion of the boundary between the ancient crystalline rocks of the Canadian Shield and the sedimentary rocks that are developed south of the St. Lawrence River (compare Figures 1 and 4). The boundary coincides with an extension of Logan's Line. Logan's Line to the southwest, particularly in New York State, is a major thrust fault which forms the boundary between folded and faulted sedimentary rocks to the east and the relatively flat-lying and undisturbed sedimentary rocks to the west. Along the St. Lawrence east of Quebec City, Logan's Line separates the deformed sedimentary series so that their boundary lies almost in contact with the crystalline rocks of the Canadian Shield.

41. The question comes up whether the seismic belt in the St. Lawrence is part of a larger trend and has developed as an intraplate

boundary. Further, what geographic pattern or patterns do such a boundary have? Woollard[11] postulated a seismic trend along the full length of the St. Lawrence River and which extended as far as Arkansas. Smith[7] postulated a northwest to southeast trend (see Figure 6) which extends from the Kelvin Seamount Chain through the vicinity of Boston and through Montreal. In the area east of Quebec City there exists the possibility of a parallel but shorter trend that would cross the main St. Lawrence trend (see Figure 4). An examination of the intensity levels of the earthquakes shows that the severe events (those to IX and X) occur in a narrow belt along the St. Lawrence. There is a rapid falling off in the maximum intensity of events of V to VI adjacent to this belt. Beyond, the values are II to IV. A cross trend is not justified by the sizes of the events. Probably most of the events would bunch together in a narrow belt along the St. Lawrence were there better control for their locations.

42. The trend along the St. Lawrence is all that one can relate to intraplate tectonics. However, it relates to large global movements only in a most general and most uncertain way. The St. Lawrence trend is not defined in this area by known active faults.

Relation to Geologic Structures

43. Historic earthquakes in this area can be related to geologic structures in a general way, as was mentioned in the discussion of intraplate boundaries. However, no earthquakes have been related to specific structures since the epicentral locations are inexact and there have been no fault movements, recognizable at the surface, that have accompanied historic earthquakes.

44. The aeromagnetic map of northern Maine (Zeitz et al.[12]) is based on sparse data in the area of the damsites. However, in Maine in the general area of the damsites and within a 40-mile radius, there are no suggestions of significant anomalies. In the adjacent portion of Canada, toward the St. Lawrence, the aeromagnetic maps (Baie-St. Paul[13] and Edmundston[14] quadrangles of the Geological Survey of Canada) again

show an absence of significant anomalies. The contours become more closely spaced only within about 5 miles of the shore of the St. Lawrence River. This change in contours coincides in a general way with down-dropped blocks that have contributed to the formation of the St. Lawrence estuary. These blocks have been sculptured by erosion, and alluvial drowning has covered them in all but their highest portions. An example of their surface appearance is seen in Figure 7, which shows an extensive area of alluvial drowning along the border of the St. Lawrence about halfway between Quebec and Rivière du Loup. This is adjacent to the area of considerable earthquake activity noted in Figure 4.

45. The area bordering the St. Lawrence is too masked with alluvium to reveal any details of the tectonism that accompanied a settlement that most likely is continuing to occur.

46. The glacial advance over this area has been discussed. The area is still participating in a rebound that resulted from the removal of the weight of ice. Rebound from glaciation would not explain major earthquakes because those require concentrated stresses of a very large order. However, small earthquakes, those of intensity IV or V or less and which occur randomly, may be related to rebound, though there is no way to establish such a relationship.

Principal Earthquake Zones

47. The most direct way of categorizing the historic seismicity in this region is to define zones to represent areas susceptible to specific levels of earthquake events. Figure 8 shows boundaries for seismic zones near the project sites. They may be compared with Figure 4. Zone A follows the narrow band of intense seismicity along the St. Lawrence. The seismicity has been discontinuous along this trend; however, the historic record is relatively short. The intense seismicity may migrate through time along the zone. Thus, Zone A is shown with continuity along the St. Lawrence Valley. Its maximum observed intensity is X. Zone A is bounded by a narrow Zone B. Zone B is believed to be not prone to the maximum earthquake of Zone A. Maximum observed

intensity is only IV; however, Zone B represents, in principle, possible secondary faults that can be activated by the major faults in Zone A. Zone C is the hinterland area and includes the sites. In Zone C, the seismicity is of a low order as the level of historic events is no greater than II to IV. About 75 miles southeast of the sites the areal seismicity is greater with events to V to VI (see Figure 4). This area forms a large Zone D, not shown in Figure 8.

PART VI: EXAMINATION FOR ACTIVE FAULTS

48. Earlier sections of this report have established that mapped faults are ancient ones which date back to orogenies during early Paleozoic time and to subsequent disturbances during the Triassic. The predominating lithologies, metamorphosed shales and graywackes, do not show up those faults that are present because of the similar characteristics of the rocks on both sides of the fault planes. Thus, the faults are extremely difficult to recognize in the field, even where the fault plane is exposed. Figure 9 shows typical ground terrain where a mapped fault crosses a road. The rocks are very poorly exposed. Even along streams, the glacial detritus is so thick that bedrock can seldom be examined. The ground cover in the forests is composed of a thick ground litter of organic matter (see Figure 10) which obscures any details of the underlying soil or rock. It is impossible in these forests to walk a fault in order to follow its trace, even were the fault recognizable at some point. In actuality, fault separations are seen almost solely on certain of the mountain slopes, and then only where bedrock changes can be noted. For the most part, the faults have been determined by stratigraphic evidence, particularly through dating of fossil remains of graptolites in the shales. Missing portions of the stratigraphic column, or repeated sequences in the stratigraphic column, are explainable as displacements caused by faults. Thus the fault traces are determined inexactly without the fault contacts having been seen.

Association of Earthquakes with Tectonism and Faults

49. The association of earthquakes with faults is on the basis of the elastic rebound theory. Strains build up in rocks of the earth's crust due to tectonism. These strains may become greater than that which the rock can sustain. The rock fails by slipping along a fault, and the strain is relieved along the plane of the fault. Thus, the strained portions of the rock can experience a sudden rebound. The movement occurs elastically, and vibratory motions (the earthquake) are set up.

50. The tectonism which developed the faults in the general project area occurred early in geologic time. Considerable erosion has taken place since then, but there has been no tectonism during the intervening time and none is evident at present. Glacial rebound is occurring. Its contribution toward the activation of faults is believed to be minor; however, many of the small earthquakes, intensity IV or less, might be attributed to glacial rebound.

51. From the evidence provided by historic earthquakes, present-day tectonism appears to be geographically restricted to an irregular belt along the St. Lawrence River. This tectonism is poorly understood, but the major earthquakes along the St. Lawrence are presumed to be the result of fault movements along this zone of activity. The historic earthquakes have not caused fault movements that are seen on the ground surface. Such movement has occurred principally in the subsurface.

Definition of Active Faults

52. Faults are considered to be active if it is judged that they may move at some time in the near future. For engineering, it means that they have the potential for moving during the life of a structure. The principal criterion for making this prediction is whether they have moved in the recent past.

53. The Nuclear Regulatory Commission (formerly the Atomic Energy Commission)[15] uses the following criteria:

- a. Datable movement during the past 35,000 yr. (The limit of accurate radiocarbon dating.)
- b. Datable movement more than once in the past 500,000 yr. (Marine terraces.)
- c. Structural interrelation whereby a fault can be shown to move if movement occurs on a different fault with proven activity.
- d. Instrumentally determined macroseismic activity relatable to a fault.
- e. Projection of a proven active fault through or into areas where all evidence of the fault or its activity is obscured, as by thick alluvium.

The International Atomic Energy Agency[16] adds the following additional criteria:

- a. Evidence of creep movement along a fault. Creep is slow displacement not necessarily accompanied by macroearthquakes.
- b. Topographic evidence of surface rupture, surface warping, or offset of geomorphic features.

54. A practice that has come into use for engineering evaluations is to call a fault active if it disturbs any Holocene deposits. Holocene is that period which encompasses the last 10,000 yr. Displacement of surficial gravels, displacement of the most recent glacial deposits, and displacement of Holocene alluvium are accepted criteria.

55. All of the above criteria presume that there are surface manifestations of fault movements. However, faults may move in the subsurface and have no surface manifestations. A lack of surface evidence is common east of the Rocky Mountains in the United States and in Canada.

Mapped Faults

56. Traverses were made across mapped faults and lineations in order to examine the faults for evidences of movement. The traverses are shown in Figure 11. No evidence of movement was seen.

57. Local residents were questioned to learn if they knew of ground breakages anywhere in the area. No one knew of any such events.

Lineations

58. Lineations, or linears, are those linear features that are found in tonal changes in air imagery and in the alignment of rivers, terrace boundaries, etc. They may be the result of a multitude of causes. Thus, they may represent actual faults or they may be entirely unrelated to faults.

59. An Earth Resources Technology Satellite (ERTS) image of northwestern Maine and the St. Lawrence Valley is shown in Figures 12 and 13. Figure 12 shows the image without retouching; Figure 13 shows a

superposition of lines which mark out the linears. The two images may be compared in order to recognize the patterns which led to the selection of the linears.

60. An attempt was made to examine these linears on the ground in the same traverses that are shown in Figure 11.

61. These linears may very reasonably represent faults. They are fault zones that could have become manifest as a result of differentials in the considerable erosion which has occurred. The features may also have been modified to some extent by the last glacial advance. However, the linears, generally, are not believed to have been the result of glaciation alone.

62. No sign of surface activity of faults was seen during the examinations of these linears.

Noises

63. Local residents were asked if they could recollect having felt any earthquake motions. Some of them knew that an earthquake had been felt strongly in 1925. They also spoke of feeling earthquakes in other years, but their recollections were uncertain.

64. Some of the people who spent time hunting in the mountains said they had heard noises that sounded like thunder at a distance. However, the sky might be clear with no suggestion of atmospheric conditions that would be associated with thunder. These noises were heard mostly in the autumn approximately with the onset of cold weather, meaning the first frosts. The noises might be heard several times in a day with individual durations of about half a minute. The noises are heard only in the mountains, notably on Rocky Mountain. They are not heard in the lowlands. These noises are never accompanied by ground motions. A thunderlike noise is typical of earthquakes. Earthquake ground motions can be transmitted into the air as audible sounds. However, such transmissions do not happen without ground shaking. The absence of ground motion tends to rule out earthquakes as the cause of these noises.

65. There are rockslides in the mountains. It is possible that frosts, through frost heave, tend to precipitate slides that were incipient earlier. Such slides could account for the noises and would explain why the noises are restricted to the mountains. As the noises are said to be never accompanied by ground motions, it is not likely that they are associated with local earthquakes.

Activity of Faults

66. None of the faults or linears show any evidences of activity in the general area of the project.

PART VII: EARTHQUAKE INTENSITIES

Maximum Intensities

67. The largest observed earthquake intensities (MM) at the points of origin (I_o) for the zones in Figure 8 are as follows:

Zone A: I_o = X
Zone B: I_o = VI
Zone C: I_o = IV
Zone D: I_o = VI

68. The data have been examined by others, principally Howell[17] and Hadley and Devine.[10]

Howell

69. Howell contoured the intensity data into a map of cumulative seismic hazard for the years 1638 to 1971. His contours (see Figure 14) are spread according to the data and are not controlled by any geologic or tectonic boundaries. His contour numbers are equivalent to the MM scale of intensity. Thus, in Figure 14 he shows an intensity of IX for Zone A. At the damsites, Zone C, he has a value of about VIII. He has generalized these contour patterns into a map which shows Average Regional Seismic Hazard Index (Figure 15). The value for a broad band along the St. Lawrence Valley is IX. At the damsites it is VII.

Hadley and Devine

70. Hadley and Devine developed their seismotectonic map in three sheets. The first sheet carried mapped faults and other tectonic elements such as folds, uplifts, arches, shield boundaries, etc. The second sheet listed earthquake events by intensity. Their final sheet (see Figure 16 for northeastern United States) attempted to relate structural control to frequency of occurrence of earthquakes and to intensity. The damsites are in an area with the lowest category for the frequency of occurrence of earthquakes. Though high intensities might be felt at the damsites, the implications are that they would be generated in adjacent areas with greater potentialities for earthquakes. The St. Lawrence Valley is shown as a narrow zone with a high frequency

of earthquake occurrence and an intensity level of IX.

Intensity Patterns

71. Isoseismal maps, containing intensity patterns for three earthquakes originating in the St. Lawrence Valley, are shown in Figures 17-19. Of these, the most severe is that of 1 March 1925. The intensity at the epicenter was VIII or IX, depending on interpretation. In the vicinity of the damsites, the intensity was VI.

72. For all three of the earthquakes, there is a distinct elongation of the isoseismal contours in a northeast to southwest direction. Correspondingly, there is a shortening of the contour interval to the southeast toward the damsites, implying a significant increase in the rate of attenuation.

Attenuation from the St. Lawrence to the Damsites

73. A comparison was made between isoseismals from the St. Lawrence toward the damsites with those of the 1971 San Fernando earthquake in California. The comparison is shown in Table 3. It may be noted that the St. Lawrence earthquake of 1925 was somewhat larger than the San Fernando earthquake of 1971. The distances to the boundaries of

Table 3

Comparison of Attenuation of St. Lawrence and San Fernando Earthquakes

Attenuation to the Southeast

	Distance (km) to Outer Boundary of MM Intensity Level					
	IX	VIII	VII	VI	V	Magnitude
St. Lawrence Earthquake: 1 March 1925	16	26	47	120	182	7.0
San Fernando, California, Earthquake: 9 February 1971	15	26	44	75	130	6.5

comparable intensity levels are slightly higher for the St. Lawrence. Essentially, the comparison suggests that attenuation from the St. Lawrence Valley toward the southeast is the same as the attenuation in California. Correspondingly, data on California earthquakes expressed in distance from the source may be used for the damsites in northern Maine.

Relation of Intensity to Magnitude

74. The relation between intensity, magnitude, and felt area of earthquakes in northern New England and adjacent parts of Canada is shown in Figure 20.

75. The modified Gutenberg and Richter formula for relating intensity to magnitude (see Krinitzsky and Chang[18]) is applicable. The formula is:

$$M = 2.1 + 1/2\ I_o$$

The formula provides a best fit, or median, for the data.

Relation of Intensity to Magnitude and Distance

76. Milne and Davenport[19] analyzed five earthquakes from eastern Canada and provided intensity versus distance graphs for them. Their plot is shown in Figure 21. The earthquakes ranged in magnitude from 5.8 to 7.2. A more general graph that related intensity to magnitude and distance for eastern Canada is shown in Figure 22.

Maximum Credible Intensities

77. The maximum observed intensities for the zones in Figure 8 have already been stated. They are tabulated with corresponding magnitudes in Table 4.

78. The observed values cannot be regarded as the worst that can

Table 4

Intensities and Magnitudes for Seismic Zones in Northern Maine and Adjacent Canada

	Maximum Intensity (MM) I_o Observed	Corresponding Magnitude	Maximum Credible Intensity I_o	Corresponding Magnitude
Zone A	X	7.0	XI	7.5
Zone B	VI	5.0	VIII	6.0
Zone C	II-IV	4.0	VII	5.5
Zone D	VI	5.0	VIII	6.0

be reasonably expected to occur. A conservative approach requires that a provision be made for larger events.

79. A consideration at this point is the maximum length of fault that might be involved in an earthquake. Zone A along the St. Lawrence Valley has a length that is measurable in many hundreds of miles. The distance from Montreal out to the Gulf of St. Lawrence is over 400 miles. Assuming that Zone A contains a major fault along this length of which a portion, one-half or one-quarter of the length, may move at one time, one can consider what size of earthquake can be generated by this movement. Bonilla and Buchanan[20] (see Figure 23) have used worldwide data to show a relation between length of surface rupture of a main fault versus earthquake magnitude. A rupture of 100 miles or 160 km may very easily be accompanied by an earthquake with a magnitude of 7.5 to 8.5 and a corresponding intensity of XI. Thus, Table 3 has been expanded in Table 4 to include a magnitude 7.5 and an intensity of XI for Zone A. These are maximum credible events, or the largest that can reasonably be expected to occur. Zone B is taken as lower, at magnitude 6.0 and intensity VIII. Zone C is magnitude 5.5 and intensity VII. Zone D is magnitude 6.0 and intensity VIII, the same as Zone B. These are maximum events that can be generated in the respective zones. Larger values are possible in portions of Zones B and C through attenuation from Zone A.

PART VIII: SELECTED EARTHQUAKE GROUND MOTIONS FOR THE DAMSITES

Intensities at the Damsites

80. The intensities of the earthquakes in Zones A, B, C, and D at their origins (I_o) must be attenuated to provide intensities at the damsites (I_s). Table 5 shows intensities at the origins, distances of attenuation, and attenuated intensities. Also indicated is the field condition (near or far) at the damsites.

Table 5

Maximum Intensities at the Damsites

	Maximum Credible Intensity (I_o)	Distance to Dams, miles	Maximum Intensity at Dams (I_s)	Field
Zone A	XI	45	IX	Far
Zone B	VIII	40	VI	Far
Zone C	VII	10	VI	Far
Zone D	VIII	75	V-VI	Far

81. The attenuations were made with the use of the chart in Figure 22 made for eastern Canada by Milne and Davenport. The intensity VII for Zone C was taken at 10 miles distant and reduced to VI on the probability that it is not likely that an earthquake would occur closer to the damsite. The intensity XI from Zone A has been reduced to IX at the sites. The latter is the dominant motion at the dams. The faults show no activity at the surface. Thus, foci for maximum local earthquakes may be taken at depths of tens of miles below the surface and epicenters may be laterally several miles from the dams. There will be no surface breakage along faults. The local conditions are those for far-field effects, as well as a low likelihood of a maximum event. However, microearthquakes, measurable by instruments only, may be expected to occur nearer to the surface, possibly within a mile of the surface, possibly

deeper. These events are not of engineering significance.

Near Field Versus Far Field

82. In the near field of an earthquake, complicated refraction and reflection of waves cause a large range in the scale of ground motions. Some motions may be intense and there are high-frequency components in such motions. In the far field the waves are more orderly; they are more muted; and the frequencies are lower.

83. Limits to the near field for data from the West Coast of the United States were assigned by Krinitzsky and Chang.[18] These limits are believed to be directly applicable to the Dickey-Lincoln study area. They are shown in Table 6.

Table 6

Limits of the Near Field of Earthquakes in the Western United States (from Krinitzsky and Chang[18])

Magnitude	Maximum Epicentral Intensity, I_o	Radius of Near Field, km
5.0	VI	5
5.5	VII	15
6.0	VIII	25
6.5	IX	35
7.0	X	40
7.5	XI	45

Intensities Versus Peak Ground Motions

84. Figures 24, 25, and 26 show the dispersion of peak accelerations, velocities, and displacements, respectively, for a group of 187 earthquake records from the western United States. In each figure, the values were plotted for appropriate intensities, and the near field and

Table 7

Peak Horizontal* Bedrock Ground Motions and Durations for Earthquakes at the Damsites

Source of Earthquake	Maximum Intensity at Dams (I_s)	Field	Acceleration cm/sec^2	Velocity cm/sec	Displacement cm	Duration sec
Zone A	IX	Far	350	65	22	18
Zone B	VI	Far	180	30	18	11
Zone C	VI	Far	180	30	18	11
Zone D	V-VI	Far	150	23	16	10

Note: An acceleration of 1 g = 980 cm/sec^2.
* Vertical components of motion may be taken as 2/3 the horizontal.

the far field have been separated. These data are from Krinitzsky and Chang.[18] For accelerations, there is a large difference between near and far fields. The differences are much less for velocities and displacements.

85. Reference to the full dispersion of data allows one to use the upper limits, or to use lower levels, consistent with the safety requirements of a structure. For dams with urbanized areas downstream, as in the case of the Dickey-Lincoln School sites, the upper boundary should be used.

86. For intensity versus duration of shaking (the full period of time in which accelerations were greater than 0.05 g), again data from the western United States were used. These are plotted in Figure 27 from work done by Chang.[21] The data in Figure 27 are for the far field.

87. No data are available for an intensity IX in the far field. However, projected values for intensity IX are shown in Figures 24 to 26 and are used in this report.

88. Peak ground motions and durations of shaking for bedrock were obtained as shown in Table 7.

Comparison with Alternative Methods

89. Comparisons can be made at this point with other methods that are commonly used.

Intensity-acceleration correlations

90. Commonly used correlations between intensity and acceleration are shown in Figure 28. Included are correlations established by Neumann,[22] Gutenberg and Richter,[23] Hershberger,[24] Medvedev, Sponheuer, and Kárnik (see Barosh[25]), and Trifunac and Brady.[26] All of these are either mean or average values made with various levels of data accumulation. They do not provide for the spread in data and they do not distinguish between near-field and far-field conditions. From Figure 28, the Hershberger line gives a peak acceleration of about 1000 cm/sec^2 for an intensity at the site of IX. The Gutenberg and Richter line gives 400 cm/sec^2. In this study, an acceleration of 350 cm/sec^2 is arrived

at because of the far-field conditions at the site. For intensity VI, the Trifunac and Brady mean line gives 75 cm/sec^2. (Other data by Trifunac and Brady are discussed separately in following sections of this report.) The Hershberger and the other lines give less. The value accepted for this study is 180 cm/sec^2.

91. The values in this report are believed to be more realistic than those which are obtained from the correlations cited above.

Nuttli's studies
for central United States

92. Professor O. W. Nuttli[27] developed the appropriate ground motions for a far-field condition for the worst earthquake that might occur in the New Madrid region of southeast Missouri. A maximum earthquake in the New Madrid area is comparable to a maximum earthquake in Zone A of the St. Lawrence Valley. The attenuations in the central United States are believed to be less than those in a southeast direction away from the St. Lawrence Valley. Thus, Nuttli's values should be relatively conservative.

93. Table 3 of Nuttli's 1973 report[27] was used. An interpolation was made for a distance of 45 miles from Zone A in the St. Lawrence to the site. The wave frequency was taken at 0.3 Hz as this gave the severest motions. Nuttli's values are:

Distance: 45 miles
Acceleration: 0.12 g
Velocity: 58 cm/sec
Displacement: 27 cm

94. Nuttli's values are not peak values. They are peak recurrent values and they are the resultant motions rather than the horizontal motions. However, the resultant motions are believed to be directly comparable to the horizontal motions. Nuttli's velocities should be comparable to peak velocities in this report, but his accelerations would be expected to be lower. His velocity of 58 cm/sec compares favorably with a velocity at the Dickey-Lincoln School sites of 65 cm/sec. Nuttli's displacement of 27 cm is high compared with 22 cm. His acceleration of 0.12 g versus 0.35 g is low, as was anticipated. Based

on the comparison of velocities, the motions at the Dickey-Lincoln School sites are comparable to motions that Nuttli would assign. The peak acceleration used in this study is more conservative than the acceleration of Nuttli.

Schnabel and Seed

95. Schnabel and Seed[28] provided values for maximum accelerations in rock for the western United States. Their curves are shown in Figure 29. For a maximum event at a distance of 45 miles, the highest acceleration from recorded observations is about 0.17 g. If an acceleration is taken from the "probable upper bound," it is about 0.25 g. The latter is less than the 0.35 g taken for the Dickey-Lincoln School sites.

U. S. Geological Survey: western United States

96. U. S. Geological Survey data for selected earthquakes of the western United States are shown in Figures 30 to 32. These relate accelerations, particle velocities, and displacements, respectively, to magnitude of earthquake and distance from source. These data were developed by Page et al.,[29] for studies related to the Trans-Alaska Pipeline. Superimposed are lines taken from Nuttli[27] which represent a maximum New Madrid earthquake for the central United States with a magnitude of 7.5.

97. Accelerations from Figure 30 show that at a distance of 72 km (45 miles) for a maximum earthquake in which M equals 7.0 to 7.9, higher values will be obtained than those cited by Nuttli. The value obtained from the USGS chart is between 0.18 and 0.20 g. Thus, the 0.35 g selected for the Dickey-Lincoln School damsites is conservative compared to the USGS data.

98. Velocities from Figure 31 for a maximum event at 72 km provide a value of about 25 cm/sec. This is much lower than 65 cm/sec obtained for the Dickey-Lincoln School damsites and is also lower than the values that Nuttli proposes. The velocity values for the Dickey-Lincoln School sites are more conservative than that which is indicated by USGS data.

99. USGS displacements (see Figure 32) also are lower than those

for the Dickey-Lincoln School sites. The USGS would obtain about 10 cm. Nuttli's value is 27 cm. The value of 22 cm for Dickey-Lincoln School falls between these.

U. S. Geological
Survey: eastern United States

100. For the eastern United States, the U. S. Geological Survey[30] uses the distance versus acceleration graph shown in Figure 33. The curves (solid lines) are taken from Schnabel and Seed[28] and were modified (dashed lines) by attenuating the lines according to the attenuations of Nuttli[27] for the central United States. At a distance of 72 km, there is very little change from Schnable and Seed for a magnitude 7.5 event, the acceleration being about 0.18 g.

Trifunac and Brady

101. The values generated by Trifunac and Brady[26] for ground motions in relation to intensity for the western United States are shown in Figure 34. The values do not distinguish between near field and far field as was done in this report. Otherwise, the data used by Trifunac and Brady and in this report are the same.

102. The values of Trifunac and Brady for one standard deviation on the plus side for an intensity IX are interpolated as:

Acceleration: 0.60 g

Velocity: 60 cm/sec

Displacement: 20 cm

103. The acceleration is double that of this report. The other values are comparable to those in this report though slightly lower.

Ambraseys

104. Ambraseys (see Johnson and Heller[31]) has reasoned that there is no upper bound to ground acceleration but that particle velocity has an upper bound. Ambraseys developed an empirical equation for the relationship between the peak particle velocity, the magnitude of an earthquake, and the distance from the focus which was developed for epicentral distances of 10 to 150 km and magnitudes 5 to 7. Figure 35 shows maximum values for the above relationships. At a distance of 72 km, Ambraseys obtains a maximum velocity of 30 cm/sec for a magnitude

7 earthquake. No magnitude 7.5 event is shown; however, an extrapolation to that level would obtain a velocity of about 68 cm/sec. Thus, the 65 cm/sec for the Dickey-Lincoln School sites closely resembles what might be projected using the Ambraseys analysis.

Milne and Davenport

105. Milne and Davenport[19] developed a contour map for eastern Canada which shows accelerations as a percent of g with a return period of 100 yr. Their map is shown in Figure 36. The Dickey-Lincoln damsites are located adjacent to the Milne and Davenport 0.10-g contour. The value of 0.35 g assigned in this report is much more conservative.

Summary

106. Table 8 provides a comparison between the values used in this report for an intensity IX earthquake at the damsites and values taken from the authors discussed above.

107. For data from the western United States used by Krinitzsky and Chang[18] and Trifunac and Brady,[26] the maximum observed far-field acceleration is about 0.25 g at intensity VII; the maximum observed far-field velocity is about 35 cm/sec at intensity VII; and the maximum observed far-field displacement is about 18 cm at intensity VI. Far-field motions greater than these are interpreted.

108. The work done in this study was reviewed by Dr. David B. Slemmons, geological consultant, and Dr. Otto W. Nuttli, seismological consultant. They concurred with the values adopted in this report. Their comments are contained in Appendix A.

Time Histories of Ground Motion

109. Dr. Nuttli was asked to select four accelerograms for scaling to provide the time histories of ground motion in bedrock at the damsites. Three records were requested for a Zone A earthquake and one for a Zone C earthquake. Zone B will be scaled, with appropriate peak motions, using the same earthquakes as used for Zone A. Similarly, Zone D will use the same earthquake as Zone C. The scaled records will provide design earthquakes at bedrock for analyses of the foundation soils and structure.

Table 8

Comparison of Peak Horizontal Ground Motions (Interpreted from Various Authors) for Bedrock at Dickey-Lincoln School Damsites

Authors	Acceleration g	Velocity cm/sec	Displacement cm
Krinitzsky and Patrick	0.35	65	22
Nuttli[27]	0.12	58	27
Schnabel and Seed[28]	0.17*	--	--
	0.25**	--	--
USGS: western United States	0.20	25	10
eastern United States[2]	0.18	--	--
Trifunac and Brady†[26]	0.60	60	20
Ambraseys[31]	--	68††	--
Milne and Davenport[19]	0.10‡	--	--

* Recorded value.
** Interpreted upper boundary.
† Mean plus one standard deviation.
†† Interpolated by Krinitzsky and Patrick.
‡ Recurrent per 100 year.

110. Nuttli's selected events are contained in his letter in Appendix A.

111. The records Nuttli selected for Zone A and Zone B earthquakes, to be scaled for the damsites, are (a) the San Fernando, California, earthquake of 9 February 1971 using the Wrightwood, California, record; (b) the El Centro, California, earthquake of 8 April 1968 using the record at the El Centro Imperial Valley Irrigation District station; and (c) the Northern Utah earthquake of 30 August 1962 using the Logan, Utah, record. For Zone C and Zone D, Nuttli recommends the record for the Hollister, California, earthquake of 8 April 1961 using the record at Hollister, California.

Induced Seismicity at the Reservoirs

112. Earthquakes are known to have occurred coincident with filling and with changes of water levels in reservoirs. The occurrences are few, less than three dozen out of the thousands of reservoirs that exist worldwide. At only one site (Koyna in India) was an induced earthquake severe enough to damage the dam. Earthquakes strong enough to be related to damage (intensity VII or greater) have been induced at only five reservoirs in the world. All of these reservoirs are large: volumes of water in billions of cubic metres; heights of dams greater than 100 metres.

113. The energy released in any significant earthquake is much greater than the energy that can be related to load in a reservoir. The earthquake is the result of tectonism, the buildup and sudden release of stresses in the earth's crust. Loading from a reservoir is no more than a triggering action. The reservoir may touch off an earthquake that is about to happen for other reasons, but the reservoir does not cause the earthquake. Hence, the maximum credible earthquakes for which the dams are designed include any earthquake that might be induced.

PART IX: SUMMARY AND CONCLUSIONS

114. Mapped faults and interpreted lineaments were examined in air imagery and in overflights. A ground reconnaissance was made of these features. No evidence of active faults was seen in the general area of the damsites. It is believed that the faults which are present are ancient ones and are inactive. Active faults are believed to be restricted to a narrow band along the St. Lawrence River. There the faults are obscured by alluvial drowning. The seismic history shows that major earthquakes occur in the St. Lawrence Valley but that the level of seismicity in the area of the damsites is low. Four zones were assigned. Zone A is a band in the St. Lawrence Valley in which the most severe earthquakes can occur. Its distance from the damsites is 45 miles. Zone B borders Zone A and has a lower level of potential earthquakes. Zone B is 40 miles from the damsites. The remaining area, which includes the damsites, is Zone C and has the lowest seismic risk. A Zone D is interpreted 75 miles to the southeast of the damsites. Zone D has a slightly higher level of seismic risk than Zone C. The most severe bedrock ground motion at the damsites will come from an earthquake in Zone A. The motion at the damsites after attenuation over a distance of 45 miles is interpreted to have a peak acceleration of 0.35 g, a peak velocity of 65 cm/sec, and a peak displacement of 22 cm. The duration is estimated at 18 sec. Possible reservoir-induced seismicity is allowed for in the postulated earthquakes. A selection of accelerographs is recommended for scaling in order to provide time histories of bedrock ground motions for dynamic analysis.

REFERENCES

1. U. S. Geological Survey, "Tectonic Map of North America," compiled by P. B. King, scale 1:5,000,000, 1969, Washington, D. C.

2. Boudette, E. L., Hatch, N. L., Jr., and Harwood, D. S., "Geology of the Upper St. John and Allagash River Basins, Maine," U. S. Geological Survey Manuscript (for U. S. Army Engineer Division, New England, CE), Washington, D. C.

3. Zen, E. et al., ed., "Regional Tectonic Map and Structure Section of Northwestern New England and Adjacent Quebec," compiled by W. M. Cady, scale 1:1,000,000, Studies of Appalachian Geology: Northern and Maritime, Interscience, New York, 1968.

4. Ballard, R. D. and Uchupi, E., "Triassic Rift Structure in Gulf of Maine," Bulletin, American Association of Petroleum Geologists, Vol 59, No. 7, Jul 1975, pp 1041-1072.

5. Flint, R. F., Glacial and Pleistocene Geology, Wiley, New York, 1957, p 319.

6. Smith, W. E. T., "Earthquakes of Eastern Canada and Adjacent Areas: 1534-1927," Publication of Dominion Observatory, Department of Mines and Technical Surveys, Ottawa, Canada, Vol XXV, No. 5, 1962, pp 271-301.

7. __________, "Earthquakes of Eastern Canada and Adjacent Areas: 1928-1959," Publication of Dominion Observatory, Department of Mines and Technical Surveys, Ottawa, Canada, Vol XXXII, No. 3, 1966, pp 87-121.

8. Coffman, J. L. and von Hake, C. A., ed., "Earthquake History of the United States," Publication 41-1, revised edition through 1970, 1963, U. S. Coast and Geodetic Survey, Department of Commerce, Washington, D. C.

9. __________, "United States Earthquakes," 1970, Environmental Data Service, National Oceanic and Atmospheric Administration, U. S. Coast and Geodetic Survey, Department of Commerce, Boulder, Colo.

10. Hadley, J. B. and Devine, J. F., "Seismotectonic Map of the Eastern United States," MF-620, 1974, U. S. Geological Survey, Washington, D. C.

11. Woollard, G. P., "Tectonic Activity in North America," The Earth's Crust and Upper Mantle, American Geophysical Union Monograph 13, 1969, pp 125-133.

12. Zeitz, I., Gilbert, F., and Kirby, J. R., "Aeromagnetic Map of Northern Maine," Open File Report, 1972, U. S. Geological Survey, Washington, D. C.

13. Department of Energy, Mines, and Resources, Geological Survey, "Aeromagnetic Map: Baie-St. Paul, Quebec," 1962-63, Ottawa, Canada.

14. Department of Energy, Mines, and Resources, Geological Survey, "Aeromagnetic Map: Edmundston, Quebec-New Brunswick," 1966-68, Ottawa, Canada.

15. U. S. Atomic Energy Commission, "Nuclear Power Plants; Seismic and Geologic Siting Criteria," Federal Register, Vol 36, No. 228, Thursday, 25 Nov 1971, p 22, 602; Vol 38, No. 218, Tuesday, 13 Nov 1973, p 31, 281- 31, 282.

16. International Atomic Energy Agency, "Earthquake Guidelines for Reactor Siting," Technical Report Series No. 139, 1972, Vienna, Austria, pp 9-10.

17. Howell, B. F., Jr., "Seismic Regionalization in North America Based on Average Regional Seismic Hazard Index," Bulletin, Seismological Society of America, Vol 64, No. 5, Oct 1974, pp 1509-1528.

18. Krinitzsky, E. L. and Chang, F. K., "State-of-the-Art for Assessing Earthquake Hazards in the United States; Earthquake Intensity and the Selection of Ground Motions for Seismic Design," Miscellaneous Paper S-73-1, Report 4, Sep 1975, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

19. Milne, W. G. and Davenport, A. G., "Distribution of Earthquake Risk in Canada," Bulletin, Seismological Society of America, Vol 59, No. 2, Apr 1969, pp 729-754.

20. Bonilla, M. G. and Buchanan, J. M., "Interim Report on Worldwide Historic Surface Faulting," Open File Series No. 16113, 1970, U. S. Geological Survey, Washington, D. C.

21. Chang, F. K., "Relation of Earthquake Intensity to Duration and Spectral Content" (in preparation), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

22. Neumann, F., Earthquake Intensity and Related Ground Motion, University of Washington Press, Seattle, 1954.

23. Gutenberg, B. and Richter, C. F., "Earthquake Magnitude, Intensity, Energy, and Acceleration," Bulletin, Seismological Society of America, Vol 46, No. 2, Apr 1956, pp 105-145.

24. Hershberger, J., "A Comparison of Earthquake Accelerations with Intensity Ratings," Bulletin, Seismological Society of America, Vol 46, No. 4, Oct 1956, pp 317-320.

25. Barosh, P. J., "Use of Seismic Intensity Data to Predict the Effects of Earthquakes and Underground Nuclear Explosions in Various Geologic Settings," Bulletin 1279, 1969, U. S. Geological Survey, Washington, D. C.

26. Trifunac, M. D. and Brady, A. G., "On the Correlation of Seismic Intensity Scales with the Peaks of Recorded Strong Ground Motion," Bulletin, Seismological Society of America, Vol 65, No. 1, Feb 1975, pp 139-162.

27. Nuttli, O. W., "State-of-the-Art for Assessing Earthquake Hazards in the United States; Design Earthquakes for the Central United States," Miscellaneous Paper S-73-1, Report 1, Jan 1973, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

28. Schnabel, P. B. and Seed, H. B., "Accelerations in Rock for Earthquakes in the Western United States," Report No. 72-2, 1972, Earthquake Engineer Research Center, University of California, Berkeley, Calif., and Bulletin, Seismological Society of America, Vol 63, No. 2, 1973, pp 501-516.

29. Page, R. A. et al., "Ground Motion Values for Use in the Seismic Design of the Trans-Alaska Pipeline System," Circular 672, 1972, U. S. Geological Survey, Washington, D. C.

30. U. S. Geological Survey, "Chart of Accelerations in Eastern United States," Newsletter, Earthquake Engineering Research Institute, Vol 9, No. 4, 1975, p 29.

31. Johnson, S. J. and Heller, L. W., "Lectures and Discussions by Professor N. N. Ambraseys on Engineering Seismology and Earthquake Engineering, U. S. Army Engineer Waterways Experiment Station, April-May 1973," Miscellaneous Paper S-74-15, May 1974, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

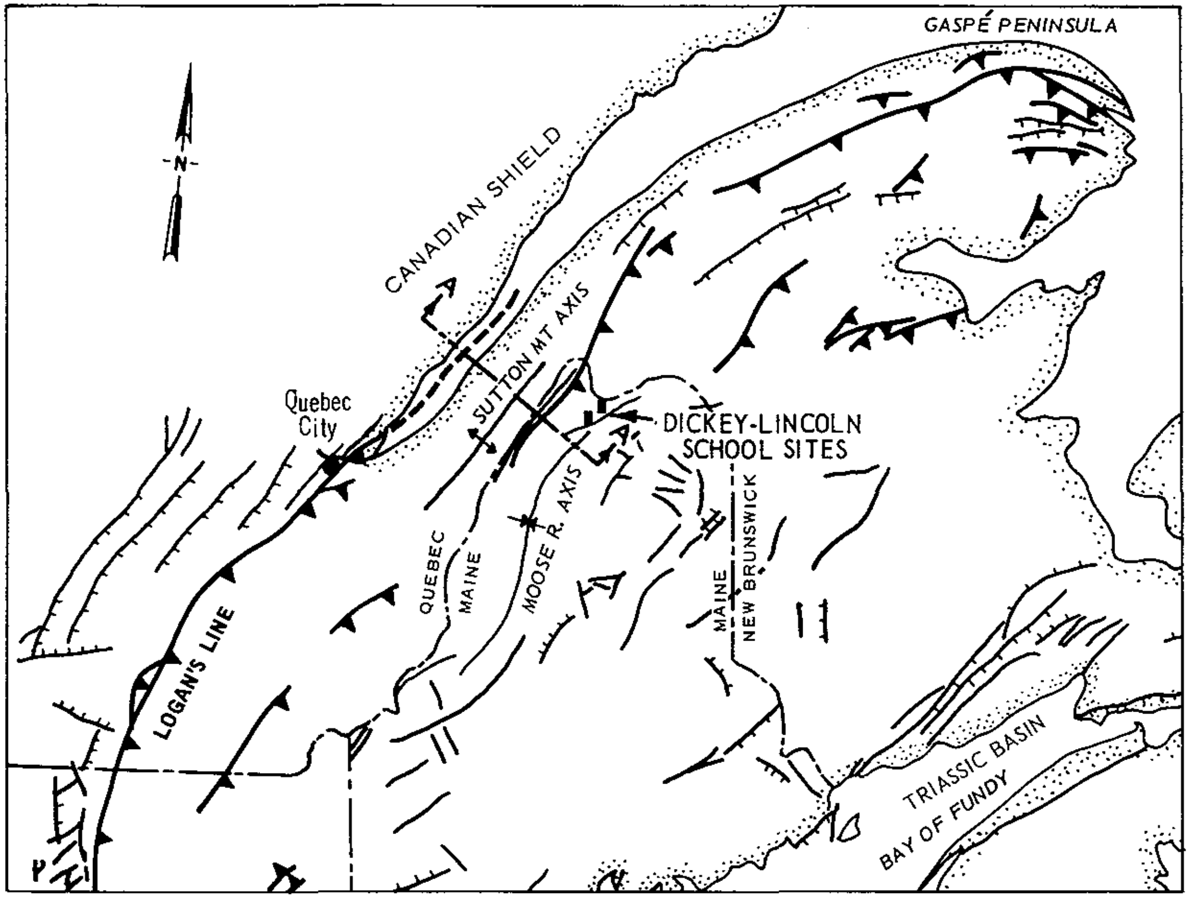


Figure 1. General tectonics, northern Maine and adjacent Canada (from USGS Tectonic Map of North America compiled by Philip B. King, 1969[1])

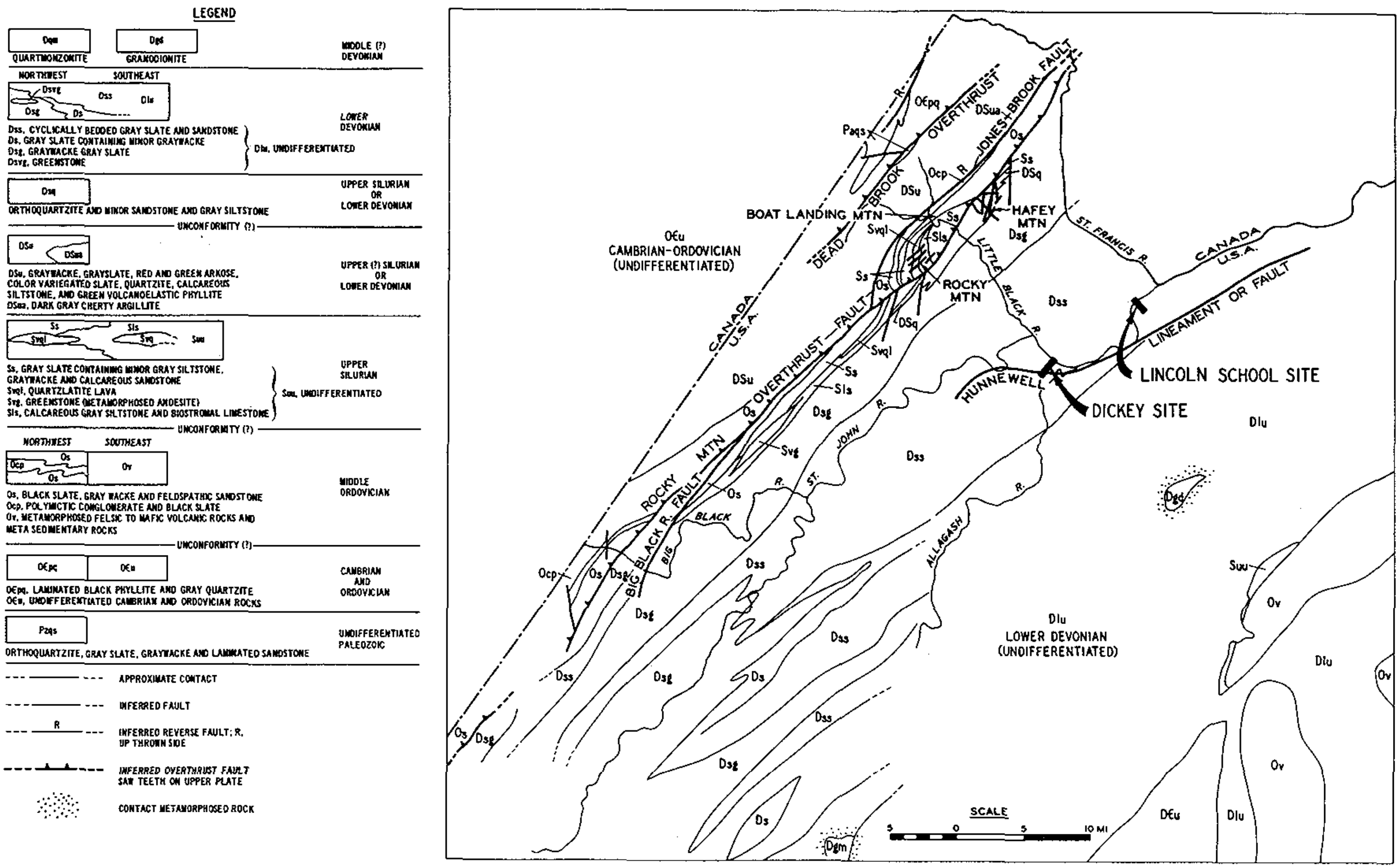


Figure 2. General geology of northwestern Maine (after Boudette et al.[2])

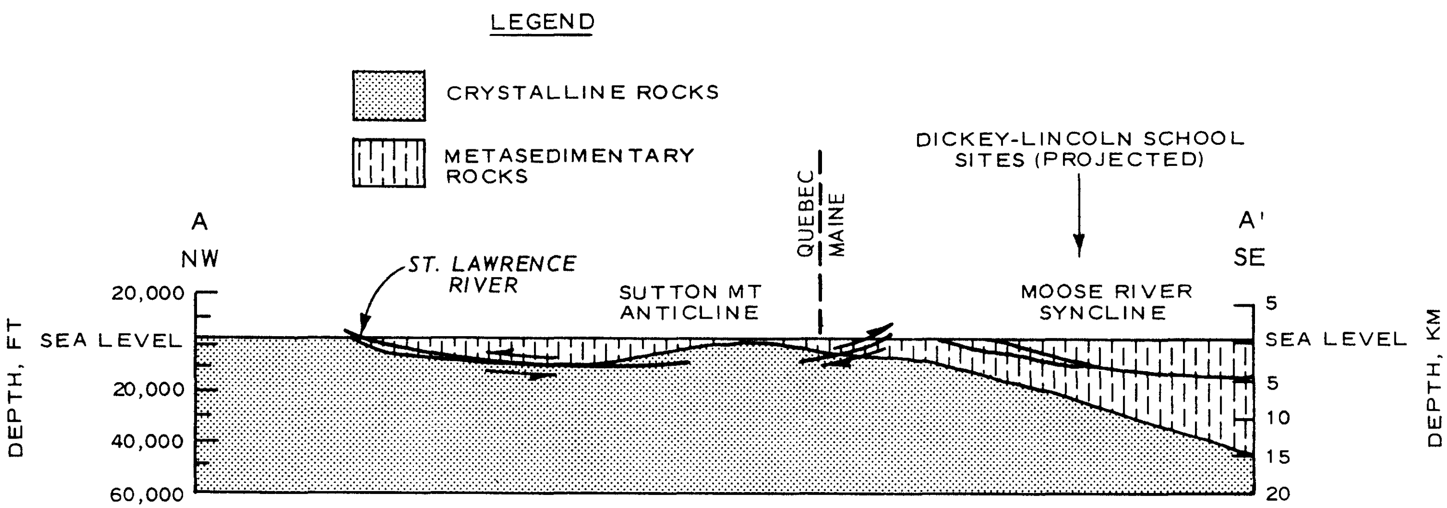


Figure 3. Schematic section from the Canadian Shield to northwestern Maine (after Cady[3])

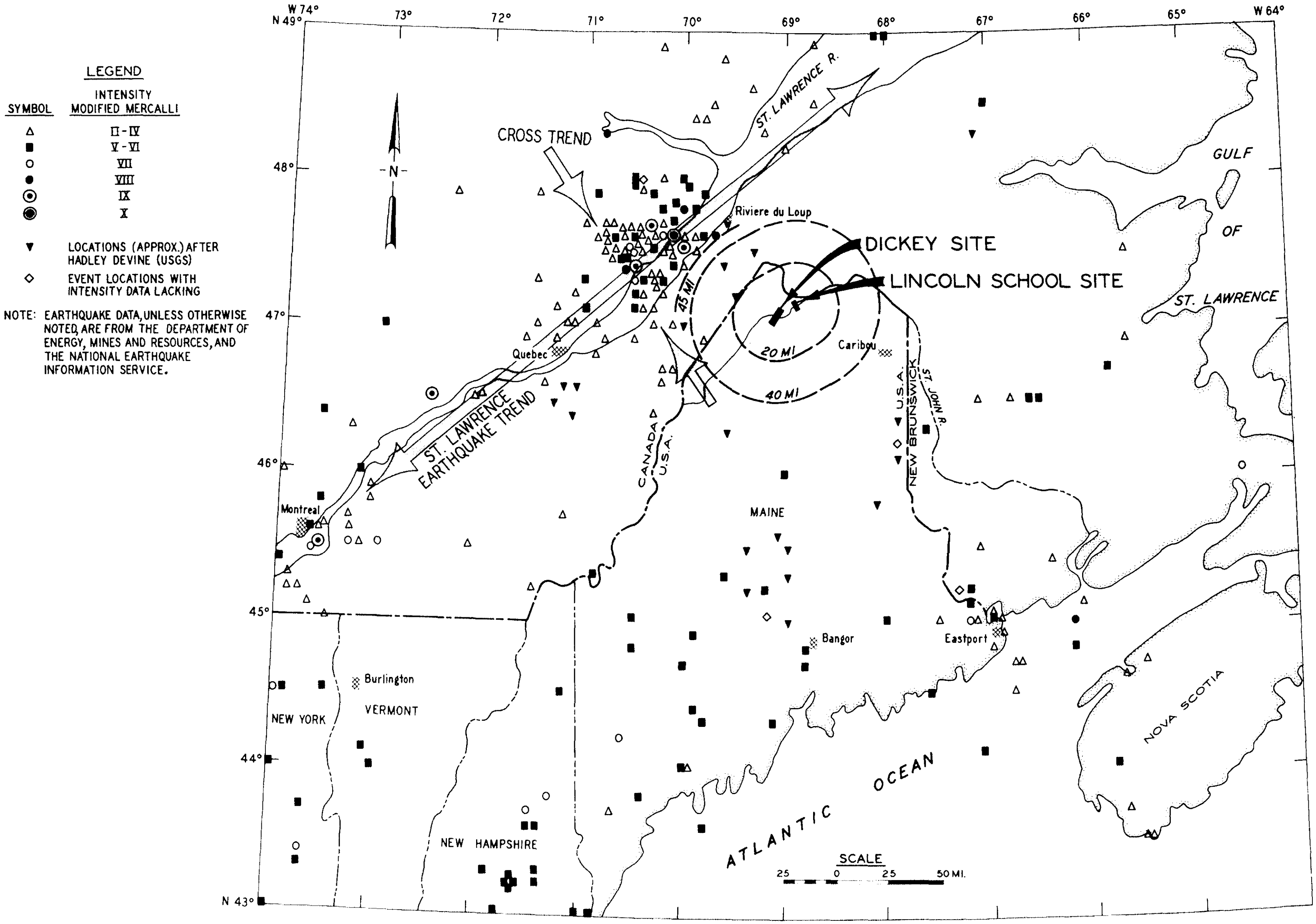


Figure 4. Historic earthquakes in northern New England and adjacent parts of Canada: 1638 to 1975

MODIFIED MERCALLI INTENSITY SCALE OF 1931

(Abridged)

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls made cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbed persons driving motor cars.

IX. Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI. Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

Figure 5. Modified Mercalli intensity scale of 1931 (abridged)

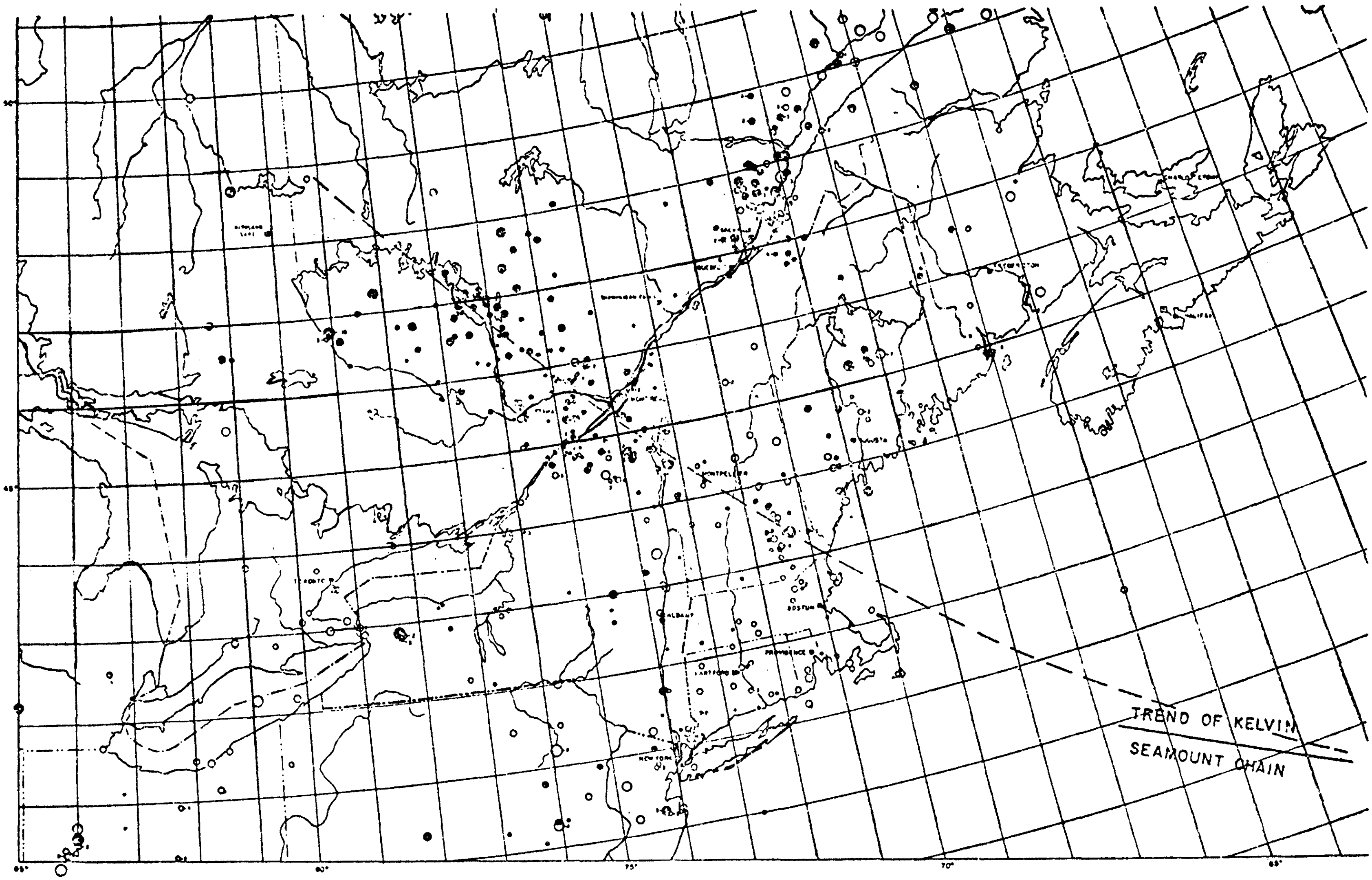


Figure 6. Seismicity in northeastern North America (1928 to 1959) with a NW-SE trend through Boston (after Smith[7])

Figure 7. Alluvial drowning along the south shore of the St. Lawrence River midway between Quebec City and Rivière du Loup

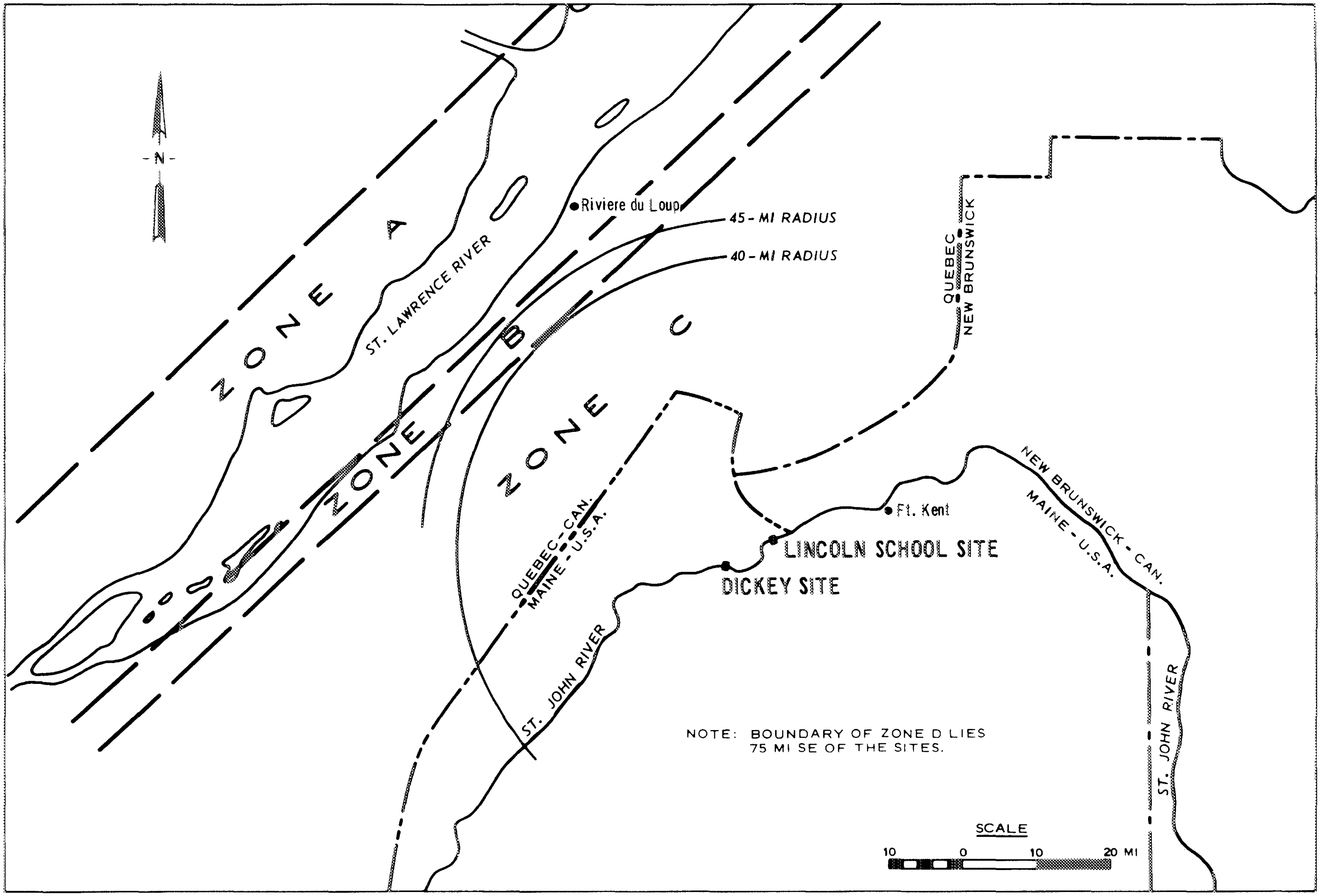


Figure 8. Seismic zones in the general area of the project

Figure 9. Typical ground terrain where a fault crosses a road in the project area

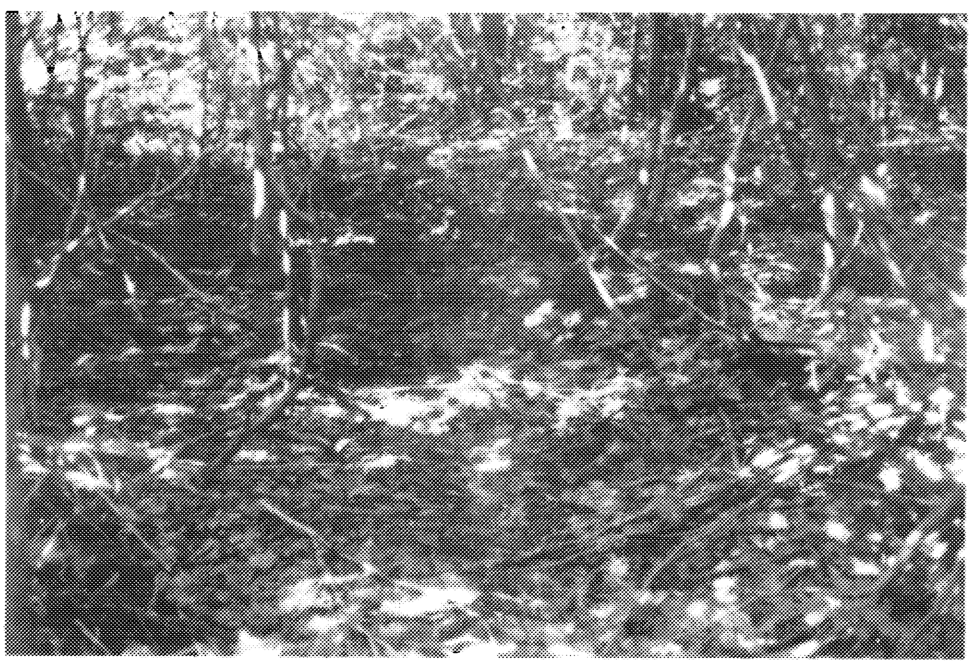


Figure 10. Example of organic ground litter in the project area

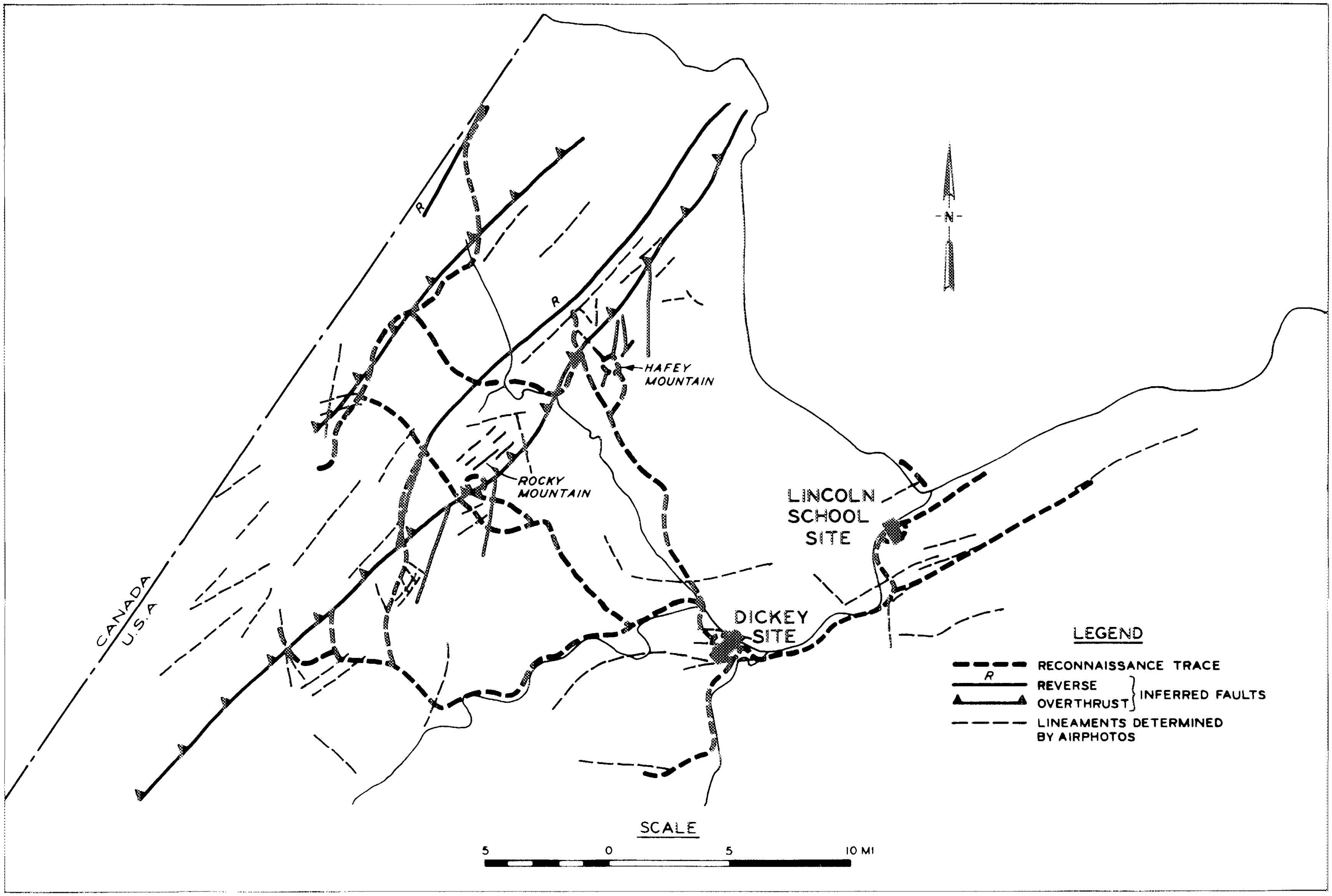


Figure 11. Ground traverses across faults and lineations in the project area

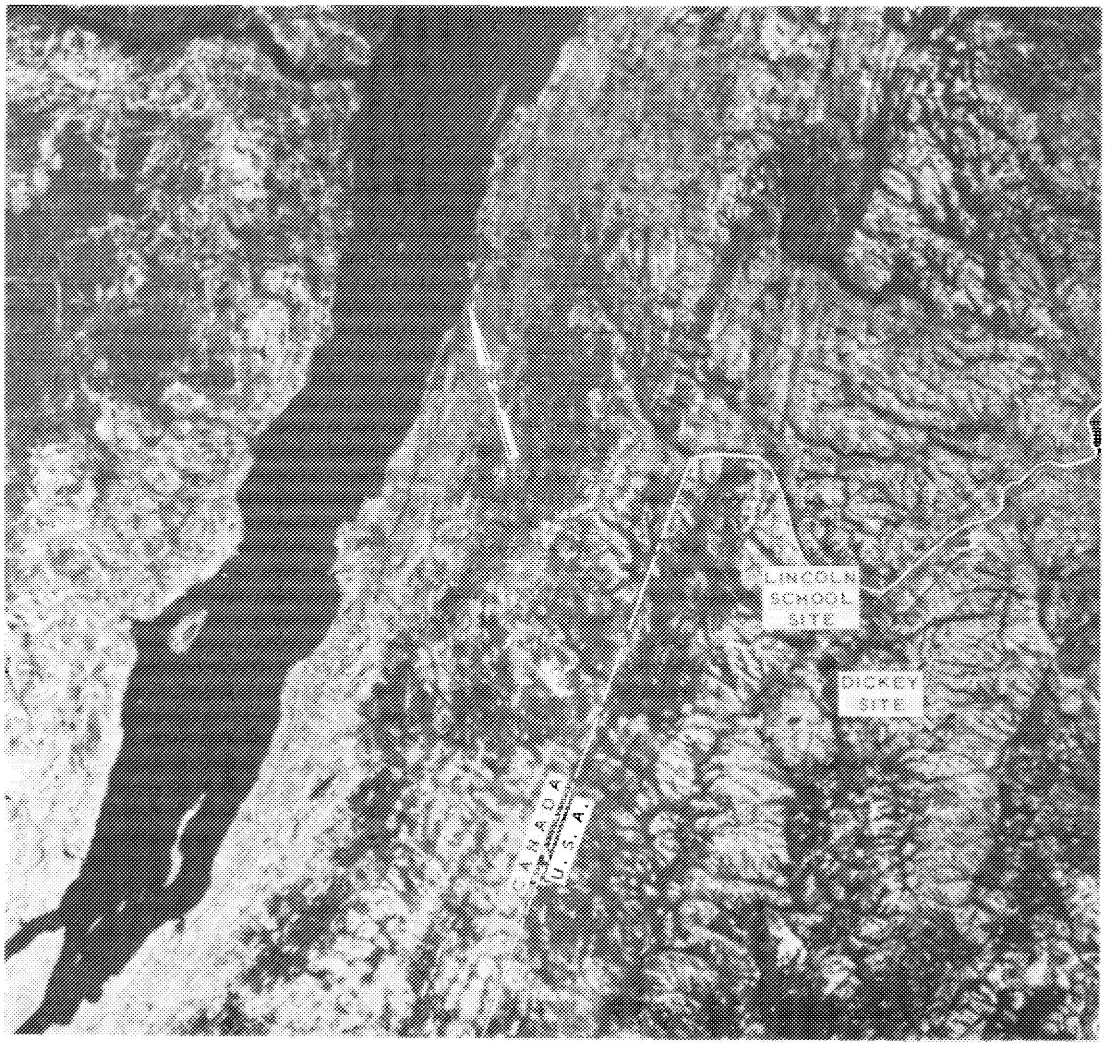


Figure 12. Earth Resources Technology Satellite (ERTS) image of northwestern Maine and the St. Lawrence Valley

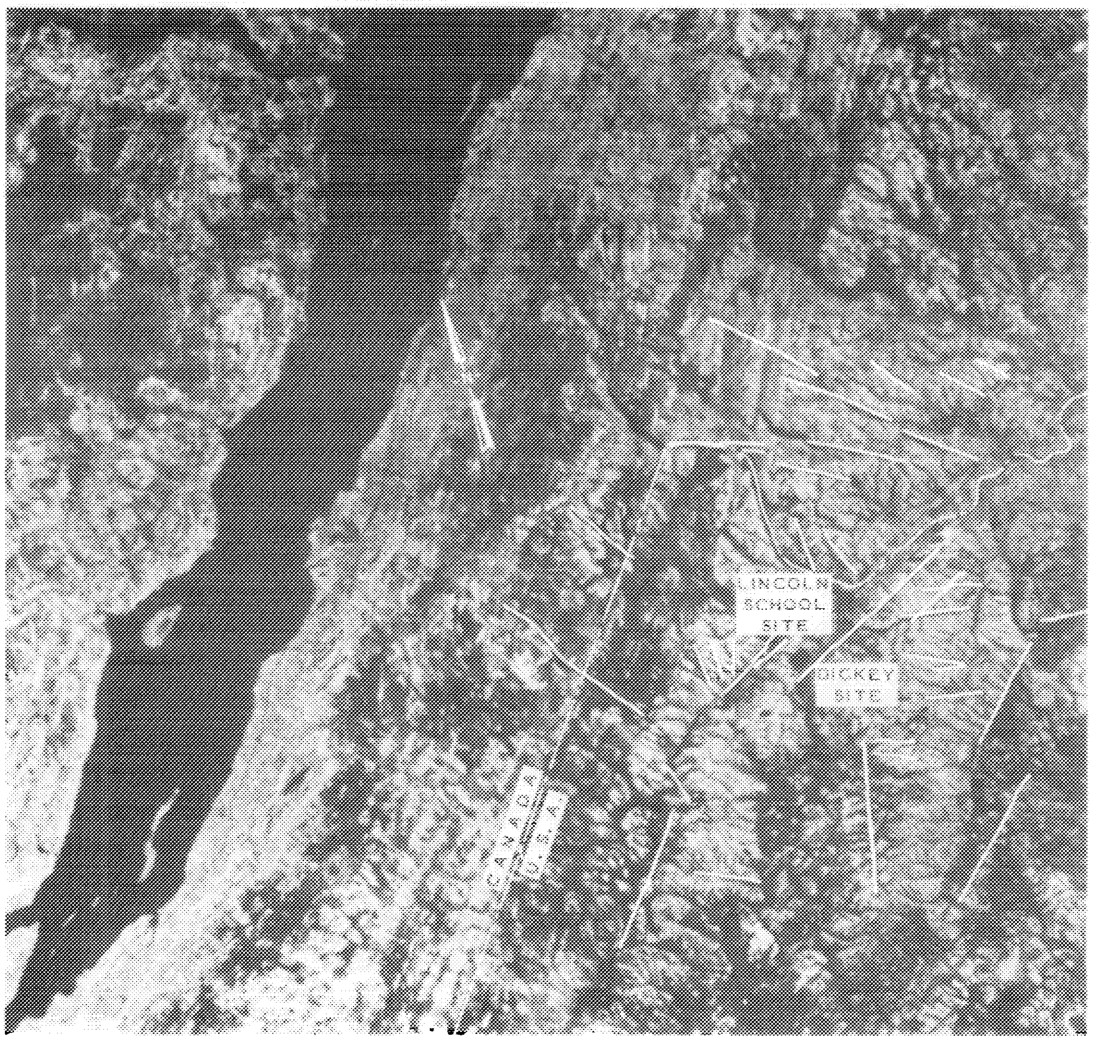


Figure 13. Selected linears superimposed on the image in Figure 12

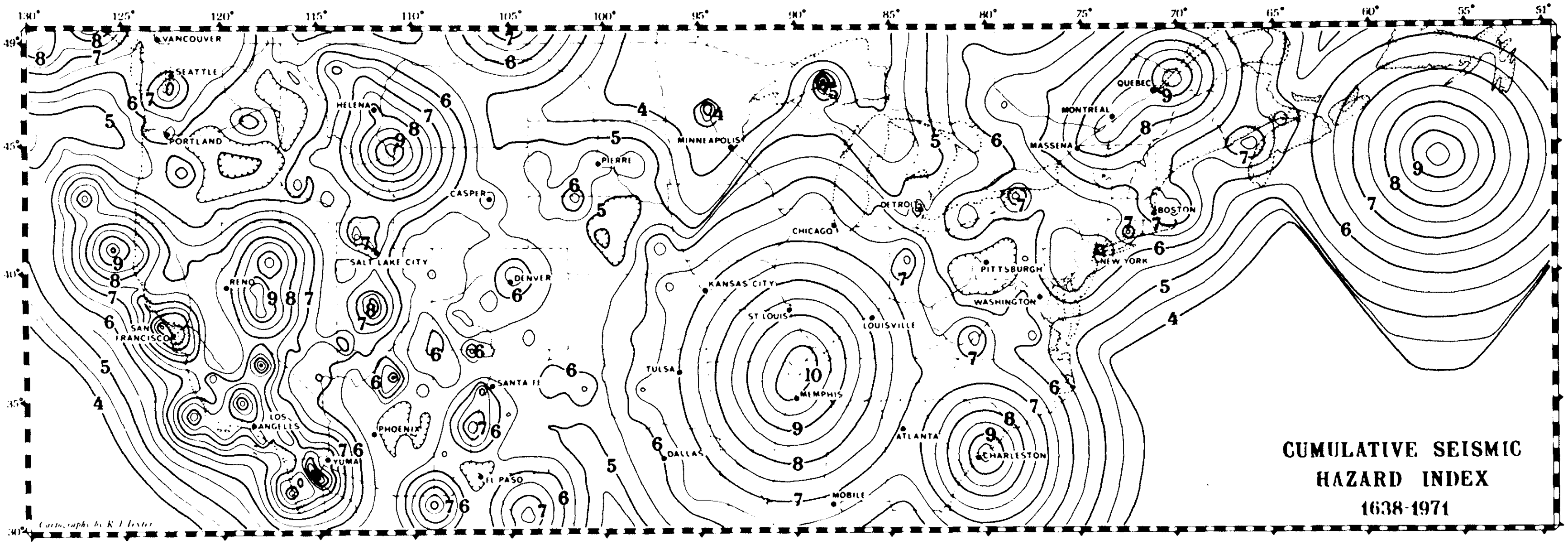


Figure 14. Cumulative Seismic Hazard Index (1638-1971) by Howell[17]

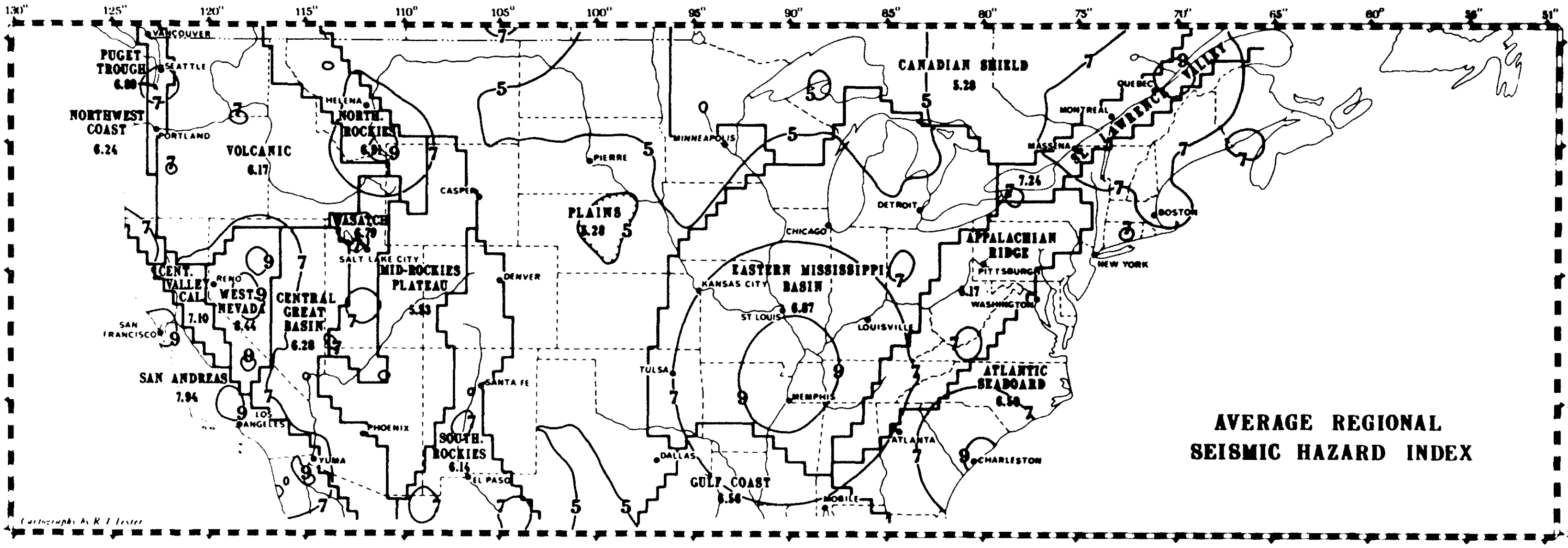


Figure 15. Average Regional Seismic Hazard Index by Howell[17]

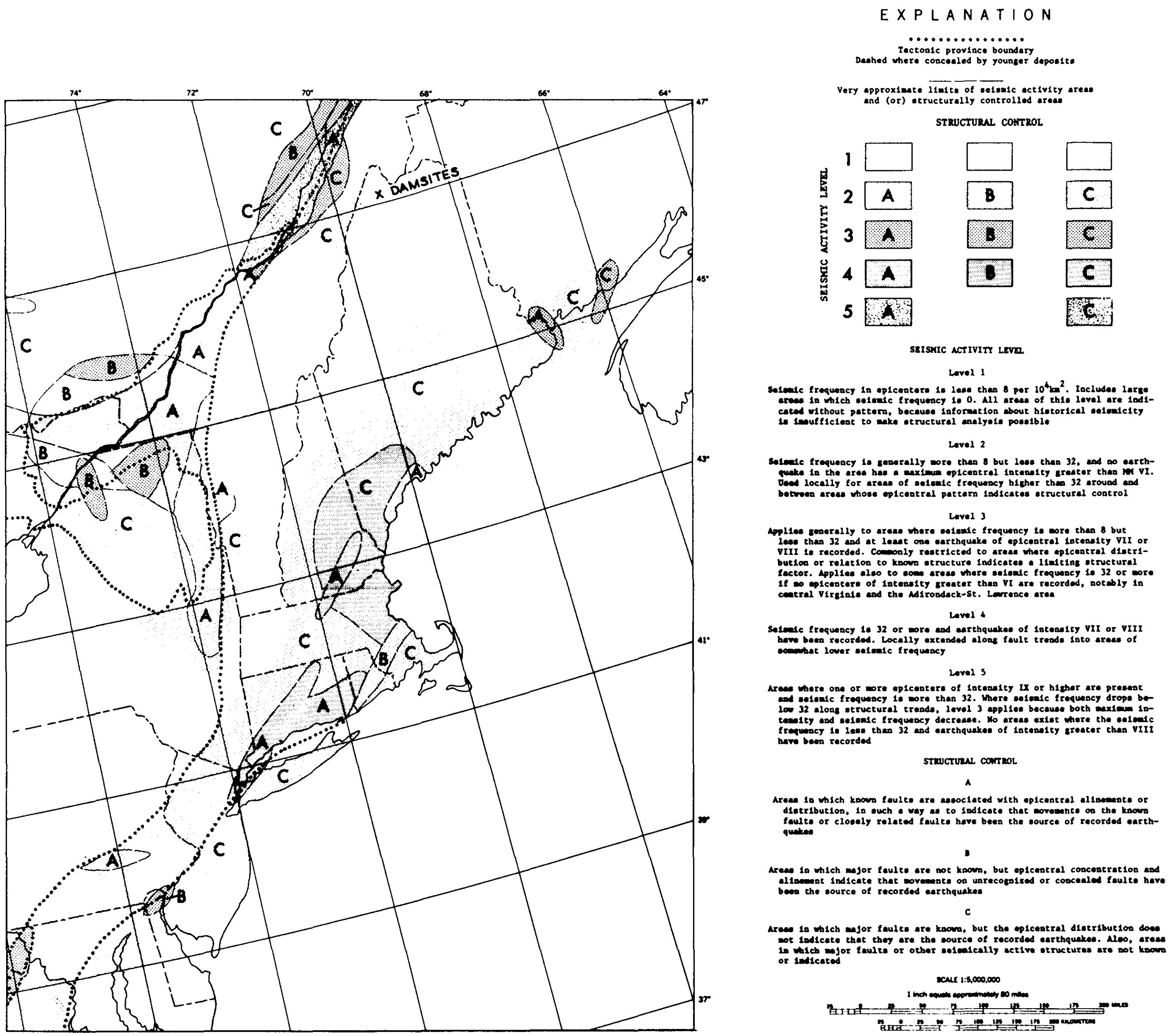


Figure 16. Seismic activity levels by Hadley and Devine[10]

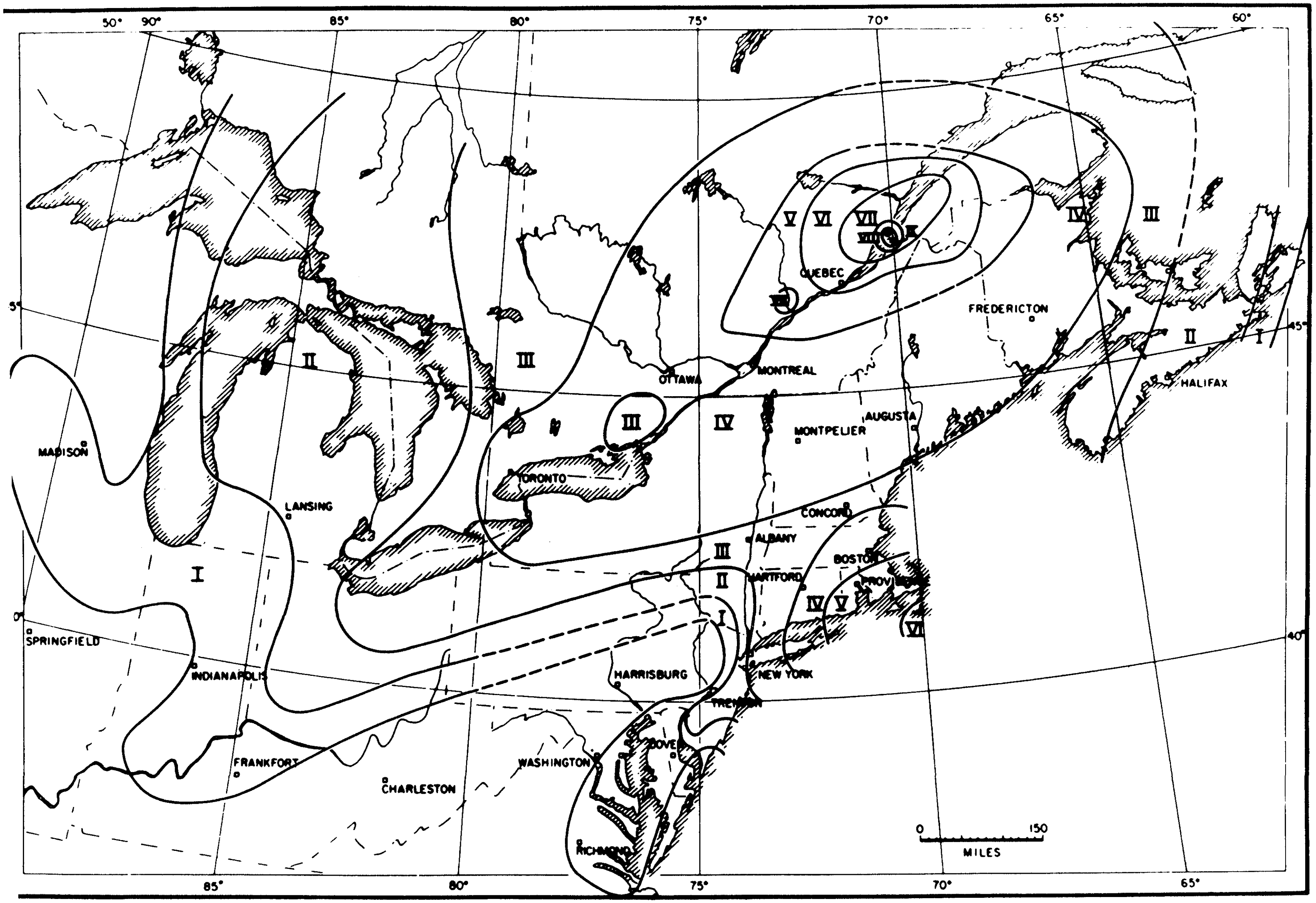


Figure 17. Isoseismal pattern for the St. Lawrence earthquake of March 1, 1925 (NEIS)

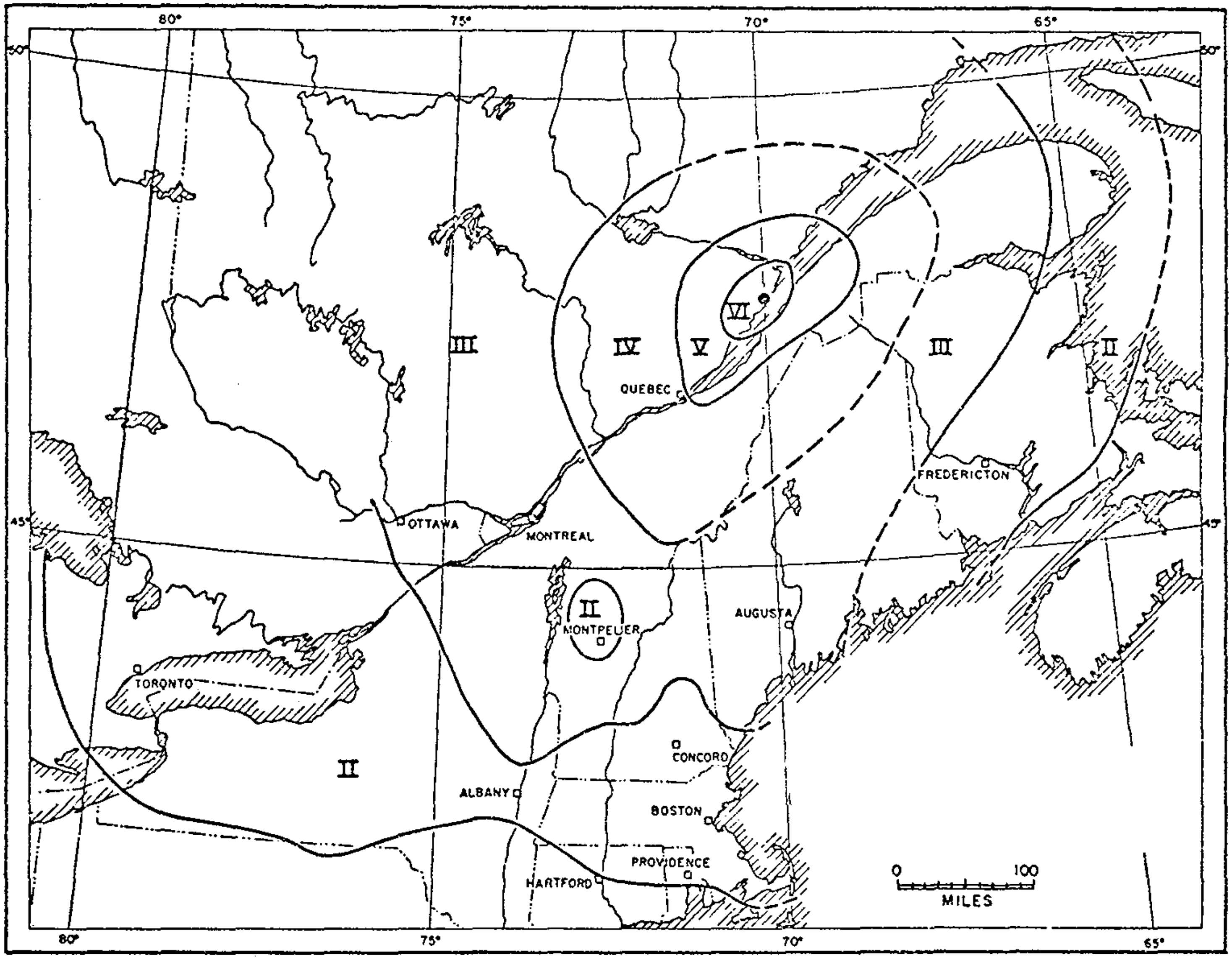


Figure 18. Isoseismal pattern for the St. Lawrence earthquake of October 19, 1939 (NEIS)

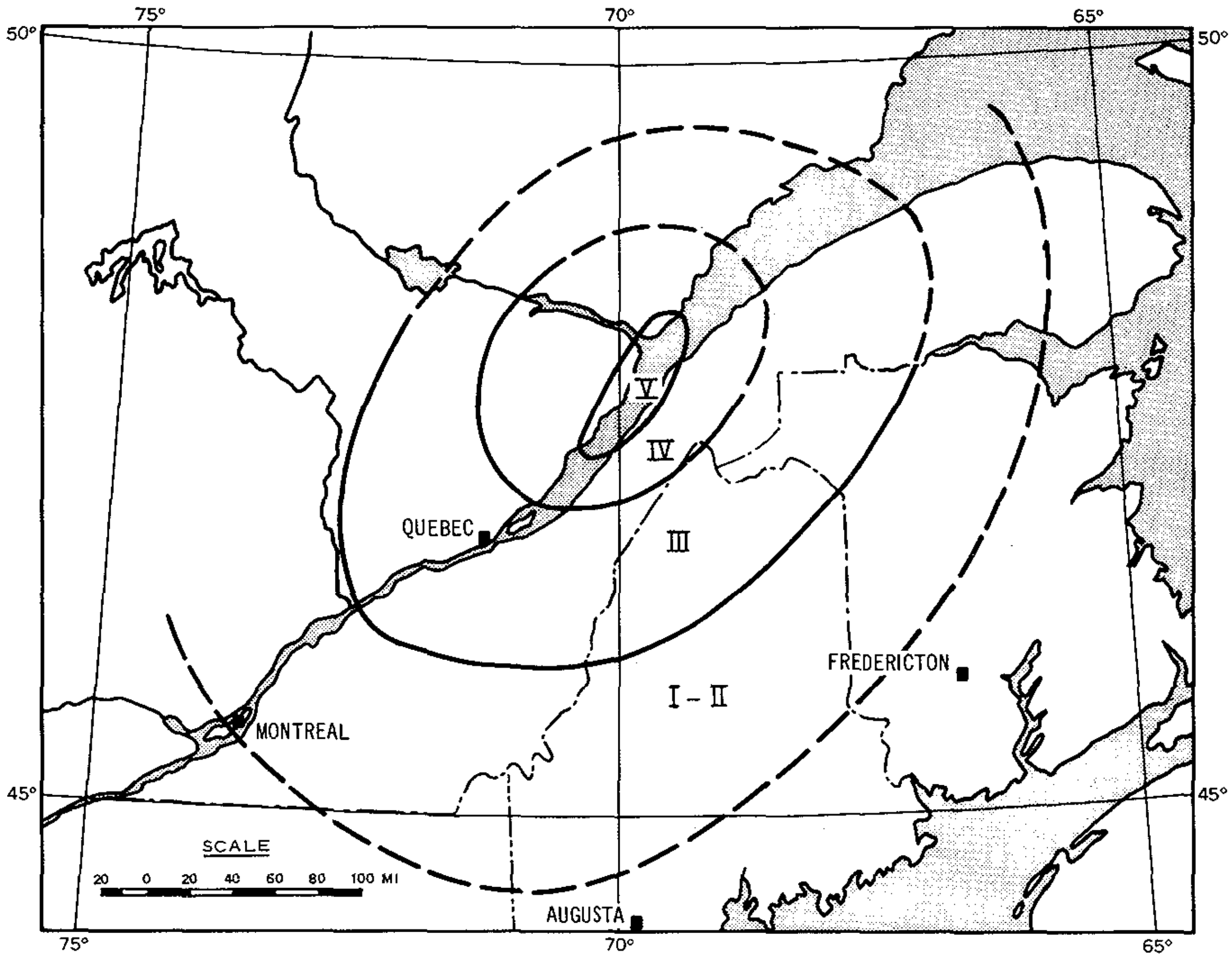


Figure 19. Isoseismal pattern for the St. Lawrence earthquake of October 14, 1952 (NEIS)

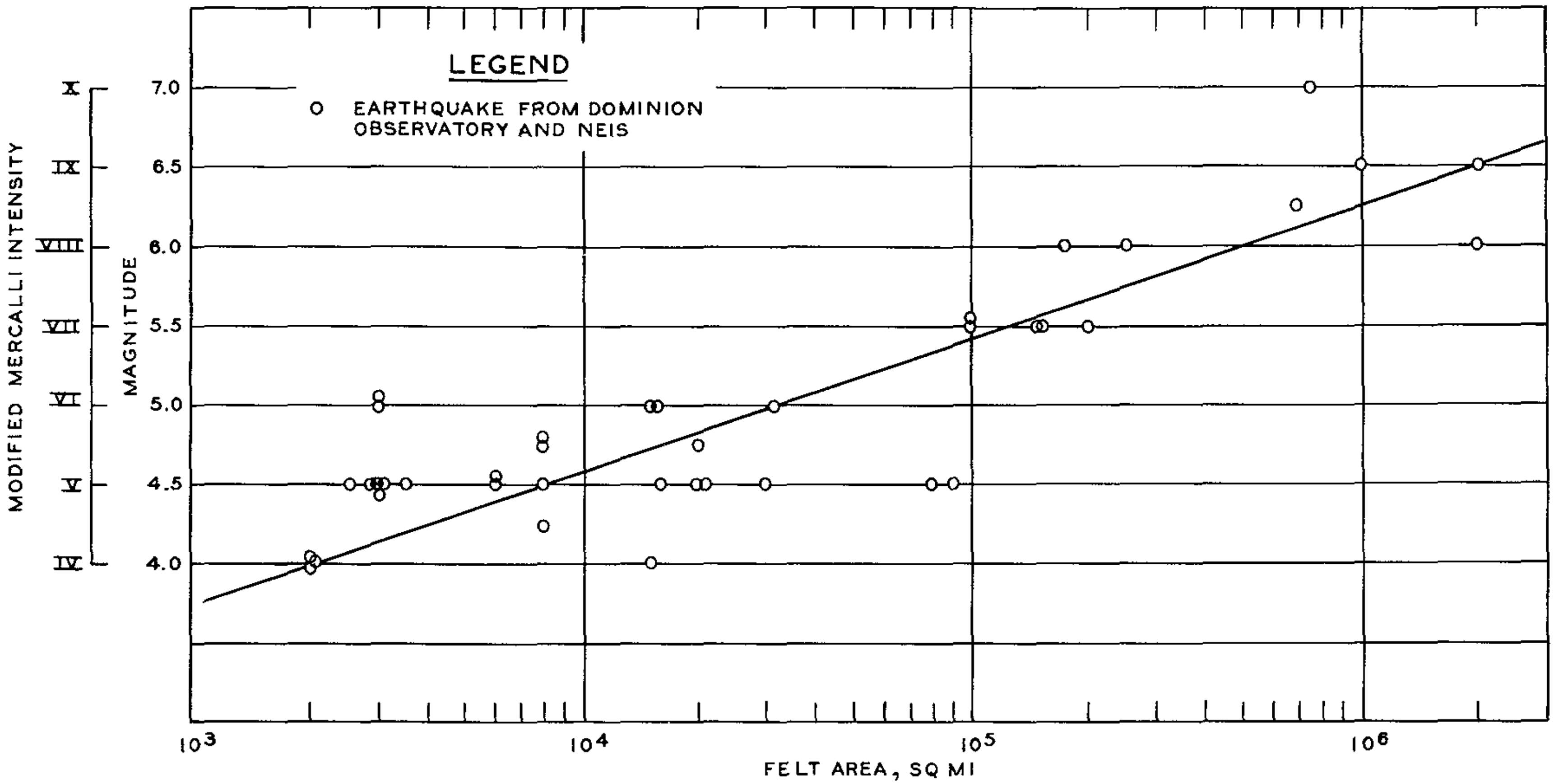


Figure 20. Relation between intensity, magnitude, and felt area in northern New England and adjacent parts of Canada

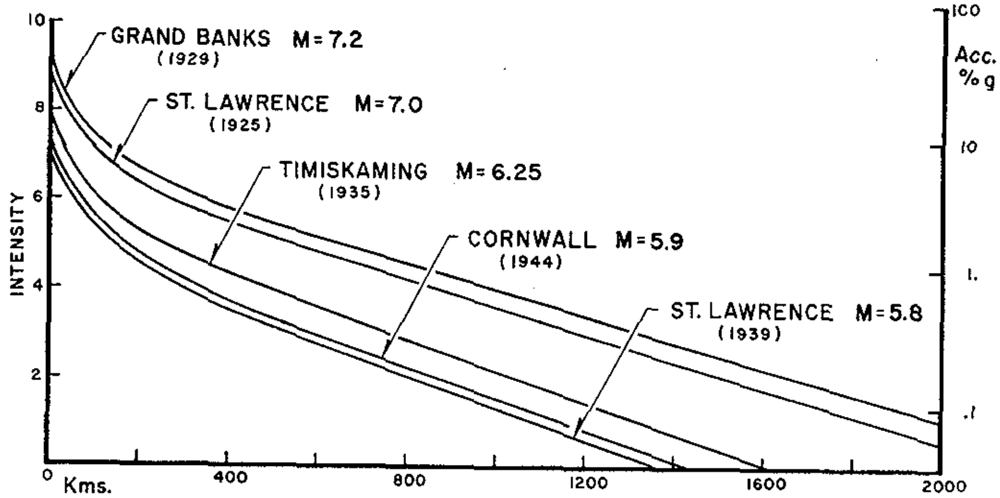


Figure 21. Plot of intensity versus distance for five earthquakes in eastern Canada (from Milne and Davenport[19])

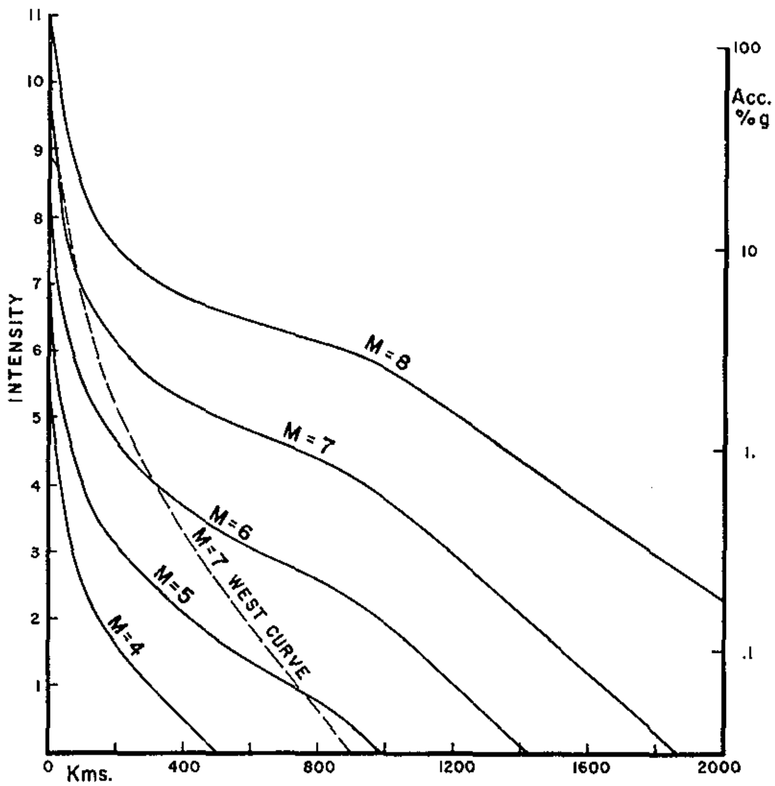


Figure 22. Intensity versus magnitude and distance for eastern Canada (from Milne and Davenport[19])

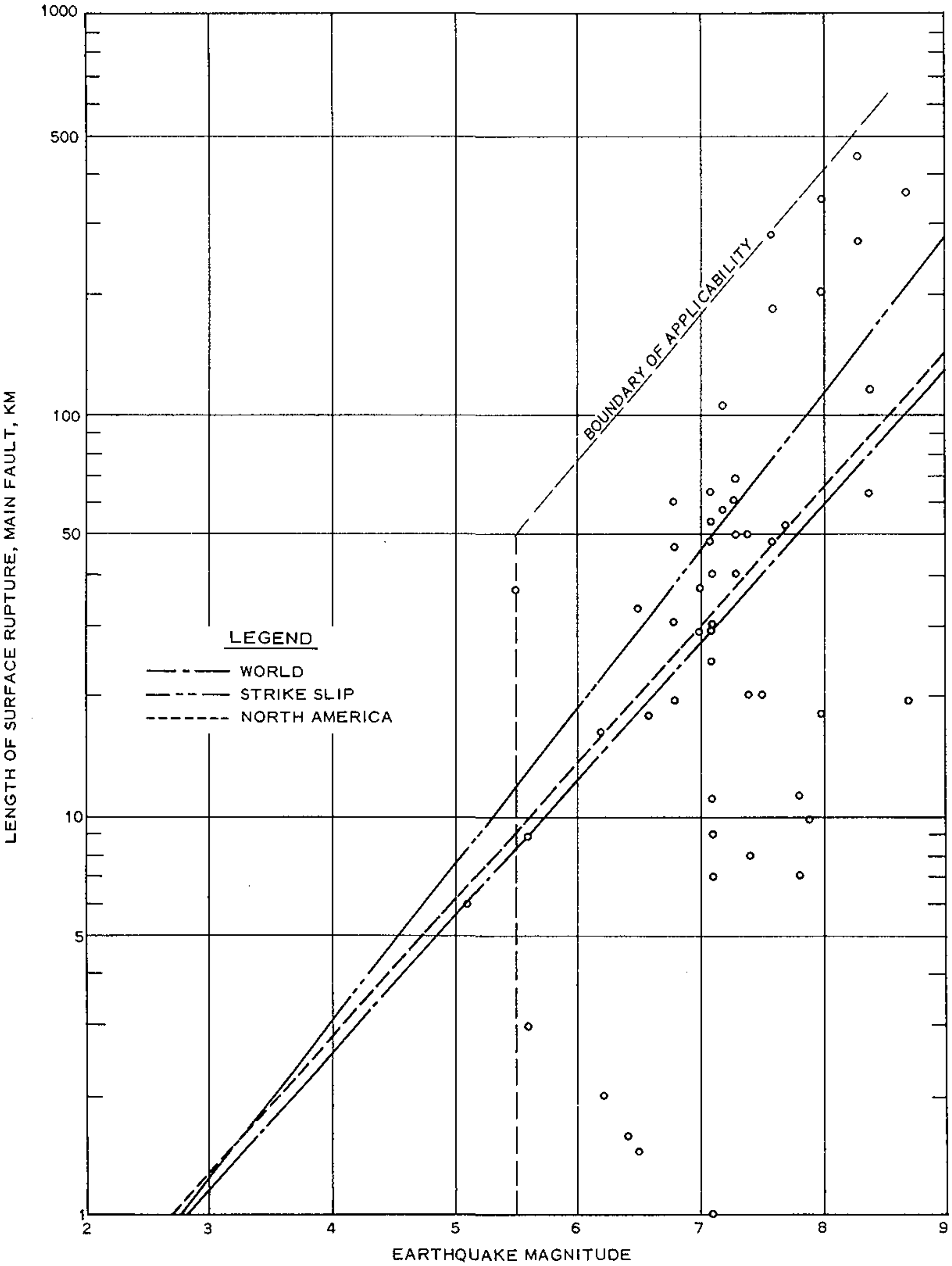


Figure 23. Length of surface rupture on main fault as related to earthquake magnitude (from Bonilla and Buchanan[20]); the boundary of applicability has been added

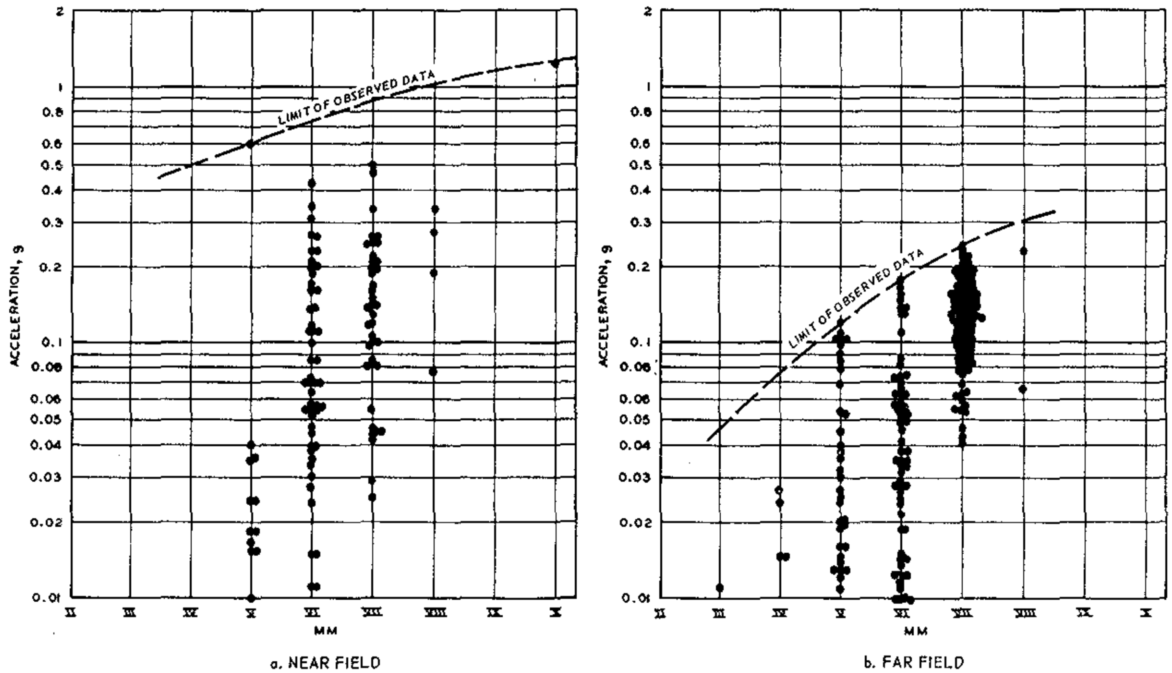


Figure 24. Intensity versus acceleration in the near and far fields

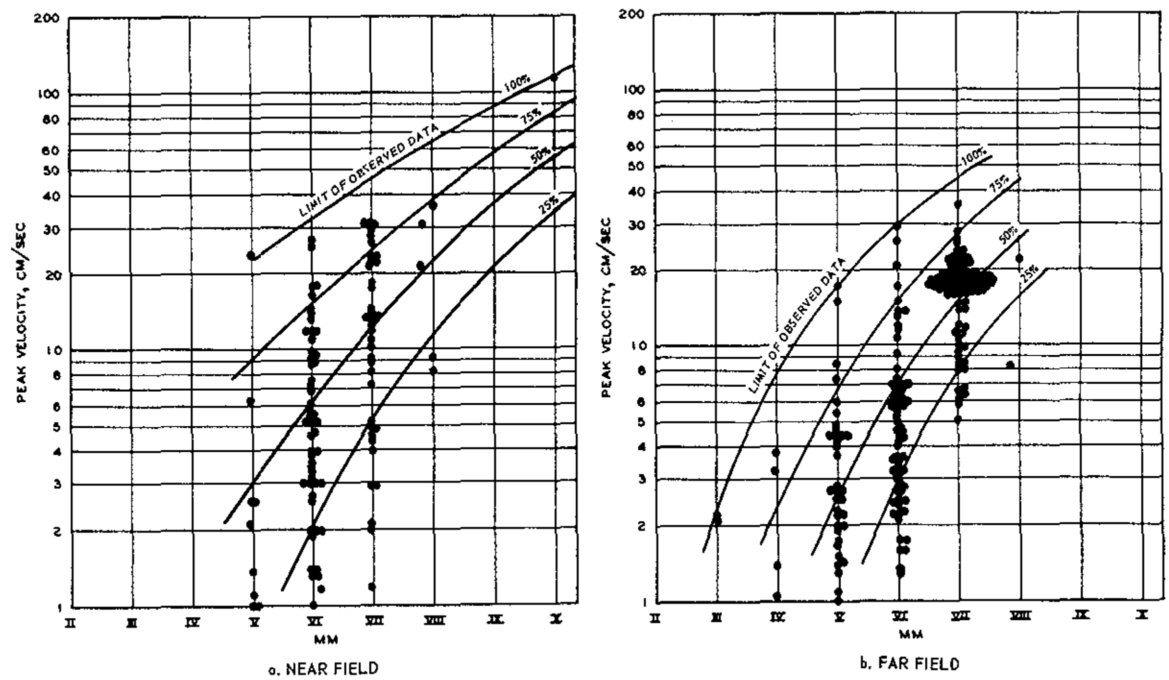


Figure 25. Intensity versus velocity in the near and far fields

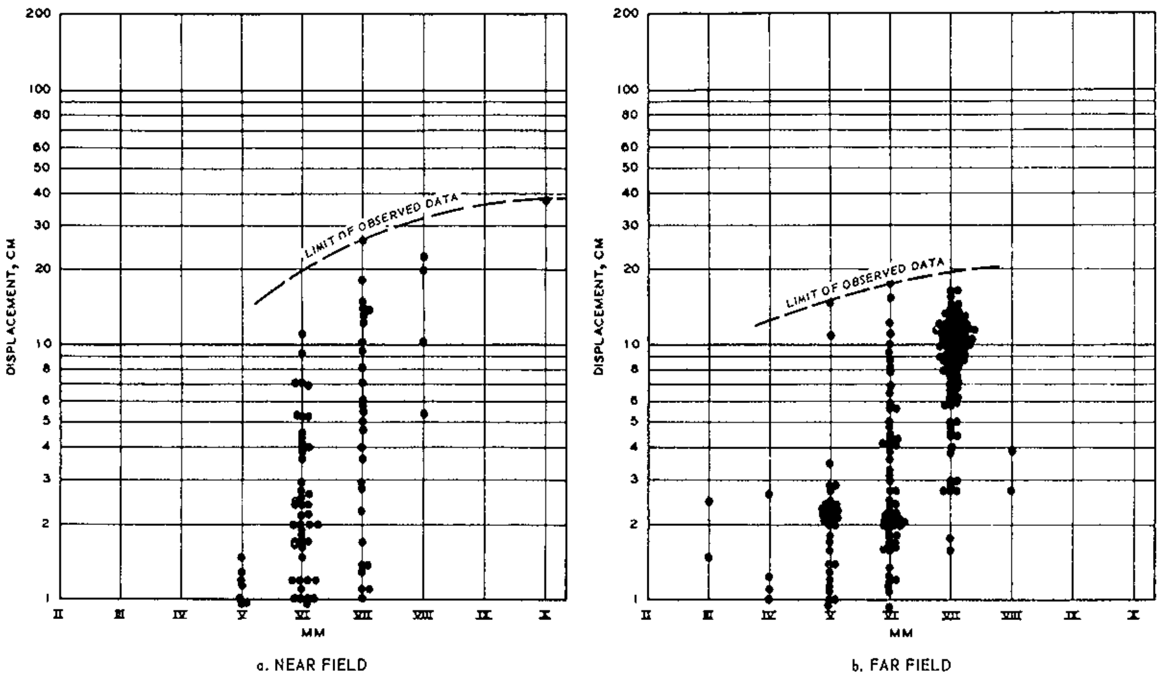


Figure 26. Intensity versus displacement in the near and far fields

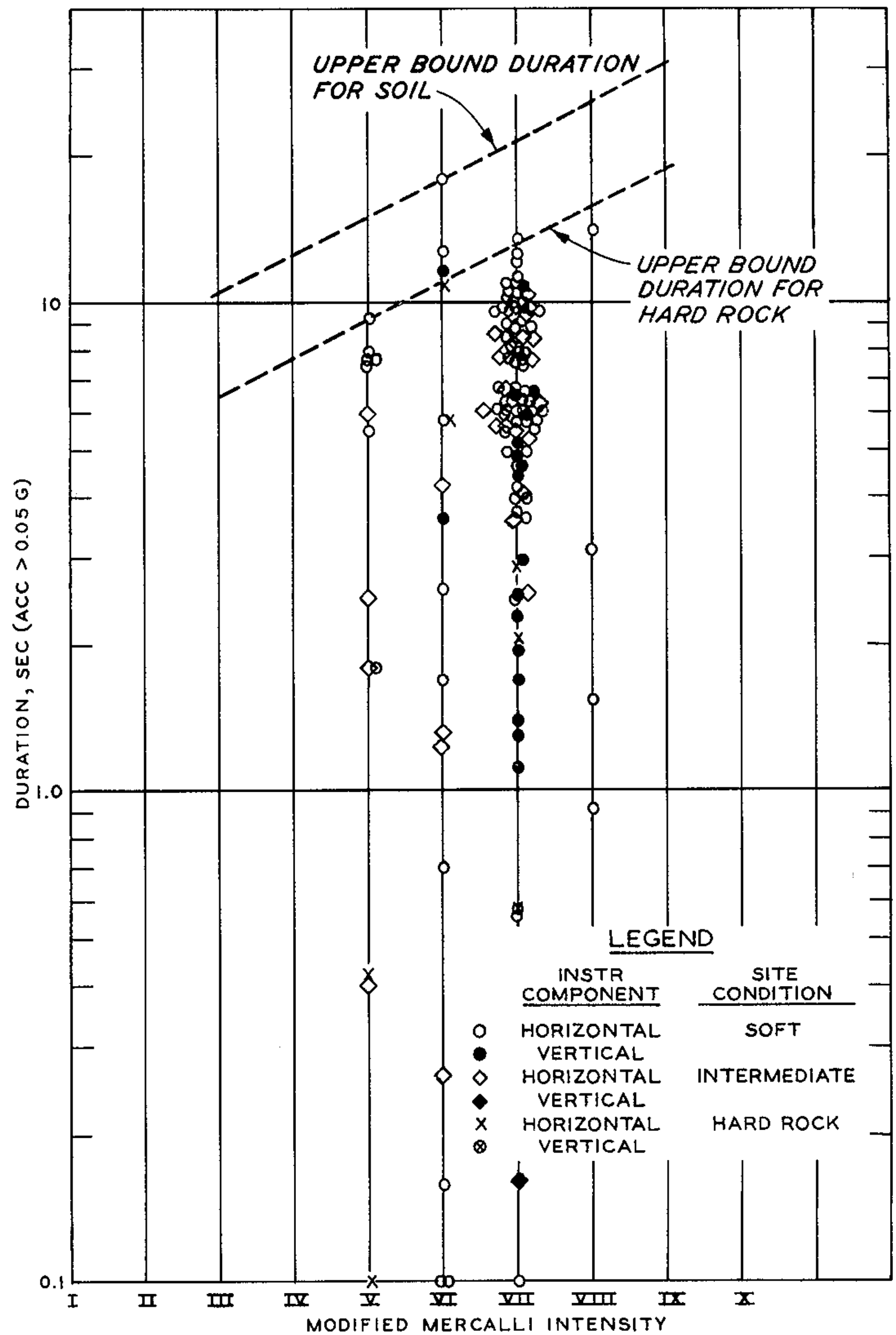


Figure 27. Relation of intensity to duration in the far field (Chang[21])

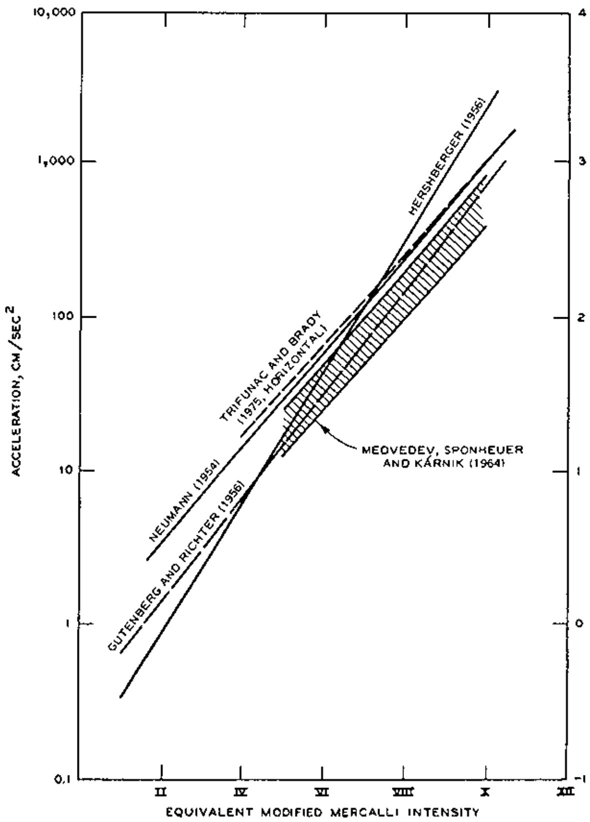


Figure 28. Commonly used correlations between intensity and acceleration

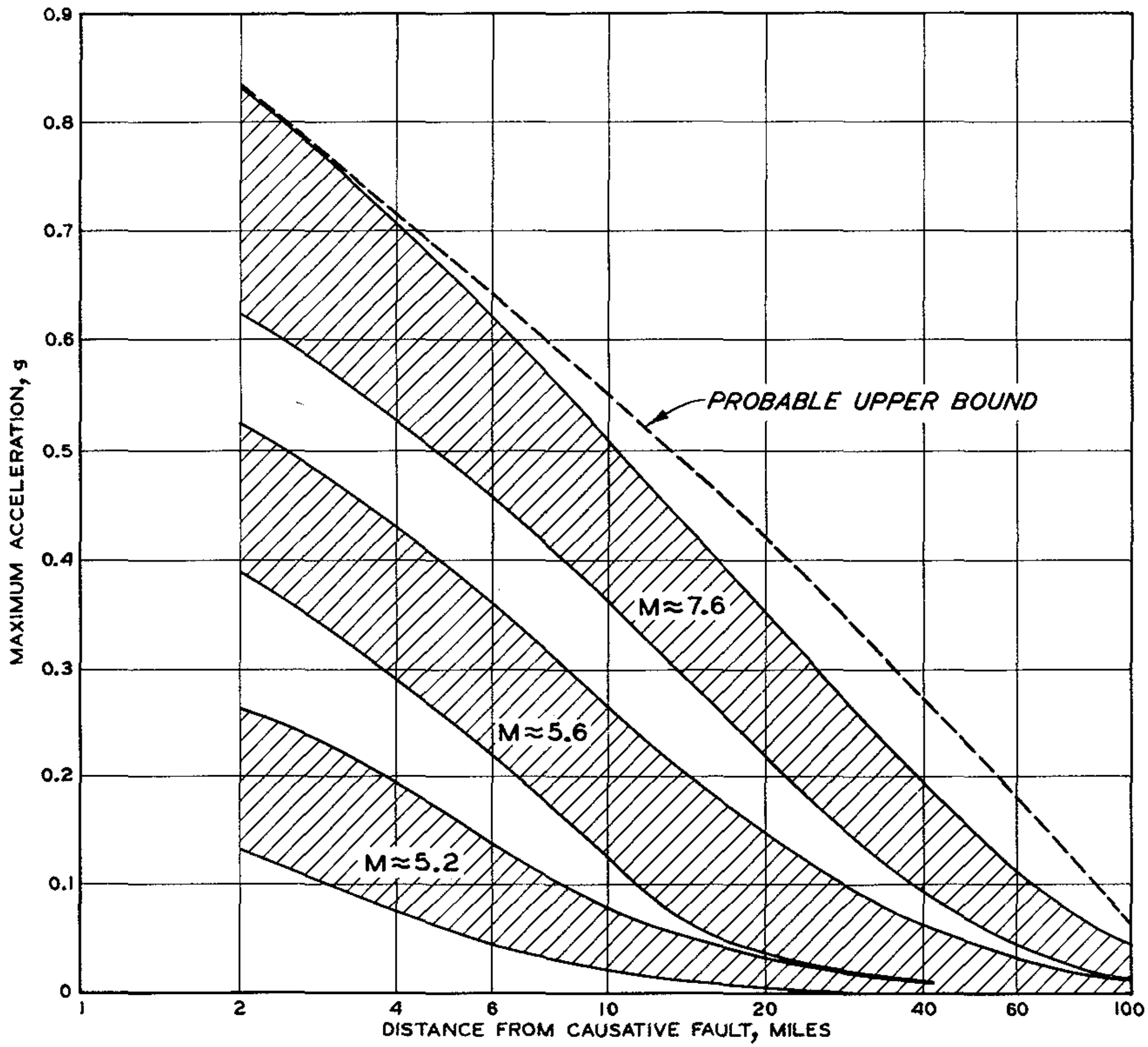


Figure 29. Ranges of maximum accelerations in rock for the western United States (from Schnabel and Seed[28])

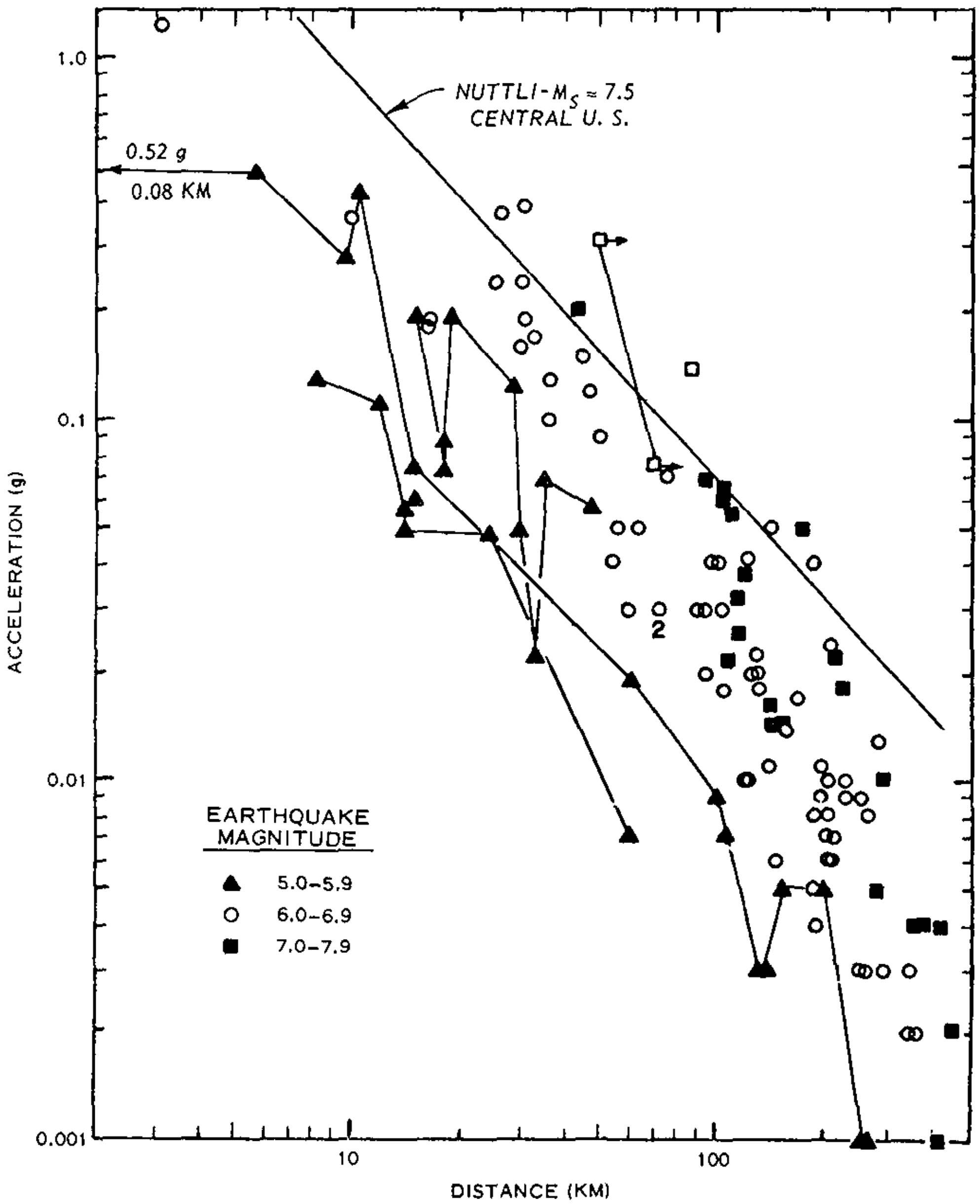


Figure 30. USGS accelerations for western United States earthquakes (Page et al.[29]) with Nuttli's[27] predictions for the central United States

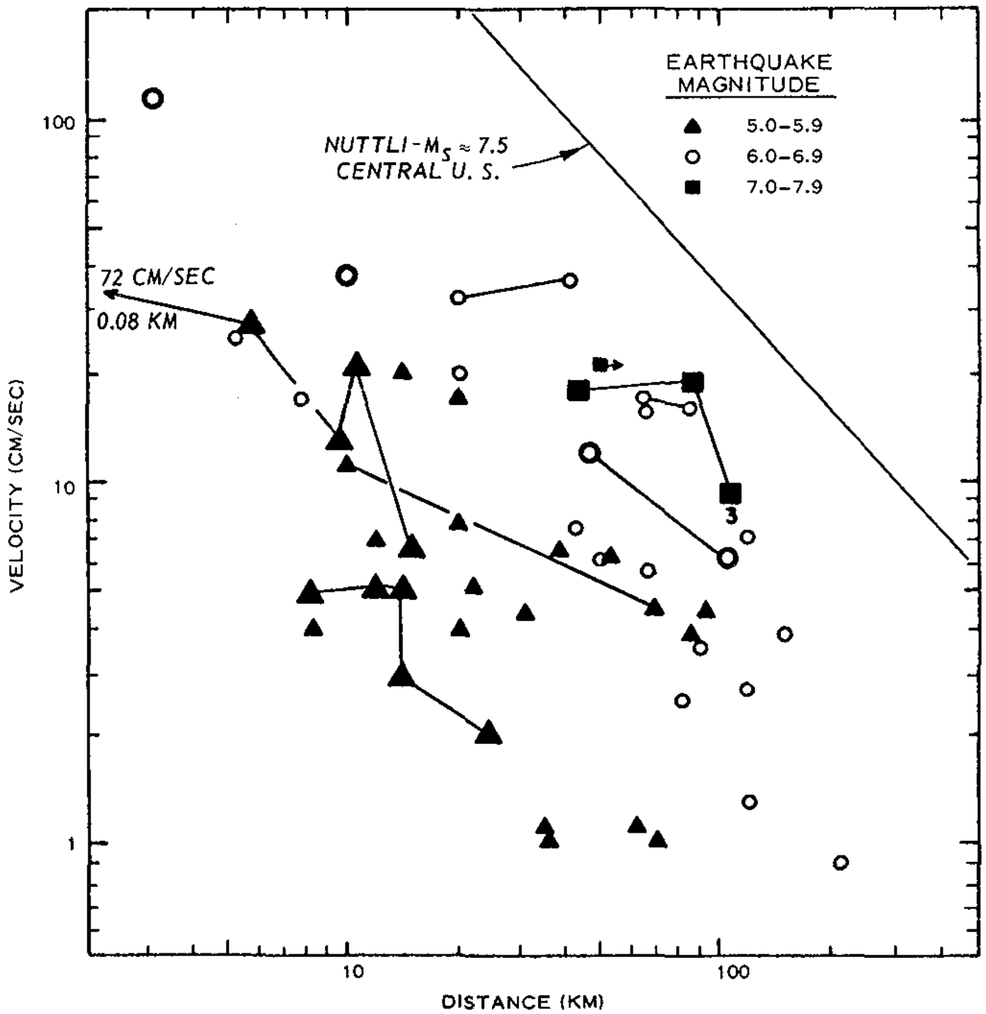


Figure 31. USGS particle velocities for western United States earthquakes (Page et al.[29]) with Nuttli's[27] predictions for the central United States

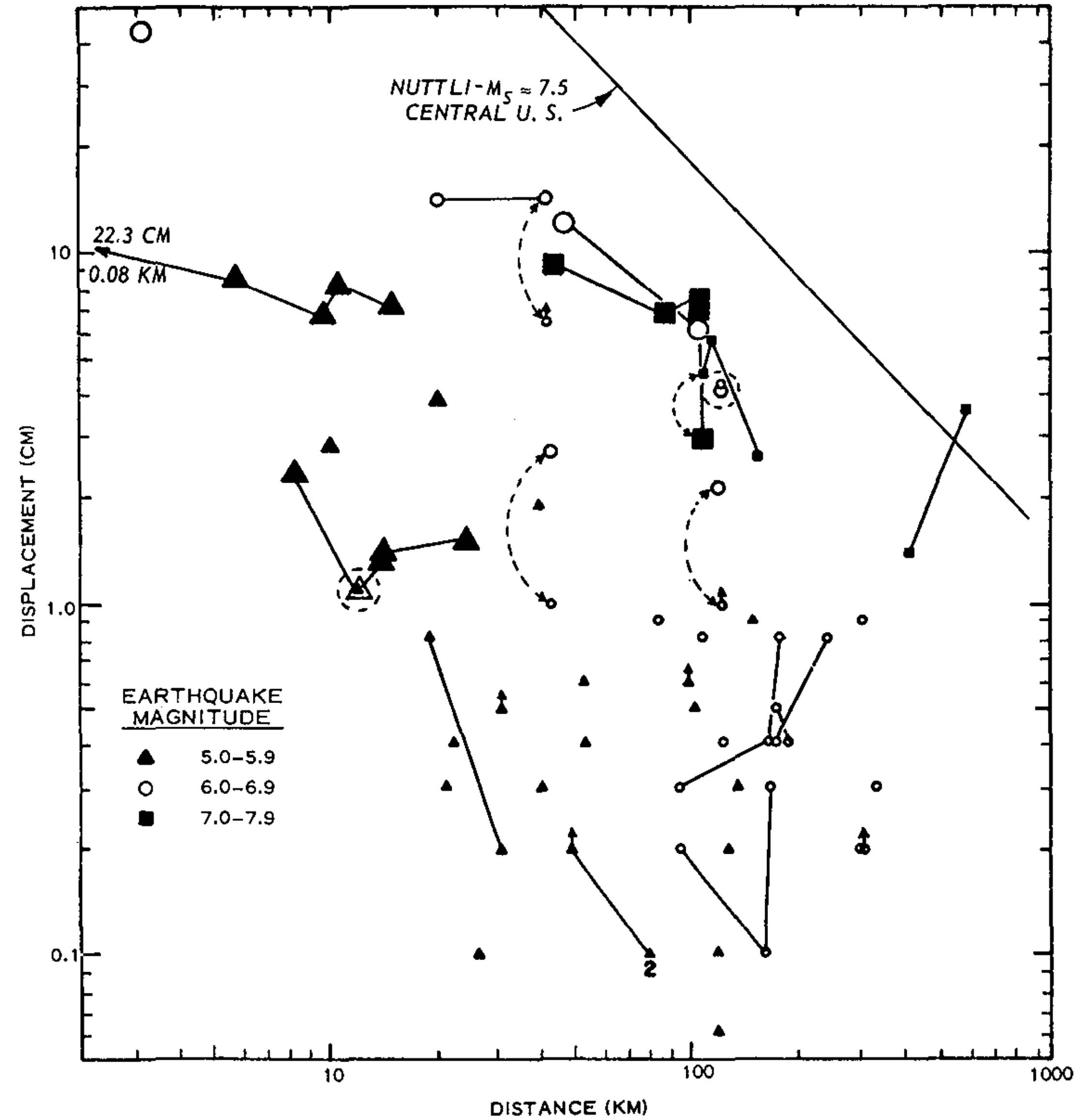


Figure 32. USGS displacements for western United States earthquakes (Page et al.[29]) with Nuttli's[27] predictions for the central United States

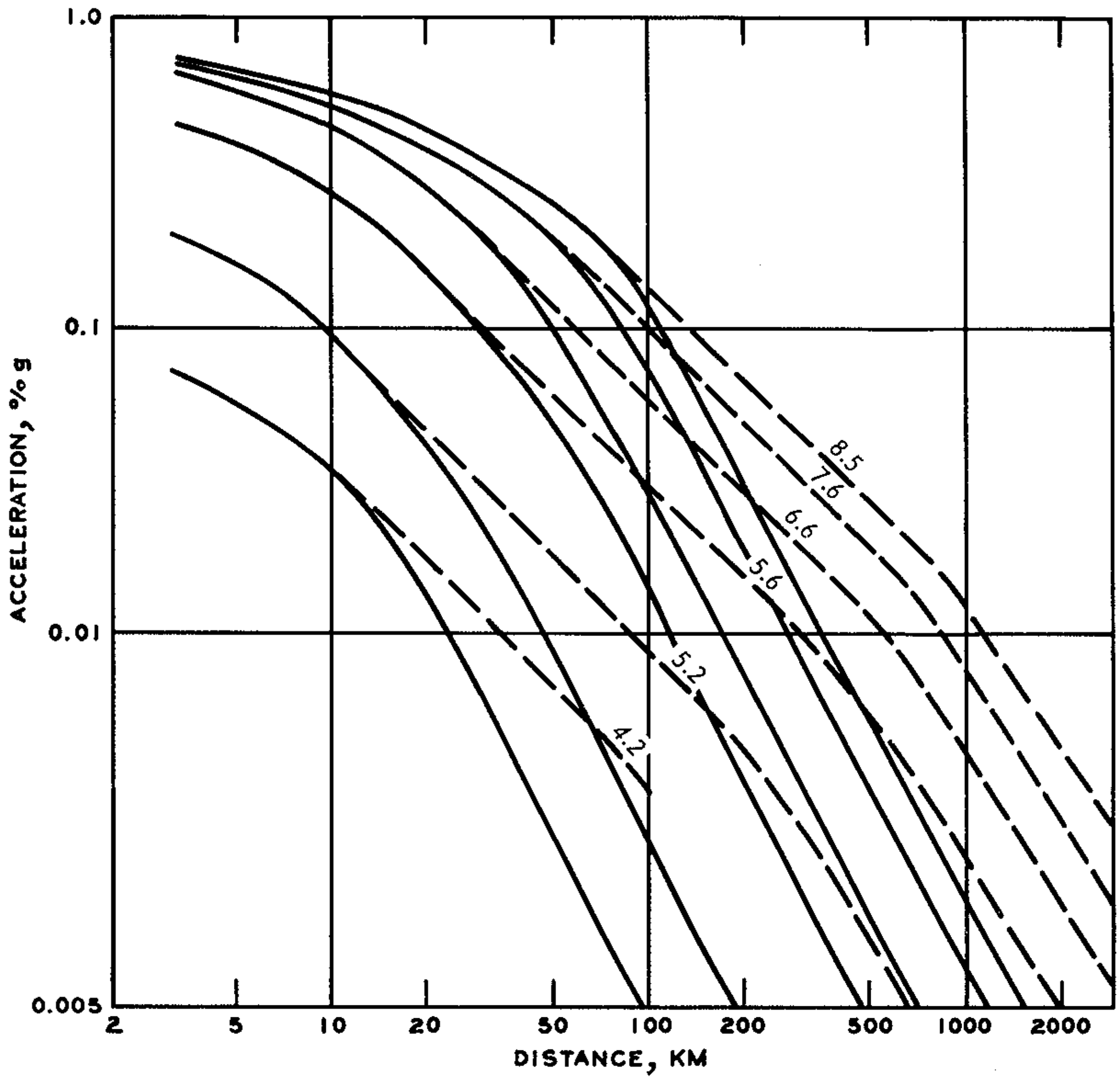


Figure 33. USGS[30] accelerations for the eastern United States (solid lines). The lines are those of Schnabel and Seed[28] and were modified (dashed lines) by imposing the attenuations of Nuttli[27] for the central United States

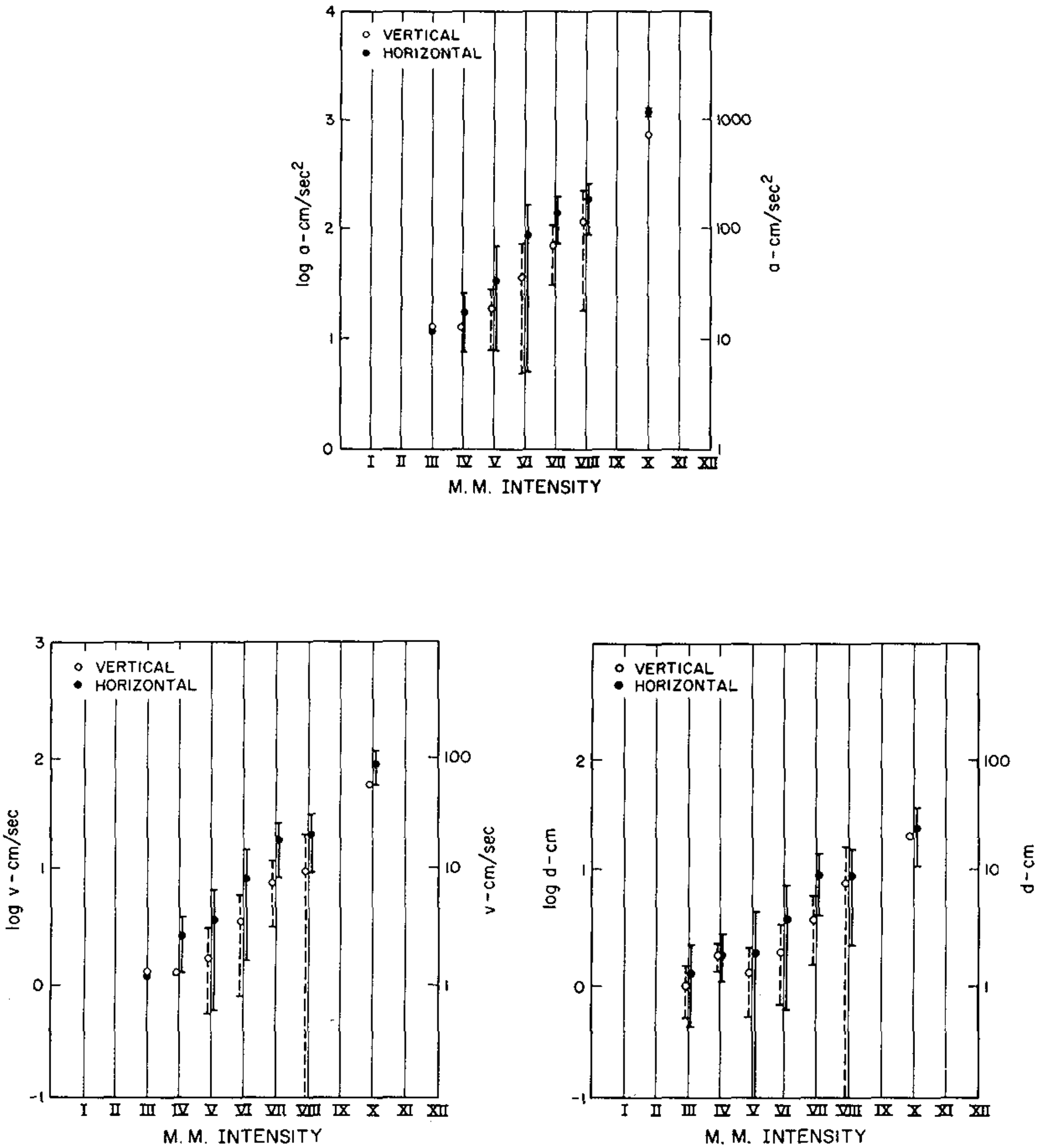


Figure 34. Ground motions versus intensity for the western United States by Trifunac and Brady.[26] Means (vertical and horizontal) plus one standard deviation are shown for (a) acceleration, (b) velocity, and (c) displacement

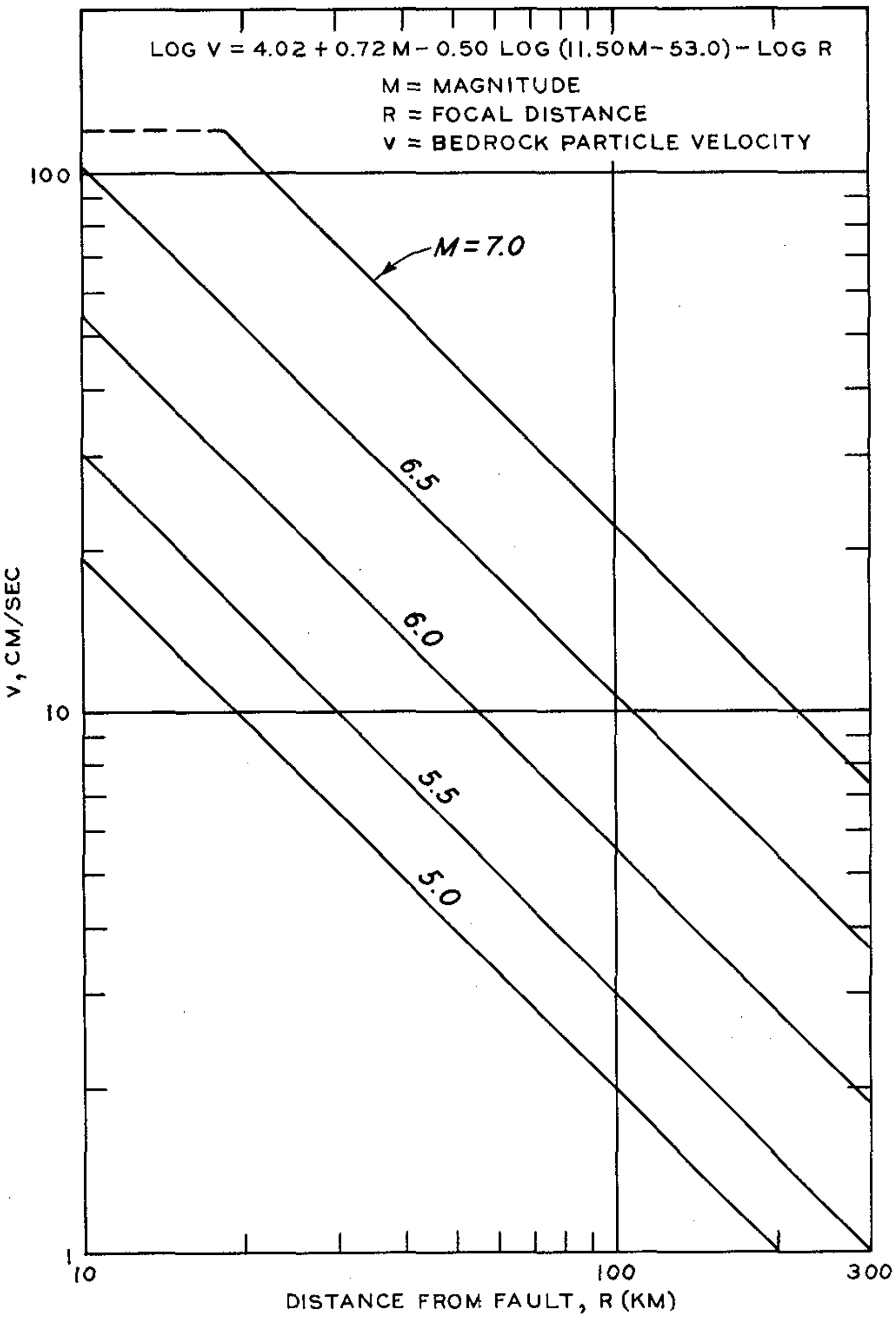


Figure 35. Maximum probable ground velocities by Ambraseys (from Johnson and Heller[31])

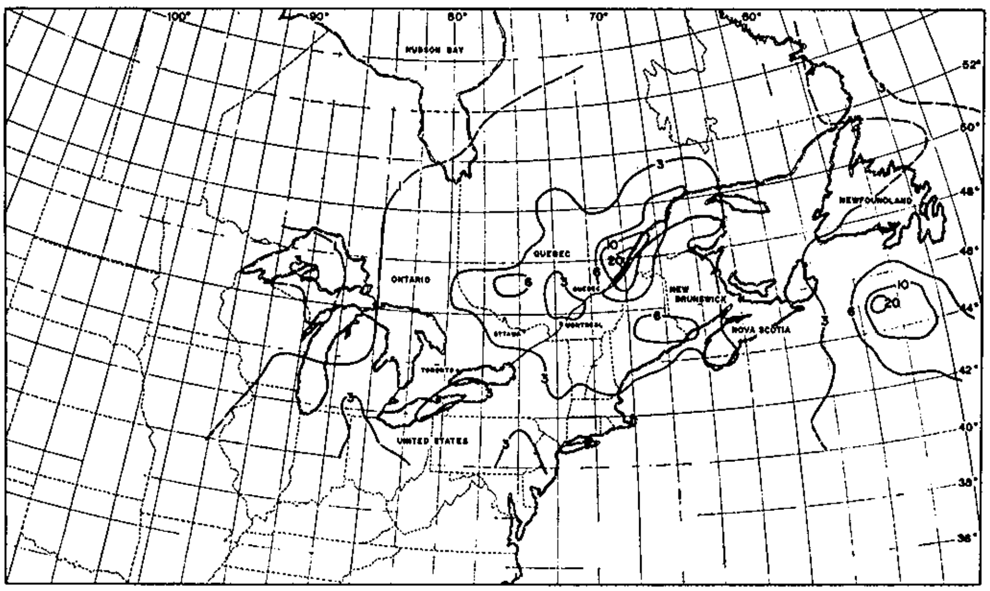


Figure 36. Accelerations as a percent of g with a 100-year return period for eastern Canada (after Milne and Davenport[19])

APPENDIX A: LETTERS FROM CONSULTANTS

Dr. David B. Slemmons
Consulting Geologist

Dr. Otto W. Nuttli
Consulting Seismologist

DAVID B. SLEMMONS
MACKAY SCHOOL OF MINES
UNIVERSITY OF NEVADA
RENO, NEVADA 89507

September 16, 1975

This letter reports on my study of the report by Ellis L. Krinitzsky and David M. Patrick on the "Dickey-Lincoln School Damsites, Maine". The results of their study were discussed at a conference at Vicksburg, Mississippi on September 16, 1975 and the Earth Resources Technology Imagery (ERTS) of the region was also reviewed.

This study is based on a special field and imagery search for active faults. No active surface faults were identified near the siting area or along the St. Lawrence Seismic Belt. My evaluation of the ERTS images corroborated the lack of any evidence of active surface faulting in this region.

The broad floor of the St. Lawrence River Valley, about 40 miles north of the siting area, has high historic seismicity with two large earthquakes of over 7 magnitude. The lack of surface faults may be due to the recency of deglaciation and the extensive cover of water and recent alluvium. The historic seismic record defines the narrow St. Lawrence Seismic Belt, which has great length and continuity (Zone A) and a sharp drop-off in frequency and magnitude of earthquakes on the southern edge of the St. Lawrence Valley (Zone B) into the stable Upland province near the site (Zone C). Zone D, a zone of higher activity, borders Zone C on the south.

I concur with the seismotectonic zoning of their report and believe that the design earthquakes are conservative and realistic for this region, and are compatible with the historic earthquake record.

Signed: David B. Slemmons
Consulting Geologist

OTTO W. NUTTLI
SAINT LOUIS UNIVERSITY
SAINT LOUIS, MISSOURI 63156

September 16, 1975

I am commenting on the seismological portions of "Earthquake Investigations at the Dickey-Lincoln School Damsites, Maine, Part I. Geological and Seismological Factors and the Selection of Design Earthquakes" by E. L. Krinitzsky and David M. Patrick.

On the basis of the historic seismicity (presented in Figure 4 of the report), I agree with the division of the region into 4 zones whose boundaries more or less parallel the boundaries of the St. Lawrence River. The authors' selection of maximum credible earthquakes (as presented in Table 4) for the 4 zones is reasonable. These maximum credible earthquakes in all four cases are of magnitude and epicentral intensity greater than that of any earthquakes which have occurred since 1600.

The quantitative relations used by the authors for attenuation of intensity with distance, and of values of ground acceleration, velocity, displacement, and duration as a function of intensity conform to the present state-of-the-art.

The values given in Table 7 are the important ones for the design of the dam. The authors of the report have considered the various methods currently used by earthquake engineers and seismologists in arriving at design values, and those which they present in Table 7 are conservative, but in a realistic sense, design parameters.

As can be seen from Table 7, the largest motions which the dams can be expected to undergo correspond to those from a Zone A type earthquake. Strong-motion records which may be scaled up to represent the ground motions at the damsites are:

Earthquake	Accelerograph Location	Epicentral Distance	Magnitude	Site Intensity	Peak Acceleration
San Fernando, Calif., Feb 9, 1971	Wrightwood, Calif. #9003	70 km	6.5		0.05 g
El Centro, Calif. Apr. 8, 1968	El Centro, Imperial Valley Irrigation District Station	41 miles	6.5		0.12 g
Northern Utah Aug. 30, 1962	Logan, Utah	46 miles	5.7	VII	0.11 g

An accelerogram which can be scaled up to represent Zone C earthquake is:

Hollister, Calif. Apr 8, 1961	Hollister, Calif.	13 miles	5.6	VI	0.16 g

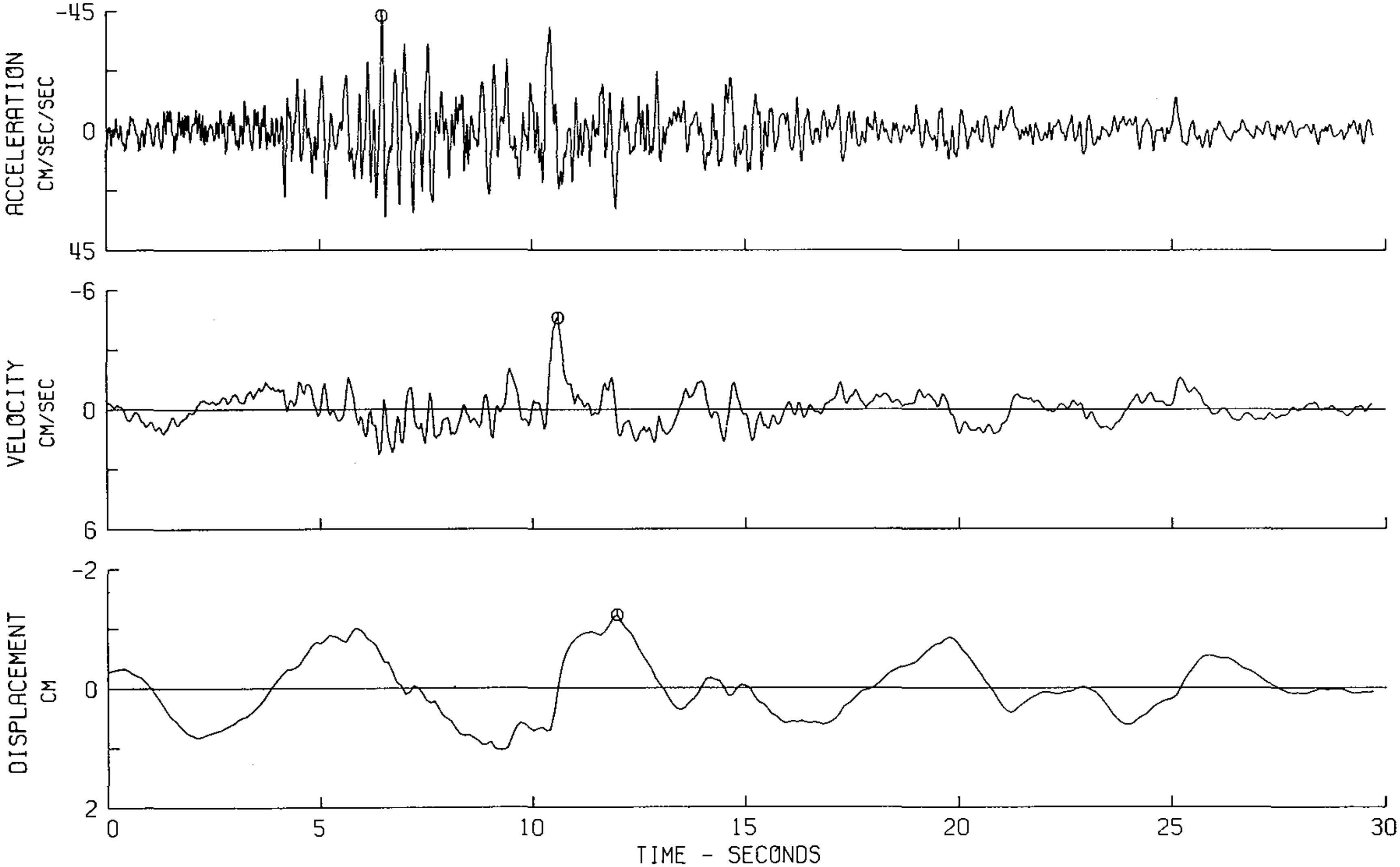
Copies of the accelerograms are attached.

Signed: Otto W. Nuttli
Consulting Seismologist

SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST

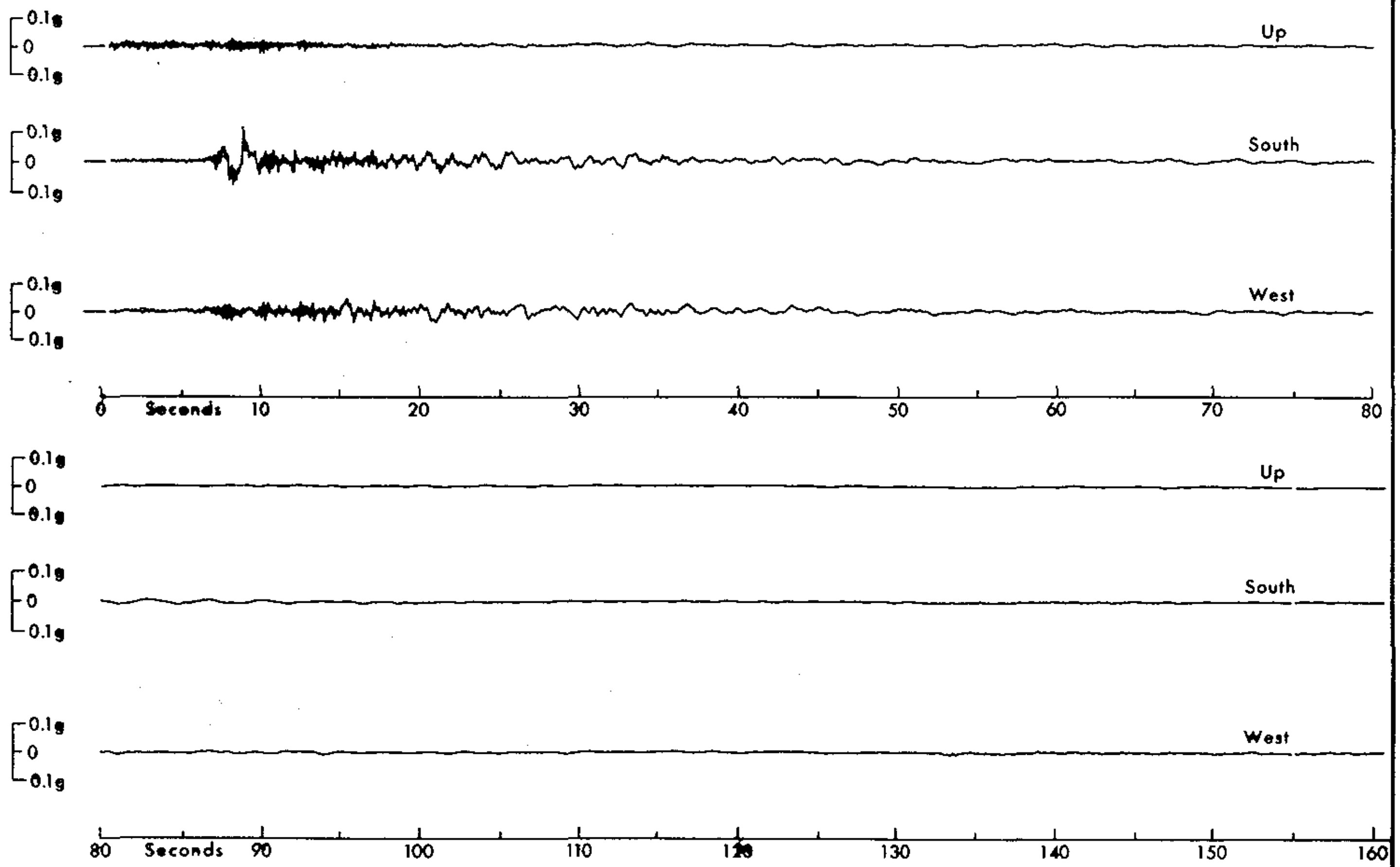
IIM184 71.159.0 6074 PARK DRIVE, GROUND LEVEL, WRIGHTWOOD, CAL. COMP S65E

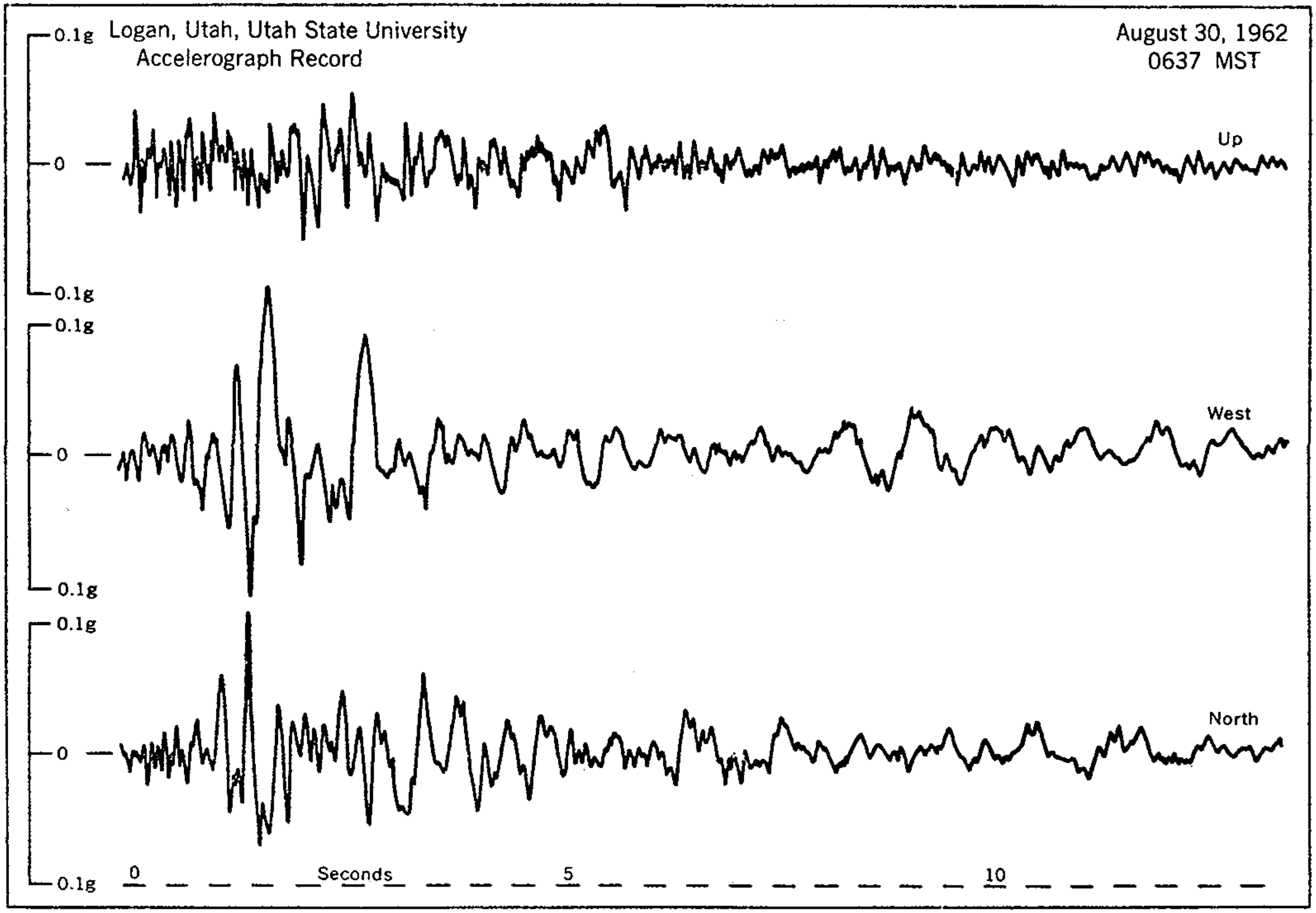
⊙ PEAK VALUES : ACCEL = -43.1 CM/SEC/SEC VELOCITY = -4.6 CM/SEC DISPL = -1.2 CM

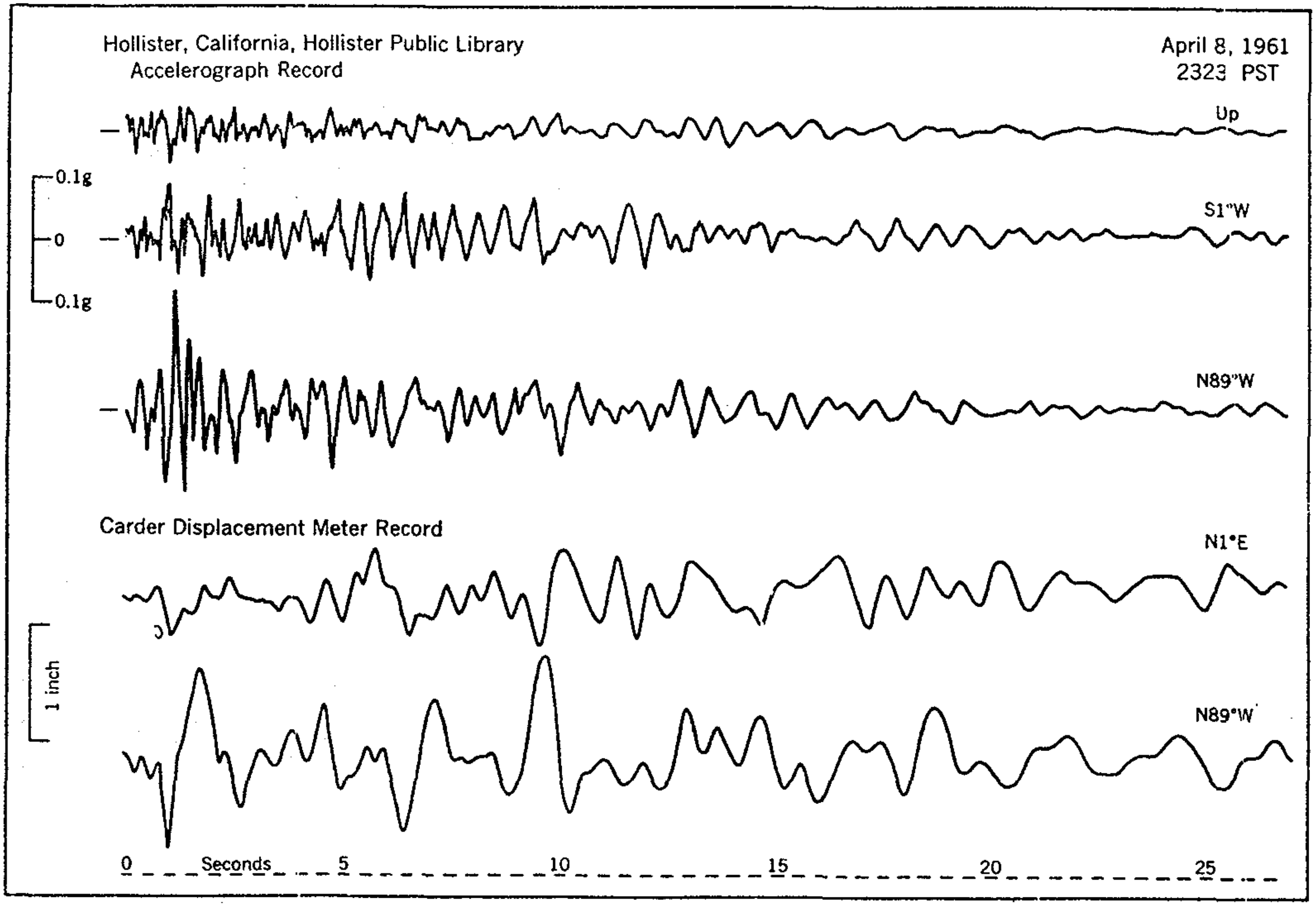


El Centro, California
Accelorograph Record

April 8, 1968
1830 PST




Logan, Utah, Utah State University
Accelerograph Record
August 30, 1962
0637 MST
0.1g
0
0.1g
Up
0.1g
0
0.1g
West
0.1g
0
0.1g
North
0
Seconds
5
10


Hollister, California, Hollister Public Library
Accelerograph Record
April 8, 1961
2323 PST
Up
0.1g
0
0.1g
S1°W
N89°W
Carder Displacement Meter Record
N1°E
1 inch
N89°W
0
Seconds
5
10
15
20
25

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Krinitzsky, Ellis Louis
Earthquake investigations at the Dickey-Lincoln School damsites, Maine, by Ellis L. Krinitzsky and David M. Patrick. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1977.
1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Miscellaneous paper S-77-2)
Prepared for U. S. Army Engineer Division, New England, Waltham, Massachusetts.
Includes bibliography.

1. Damsites. 2. Dickey Dam. 3. Earthquake hazards. 4. Geological investigations. 5. Lincoln School Dam. 6. Seismic investigations. 7. Site investigations. I. Patrick, David M., joint author. II. U. S. Army Engineer Division, New England. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper S-77-2)
TA7.W34m no.S-77-2

SR 242 Pt I

Special Report 242 Pt. I

USE OF REMOTE SENSING TO QUANTIFY CONSTRUCTION MATERIAL AND TO DEFINE GEOLOGIC LINEATIONS

Dickey-Lincoln School Lakes Project, Maine

H.L. McKim and C.J. Merry

December 1975

Prepared for
U.S. ARMY ENGINEER DIVISION, NEW ENGLAND
By
CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) USE OF REMOTE SENSING TO QUANTIFY CONSTRUCTION MATERIAL AND TO DEFINE GEOLOGIC LINEATIONS Dickey-Lincoln School Lakes Project, Maine	5. TYPE OF REPORT & PERIOD COVERED
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) H.L. McKim and C.J. Merry	8. CONTRACT OR GRANT NUMBER(s) Order No. 75-C-28
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Cold Regions Research and Engineering Laboratory Hanover, NH 03755	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS New England Division Corps of Engineers	12. REPORT DATE
	13. NUMBER OF PAGES 26
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified
	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)

Construction materials
Dams and dikes
Geological survey

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

A potential site for construction of a series of earth dams and dikes with a maximum height of 335 ft, the Dickey-Lincoln School Lakes Project, is being evaluated by the New England Division, Corps of Engineers. The site is located on the St. John River in Aroostook County, Maine, approximately 30 miles west of the town of Ft. Kent. The project is primarily designed to generate hydroelectric power, but it is also intended to provide flood control. During November 1974 a study was initiated to apply state-of-the-art remote sensing techniques to the delineation and quantification of surficial geology units to locate construction material within the headwaters of the St. John River Basin. A photomosaic was prepared from 1966 black and white photography (scale 1:33,600). Fourteen surficial geology units were delineated

in an 1100-square-mile area: alluvial fan, alluvial terrace, esker, floodplain, glacial moraine, kame, kame terrace, outwash, outwash terrace, bedrock, till, till over bedrock, wet outwash and wet till. These units were field checked and the depths estimated utilizing initial boring data, field measurements and seismometer values. The areal extent of each surficial geology unit within a four-mile radius of the three dike sites and a six-mile radius of the main dam site was quantified using a planimetric color densitometer. The volume of construction material was computed based upon these areal determinations and estimated depths. Considerable time was saved using remote sensing techniques compared with conventional ground surveys. The volume estimates obtained from this investigation were compared with the estimates of required construction material computed during the 1967 initial design phase. This comparison showed that the required construction material could be found within the prescribed area around the dam and dike sites. Because transportation of materials is a major cost in dam construction, the reduction in transportation distances determined from this study could result in considerable savings. In addition, the lineations observed on the LANDSAT imagery provided a sound base for analysis of possible tectonism in the Dickey-Lincoln area. It is believed that future movement along the east, northeast, north and N60°W lineations will be negligible.

PREFACE

This report was prepared by Dr. Harlan L. McKim, Research Soil Scientist, and Carolyn J. Merry, Research Geologist, Earth Sciences Branch, Research Division, U. S. Army Cold Regions Research and Engineering Laboratory (USA CRREL). The study was sponsored by the Foundations and Materials Branch of the New England Division, Corps of Engineers.

The study was funded by the New England Division, Corps of Engineers, Order No. 75-C-28.

This report was reviewed technically by Dr. Duwayne M. Anderson and Lawrence W. Gatto of USA CRREL and by Edwin A. Blackey of NED-CE.

The authors express their appreciation to Roy Gardner for his invaluable assistance during their field reconnaissance; to Matthew H. Pacillo and Heidi A. Deering for their assistance in drafting; to Vernon Anderson for his assistance in preparation of the drainage and surficial material maps; to James Gilbert for his assistance in analysis of lineation patterns; to Dr. Duwayne M. Anderson for his support throughout the project; to Thomas L. Marlar for his assistance as a pilot in the field; and to Edwin A. Blackey for his field assistance and technical review of this report.

CONTENTS

ILLUSTRATIONS

TABLES

USE OF REMOTE SENSING TO QUANTIFY CONSTRUCTION MATERIAL AND TO DEFINE GEOLOGIC LINEATIONS
Dickey-Lincoln School Lakes Project, Maine

by

H.L. McKim and C.J. Merry

INTRODUCTION

During November 1974, the U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL) and the New England Division - Corps of Engineers (NED-CE), Foundations and Materials Branch, began a study to evaluate the use of state-of-the-art remote sensing techniques in the delineation and quantification of surficial geology units to define various types of construction material. The primary objective of this study was to prepare a photogeologic base map to map surficial geology units within a six-mile radius and a four-mile radius of the major Dickey-Lincoln School dam site and dike areas, respectively. The secondary objective was to prepare a regional geologic lineation map from LANDSAT imagery.

This report discusses the preparation of the photogeologic base map, the mapping of the surficial geology units and the calculation of available construction material within the project area. This report also presents an analysis of the lineation patterns observable on LANDSAT imagery for the Dickey-Lincoln area.

BACKGROUND

Glacial geology

Very little is known about the glacial geology of the St. John and Allagash Rivers, located in the northernmost portion of Maine (Fig. 1). However, the headward areas of these rivers were once occupied by the Laurentide ice sheet (Fling 1971), which originated from a Labrador center during the Wisconsin glacial period (Leavitt and Perkins 1935).

The St. John River valley is an alluvial floodplain bordered by low terraces of fine gravel and sand and higher level terraces composed of irregular kame and till gravels. Above the confluence of the Allagash and Little Black Rivers, the St. John River valley widens. A lake formed in this area during the Wisconsin glaciation period, whereas ice filled the remainder of the valley (Leavitt and Perkins 1935). In many instances large gravel deposits are now located within the formerly ice-filled valley.

The preglacial Little Black River flowed parallel to the direction of ice movement over sandstones and shales. The Little Black River valley has the steep sidewalls and relatively flat stream bottom of a typical glaciated U-shaped valley (Flint 1971). In contrast, the St. John River valley lies perpendicular to the direction of ice movement and is asymmetric, with a steep northwestern

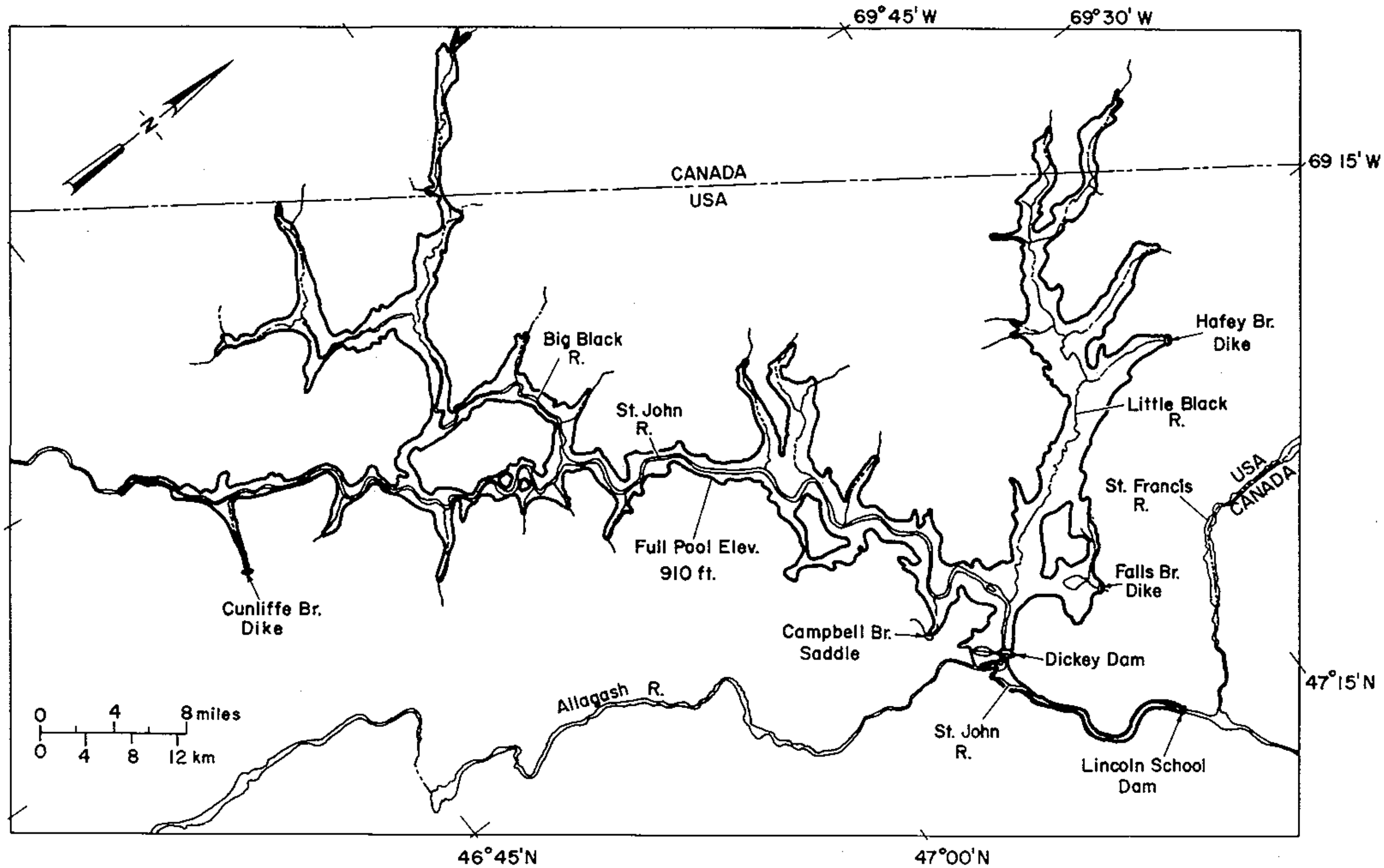


Figure 1. Site location map of Dickey–Lincoln School Lakes Project, Maine.

side and a gently sloping southeastern side. In other areas of Maine, northeast-southwest-trending valleys are also found. The steepened sidewalls are not attributed directly to jointing in the rocks, but result from glacial erosion and plucking action occurring along joint patterns (Leavitt and Perkins 1935).

Tectonics

Appalachian stratigraphic-tectonic zones and deformational sequences are related to late Precambrian to Ordovician expansion, followed by Ordovician through Devonian contraction of a Proto-Atlantic Ocean (Bird and Dewey 1970). During the late Precambrian, a continuous North American/African continent began to distend along a narrow zone associated with the early development of a tensional plate margin. Distension eventually led to the establishment of an accreting plate margin along an Appalachian Atlantic midoceanic ridge. A new oceanic lithosphere was produced during the spreading-expanding phase of Appalachian Atlantic development and lasted until Ordovician times. A miogeoclinal carbonate/starved continental rise couple was established, separated by a sharply defined bank edge after the postglacial Cambrian transgression of the continental shelf. This was deformed during the Ordovician by processes associated with the continental plate consumption. During Devonian times, a continental collision resulted in the Acadian deformation (Bird and Dewey 1970).

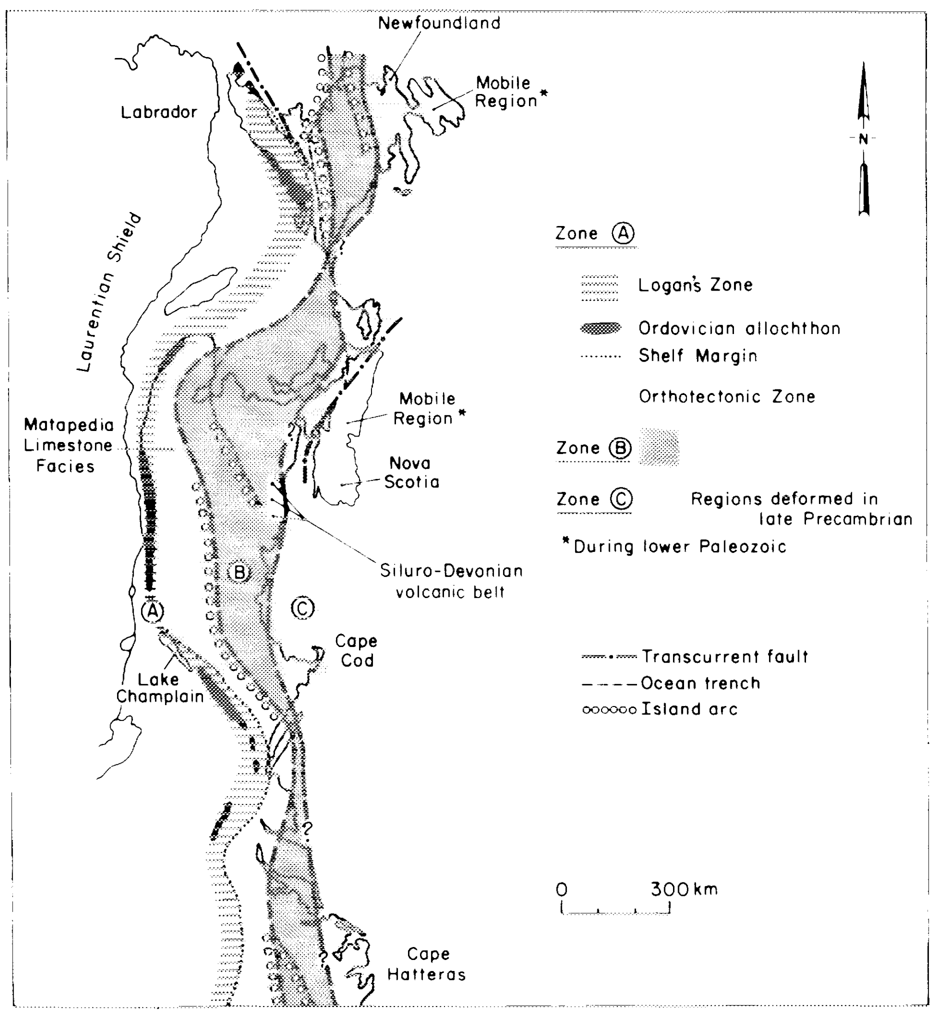


Figure 2. Zones of the Appalachian orogen (modified from Bird and Dewey 1970).

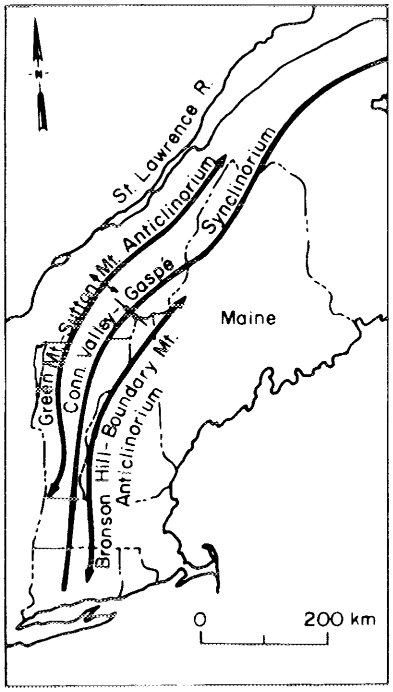


Figure 3. Regional tectonic structures in New England (modified from Zen et al. 1968).

The Appalachian orogen in New England consists of a group of three distinct zones, A, B, and C, shown in Figure 2 (Bird and Dewey 1970). Zone A, in the Dickey-Lincoln area, consists of a region dominated by the Ordovician orogeny (Taconic), but also affected by the Devonian orogeny (Acadian). A northwest-trending strip called Logan's Zone acted as a stable, nonvolcanic, orthoquartzite-carbonate miogeocline before the Taconic orogeny and then became a linear zone of exogeosynclinal subsidence and westward thrusting (Dietz and Holden 1967). Within Logan's Zone the basement rock occurs as brittle uplifts and thrust welts dating from the Taconic orogeny.

Zone B comprises Cambrian to lower Devonian sediments and volcanics that have undergone Acadian deformation. Zone C is composed of late Precambrian volcanics and sediments, deformed by Precambrian folding and block faulting.

The major regional tectonic structure present in this area is the Connecticut Valley-Gaspé synclinorium with middle Paleozoic beds transitional between the miogeosynclinal and eugeosynclinal zones (Cady 1969). The Green Mountain-Sutton Mountain anticlinorium lies to the northwest of this structure, while the Bronson Hill-Boundary Mountain anticlinorium is located to the southeast (Fig. 3). It has been suggested that the Bronson anticlinorium was the late Cambrian/early Ordovician axial site of a major deformation (Penobscot orogeny) which spread westward to become the Taconic event of Logan's Zone in middle to upper Ordovician times (Bird and Dewey 1970). This zone was a region of persistent instability and volcanism in late Ordovician times. The entire area lies within the New England-Maritime belt tectonic province (King 1951). The structural features of this tectonic province are summarized as being dominantly supracrustal Precambrian rocks underlying a relatively thin cover of Paleozoic units (Hadley and Devine 1974). Most of the structural trends have been overprinted by Paleozoic deformation so that any Precambrian structure cannot be related to regional seismic activity.

A principal region of earthquake activity (Fig. 4) occurs in northeastern New York and parts of Quebec (Hadley and Devine 1974). Many earthquakes have been recorded since the 17th century, some with a Modified Mercalli intensity of IX or higher. More than 64 earthquakes have occurred in the Montreal area and in the area northeast of Quebec City, and seismic activity still continues. This region is also characterized by a west or west-northwest-trending high-angle fault set extending into the Laurentian Shield (Hadley and Devine 1974). A northeast-trending set is limited mainly to the eastern border of the Canadian Shield along the boundary of the Appalachian tectonic system. Epicenter alignments indicate control by these fault sets; however, individual trends cannot be determined in places of high earthquake activity. Most of the earthquakes have occurred in the high-angle fault region associated with relatively late disruption of the shield, which indicates that the Precambrian structures are not involved.

Bedrock geology

A reconnaissance geologic map of the Dickey-Lincoln area (Fig. 5) shows units ranging in age from middle Ordovician to probably middle Devonian (Boudette et al. 1968). Within the immediate dam site area five bedrock geologic units out of a total of 10 mappable stratigraphic units were

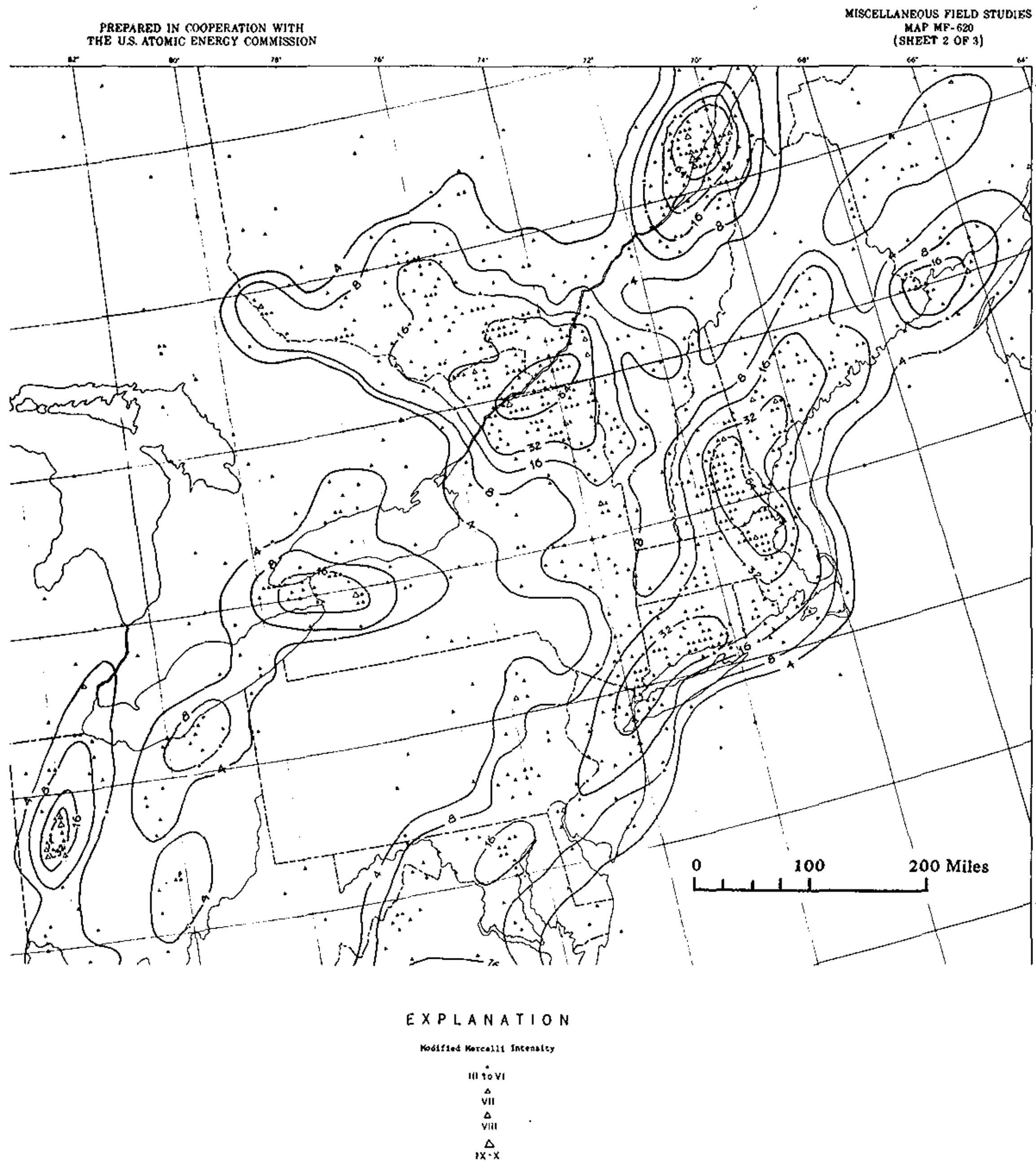


Figure 4. Major historic earthquakes in the northeastern United States (modified from Hadley and Devine 1974).

The center of each triangular symbol indicates the epicentral location of one or more seismic events, plotted to the nearest 0.1 degree of latitude and longitude. The intensity shown is maximum Modified Mercalli (MM) intensity in the epicentral area of the largest event at the plotted location. Most locations are based on observations of intensity rather than on instrumental records.

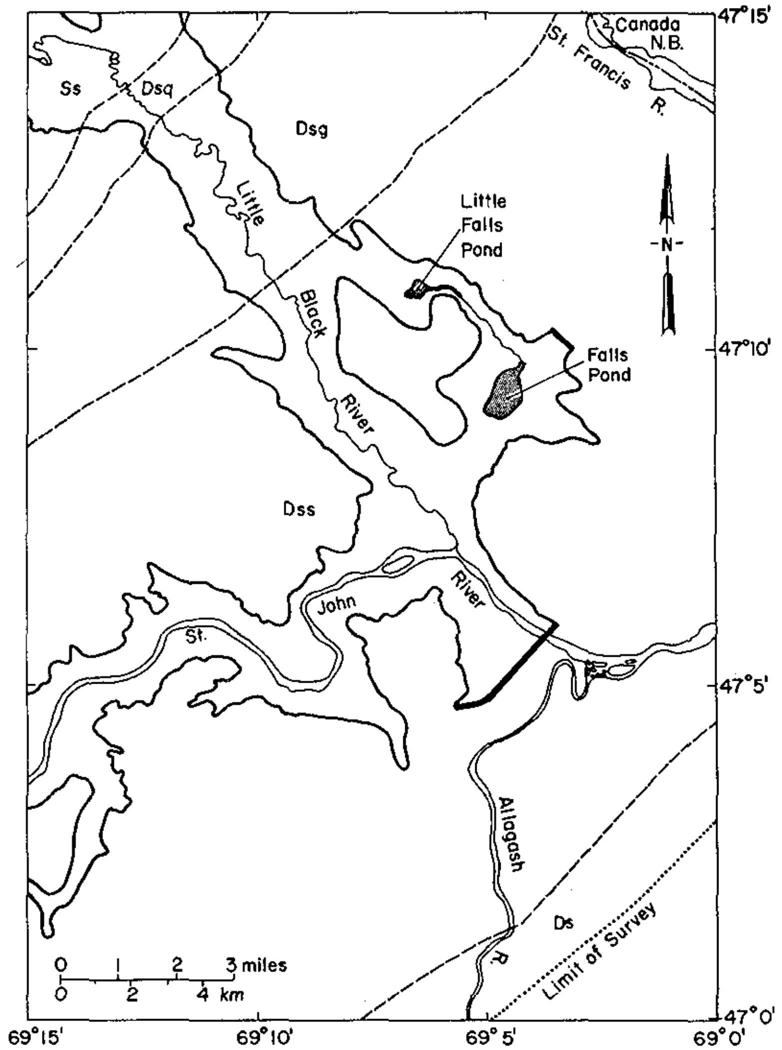


Figure 5. Reconnaissance geologic map of Allagash U.S. Geological Survey quadrangle (modified from Boudette et al. 1968).

delineated on the Allagash U.S. Geological Survey topographic quadrangle: 1) an upper Silurian unit (Ss), a gray slate with minor gray siltstone and calcareous sandstone; 2) an upper Silurian-lower Devonian unit (Dsq), orthoquartzite and minor sandstone and siltstone; 3) a lower Devonian unit (Dsg), graywacke and gray slate; 4) a lower Devonian unit (Ds), gray slate and minor graywacke; and 5) a lower Devonian unit (Dss), cyclically bedded gray slate and sandstone.

The stratigraphic units within the St. John River Basin trend northeast and generally parallel the St. John and Allagash Rivers. Polymictic conglomerate, limestone, felsite, quartz-pebble conglomerate, orthoquartzite and greenstone were found to be locally important as distinctive marker units, with slate, graywacke and arkose composing the largest volume of rock (Boudette et al. 1968).

Figure 6. Aerial view of St. John River, west of Fort Kent, Maine, showing three directions of lineations.

LINEATION ANALYSIS

An aerial reconnaissance was accomplished 15 May 1975 to check the major lineations observed on the LANDSAT imagery (Fig. 6). A lineation map of the Dickey-Lincoln area is shown in Appendix A.*

Many of the linear features observed on the LANDSAT imagery may or may not be directly correlated to faults. However, the intent of this study was not to field check all the linear features. The locations of lineations close to the dam and dike sites were of primary importance in this study.

Folded Cambrian-Ordovician rocks occur in the western part of the St. John River Basin, and Devonian-Silurian rocks occur over the remainder of the basin (Fig. 7). The compressional force of the latest pulse in the Acadian orogeny resulted in thrust faulting along lines of weaknesses. Later, normal and reverse faulting active from the Devonian throughout the Triassic offset the thrust faults at a 60° angle. This separated the strike directions of the deposited Cambrian-Ordovician-Devonian sediments. From the late Triassic to the present, the North American and African continents separated, releasing the compressional force and allowing an influx of basaltic magma to intrude along the fault planes. The last extensive Wisconsin glacial advance retreated

* Appendixes A and B are published in Part II of this report.

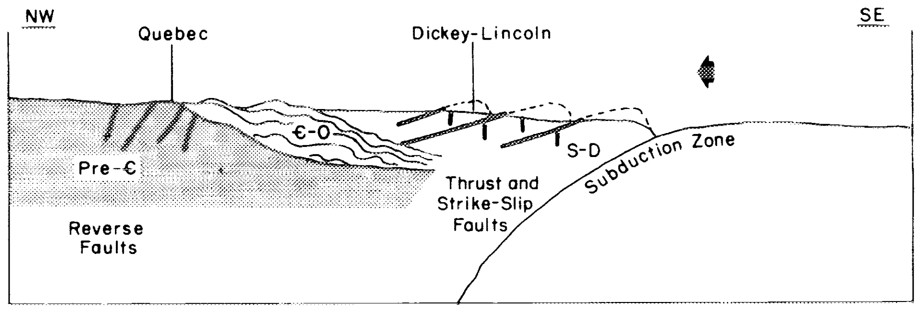


Figure 7. Schematic cross section from Quebec to Dickey-Lincoln area, Maine.

northwest across Maine and eastern Quebec, eventually uncovering the St. Lawrence lowland. The subsequent release of pressure resulted in an unstable equilibrium situation. As a result, the area underwent isostatic equilibrium as the Devonian rocks moved downward, causing the edge of the Precambrian silicic basement rock near Quebec to fracture.

Today the Quebec region is still tectonically active and will remain so until this area reaches isostatic equilibrium within the Precambrian basement rock. Because the Dickey-Lincoln area has been gradually adjusting to isostatic equilibrium deep within the sediments overlying the Precambrian basement, major earthquakes do not occur in this region. The east- and northeast-trending lineations in this region are probably thrust faults dipping 45° to the northwest, along which the major rivers presently flow (App. A). These faults in places offset the major drainage, and as a result, smaller streams have formed which drain into the main drainage channels. The lineations occurring immediately south-southeast of the St. Lawrence River are attributed to bedding folds of the Cambrian-Ordovician rocks (App. A).

APPROACH

Geologic terms

The following definitions of surficial geology units were used in this study (Gary et al. 1973):

Alluvial fan — A low, relatively flat to gently sloping mass of rock material deposited by streams and usually shaped like a segment of a cone.

Alluvial terrace — A stream deposit composed of unconsolidated alluvium.

Esker — A low, narrow, sinuous, steep-sided ridge composed of irregularly stratified sands and gravels.

Floodplain — An area of relatively smooth land composed of sand and clayey alluvial sediments deposited adjacent to a stream channel.

Glacial moraine — An accumulation of unsorted, unstratified till.

Kame — A long, low, steep-sided hill or short, irregular ridge composed of poorly sorted and stratified sand and gravel.

Kame terrace — A ridge consisting of stratified sands and gravels deposited by a glacial meltwater stream.

Outwash — Stratified sands and gravels removed or "washed out" from a glacier by meltwater streams.

Outwash terrace — A dissected and incised benchlike deposit composed of stratified sands and gravels.

Bedrock – A general term for outcrops or the solid rock underlying the soil or other unconsolidated, superficial material.

Till – Unsorted and unstratified drift, generally unconsolidated, deposited directly by and underneath a glacier, and consisting of a heterogeneous mixture of clay, sand, gravel and boulders varying widely in size and shape.

Till over bedrock – A layer of till overlying bedrock.

Wet outwash – Generally moist, tightly compacted sand and gravel material occurring in low-lying areas.

Wet till – Generally moist, tightly compacted till occupying low-lying or depressional areas.

Acquisition and use of photography

All available high- and low-altitude aerial photography of the study area is shown in Table I. Initial analysis of the data products indicated that the most appropriate scale and resolution required for the surficial geology mapping was the black and white 1:33,600 scale photography taken in 1966, whereas the geological lineation map could best be prepared from the LANDSAT multispectral imagery (scale 1:500,000). Therefore, a working photomosaic of the entire St. John River Basin above the confluence of the Allagash and St. John Rivers was used as a data base to identify construction material based on surficial geology units (App. B). This required separation of the photography into three sections with each section placed on a 4- X 6-ft Celotex board to facilitate ease in mapping, layout and handling. The following overlays were prepared:

Drainage – Drainage patterns were delineated within the entire reservoir system. The full pool elevation (910-ft) contour was transferred from the U.S. Geological Survey topographic maps to the drainage overlay utilizing a Bausch and Lomb Zoom Transfer Scope.

Surficial geology – The relationship of the tones and textures evident on the photography to topographic and geomorphic expression enabled 14 surficial geology units to be delineated. The following surficial geology units were mapped: alluvial fan (AF), alluvial terrace (AT), esker (E), floodplain (FP), glacial moraine (GM), kame (K), kame terrace (KT), outwash (O), outwash terrace (OT), bedrock (R), till (T), till over bedrock (T/R), wet outwash (WO) and wet till (WT).

Boring data locations – An overlay was prepared of selected boreholes drilled in 1966 by NED-CE in the Dickey Dam area. The logs from these were used to estimate the thickness of the 14 surficial geology units.

RESULTS AND DISCUSSION

Verification of surficial geology mapping units

On 12–16 May 1975 a field trip was conducted in the Dickey-Lincoln area to verify the mapped surficial geology units (App. B). Field descriptions of surficial material exposures, soil samples and geomorphic positions were recorded and photographs were obtained of representative surficial units within a six-mile radius of the proposed dam site. Surficial units were also field checked along the Little Black River, the Hafey Brook dike area, the Falls Brook dike area and the Campbell Brook saddle area.

Seismic surveys were accomplished at selected sites to estimate the depths of surficial geology units (Table II). In addition, depths were estimated from the field descriptions, the soil auger test holes and the 1966 NED-CE boring data.

Table I. Available photography for the Dickey-Lincoln area, Maine.

Flight	*Sensor*	*Focal length (in.)*	*Scale*	*Film type*	*Flight date*	*Format size (in.)*
U-2	RC-10	6.0	1:300,000	Aerochrome IR, type 2443 (510-900 nm)	3 June and 17 Sept 1973	9 X 9
U-2	Vinten (4 cameras)	1.75	1:445,715	Black and white plus-X, type 2402 (475-575 nm)	3 June and 17 Sept 1973	2.25 X 2.25
				Black and white plus-X, type 2402 (580-680 nm)	3 June and 17 Sept 1973	2.25 X 2.25
				Black and white IR, aerographic, type 2424 (690-760 nm)	3 June and 17 Sept 1973	2.25 X 2.25
				Color IR, aerographic, type 2422 (510-900 nm)	3 June and 17 Sept 1973	2.25 X 2.25
Forest* Service	–	8.25	1:15,840	Panchromatic black and white	1969	Photo index sheets of Dickey-Lincoln area
NED-CE	Zeiss	3.9	1:33,600	Panchromatic black and white	June 1966	9 X 9 prints; photo index sheets
SCS*	–	8.25	1:20,000	Panchromatic black and white	1966	Index sheet for Allagash Plantation
CRREL	RMK/15	6.0	1:20,000	Panchromatic black and white	Feb 1975	9 X 9
CRREL	Zeiss	6.0	1:20,000	Panchromatic black and white	May-July 1975	9 X 9
LANDSAT	Multi-Spectral Scanner (MSS)	–	1:1,000,000	Black and white	Available at 18-day intervals	9 X 9

*U.S. Department of Agriculture

Table II. Estimated depths of surficial geology units.

Unit	Estimated Depth (ft)	Number of Observations: Boring Data	Seismometer	Field measurement
Alluvial fan	15			1
Alluvial terrace	27	3		2
Esker	175			2
Floodplain	10	1		2
Glacial moraine	3			
Kame	15			2
Kame terraee	15			1
Outwash	28	7	1	3
Outwash terrace	33	8	1	4
Bedrock				10
Till	38	8	4	10
Till over bedrock	5	1		10
Wet outwash	15			2
Wet till	10			2

The surficial geology units that were investigated in the field are described below:

Alluvial fan (AF) Coarse sands and gravels; depth 15 ft.

Alluvial terrace (AT) — Fine-grained interstratified sands and silts; depth 27 ft; terrace position bordering major rivers and streams. (Fig. 8)

Esker (E) Fine earth fabric with 65% <¾-in. size, 25% ¾-4-in. size, 10% >4-in. size with few boulders >10-in. size; depth 175–200 ft. (Fig. 9)

Floodplain (FP) — Fine-grained sands and silts; depth 10–15 ft; adjacent to major rivers and streams. (Fig. 10)

Glacial moraine (GM) — Till; at two locations within the St. John River Basin.

Kame (K) — Well graded sands; depth 15 ft.

Kame terrace (KT) — Surface 4 ft fine to coarse sand; stratum from 4-8 ft 70% rocks of 0.1-2-in. size; depth 15 ft. (Fig. 11)

Outwash (O) — Well-graded, very fine to coarse sand; material >¾-in. diameter increases significantly below 20 in.; some stratification but lenses usually not greater than 6–8 in. thick; depth 28 ft; usually on 0–8% slopes. (Fig. 12 and 13)

Outwash terrace (OT) — Very coarse matrix with silt and sand seams occurring randomly throughout the 0-5 ft zone; size distribution estimated as follows: 25% < 0.1 in., 30% 0.1-¾ in., 25% ¾-4 in., 15% 4-6 in., 5% >6 in.; depth 33 ft. (Fig. 14)

Bedrock (R) — Lower Devonian Seboomook formation which varied from a fissile slate to competent, massive, blocky quartzitic slate (strike N35–45°W, jointing N50–60°W, dip 70–75°) and orthoquartzite; hilltop position. (Fig. 15, 16 and 17)

Till (T) — Generally unweathered till which varied from blue-gray compact clayey silt to a loose, silty sand; large cobbles below 24 in.; depth 38 ft; 0–30% slopes. (Fig. 18 and 19)

Till over bedrock (T/R) — Similar to till unit; depth 5 ft; 0-20% slopes.

Wet outwash (WO) — Very coarse gravel and cobbles, moist and tightly compacted; depth 15 ft; lowland position.

Wet till (WT) — Tightly compacted, similar to the wet outwash, but with more clay and silt; depth 10 ft.

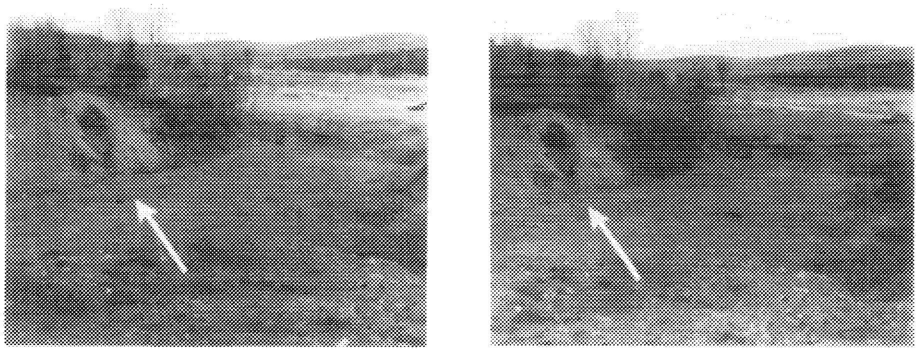


Figure 8. Alluvial terrace sands and gravels along St. John River.

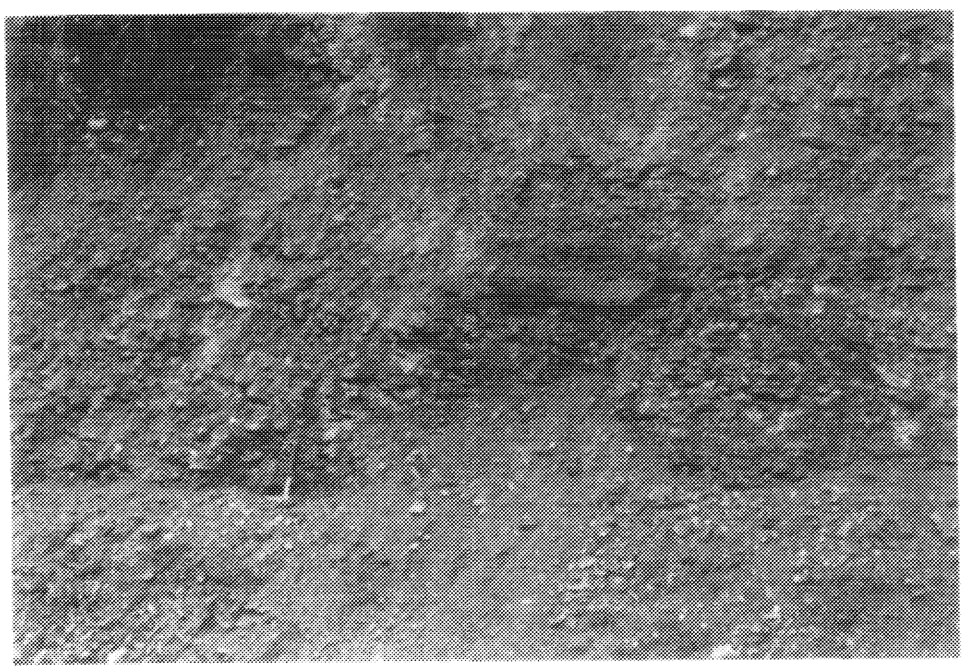


Figure 9. Esker along St. John River.

Figure 10. Floodplain unit along Little Black River.

Figure 11. Kame terrace unit along St. John River.

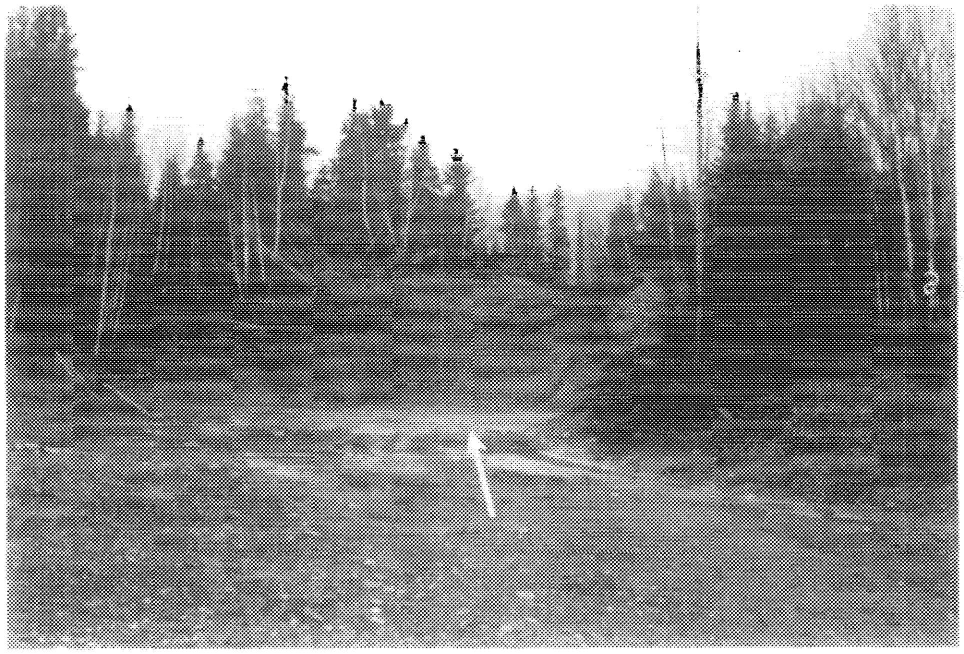


Figure 12. Fine-textured outwash unit along St. John River.

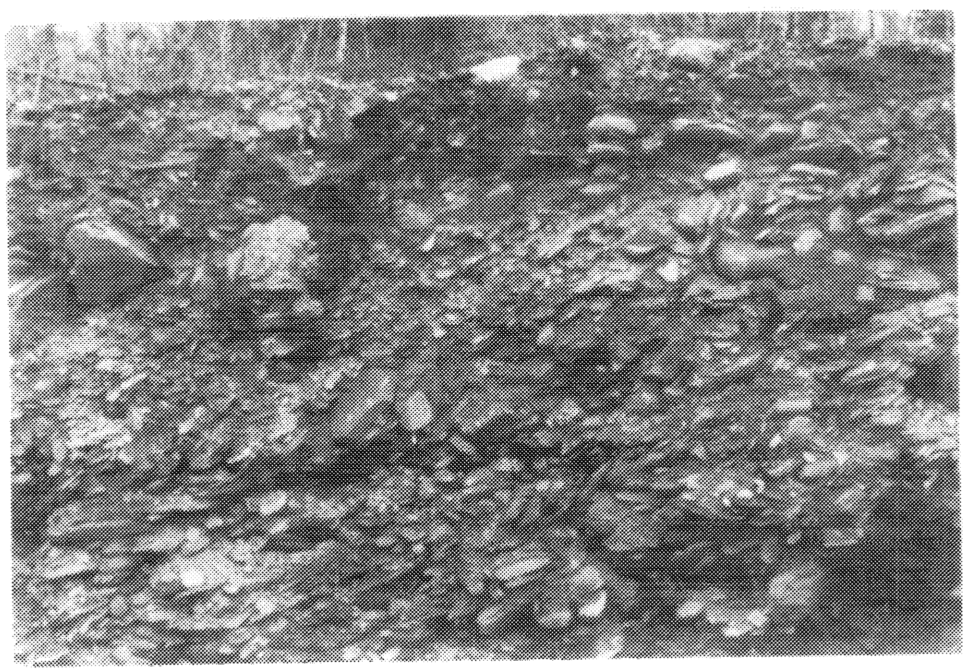


Figure 13. Coarse-textured outwash unit along St. John River.

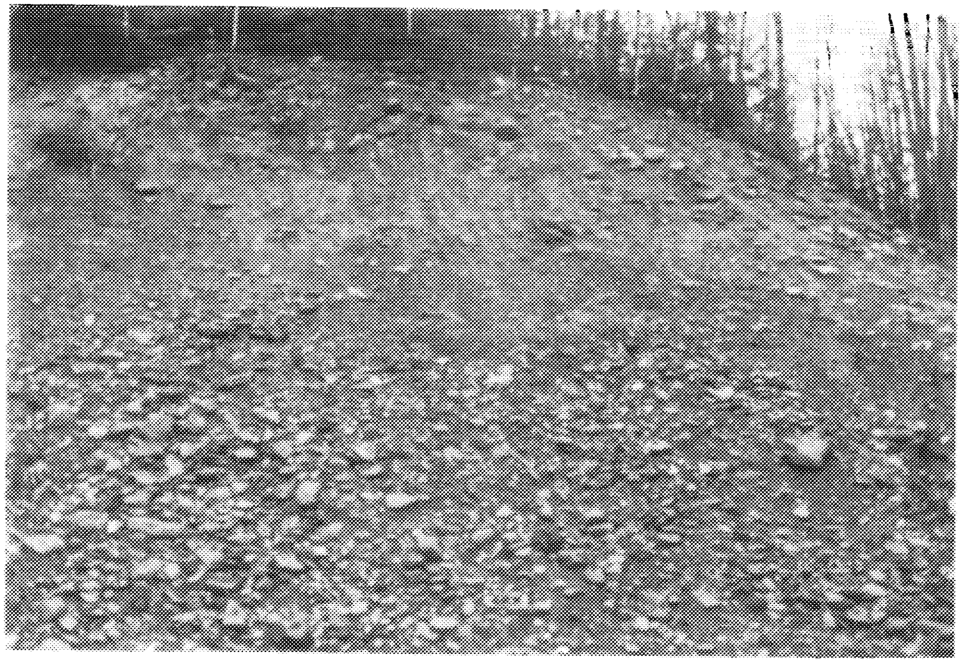


Figure 14. Outwash terrace along Allagash River.

Figure 15. Fissile slate bedrock exposure.

Figure 16. Quartzitic slate bedrock exposure.

Figure 17. Bedrock exposure along northern shore of St. John River near the dam centerline.

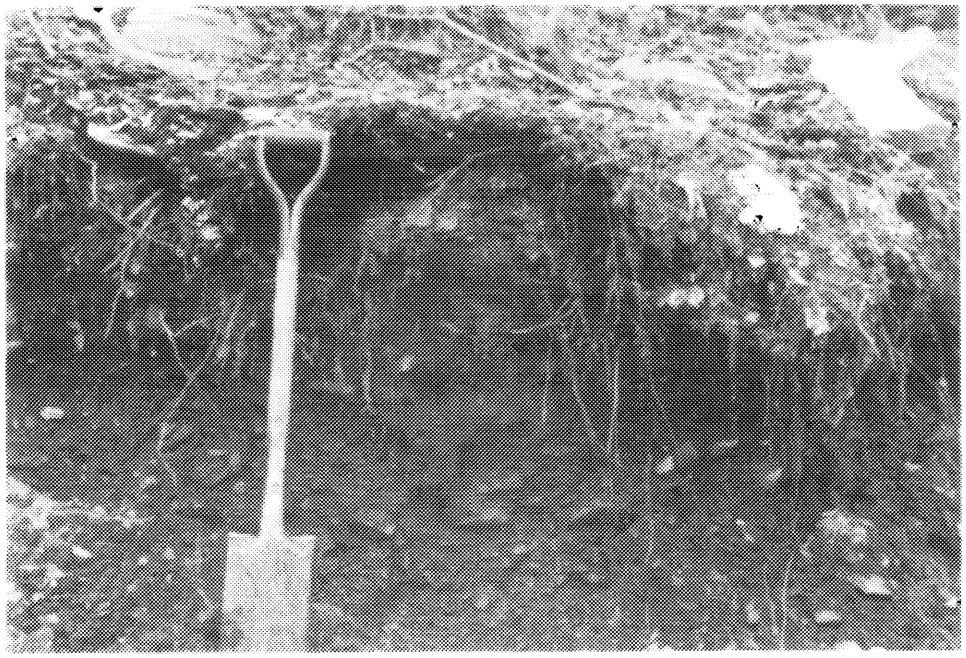


Figure 18. Fine-textured till unit.

Figure 19. Coarse-textured till unit.

Table III. Areal extent of surficial material available for the Dickey dam site (six-mile radius) and for Falls Brook, Hafey Brook and Cunliffe Brook dike sites (four-mile radius).

Unit	*Symbol*	*Dickey dam site (yd^2)*	*Falls Brook dike site (yd^2)*	*Hafey Brook dike site (yd^2)*	*Cunliffe Brook dike site (yd^2)*
Alluvial fan	AF	620,000		310,000	
Alluvial terrace	AT	8,360,000	1,860,000	1,240,000	198,000
Esker	E	1,860,000			
Floodplain	FP	3,720,000	5,260,000	3,410,000	2,920,000
Glacial moraine	GM		310,000		
Kame	K			310,000	
Kame terrace	KT	6,200,000	4,030,000	8,980,000	1,730,000
Outwash	O	16,700,000			
Outwash terrace	OT	22,300,000	2,480,000	1,240,000	
Bedrock	R	28,800,000	18,600,000	13,300,000	4,340,000
Till	T	128,000,000	53,600,000	65,400,000	81,800,000
Till over bedrock	T/R	101,000,000	52,000,000	24,200,000	36,900,000
Wet outwash	WO	6,490,000	7,430,000		
Wet till	WT	4,030,000	3,100,000	4,030,000	14,600,000

Calculation of volume estimates of construction material

The areal extent of the surficial geology units found within a six-mile and a four-mile radius surrounding the main Dickey dam site and the three dike sites, respectively, were quantified by using an Antech Inc. planimetric color densitometer (Table III). The estimated depth of each surficial geology unit was primarily selected from measurements made of field exposures (Table II). In most instances the seismometer and well core data indicated greater depths than the field measurements. However, some of the values may have been overestimated as higher elevations were approached. This is especially true for the till and terrace units. The estimated depth of each surficial geology unit (Table II) was multiplied by the areal estimate of each unit (Table III) to compute the volume of construction material within the defined area (Table IV).

The quantities of impervious borrow required for construction of structures as detailed in Design Memorandum no. 4 (NED-CE 1967) were determined by combining the till (T), till over bedrock (T/R), wet till (WT) and glacial moraine (GM) surficial geology units (Table V). These units were combined because all contained large quantities of fine-grained impermeable material. The required quantities of random and select pervious borrow were calculated by combining the alluvial terrace (AT), kame (K), kame terrace (KT), floodplain (FP) and wet outwash (WO) surficial geology units because the primary particle sizes of these materials are those of sands and gravels. The required gravel bedding and processed gravel are available from the alluvial fan (AF), esker (E), outwash (O) and outwash terrace (OT) units (Table V).

Comparison of the estimates of available construction material determined by using remote sensing techniques and ground surveys with those required for construction in Design Memorandum no. 4 (NED-CE 1967) indicates that the required amount of material is available within a six-mile radius of the Dickey dam and within a four-mile radius of the three dike sites. In most instances the volume of available construction material was greater by a factor of 10. The only exception occurred in the amount of gravel material required at the Cunliffe dike area. However, the total gravel material can possibly be obtained by substituting the excess volume of pervious material found at Cunliffe Brook.

Table IV. Volume estimates of surficial material available for Dickey dam site (six-mile radius) and for Falls Brook, Hafey Brook and Cunliffe Brook dike sites (four-mile radius).

Unit	*Symbol*	*Dickey dam site (yd^3)*	*Falls Brook dike site (yd^3)*	*Hafey Brook dike site (yd^3)*	*Cunliffe Brook dike site (yd^3)*
Alluvial fan	AF	3,100,000		1,550,000	
Alluvial terrace	AT	75,200,000	16,700,000	11,200,000	1,780,000
Esker	E	108,000,000			
Floodplain	FP	12,300,000	17,400,000	11,200,000	9,640,000
Glacial moraine	GM		310,000		
Kame	K			1,550,000	
Kame terrace	KT	31,000,000	20,200,000	44,900,000	8,650,000
Outwash	O	155,000,000			
Outwash terrace	OT	245,000,000	27,300,000	13,600,000	
Bedrock	R				
Till	T	1,620,000,000	681,000,000	830,000,000	1,040,000,000
Till over bedrock	T/R	172,000,000	88,400,000	41,100,000	62,700,000
Wet outwash	WO	32,400,000	37,200,000		
Wet till	WT	13,300,000	10,200,000	13,300,000	48,200,000

Table V. Comparison of estimates of available construction material.

Material type	*Dickey dam (yd^3)*	*Falls Brook dike (yd^3)*	*Hafey Brook dike (yd^3)*	*Cunliffe Brook dike (yd^3)*
a. Quantification of surficial material units for the Dickey-Lincoln School Lakes Project, Maine, obtained from this study.				
Impervious material (T, T/R, WT, GM)	1,800,000,000	780,000,000	884,000,000	1,150,000,000
Pervious material (AT, K, KT, FP, WO)	151,000,000	91,500,000	68,800,000	20,100,000
Gravel bedding (AF, E, O, OT)	511,000,000	27,300,000	15,200,000	0
b. Estimated quantities of borrow material required for construction of Dickey-Lincoln School Project [from Design Memorandum no. 4 (NED-CE 1967)]				
Impervious borrow	9,110,000	1,760,000	290,000	55,000
Random and select pervious borrow	46,000,000	1,180,000	400,000	
Gravel bedding and processed gravel	798,000	113,000	31,000	7,000

CONCLUSIONS

Fourteen surficial geology units were delineated in an 1100-square-mile area in northern Maine from a photomosaic prepared from 1966 black and white photography (scale 1:33,600): alluvial fan, alluvial terrace, esker, floodplain, glacial moraine, kame, kame terrace, outwash, outwash terrace, bedrock, till, till over bedrock, wet outwash and wet till. An initial surficial geology map was prepared from the aerial photography and then verified by a field trip during May 1975. The surficial geology map was subsequently updated from the field reconnaissance (App. B).

The areal extent of each surficial geology unit within a four-mile radius for the three dike sites and a six-mile radius for the main dam site was quantified using a planimetric color densitometer. The volumes of construction material were computed based upon these areal determinations and estimated depths. Considerable time was saved using remote sensing techniques instead of conventional ground surveys.

The volume estimates obtained from this investigation were compared with the estimates of required construction material computed during the initial design phase (NED-CE 1967). This comparison showed that more material could be found within the prescribed area around the dam and dike sites than was required for construction. Transportation of materials is a major cost in dam construction. The reduction in transportation distances determined from this study could result in considerable savings in cost.

The lineations observed on the LANDSAT imagery provided a sound base for analysis of possible tectonism in the Dickey-Lincoln area. It is believed that the east- and northeast-trending lineations are thrust faults dipping 45° to the northwest. The north-trending and N60°W lineations are probably strike-slip normal and reverse faults dipping 80° to nearly vertical. It is felt that future movement along these faults will be negligible.

RECOMMENDATIONS

1. It is recommended that specific sites within the six-mile and four-mile radius areas be selected for more detailed surficial geology mapping with the lower altitude 1:20,000 aerial photography obtained in May and June 1975. With this photography, the accuracy of the surficial geology unit delineations will be increased as compared with the accuracy obtained with the 1:33,600 photography.

2. A more detailed field reconnaissance should be conducted to delineate the orthoquartzite unit observed near Negro Brook and north of the St. John River near the Campbell Brook area. This reconnaissance would enhance the possibility of obtaining more adequate quantities of competent bedrock for riprap purposes closer to the construction sites at reduced transportation costs.

3. The surficial geology units mapped at a scale of 1:33,600 should be transferred to the photogrammetric maps (scale 1 in. = 400 ft) to establish depth estimations that can be used to determine more accurately the quantities of construction material available.

LITERATURE CITED

Bird, J.M. and J.F. Dewey (1970) Lithosphere plate-continental margin tectonics and the evolution of the Applachian orogen. *Geological Society of America Bulletin*, vol. 81, p. 1031–1060.

Boudette, E.J., N.H. Hatch and D.S. Harwood (1968) Geology of the upper St. John and Allagash River Basins, Maine (abs.) *Geological Society of America* Special Paper 115, p. 251–253.

Cady, W.M. (1969) Regional tectonic synthesis of northwestern New England and adjacent Quebec. *Geological Society of America* Memoir 120, 181 p.

Dietz, R.S. and J.C. Holden (1967) Miogeoclines in space and time. *Journal of Geology*, vol. 65, p. 566-583.

Flint, R.F. (1971) *Glacial and quaternary geology.* New York: John Wiley and Sons, Inc., 892 p.

Gary, M., R. McAfee and C.L. Wolf (Ed.) (1973) Glossary of geology. American Geological Institute, Washington, D.C., 805 p.

Hadley, J.B. and J.F. Devine (1974) Seismotectonic map of the eastern United States,.U.S. Geological Survey MF–620.

King, P.B. (1951) *The tectonics of middle North America.* Princeton, N.J.: Princeton University Press, 203 p.

Leavitt, H.W. and E.H. Perkins (1935) A survey of road materials and glacial geology of Maine. Orono, Maine: University Press.

New England Division, Corps of Engineers (1967) Dickey-Lincoln School Project, Design Memorandum no. 4.

Zen, E., W.S. White, J.B. Hadley and J. B. Thompson (Ed.) (1968) *Studies of Appalachian geology: Northern and maritime.* New York: Interscience Publishers, 475 p.

☆ U. S. GOVT. PRINTING OFFICE 1976-602-448 #143

GOUVERNEMENT
DU QUÉBEC
DEPARTMENT
OF NATURAL
RESOURCES
HÔTEL DU GOUVERNEMENT
QUÉBEC

Quebec, March 12, 1976

Mr. John WM. Leslie,
Chief Engineering Division,
Department of the Army,
New England Division,
Corps of Engineers,
424 Trapelo Road,
Waltham, Massachusetts 02154

Dear Sir:

I am answering your letter of February 27th.

Your request for information about the mineral deposits underlain by the up-water portion of the Dickey-Lincoln School Lakes reservoir in the Province of Quebec was investigated. Our data search did not uncover any known mineral deposits in the area concerned, which does not mean it is worthless from a mineral economics standpoint.

Hoping the above will be useful,

Yours truly,

The director of Geological Services,

André F. Laurin

AFL/FD/hb

United States Department of the Interior

BUREAU OF MINES
Liaison Office--Maine
Federal Bldg. & P. O.
Augusta, Maine 04330

March 22, 1976

Mr. George T. Sarandis
Acting Chief
Engineering Division
Army Corps of Engineers
424 Trapelo Road
Waltham, MA 02154

Dear Mr. Sarandis,

This is in reply to your letter dated February 17, 1976, regarding my assistance in obtaining data for the environmental impact statement for Dickey-Lincoln School Lakes Project.

I reviewed the reports entitled, "Scope of Work -- Environmental Impact Statement for the Dickey-Lincoln School Lakes Project" dated September 1975. The statement on pages A-6 and A-7 of Vol. II covers the scope of what is known about the area regarding minerals. I also agree with the statement on page 46 of Vol. I where it was mentioned that geological studies of the site area should be undertaken to ascertain whether there is any mineral resource potential.

After receipt of your letter, I discussed the matter with Robert Doyle, Maine's state geologist. He said that the area has had very brief reconnaissance work done regarding the geology. He also said that his office, the U. S. Geological Survey and the University of Maine Department of Geology recommended that at least 68 man weeks are required to study the basic geology of the upper St. John River Basin.

Based on the information available, this office is not able to site location, magnitude or the estimated worth of the mineral deposits within the resevoir areas.

HERBERT R. BABITZKE
USBM Liaison Officer--Maine

cc:
R. G. Doyle
R. S. Babb

CRREL
REPORT 76-37

CRREL

Airborne resistivity and magnetometer survey in northern Maine for obtaining information on bedrock geology

CRREL Report 76-37

Airborne resistivity and magnetometer survey in northern Maine for obtaining information on bedrock geology

P.V. Sellmann, S.A. Arcone and A. J. Delaney

October 1976

Prepared for
U.S. ARMY ENGINEER DIVISION, NEW ENGLAND
By
CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: CRREL Report 76-37	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE *(and Subtitle)*: AIRBORNE RESISTIVITY AND MAGNETOMETER SURVEY IN NORTHERN MAINE FOR OBTAINING INFORMATION ON BEDROCK GEOLOGY	5. TYPE OF REPORT & PERIOD COVERED
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): P.V. Sellmann, S.A. Arcone and A.J. Delaney	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire 03755	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: DA Project 4A762719AT24, Task A2, Work Unit 003
11. CONTROLLING OFFICE NAME AND ADDRESS: U.S. Army Engineer Division, New England, Waltham, Massachusetts 02154	12. REPORT DATE: October 1976
	13. NUMBER OF PAGES: 24
14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*	15. SECURITY CLASS. *(of this report)*: Unclassified
	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

Partially funded by Directorate of Military Construction, Office, Chief of Engineers, Washington, D.C. 20314

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

Aerial surveys
Allagash, Maine
Electrical resistivity
Geophysics
Structural geology
Subsurface investigations

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

Geophysical studies were conducted during September and October of 1975 in northern Maine to locate rock types suitable for construction purposes for the proposed Dickey-Lincoln School Dam Project. Simultaneous airborne magnetometer and VLF electrical resistivity surveys were performed over an area of approximately 920 km^2 surrounding the confluence of the St. John and Allagash rivers. The resulting data were used to construct contour maps of apparent resistivity and of total magnetic intensity above the earth's background magnetic field. During the same time period, ground and multi-elevation surveys were performed over a special test sector of known geology. The ground and airborne study in the test sector aided in interpretation of the data by revealing a strong correlation

20. Abstract (cont'd)

between igneous geology, resistivity, and magnetic intensity. Lack of a similar correlation between resistivity and magnetic data in the remainder of the survey area suggested an absence of additional areas of igneous rocks. The multi-elevation survey of the test area indicated that changes in flight altitude, necessitated by the topographic relief encountered, would not seriously affect the regional resistivity patterns. Although there was no strong evidence of igneous rocks outside the test sector, suitable rock types may exist within the Dss geologic unit (cyclically bedded gray slate and sandstone) in the central part of the main survey area, where most of the high resistivity contours occur.

PREFACE

This report is a presentation and analysis of the electrical resistivity and magnetometer airborne surveys flown in September and October of 1975 in coordination with the proposed Dickey-Lincoln School Dam Project in northern Maine. It was prepared by Paul V. Sellmann, Geologist, of the Northern Engineering Research Branch, Experimental Engineering Division, and by Steven A. Arcone, Geophysicist, and Allan J. Delaney, Physical Sciences Technician, of the Physical Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. The Foundations and Materials Branch of the U.S. Army Engineer Division, New England funded the research. Previous CRREL participation in this project includes investigation of the surficial geology of the area and tectonic activity of the region (McKim and Merry 1975).

The airborne surveys were flown by Barringer Research Ltd. of Toronto, Canada, under contract to the New England Division of the U.S. Army Corps of Engineers. The multi-elevation surveys and ground studies were supported by DA Project 4A762719AT24, *Design, Construction and Operation Technology for Cold Regions*, Task A2, *Soils and Foundation Technology for Cold Regions*, Work Unit 003, *Electromagnetic Methods for Subsurface Exploration* (QCR 1.07-CARDS 114). Upon completion of the surveys all data, maps, flight records, photography, and daily logs were sent to CRREL where further processing, evaluation, and geologic interpretations and correlations were performed.

Pieter Hoekstra and Frank Jagodits technically reviewed the manuscript.

The contents of this report are not to be used for advertising or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

CONTENTS

ILLUSTRATIONS

TABLES

SUMMARY

Simultaneous airborne magnetometer and VLF resistivity surveys were conducted in northern Maine to locate rock types suitable for construction purposes. This was done for the New England Division of the U.S. Army Corps of Engineers in response to anticipated requirements for the proposed Dickey-Lincoln School Dam Project. The surveys covered approximately 920 km^2. In addition, a small, special test area of known bedrock geology was surveyed to establish specific ground correlation and to examine the effects of flight altitude upon resolution.

Over the special test area both the contoured magnetometer and resistivity data differentiated the known igneous geology from the surrounding slate. Resistivity data obtained by ground VLF methods correlated well with the airborne resistivity results. The magnetic data indicated a normally expected degree of magnetic mineralization associated with the granodiorite and syenite in the test area, which can contain magnetite as an accessory mineral (Boone 1962). The multi-elevation surveys were flown at mean flight altitudes of 150 m and 300 m. The general distribution of anomalies at the higher altitudes remained unchanged, although detail was decreased. These results implied that local changes in altitude occurring during this survey would not cause any significant loss in resolution. In general, the test area results ensured the reliability of the overall survey and established a basis for airborne identification of igneous rocks for this study.

The data from the entire survey indicated the following results:

1) No other resistivity anomalies occurred with values as high as those associated with the igneous rocks of the test area.

2) No magnetic anomalies were found outside the test sector.

3) The more resistive areas outside the test sector corresponded with a cyclically bedded gray slate and sandstone unit in the central part of the survey area.

4) The resistivity data corresponded well with mapped reconnaissance geology of the region (Boudette et al. 1966).

From these results it was concluded that no new sources of igneous rocks are apparent. Rocks most suitable for construction purposes near the dam site may occur in the central part of the survey area, which is associated with areas of high resistivity.

AIRBORNE RESISTIVITY AND MAGNETOMETER SURVEY IN NORTHERN MAINE FOR OBTAINING INFORMATION ON BEDROCK GEOLOGY

P.V. Sellmann, S.A. Arcone and A.J. Delaney

INTRODUCTION

Knowledge of the distribution and quality of bedrock within the area of the proposed Dickey-Lincoln School Dam Project is important for development of construction plans and environmental impact statements. At the conception of this study known sources of rock suitable for construction purposes were of limited extent, since the most common rock type in the area is slate. The most suitable rocks are part of a remotely situated intrusive body more than 19 kilometers from the proposed dam site. Background geologic information is available from a regional reconnaissance study and a detailed investigation of the known intrusive complex (Boudette et al. 1966, Boone 1962). Based on these studies the New England Division of the Corps of Engineers (NED) felt that additional data were required to determine if unknown sources of rock suitable for construction purposes could be located nearer the project sites. As a result, CRREL was approached to determine if resistivity techniques could be used as an aid in obtaining this information.

In March 1975 a preliminary study was made to determine if resistivity contrasts of known rock types in the region were great enough to justify an extensive ground or airborne survey using the radiowave resistivity technique at VLF (very low frequency) which is the frequency range best suited for a bedrock study. It indicated that contrasts in the electrical properties between the intrusive rocks and other rock types in the area were great enough to permit this method to be considered for the proposed purpose, as well as for providing additional general information on bedrock properties (Sellmann et al. 1974, 1975). As a result of this work CRREL recommended that additional field investigations were warranted, and both an airborne resistivity and magnetometer survey were contracted. The surveys were used to complement each other, providing both electrical and magnetic property data for the rock types as well as a means of detecting magnetic mineralization.

The extent of airborne survey coverage was jointly determined by NED and CRREL project personnel (Fig. 1). Because of the large size and irregular shape of the total reservoir impoundment limits, complete airborne survey coverage was not practical or considered necessary. With the emphasis of this project placed on obtaining bedrock data, the more central part of the area near the proposed major construction activity was covered in detail. For control purposes these limits were also adjusted to include all previously mapped major rock types. Other factors influenced shape, e.g. the minimum practical length of flight lines, which is approximately 16 km, and the spacing of flight lines. A flight line spacing of 0.4 km was used for this study, in contrast to a tenth of a mile used on some previous surveys (Hoekstra et al. 1974).

In areas outside the main survey, pairs of magnetometer profiles were flown along the drainage networks. Only magnetometer data were obtained, since these can be acquired independently of flight line orientation, while resistivity lines must be flown at a fixed orientation for maximum coupling with the remote VLF transmitter.

During the first week of the airborne survey extensive ground measurements were performed in a special test sector of known bedrock geology, shown

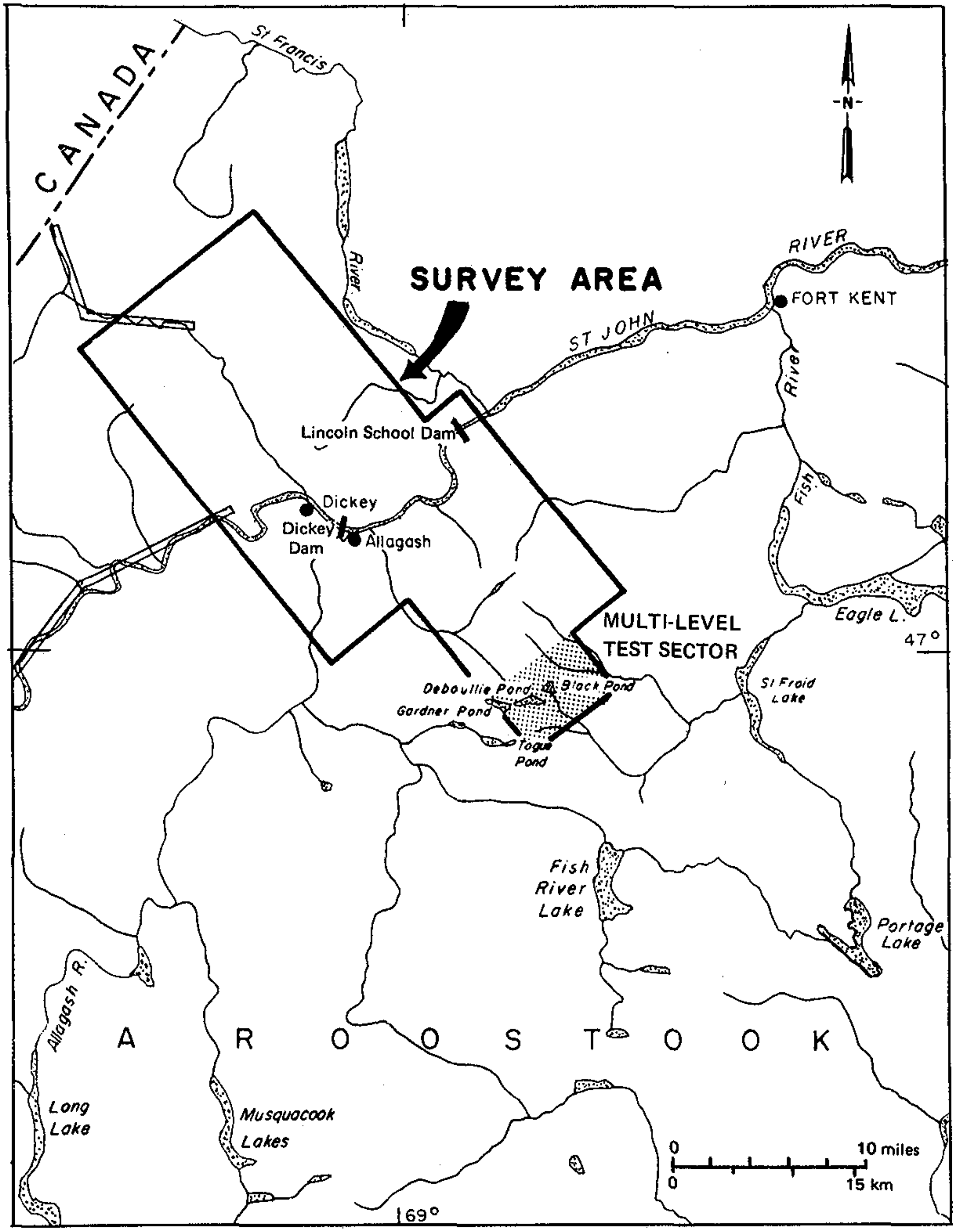
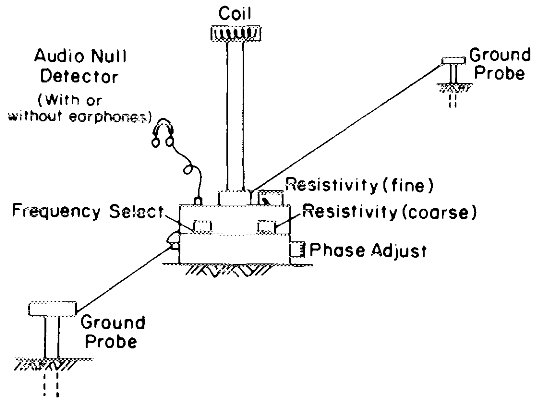
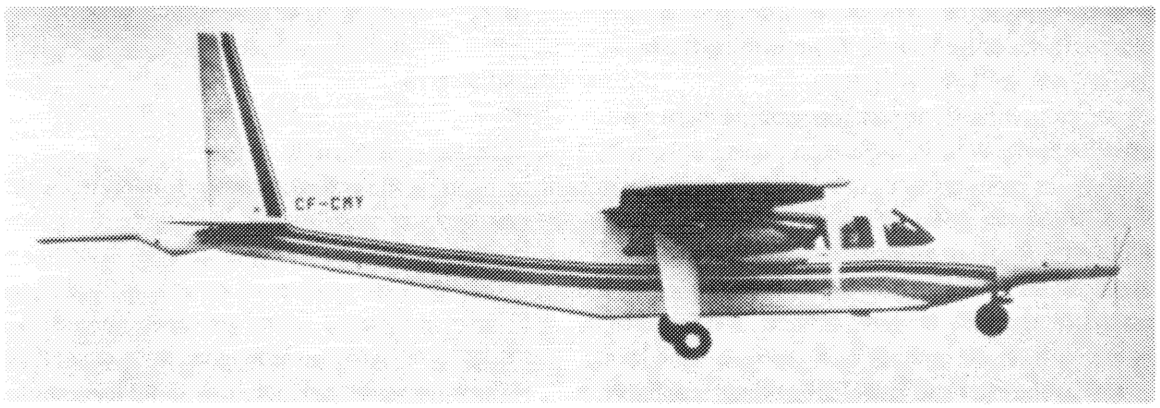


Figure 1. Index map showing the extent of airborne coverage. The survey area was flown with both the resistivity and magnetometer systems. Pairs of magnetometer lines were flown along the major drainage networks.



a. Ground unit (Geonics EM16R) for measuring resistivity at VLF by using the surface impedance method.



b. STOL aircraft with E-PHASE antennas in the nose cone and a magnetometer sensor extended to the rear (photograph courtesy of Barringer Research Ltd.).

Figure 2. Systems for measuring resistivity at VLF.

in Figure 1. In addition two separate surveys in this sector were conducted at mean altitudes of 150 and 300 m. These special studies were made to verify the quality of the entire airborne survey, with respect to both rock type differentiation and the effect of flight altitude upon resolution of resistivity anomalies.

MEASUREMENT TECHNIQUES EMPLOYED

Ground

A commercially available Geonics EM16R ground unit for measuring resistivity, illustrated in Figure 2a and on the cover of this report, was used for monitoring the VLF transmitter (NAA, 17.8 kHz) located near Cutler, Maine. The instrument is calibrated directly in apparent resistivity and phase for the particular frequency desired. The measurement is performed by determining the ratio of E_x (the horizontal electric field), measured between two probes spaced at 10 m and oriented in a radial direction towards the transmitter, and H_y (the horizontal magnetic field), measured with a small coil near the ground surface orthogonally to E_x. Since no current need flow from the ground to the probes the system is virtually free of contact resistance problems.

The coil is used to find the direction to the station, and the correct apparent resistivity values are found by tuning for an inaudible null with both the resistivity (i.e. amplitude) and phase dials. The accuracy of the instrument depends upon distance to the transmitter, as great distances can cause much noise and limit the null detection. Since Cutler, Maine, is within 300 km of the survey sight and operates at a radiated power of 1 MW, noise was not a limitation.

Airborne

The Barringer Research Ltd. E-PHASE* system was used for the aerial survey (Barringer 1972-73).

* *E-PHASE is the trade mark of the Barringer Ltd. system.*

This system employs a Britton Norman Islander, a short takeoff and landing (STOL) aircraft, specially modified to include a nose stinger on which horizontal and vertical dipole antennas are mounted as shown in Figure 2b. The E-PHASE system is capable of monitoring as many as four frequencies. For this survey only one frequency was used, station NAA (17.8 kHz), located near Cutler, Maine. The survey was flown with an average flight line orientation of 55° (true azimuth) for an average coupling angle of 80.5° with the transmitter. The survey altitude of the aircraft varied around 150 m. The mean flight line spacing was 0.4 km.

Airphoto mosaics and/or topographic maps were used for navigation. A flight path camera obtained continuous photographic coverage along the flight lines. Reference points (fiducials) were placed in the flight path recovery photography and at corresponding locations on data stored on an analogue (pen trace) recorder. Manually triggered fiducials were used to note points on the ground, such as streams and lakes, as well as the start and end of flight lines. Each day the flight path recovery film was developed, and recorded data were printed and inspected by Barringer Research Ltd. to ensure that all information was obtained. In the case of missing or unusable photo coverage, malfunction of the instrumentation, or transmitter problems, portions of lines or entire flights were flown again (Barringer 1975).

Additional information on the E-PHASE system, such as calibration, navigation and data reduction, has been discussed by Hoekstra et al. (1974) and by Palacky and Jagodits (1975). A review of the theory of electromagnetic resistivity surveying is given in Appendix A.

Magnetometer survey

A special tail stinger was installed on the survey aircraft to accommodate the magnetometer sensor. The airborne magnetometer, which records variations in the earth's magnetic field, and the reference ground base unit, measuring the total field, both utilize the principle of proton precession. A Barringer Research airborne AM-104 proton precession magnetometer was used to determine the variations of the earth's magnetic field. The resolution of this instrument is 1 gamma,* with a cycling rate of 1.1 s. The magnetic data were recorded on an analogue recorder and on magnetic tape.

A GM-123 field proton precession magnetometer, manufactured by Barringer Research Ltd., was located at Madawaska, Maine (32 km east of Ft. Kent) and used as the station magnetometer. During magnetic storm activity, which occurred between 6 and 8 October 1975, the surveying was suspended.

In Appendix B a brief review of magnetic surveying is given.

* *1 gamma = 1 × 10^{-9} tesla.*

RESULTS

Ground control study

During the airborne survey of the test sector ground control was established by measuring the apparent resistivity and phase by the surface impedance method. Readings were made every 60 m along the traverses shown in Figure 3, which are superimposed upon the bedrock geology as mapped by Boone (1962). The traverses primarily followed old logging roads, except for line A which cut along the steep ridges of Gardner Mountain. A few sample readings were taken at the pond shores where the apparent resistivity invariably dropped to less than 200 ohm-m.

The first three columns of Table I present a statistical summary of the data collected over the various rock types. Bedrock was rarely more than several meters below the surface along all of these traverses. The large dispersions in the resistivities, noted by the standard deviations in parentheses, primarily result from variations in bedrock properties. The highest resistivities were obtained over the intrusive rocks. Dispersion in phase was largest for the slate, with readings varying from 3° to 54°. Over the intrusive rocks the phase quickly stabilized, as indicated by the decrease in standard deviation.

For direct comparison of the results of the ground and airborne surveys, the ground data must be modified, based on the same assumptions used in calculating the airborne values. The ground data are recomputed using only the quadrature component of the surface impedance and an assumed phase angle of 45° (eq A2, App. A). A normalized distribution of the modified ground data is plotted in Figure 4, showing a clear distinction between the slate and intrusive rocks in the control area. (A summary of the modified data is provided in the last column of Table I). The

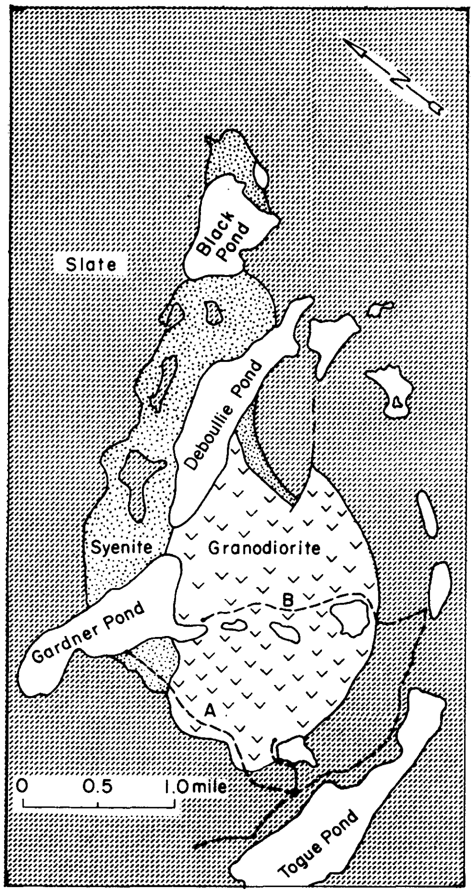


Figure 3. Ground control traverses along which surface impedance measurements were made, shown superimposed upon the bedrock geology as mapped by Boone (1962).

Table I. Apparent resistivity data obtained during ground survey. The last column presents modified ground resistivity values, based on the assumptions used in calculating airborne values. Standard deviations for the data are shown in parentheses.

Bedrock type	*Number of samples*	*Mean apparent resistivity (Ω-m)*	*Mean phase (°)*	*Mean quadrature resistivity (Ω-m)*
Seboomook slate	94	5481 (0.89)	23.93 (0.43)	1871 (0.85)
Granodiorite Section A	22	9009 (0.44)	28.86 (0.15)	4374 (0.47)
Granodiorite Section B	35	7086 (0.70)	35.90 (0.17)	4597 (0.62)
Syenite	8	5937 (0.56)	43.25 (0.11)	5342 (0.53)

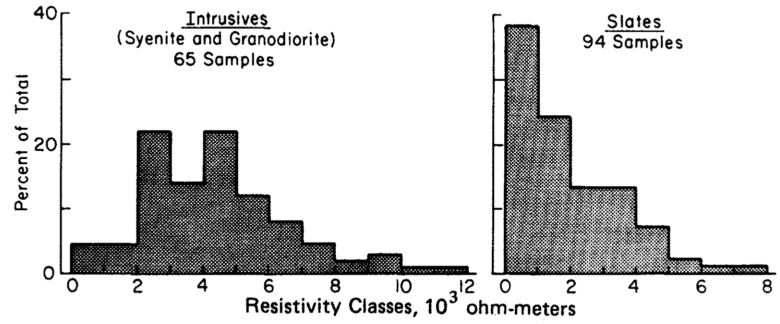


Figure 4. Normalized distribution of the ground data showing a clear distinction between the slate and intrusive rocks.

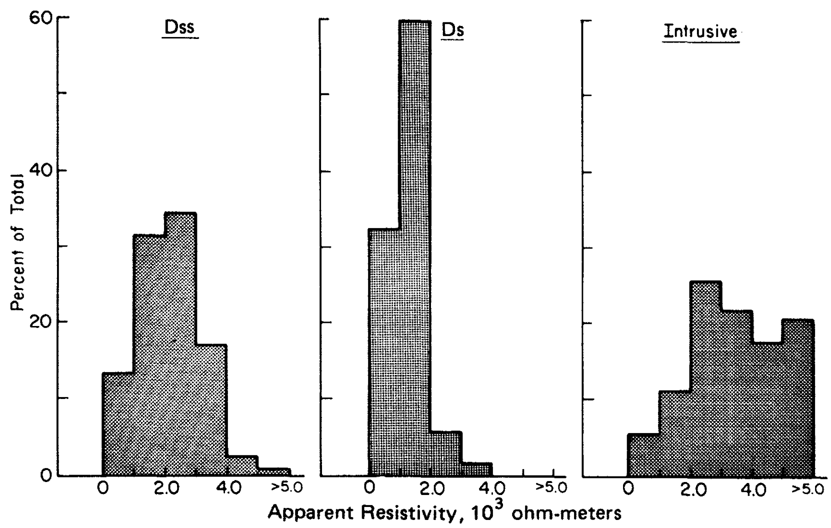


Figure 5. Airborne resistivity data for the various mapped rock types (Dss-cyclically bedded gray slate and sandstone, Ds-gray slate and minor graywacke). Values were obtained by sampling at regular intervals along the flight lines.

suppression of values for the slate is due to the low range of phase values caused by the till cover and/or the extremely high permittivity of slate (Parkhomenko 1967).

When resistivity values in Figure 4 and the last column of Table I are compared to those obtained along the flight lines of the airborne survey shown in Figure 5, the agreement may be seen between the ground and airborne observations. Slate values in Figure 4 should be compared to values for the same rock type, shown as Ds values in Figure 5.

The rapidly changing topography in the whole survey area made it unfeasible to always maintain a constant altitude. Therefore, as mentioned previously, a multi-elevation test was conducted in a small test sector to determine the effect of survey altitude, necessitated by topographic changes, upon resolution. Two separate surveys were flown at mean altitudes of 150 m and 300 m, both surveys containing the same number of flight lines.

In Figure 6 the comparisons between the contoured data from both surveys can be made. The general distribution of resistivity anomalies remains unchanged while the detail has decreased at the higher altitude. At this higher altitude there is a greater emphasis of the 4000 ohm-m contour over the intrusives, which is in near agreement with the mean values in the last column of Table I and is indicative of the averaging effect of altitude.

In general an excellent level of correlation was found between the airborne and ground readings for the test sector, ensuring the quality of the remaining resistivity survey.

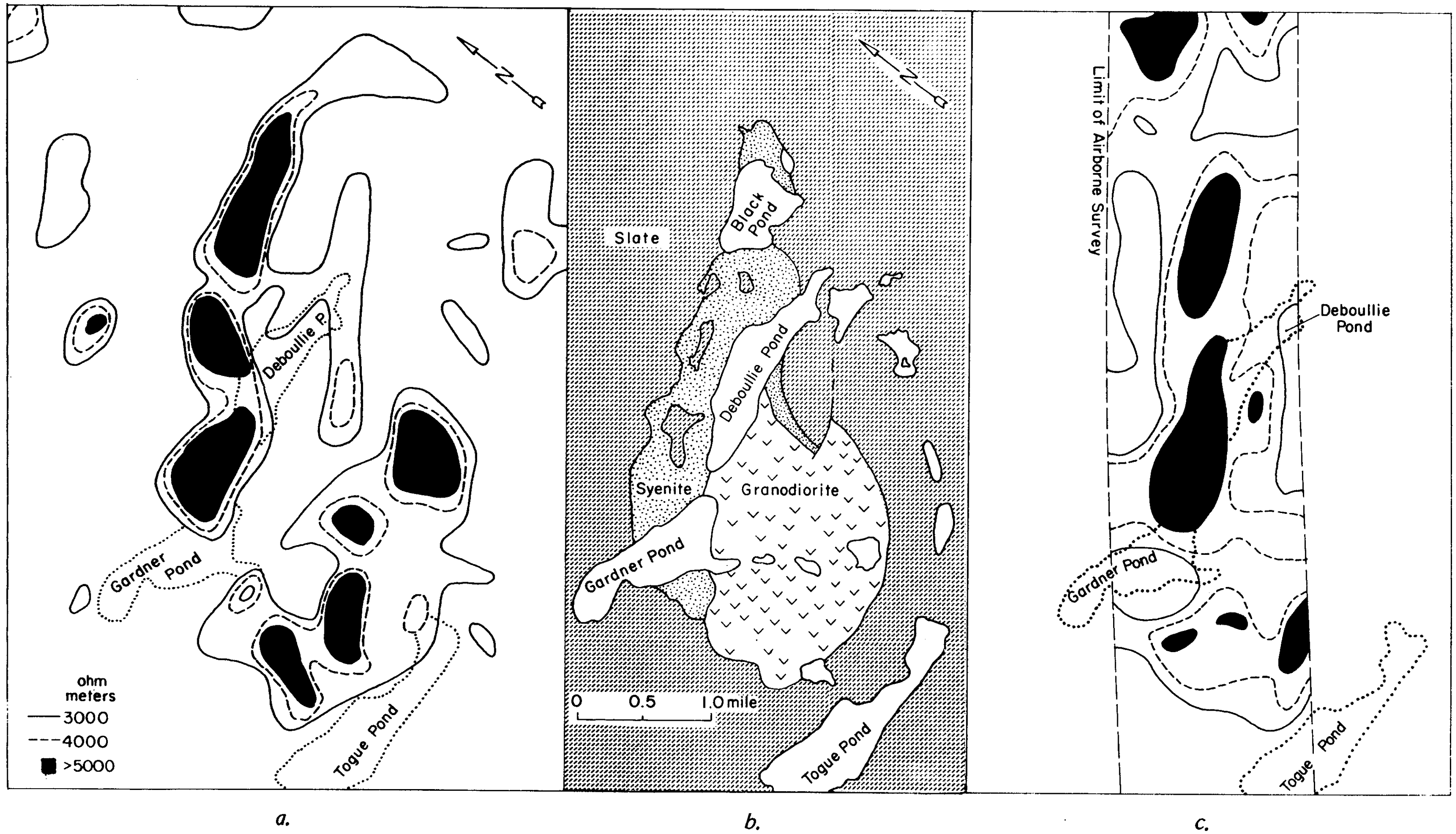


Figure 6. Multi-level contoured VLF apparent resistivity contours over the Gardner Mountain stock. The bedrock geology as mapped by Boone (1962) is shown in the center (b). Airborne measurements were taken at 150 m (a) and 300 m (c).

No ground studies were conducted for the airborne magnetometer survey, since past research and employment of this technique have already established its value.

VLF survey

The most noticeable features of the VLF data are the numerous tightly clustered, closed-contour resistivity highs shown in Figure 7. This pattern reflects the complicated surficial and bedrock geology of the area. In general the highest resistivity areas are associated with areas of major relief. This correlation is based on the fact that these are the locations where the conductive till is the thinnest and values reflect the generally more resistive bedrock which is near the surface. A generalized topographic map is provided (Fig. 8) as an aid in illustrating that the bedrock types can best be examined in areas of greatest relief. Virtually all the areas of high resistivity (> 3000 ohm-m) agree with units mapped as bedrock, or bedrock with a till cover, in the earlier surficial geologic study conducted by CRREL (McKim and Merry 1975).

A quantitative demonstration of these observations is shown in Table II. The table gives the distribution of areas with greater than 3000 ohm-m resistivity in relation to the topographic features they contain. Seventy-three areas were delineated, none containing only a valley. Approximately 70% of the areas contained only flanks and/or ridges.

Table II. VLF apparent resistivity contours greater than 3000 ohm-m.

Topographic situation	*Number*	*Percentage*
Ridge	14	19.2
Flank	17	23.3
Ridge and flank	20	27.4
Ridge, flank and valley	16	21.9
Flank and valley	6	8.2
Valley	0	0
Totals	73	100.0

It is also apparent from a comparison of Figure 7 and Figure 8 that many mountainous areas are also of relatively low resistivity (< 3000 ohm-m). Therefore, the lack of conductive overburden is not a major influence upon resistivity distinctions within these areas. The most plausible explanations for the resistivity distinctions among mountain types are the following:

1) There is a difference in bedrock type.

2) Certain flights passed directly over mountain peaks where it is known (Harrison et al. 1971) that the vertical electric field increases because of the sharp features, thereby suppressing resistivity values.

The second explanation is applicable to individual peaks such as in the Hafey, Gardner, and Deboullie mountains. Along these high elevations, ground readings (granodiorite Section A in Table I and Sellmann et al. 1975) that were modified for comparison to the airborne method indicated a suppression of airborne values. However, most flightlines in mountainous areas passed over the flanks, rather than peaks.

Bedrock geology and resistivity

When the reconnaissance bedrock geology of this area (Boudette et al. 1966 and Boone 1962) is examined, general distribution patterns become apparent. As shown in Figure 9, in the central part of the study area the bedrock units occur in broad bands, while to the northern end of the area these bands become more contorted and narrow, including a greater contrast in rock types. A large intrusive rock unit occurs near the southern limit of the area.

The southern and central parts of the region were characterized by three main units of lower Devonian age. The southernmost unit, Ds, was defined as gray slate and minor graywacke. The southern limit of this slate unit is not mapped, but it probably extends beyond the limits of the bedrock reconnaissance study, to the southern extent of the present study. The central part of the area was mapped as a cyclically bedded gray slate and sandstone (Dss). North of this unit another lower Devonian unit (Dsg), composed of graywacke and gray slate, was defined. North of these large units the structure becomes more complex and rock units range in age from Ordovician to Devonian. A greater range in rock types also occurs, including limestone, orthoquartzite, and siltstone. The intrusive body found in the southern part of the area is composed of granodiorite and syenite.

When the resistivity contours are placed upon Figure 9 several correlations become apparent. The highest resistivity values (> 6000) are associated with the intrusive rocks in the Gardner Mountain area. The next most obvious correlation is seen when areas of greater than 3000 ohm-m are examined. A belt containing

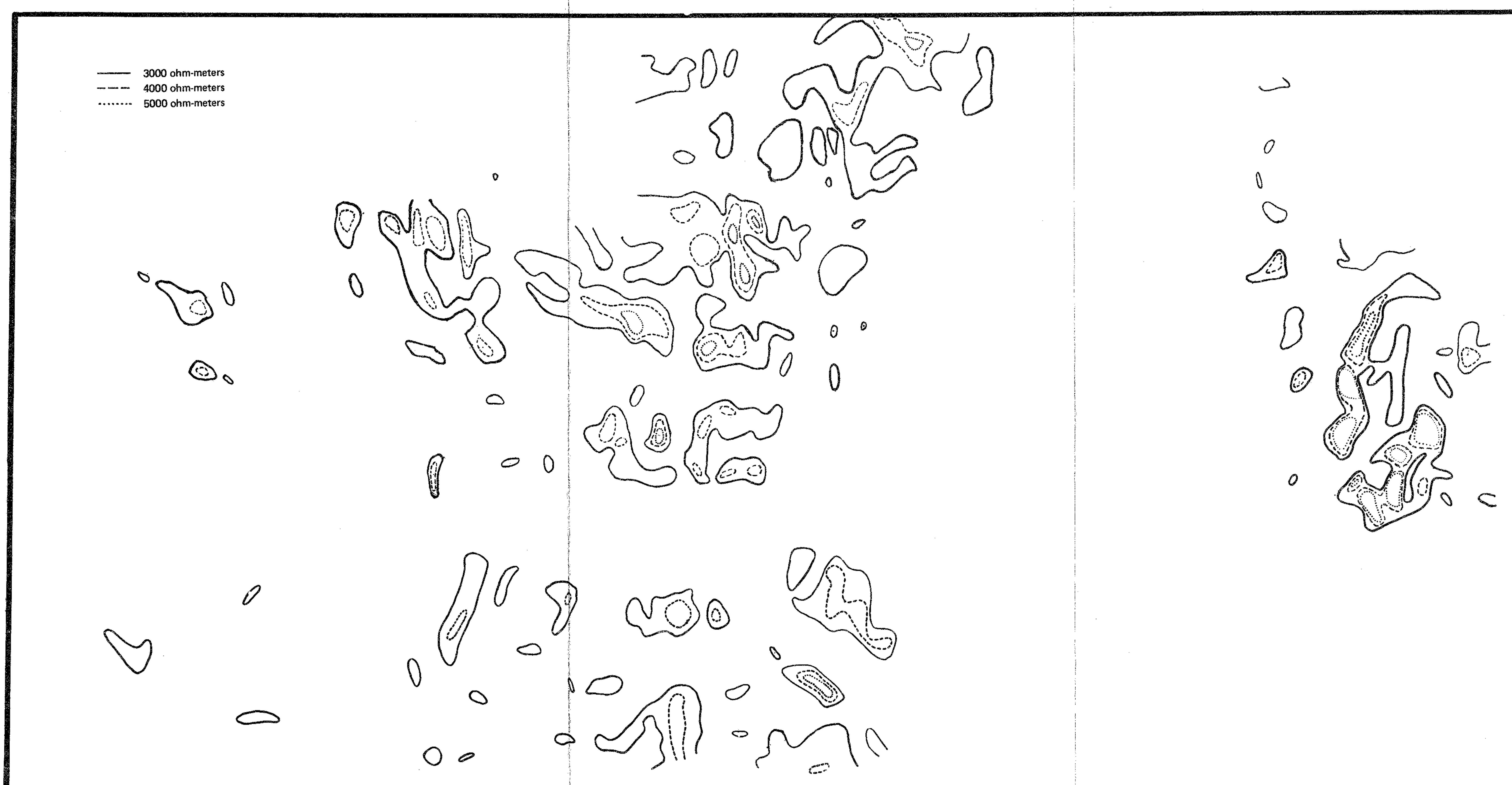


Figure 7. Generalized VLF apparent resistivity contour map. Contoured values in ohm-meters.

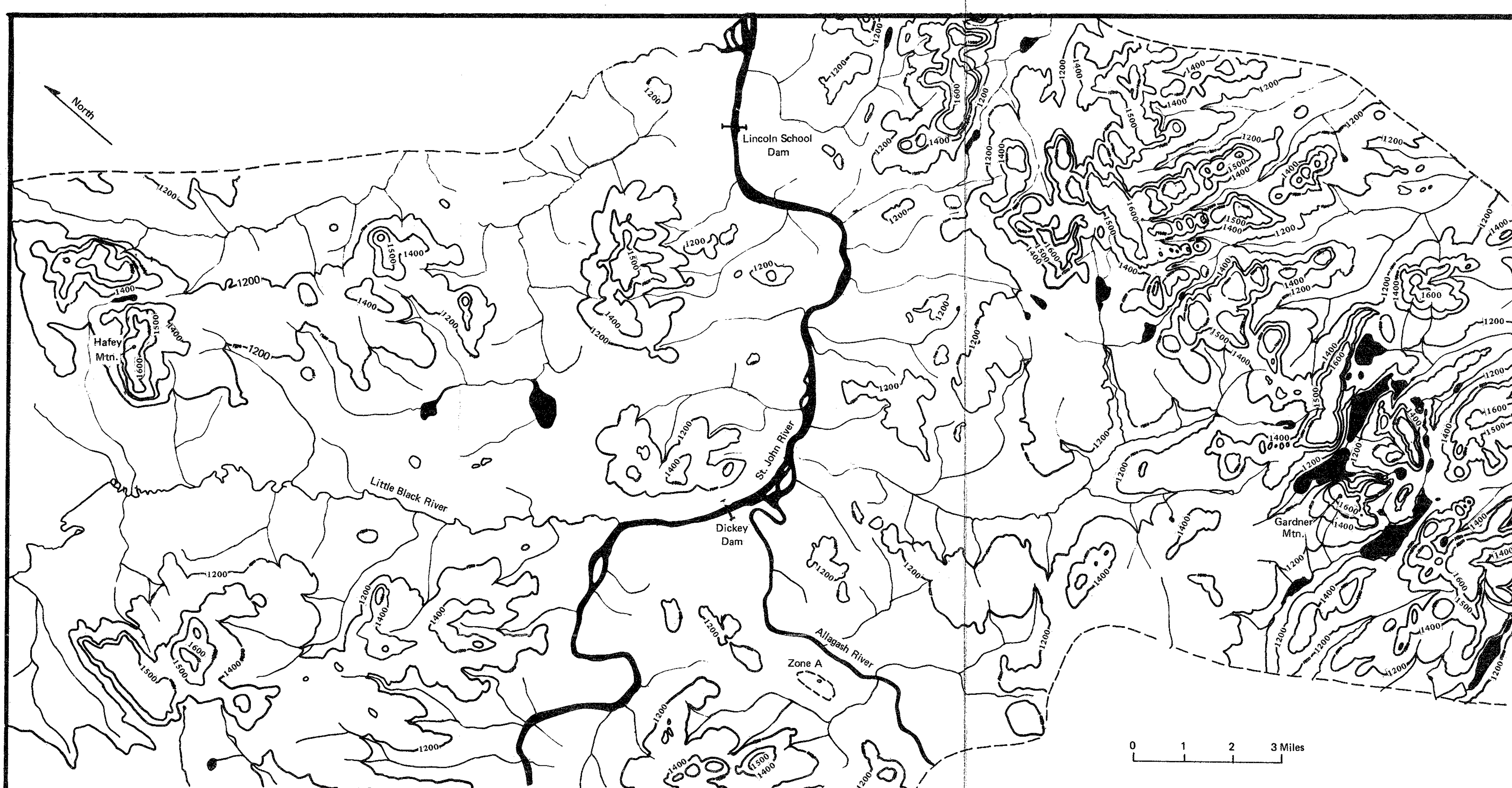
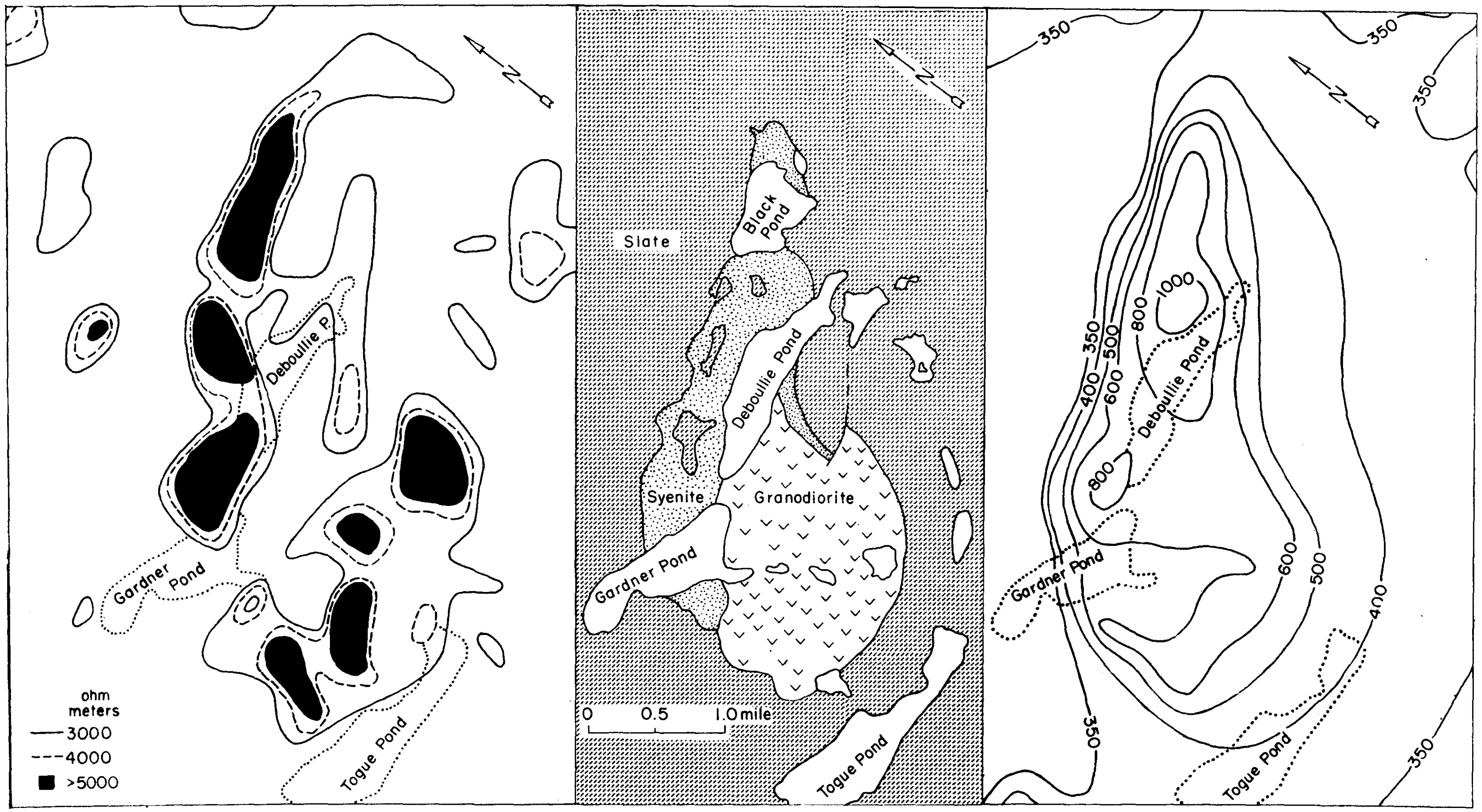


Figure 8. Generalized topographic map with selected contour intervals (ft) and drainage patterns (after USGS topographic maps, 1:62500 series).

Figure 9. Bedrock distribution map (after Boudette et al. 1966, Boone 1962).



a.   b.   c.

Figure 10. VLF apparent resistivity (a) and magnetic contours (c) over the Gardner Mountain stock. The bedrock geology as mapped by Boone (1962) is shown in the center (b) for comparative purposes. (Magnetic contour values are in gammas above the background intensity.)

many high resistivity zones is noticeable in the central part of the study area, coinciding with the mapped limits of the Dss bedrock unit. In this belt, the high resistivities are found in areas of high relief. The values commonly exceed 3000 ohm-m and locally reach a maximum of 5500 ohm-m.

The remaining rock types, such as the Ds geologic unit, have very low resistivities, with few areas having values that exceed 3000 ohm-m. This occurs despite the wide range of rock types and large number of areas of high relief where bedrock is near the surface. The resistivity data from the Dss, Ds, and intrusive units in Figure 5 show these same trends. The intrusive unit with the highest resistivities, Dss, has more than 20% of its values greater than 3000 ohm-m while less than 2% of the values in the Ds unit exceed 3000 ohm-m.

Aeromagnetic survey results

The aeromagnetic survey did not outline anomalies usually associated with abnormally high magnetic mineralization in either the main study area or along flight line pairs flown along the major drainage networks. In general, the magnetic intensity data were featureless, with the only significant anomaly being associated with the known intrusive rocks in the southern part of the area. This anomaly is shown in Figure 10 for comparison to the resistivity data and the bedrock geology. Fifty-seven thousand gammas have been subtracted from all values to eliminate the background intensity of the earth. Modal analysis of the granodiorite and syenite (Boone 1962) indicated that magnetite is a common and, in some cases, abundant accessory mineral. This fact alone can account for this distinctive feature, although the patterns and intensities seen are considered normal for these rock types.

CONCLUSIONS

The combined results of the aeromagnetic and E-PHASE survey allow several conclusions to be drawn concerning sources of rock suitable for construction purposes. These conclusions are based on the fact that the most suitable rocks will be the most electrically resistive, with further distinctions based on mineralization to be inferred from the presence of magnetic data.

The conclusions are:

1. The highest resistivity values are associated with the known Gardner Mountain intrusives. This is also the location of the only significant magnetic anomaly. The correlation of the VLF and magnetic data in this area was shown in Figure 10.

2. The lack of similar resistivity-magnetic correlations in other locations suggests little or no other occurrence of these rock types.

3. Local resistivity highs in the Dss unit suggest locations for field study as possible sites of rock types suitable for construction purposes. The Boudette et al. (1966) study indicates this as an area of slate and sandstone. The distribution of these rock types is not known; therefore, it can only be assumed that the sandstones may be the most resistive rock type. No magnetic anomalies occur in this area.

LITERATURE CITED

Barringer, A.R. (1972, 1973) Geophysical exploration method using the vertical electric components of a VLF field as a reference. Canadian Patent no. 1,261,732: USA Patent no. 3,594,633 and 3,763,419.

Barringer Research Limited (1975) Operational report on the airborne resistivity E-PHASE and magnetometer surveys Allagash River area, Aroostook County, Maine.

Boone, G. (1962) Potassic feldspar enrichment in magma: Origin of syenite in Deboullie district, northern Maine. *Geological Society of America Bulletin*, vol. 73, p. 1451-1476.

Boudette, Hatch and Harwood (1966) Reconnaissance geologic maps of the St. John and Allagash river basins, Maine. U.S. Geological Survey.

Collett, L.S. and A. Becker (1967) Radiohm method for earth resistivity surveying. Canadian Patent no. 795919.

Culley, R.W., F.L. Jagodits and R.S. Middleton (1975) E-PHASE system for detection of buried granular deposits. *Proceedings, Symposium on Modern Innovations in Subsurface Exploration*, 54th Annual Meeting of the Transportation Research Board, Washington, January 1975.

Eliassen, K.E. (1956) A survey of ground conductivity and dielectric constants in Norway within the frequency range of 0.2-10 mc. Oslo: Geofs. Publ., vol. 19, no. 11, p. 1-30.

Frischknecht, F.C. (1973) Electromagnetic scale model studies of geophysical methods using a plane wave source. University of Colorado, Department of Electrical Engineering, Ph.D. thesis (unpublished).

Grant, F.S. and G.F. West (1965) *Interpretation theory in applied geophysics.* New York: McGraw Hill.

Harrison, R.P., J.L. Hecksher and E.A. Lewis (1971) Helicopter observations of very low frequency waves over certain mountains and shorelines. *Journal of Atmospheric and Terrestrial Physics*, vol. 33, p. 101-110.

Hoekstra, P. and A.J. Delaney (1973) Ground resistivity survey in the area of the Tennessee-Tombigbee Waterway. CRREL Special Report 191. AD 767246.

Hoekstra, P., P.V. Sellmann and A.J. Delaney (1974) Airborne resistivity mapping of permafrost near Fairbanks, Alaska. CRREL Research Report 324. AD A000694.

McKim, H. and C.J. Merry (1975) Use of remote sensing to quantify construction material and to define geologic lineations: Dickey-Lincoln School Lakes Project, Maine. CRREL Special Report 242.

Olhoeft, G.R. (1975) The electrical properties of permafrost. University of Toronto, Ph.D. thesis (unpublished).

Palacky, G.J. and F.L. Jagodits (1975) Computer data processing and quantitative interpretation of airborne resistivity surveys. *Geophysics*, vol. 40, p. 818.

Parkhomenko, E.I. (1967) *Electrical properties of rock.* New York: Plenum Press.

Sellmann, P.V., P. Hoekstra and A.J. Delaney (1974) Airborne resistivity near Fairbanks, Alaska: An aid in bedrock geology reconnaissance. CRREL Special Report 202. AD 777792.

Sellmann, P.V., A.J. Delaney and P. Hoekstra (1975) Radiowave resistivity measurements in northern Maine for identifying bedrock type. CRREL Special Report 238.

Wait, J.R. (1962) *Electromagnetic waves in stratified media.* New York: Pergamon Press.

Ward, S.H. (1967) Electromagnetic theory for geophysical applications. In *Mining Geophysics*, vol. 2, Society of Exploration Geophysicists, Tulsa, Oklahoma.

Waterways Experiment Station (WES) U.S. Army (1953) The unified soil classification system. Technical Memorandum no. 3-357, vol. 1, App. A, B (revised April 1960).

APPENDIX A. THEORY OF ELECTROMAGNETIC RESISTIVITY SURVEYING

RESISTIVITY SURVEYING

The physical property, electrical resistivity, spans a large range of magnitude. Values ranging from 10^{-7} ohm-m for metallic elements to 10^{10} ohm-m for some granitic rocks are well documented (Parkhomenko 1967). The most common range encountered in d.c. and electromagnetic surveying is approximately 10 to 10,000 ohm-m. Within this range fall many materials of economic and geologic importance that can be detected as a result of contrasts in resistivity with adjacent materials.

A primary influence on the resistivity of sediments is the amount of ions associated with adsorbed surface water on particles. Therefore, there is a correlation between resistivity and grain size. In some earth materials, such as crystalline rocks, a more important factor may be the amount of ions dissolved within the pore water. The general resistivity range for most earth materials is illustrated in Figure A1 (Culley et al. 1975, Hoekstra and Delaney 1973). Other factors, such as temperature, pressure and ice content, also influence resistivity but are not significant factors in the present study.

Radiowaves propagating over the earth's surface are influenced by the electrical properties of the subsurface materials. By comparing the various field components of the radio surface wave it becomes possible to obtain ground resistivity data.

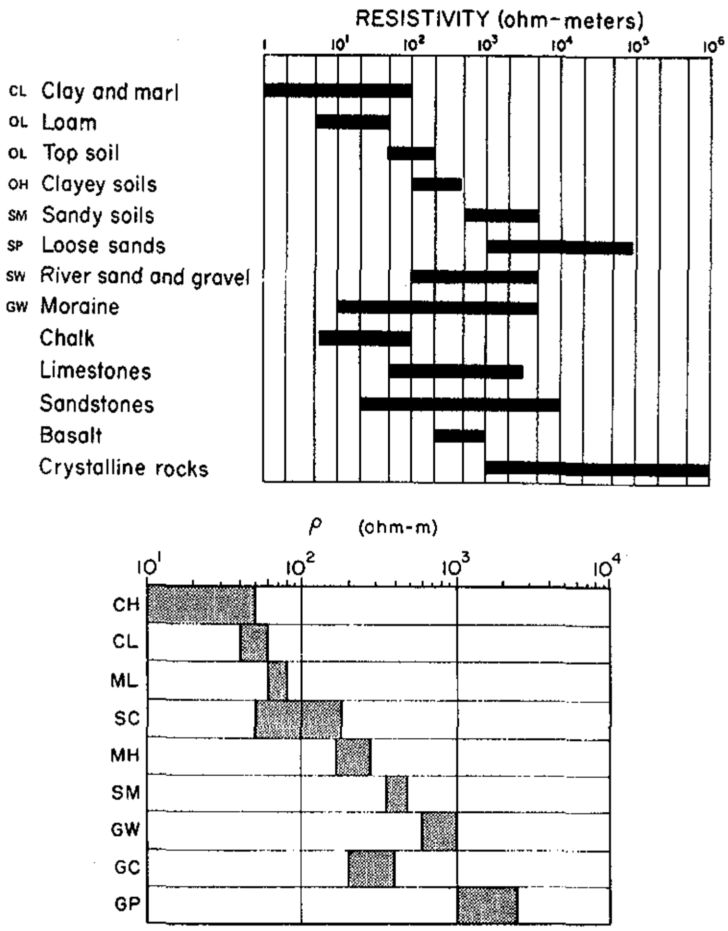
Since literature on the interaction between radiowaves and the earth is available (Wait 1962, Frischknecht 1973, Eliassen 1956), only a short discussion of the principles is presented here.

The electromagnetic ground wave field vectors in the far-field of a vertically polarized transmitter are shown in Figure A2. At the ground surface there are three field vectors: the horizontal, radially oriented electric field E_x, the horizontal, azimuthally oriented magnetic field H_y, and the vertical electrical field E_z (x, y, z refer to a local Cartesian coordinate system). All three field vectors decay equally in amplitude with increasing distance from the transmitter. In the ground wave mode the relative amplitudes and phases of these fields at VLF are not influenced by the total path of propagation but only by local resistivity conditions. At distances approaching 1000 km sky mode transmission becomes important. (For the survey discussed in the text, the proximity of the test site to the transmitter (300 km) ensured that only the ground wave was present and hence that there was no possibility of ionospheric interference.)

Because of the large refractive index of the ground at radio frequencies, a near vertical wave propagates into the ground with horizontal vectors H_y and E_x. In the ground the amplitudes of E_x and H_y attenuate with depth, and in homogeneous ground the distance over which the field decays to 37% of its surface value is called the skin depth of the radiation. Figure A3 illustrates the dependency of the skin depth on the frequency of the transmitted signal and the resistivity encountered for a homogeneous earth. The skin depth of the radiation is an important parameter, since it approximately indicates the depth to which information is obtained by a measurement at the surface.

Both E_x and H_y are continuous across the ground surface, but E_z becomes negligible in the ground. E_x can therefore be measured by a dipole antenna above the earth's surface or in the ground by measuring the field strength between two probes. H_y is measured by a coil located near the surface, and E_z is measured with a vertical dipole antenna above the ground.

The basis for obtaining a local measurement of ground resistivity is illustrated in Figure A4, where



After Culley et al. (1975).

From Hoekstra and Delaney (1973).

Figure A1. Examples of resistivity ranges for common earth materials. Soil types are described using the Unified Soil Classification System.

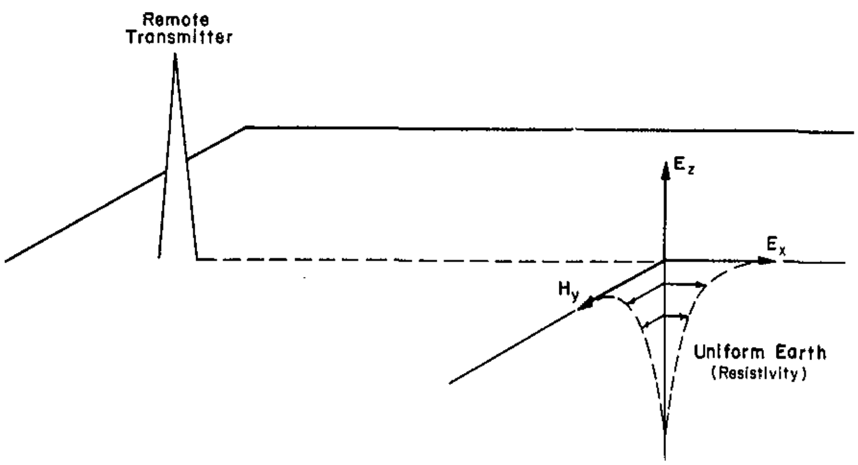


Figure A2. Electromagnetic field components of a vertically polarized radio surface wave.

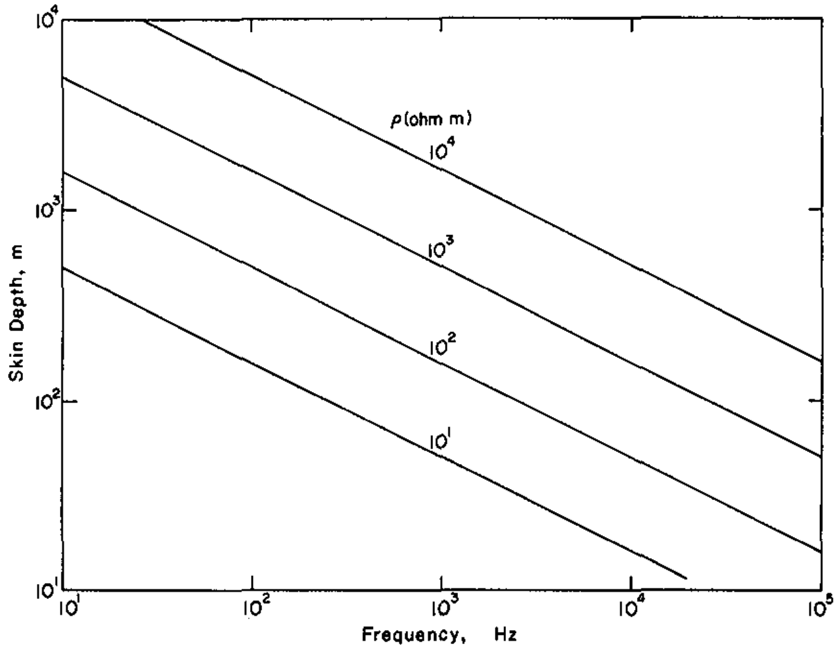


Figure A3. Skin depth of electromagnetic plane waves as a function of frequency with varying ground resistivity ρ.

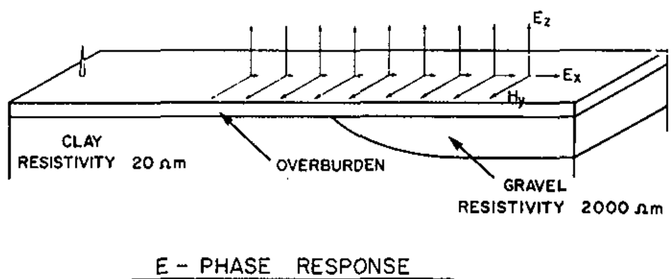


Figure A4. Schematic representation of the local changes in the magnitude of the electromagnetic field vectors of a vertically polarized groundwave when earth materials having different resistivities are traversed.

a wave propagates over a change in ground conditions. Changes in local subsurface conditions cause perturbations in amplitude and phase of E_x, while local changes marginally affect E_z and H_y. Therefore, by measuring the ratio of E_x/H_y (called surface impedance) or E_x/E_z (called wave tilt) a measurement is obtained of the local electrical resistivity.

The computation of ground resistivity, at present, neglects the effects of the permittivity of the ground, and there are circumstances when such procedures may introduce substantial errors (Olhoeft 1975). However, in many applications the delineation of changes in subsurface conditions is the primary object, and a determination of the exact value of ground resistivity is less important.

Over the past decade several schemes for measuring the resistivity of ground from radiowaves by using the principles discussed above have been tried. Two approaches have proven to be practical: a ground-based technique (Collett and Becker 1967), and an airborne technique (Barringer 1972, 1973). The ground technique relies on a measurement of surface impedance (E_x/H_y), while the airborne method uses the wave tilt phenomenon (E_x/E_z) for plane waves at grazing incidence. For plane waves at grazing incidence over a smoothly layered earth, the two measurements are related by the free space impedance, 377 ohms, as follows:

$$W = Z_s/377$$

where W is the wave tilt and Z_s the surface impedance.

Since Z_s and W are complex quantities, they both have an associated amplitude and phase. The amplitude is converted to "apparent" resistivity by using the formula for a homogeneous earth (Wait 1962) such that

$$\rho_{app} = Z_s^2/2\pi f \mu_0 = W^2/2\pi f \epsilon_0 \qquad \text{(A1)}$$

where ρ_{app} is the apparent resistivity measured in ohm-meters, f the operating frequency in Hz, μ_0 the magnetic permeability of free space and ϵ_0 the free space permittivity. Theoretical modifications in apparent resistivity and phase due to layering of materials with differing resistivities are well documented (Wait 1962). In general when resistivity increases with depth, phases are below 45°, and when resistivity decreases with depth the phases are greater than 45°. Phases of 45° are indicative of uniform resistivity with depth.

For the airborne system only the quadrature value of wave tilt can be measured, because aircraft roll instability causes an in-phase coupling of the vertical field with the (offset) horizontal antenna. Therefore, present data processing assumes an arbitrary phase angle of 45° between E_x and E_z and the computation of apparent resistivity uses the formula:

$$\rho_{app} = W^2/\pi f \epsilon_0 \qquad \text{(A2)}$$

where W = quad (E_x/E_z).

This inability to distinguish the separate effects of phase and amplitude limits the degree of airborne subsurface interpretation. Therefore, it often becomes necessary to conduct preliminary ground studies to determine if the combined effect of phase and amplitude will still allow extensive airborne differentiation of material type.

Ground measurements are performed with the surface impedance (E_x/H_y) technique. The technique must be used for groundbased surveys because E_z is disturbed by vegetation and is therefore an unreliable reference. In the airborne survey it becomes necessary to use the quadrature wave tilt method to eliminate the undesirable coupling mentioned above. In this case E_z is more reliable since the observation is made well above the ground surface, substantially removed from vegetation effects. However, mountain ridges are known to sometimes enhance this reference field (Harrison et al. 1971) thereby depressing the actual resistivity values but not altering regional resistivity patterns, as is discussed in *Results*.

Since the radiation wavelength used is so great (> 15 km at VLF), a flight altitude of 150 m is equivalent to less than 0.01 wavelength. However, the resolution in airborne mapping of resistivity anomalies is reduced, compared to ground measurements.

APPENDIX B. MAGNETIC SURVEYING

Magnetic data are a result of both the intensity of the earth's magnetic field and the magnetic properties of minerals present in the surveyed area. Magnetic anomalies are disturbances in the earth's magnetic field that are caused by changes in the amount and type of magnetic minerals associated with various rock types. The magnetic minerals usually responsible for these disturbances are magnetite, pyrrhotite, ilmenite, and hematite.

Magnetic disturbances present themselves in various ways, such as changes in field direction (usually termed a "dip" or change in declination), and as changes in total field strength or intensity. The most common method of presentation is contouring lines of total magnetic intensity above a background value measured at some reference station. Values are presented in terms of gammas above the reference station value, one gamma being equal to 10^{-5} gauss. The earth's magnetic field varies with position and time of year but generally falls in the magnitude range of 0.5 to 1 gauss. Contours do not necessarily outline a rock formation but can be highly indicative of the rock types present.

Additional information on magnetometer surveying can be found in the texts by Grant and West (1965) and Ward (1967).