SEISMOLOGICAL STUDIES OF EARTH STRUCTURE

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SEISMIC STUDIES OF EARTH STRUCTURE

RESEARCH SUB-PROGRAMME

(Group 9)

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CONTENTS

TERMS OF REFERENCE

The terms of reference as defined by the Chief of the Division are as follows: to assess current plans and to develop a research sub-programme that, taking into account the talents of the staff and the available budget, and taking full advantage of the developing new instrumentation, addresses the significant problems of the new geology, and with due reference to other Earth Science groups within the Branch, GSC and Industry.

GENERAL GOALS

The overall goal of the Section is to study the Earth's structure by seismological means, taking into account the latest developments in tectonophysics and plate tectonics, earthquake prediction studies, other branches of solid earth geophysics, structural geology, theoretical seismology and methods of signal processing, and new experimental techniques of the exploration industry.

It is recognized that a large part of the efforts of the group should be and are directed towards a study of the crust and lithosphere under Canada. However, it is also recognized that anomalies in the Earth below the lithosphere are related to the processes that have moulded the near-surface features of Canada and must, therefore, also be studied, both to elucidate Canadian problems and to understand the Earth's structure in general.

The goal is to be achieved through a number of on-going and future programmes consisting of field, laboratory and theoretical studies in collaboration with other Divisions, Branches or other pertinent agencies. Along with the termination of certain studies, the programmes will, from time to time, be re-evaluated to accommodate changing priorities and manpower constraints.

Presently, some of the major objectives of the Section, particularly

for field work, are and will be to study the deep crust and lithosphere beneath Canada with an emphasis on those regions that are (a) seismically active regions such as Charlevoix County, Québec, and the Eastern Yukon, (b) of tectonic significance such as the Rocky Mountain Trench and Canadian shield boundaries, and (c) being developed and are of economic importance such as the Mackenzie Valley and James Bay.

The above general objectives are presently subdivided into eight areas of study, which are listed below. It is expected that these areas will change only slowly with time.

These objectives are being met by eleven currently on-going projects, which are listed in Appendix A, and these will be updated annually. Dates of field projects and budget figures are given in the Time Table.

Appendix B contains some preliminary field projects for the years 1975 to 1977, with approximate budget figures also in the Time Table.

Appendix C contains a collection of very preliminary projects without dates or budget figures. These are at the moment the beginnings of feasibility studies that should be updated in about six months.

AREAS OF STUDY

1. Crustal Studies

Studies of the complexity and anistrophy of structure in the Arctic Islands, the Arctic Ocean, the Rocky Mountain Trench, Western Ontario, the St. Lawrence rift by standard reflection and refraction methods and repetitive methods such as vibroseis or small charges.

2. Studies of broad variation in lithosphere and asthenosphere beneath Canada

This includes surface wave studies with some lateral variations

near plate margins or in different tectonic provinces; studies of short-period P-wave arrival differences and amplitudes of long-period waves.

3. Evaluation of techniques used in crustal studies

The critical appraisal of the usefulness of the Vibroseis source for deep crustal studies and the Aquaflex method for small repeated sources is imperative.

4. Development and assessment of new techniques for processing seismic signals

The emphasis should be on those techniques that have the most general application to crustal reflection and refraction studies, array processing and surface wave analysis. Examples are:

a. adaptive processing,

b. the use of the Walsh transform,

c. f-k method,

d. maximum entropy and maximum likelihood methods of spectral analysis,

e. deconvolution.

5. Array studies

Studies of the base of the mantle, core and lateral variations in the upper mantle. There is also a need to explore the implications and applications of scattering theory, particularly the Chernov approach, to the analysis of seismogram codas, the structure beneath array and other station sites, and to structure in the crust and upper mantle between source and receiver.

6. Integration of seismic and other studies

The results of seismic studies need to be integrated into the framework of plate tectonics and associated tectonic processes. Thus,

attempts are to be made to relate the Section's work to the results of heat flow studies, gravity, known magnetic and electrical conductivity anomalies, petrology, geochemistry, stratigraphy and geochronology, crustal stress and rock fracture studies.

7. Instrumentation

To ensure efficient data collection and analysis, it is necessary to keep abreast of instrument development for field work and related computer hardware for data analysis.

8. Dilatancy

The recently proposed dilatancy hypothesis has so far not been tested because of lack of suitable, sufficiently repetitive sources. Should such source, either artificial or natural, be found, the hypothesis should be tested.

CONCLUSIONS

Future projects must be integrated to allow for the efficient use of manpower, budgeting constraints and the talents of the members of the Section. On the one hand, laboratory work must be balanced with field work. On the other hand, projects must be rated as to their importance to the goals of the Division.

Thus, it is recognized that one large field experiment with virtually the whole Section participating should be undertaken once a year. Smaller experiments can be undertaken at irregular intervals.

From the project listing in Appendix A, it is evident that after the spring of 1977 the geographically diverse field projects in the Arctic will have terminated. Concurrently and from then on, the main focus of our field work, supported by theoretical studies, will be concentrated in two areas

of interest: in Eastern Canada it will be the La Malbaie area of Québec, in the Northwest it will be northern British Columbia and the Yukon.

The La Malbaie area offers at least 4 objectives: understanding the seismicity, delineating Logan's line at depth, determination of the Charlevoix structure and a test of dilatancy.

The region of the Northwest belongs to the youngest tectonic province in Canada. The structure is extremely complex, with high heat flow values and earthquakes occurring on either side. Crustal seismic data will greatly aid in understanding this area.

Theoretical work by one or two Section members that aids in the analysis of the above general projects should be given some priority. Projects that involve the analysis of data not obtained by field experiments should, if possible, be classified according to the above schedule, taking due account of the Section members' interests and talents.

Branch or Departmental objectives, whether based politically or scientifically, will from time to time change and override the priorities of the Section or Division. However, in the absence of such objectives, the Section's projects should be ordered as indicated above.

Projects proposed by other Sections or Divisions to this Section should be considered carefully for their merit. If they are found to be feasible and particularly if they support the aims of the Section, they should be undertaken.

APPENDIX A

Current Projects

Project 4-1. Fine Structure of the Earth's Upper and Lowermost Mantle

To study a number of specific regions of the earth's interior by various core phases recorded by the Canadian networks and especially by the Yellowknife medium aperture array. In 1975 the regions will include the lowermost mantle beneath the Pacific, especially beneath Hawaii, and the Caribbean Sea, the earth's central core and the earth's liquid outer core.

1.45

Project 4-2. <u>The Implementation of New Analytical Techniques for Placing Confidence Limits on Earth Models and for the Futher Development of Existing Array Processing Facilities.</u>

To study scattering phenomena and the lateral variations of earth structure that they imply requires that new analytical techniques be developed, which will allow reliable estimates to be made of the magnitude of possible variations. This project will attempt to develop these new techniques. Three approaches will be used. The first will study in detail the statistical properties of slowness and azimuth measurements and will incorporate these results within body wave inversion schemes. The second will explore proposed lateral variations of deep structure by the extensive application of newly developed ray-tracing techniques. The third approach will refine present array processing techniques to make them more sensitive to the needs of studies of earth structure rather than nuclear event detection and identification.

Project 4-3. Structure of the Lithosphere beneath the Southern Canadian Cordillera

To study the structure of the southern Canadian Cordillera by using the dispersion characteristics of surface waves as they propagate between the stations of the Canadian Network in the region.

The Canadian Cordillera is the youngest of the Canadian orogenic belts. As such its complex geology is the thumbprint of its tectonic development without the usual complication of secondary and tertiary overprinting such as is found elsewhere in the Canadian Shield and in Appalachia.

Extensive seismic refraction data have provided the general crustal structure of the region, but have not penetrated to greater depths than the M discontinuity. The surface wave studies will provide information on the whole lithosphere.

Project 4-4. AIDJEX Refraction Experiment

To determine the detailed crustal structure of the oceanic crust beneath the Canada Basin of the Arctic Ocean and to explore the possibility of seismic anisotropy in the material of the upper mantle.

The timing of this experiment will depend upon the overall co-ordination of the main AIDJEX experiments, but is at present tentatively scheduled for April 1976. Detailed planning for the experiment will take place during FY 1975-76.

Project 4-5. Tuktoyaktuk Refraction Experiment

To determine the crustal structure along a profile from Tuktoyaktuk out towards the Arctic Ocean. A knowledge of the structure is needed in this region in order to place constraints upon the interpretation of the abundant gravity data that are now available along most of the Canadian Polar Continental Shelf. The gravity data reveal a line of unusual anomalies along the Arctic Continental Shelf which cannot be interpreted with confidence without the additional constraints that this Project should provide.

The exact position and timing of the profile await the results of an ice study and the availability of an improved navigational and surveying system; however, it is expected that it will be conducted in conjunction with Project 4-4 (AIDJEX) in 1976 with detailed planning taking place during FY 1975-76.

Project 4-6. Evaluation and Application of the Vibroseis Technique for Crustal Studies

This project seeks to apply the sophisticated, ecologically clean Vibroseis and related techniques of the oil industry to the detailed study of the whole crust. If such techniques can be applied in practical and economical ways, they will be used in a number of key locations, especially in the Cordillera and at the boundaries of the Precambrian Provinces to refine our understanding of the tectonic framework of these regions.

The project is a continuing one with a number of discrete phases.

Phase 1. 1973:

Vibroseis trials in those areas of the Cordillera where the service already has detailed information on crustal structure from extensive reflection-refraction experiments conducted in 1972. The data from the 1973 trials are encouraging and a detailed assessment will be completed by the end of FY 1974-75.

Phase 2. 1974:

A Vibroseis trial in southern Ontario using a simplified (and cheaper) recording system. These data will be reduced in FY 1975-76, with considerable attention being given to the true costs resulting from the simplified recording.

Phase 3. 1975:

A careful assessment of the Vibroseis approach to result in clear recommendations about its applicability to studies of crustal structure in limited key areas.

1.2.

Project 4-7. P-Wave Residuals across Canada

To determine the P-wave residuals at the stations of the Canadian Network from events recorded there in order to provide for the more accurate location of Canadian earthquakes and to explore the possibility of detecting time-varying residuals.

Project 4-8. Crustal Structure near La Malbaie, P.Q.

To determine the fine structure of the crust on either side of Logan's line in the earthquake-prone region near La Malbaie.

Data recorded during the La Malbaie field survey (1974) from explosions and quarry blasts will be used to determine a crustal model to aid in the location of earthquakes recorded during the experiment. The same data and the data from the earthquakes themselves will be used to test whether the new dilatancy theory and the sometimes observed V_p/V_s precursory phenomena are relevant to the earthquakes in the region.

W.A.C.

Project 4-9. Williston ~~Basin~~ Lake Experiment

To determine the crustal structure under the Rocky Mountain Trench by using close-in reflection techniques and the new Williston Lake Reservoir. The true nature of the crust in the vicinity of the Trench remains something of an enigma despite several attempts to study it by several university groups. Previous studies have all used long-range refraction techniques with the consequent averaging that such approaches imply. The new reservoir behind the W.A.C. Bennett Dam provides an opportunity to conduct an economical detailed expanding spread reflection experiment. Plans call for the use of very small shots being detonated just beneath the surface of the frozen lake, and for recording crews also to move along the ice.

Not corp.

Project 4-10. Arctic Study Task Force

Aim: to look into questions of the Arctic Ocean and bordering terrains, their development in time and space.

The objectives are:

1) summary and organization of all available geoscience data in computer-readable form, as far as possible, from Arctic Canada and USSR.

2) presentation of data mainly in the form of Arctic-centered maps, e.g., seismicity and heat flow,

3) interpretation and publication of time/space history of the Arctic and its possible relation to resource potential,

4) to provide a framework for informed future Arctic work.

Project 4-11

Structure of the Earth and Tectonic Framework of the Canadian Lithosphere

The objective of the sub-program is to improve our knowledge of the structure of the earth and particularly the lithosphere beneath Canada as a necessary aid to the study of Canadian and world-wide seismicity and for the use of other earth scientists in government, university and the resource industries.

To work towards this general objective, several field projects are undertaken that range from small field experiments, designed to test new approaches, to large field experiments using established techniques. Theoretical studies are occasionally undertaken to provide improved interpretation techniques. Extensive use is made of the data from the Canadian network of stations. The array station at Yellowknife is especially valuable for studying deep mantle and core structure, while the long-period instruments of the standard and special stations provide data for the study of the upper lithosphere.

APPENDIX B

Possible topics for work for 1977 and beyond.

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ST. LAWRENCE RIVER AREA

During the two-month-long La Malbaie experiment, a large number of small earthquakes and 3 larger events were recorded. To determine their epicenters, the crustal velocity structure should be known. At present, the sedimentary section on the south shore down to about 18,000 feet is known from data supplied by SOQUIP. On the north shore, extrapolation could be made from data of the 1968 Grenville Front experiment. Quarry or mine explosions in Québec may yield some additional P_l velocity data as well as P_n velocities. These explosions, although large, are always multiply-delayed events and thus yield poorly readable phases. Before the experiment got underway, it had been planned to have at least 4 explosion sites to calibrate the net. However, only one usable site could be found in an abandoned open-pit, water-filled mine. To test the dilatancy hypothesis, this shot point can be considered to be the first in an annual sequence.

Thus, there is need for more calibration shots, which may necesisitate drilling holes or contracting for large shots with quarry or mine operators.

The results from such an experiment would throw more light on displacements along Logan's Line and possibly the Charlevoix structure. The latter structure is now under investigation by the Division of Geomagnetism and the Gravity Division with the installation of instruments near the center of the structure. Finally, the Seismology Division is planning to install a regional seismic station in the structure for a long-term study of seismicity.

If a greater amount of funds become available and a Vibroseis crew could be found in the East, a Vibroseis line could be run over one rim of the Charlevoix structure, over both and over the central region. Exact locations should await analysis of the 1974 survey data.

Costs are as follows.

Year	K$	man-years	
1975	3.5	0.1	dilatancy test shot in St. Urbain mine
1976	4.0	0.1	"
1977	4.5	0.1	"
1977	40.		10 miles of Vibroseis.

PORTABLE LP NETWORK

Presently the stations are located at Alexis Creek, Wells and Smithers, forming a quadrilateral with Fort St. James. This configuration will remain until 1976.

Redeployment. Results from the former network of Alexis Creek, Wells, Revelstoke, Victoria, Penticton and Port Hardy suggest that a deployment from Nanaimo orthogonal to the coastline on a line midway through the old net will produce useful information in the years 1976-77.

New Development. Four additonal LP systems could be usefully deployed in the La Malbaie area, two on either coast some distance inland, 200 km apart.

The aim would be twofold: to derive the upper mantle structure on either side of Logan's line, and to yield long period information on local earthquakes. For the first part, earthquakes on the mid-Atlantic

ridge south of Iceland and southern Mexico events are useful.

Year	K$	man-years	
1976	40		2 systems
1977	40		2 systems
annually	5	.25	servicing
annually	3		operating 8 stations

INSTRUMENTATION Back-pack system: 6 systems should be ready for September 1975 to be used in La Malbaie recalibration shot.

With the large capacity programmer that is envisaged, two provisions should be made in the system: a) sampling rate should be adjustable to be used also at about 60 samples/s for use in discriminating earthquake recording; b) programmer should be programmed to record only high frequency local events.

WILLISTON LAKE, B.C.

This will be an extension of the 1975 project, modified by the experience gained in 1975. The goal here will be to obtain Moho and intermediate reflection energy, essentially orthogonal to the 1975 line, that is, from the Omineca's across the Rocky Mountains to the Foothills.

Year	$K	man-years	
1977	30.	.6	or,
1978	30.	.6	

B.C. AND YUKON

The Alaskan Highway between Fort Nelson, B.C., and Haines Junction, Y.T., provides access to an East/West line of over 600 km in length. From the interior plains it crosses the Rocky Mountains, the Liard Plain, the Cassiar Mountains to the St. Elias Mountains. If suitable shot points can be obtained, a refraction profile along this road would be of national importance and international interest.

Given the regional structure and velocities obtained by this refraction profile, a detailed reflection study of the Atlin Horst structure might be undertaken. Atlin Lake, located 30 miles south of Whitehorse, Y.T., crosses a major fault. On the East, rock types are Permian and older with known volcanoes and ultrabasic intrusives, becoming mainly Laramide modified rocks to the West. By 1977/78, if the techniques developed for lake reflection work are satisfactory, it would be attempted to determine whether this feature is a surface expression of a Laramide subduction zone.

Year	$K	man-years
1977	30	.5

BRITISH COLUMBIA

The UBC Georgia Strait Programme will not now be funded by NRC. This allows a greater input from Earth Physics in a cooperative effort with UBC, specifically to undertake an East/West refraction--wide-angle reflection line at the North end of the Strait of Georgia from Nootka on the west side of Vancouver Island to the Toba River, a profile of some 180 km in length across a seismically active and geologically interesting section of Canada.

Years	$K	man-years
1978	25	.3

NEW CASSETTE SYSTEMS

To improve on the length of time spent in the field with cassette systems, and to use shots more efficiently, six new systems should be addded if the initial six work satisfactorily.

Year	$K	man-years
1977 or 1978	50	?

APPENDIX C

Preliminary Feasibility Studies

(to be updated and enlarged in 6 months)

NEW QUEBEC

In New Québec are a number of boundaries of différent shield provinces. Only the southern boundary, the Grenville Front, has been studied by seismological means. All boundaries represent age transitions and their structure is important to the understanding of their formation. With these boundaries are also associated gravity anomalies, which cannot be interpreted uniquely in terms of a density model without knowledge of the structure of the bottom of the crust. A coarse grid gravity survey has been done for all the boundaries; for the Superior-Churchill Province boundary, running N-S, whose southern section is also known as the Labrador trough, a fine grid gravity survey has also been undertaken, but the results will not be finally interpreted until late 1975. Over the northern boundary no fine grid gravity survey has yet been undertaken. Thus, the interpretation of the gravity data and the general understanding of the evolution of the shield would be aided by a determination of the deep structure of the crust by seismological means.

ARCTIC ISLANDS REGION

Canada has at least three possible continental-oceanic collision provinces within its continental margins. Based on the criteria that a survey should be proposed to help answer tectonic questions, the following areas are proposed as being interesting and should be considered in planning seismic exercises.

The Franklinian-Sverdrup complex has already been examined, by the GSC and ourselves, in its interior.

The relationship of how the structures intermesh at their margins is important from a tectonic viewpoint. There also exists the major question as to the age of the Canada Basin floor. A survey across the continental-oceanic margin between Prince Patrick Island and norteastern Ellesmere Island might be revealing. The Mclintock Inlet area structure has been suggested as being continuous with the Lomonosov Ridge. This area, in particular, might be considered for a survey - both shallow and deeper features would be significant.

The Hazen Trough area was at one time the axis for both the Franklinian and later Sverdrup geosynclines. The structure at depth of this feature might be revealing from a tectonic viewpoint.

Do Precambrian uplift structures such as the Prince Patrick uplift and the Boothia uplift have tectonic significance at depth? Does the Boothia structure terminate at the southern edge of the Franlinian structure or is it continuous with the Rens Fiord complex? These questions appear unanswerable on geologic evidence -- the seismic structure a little deeper might provide the answer.

The question of whether it is possible or not to distinguish between what were once separate continental plates on a seismic basis is still open. Will the further development of the close-in reflection technique enable one to distinguish, more quantitatively, the shield provinces?

THE YUKON

The most interesting parts of the Yukon seem to be:

a) the Tintina and Shakwak trenches, 300 miles and 200 miles long, north and south, respectively, of the upper Yukon Platform. Both of these trenches are 1-10 miles wide, and are similar in structure to the Rocky Mountain Trench.

b) the Richardson Mountains, the Porcupine Plateaus and the northern part of the Mackenzie Mountains where most of the seismic activity within the Yukon is found.

A detailed evaluation of both of these regions as potential areas for future reflection, refraction, seismicity or vibroseis studies will be made within the next six months.

MACKENZIE VALLEY REGION

Physiographically, the Mackenzie River flows largely on flat-lying sediments of the Interior Plains, which separate the mountains of the Cordilleran Region (part of the Circum-Pacific Belt) from the Kazan Region of the Precambrian Shield. The Delta forms part of the Arctic Coastal Plain.

Features of particular interest include the following:

1. the seismically active Mackenzie-Richardson Mountain Complex to the west,
2. the close conjunction of the Bear, Slave and Churchill provinces of the Shield to the east,
3. the nature and location of the subsurface boundary separating the stable North American Craton from the Cordilleran Geosyncline, and its possible relationship to plate tectonics,
4. the unexplained persistence of Cordilleran-type heat flow values right to the Shield boundary,
5. possible changes in crustal thickness, nature of the Moho and seismic velocities from one geotectonic unit to the next, including the Delta.

Some broad proposals for seismic surveys and the problems they address are:

a) A series of E-W refraction/reflection profiles across the major geotectonic and geologic boundaries (1-5). This would complement and perhaps elucidate the results of the Yellowknife '69 experiment.

b. A reflection survey on the ice at Great Bear Lake to delineate the obscured boundary between the Phanerozoic sediments and the Bear Province at the Shield (2-5).

c) A roughly N-S line on land to tie in with the proposed refraction survey on the ice north of Tuktoyaktuk in 1976, giving a comprehensive profile from the Interior Platform across the Delta, and down the Continental Shelf (3, 5, 4?).

d) A series of refraction profiles along portions of the Great Circle paths between the seismically active areas of the Eastern Yukon and nearby standard stations (e.g., RES, YKC). The resulting values of crustal thickness and P_n would greatly facilitate epicentral determinations and, along with the other surveys, permit refinement of the simple, 2-layer velocity models used in the interpretation of the Yukon 72 experiment. A further spinoff would be more precise assignment of seismic risk (1, 3 - 5).

e) Most of the above might be incorporated into a single, ambitious, geotraverse-like Mega-survey along an E-W line of some 600-700 km extent, from the Richardson Mountains, across Great Bear Lake, and as far east as the Slave/Churchill boundary. It could combine refraction with wide-angle and near vertical reflection, with the degree of detailing tailored to fit points of special interest along the line. For economical reasons, the line could be shortened or segmented, and the experiment carried out over a number of years.

Any increased knowledge of the structure, tectonics and seismic risk in this region is relevant to the viability of a Mackenzie Valley Communication Corridor (pipelines, hydro tower lines, transportation systems, etc.). We might, therefore, expect cooperation and logistic support from other interested groups for any work we might undertake. The Gravity Division, for example, although planning no detailed work here itself for the present, would be interested in a joint project (communication from Brian Boyd). There is also the possibility of obtaining velocity and depth information from the oil companies which would aid in the design of our experiment.

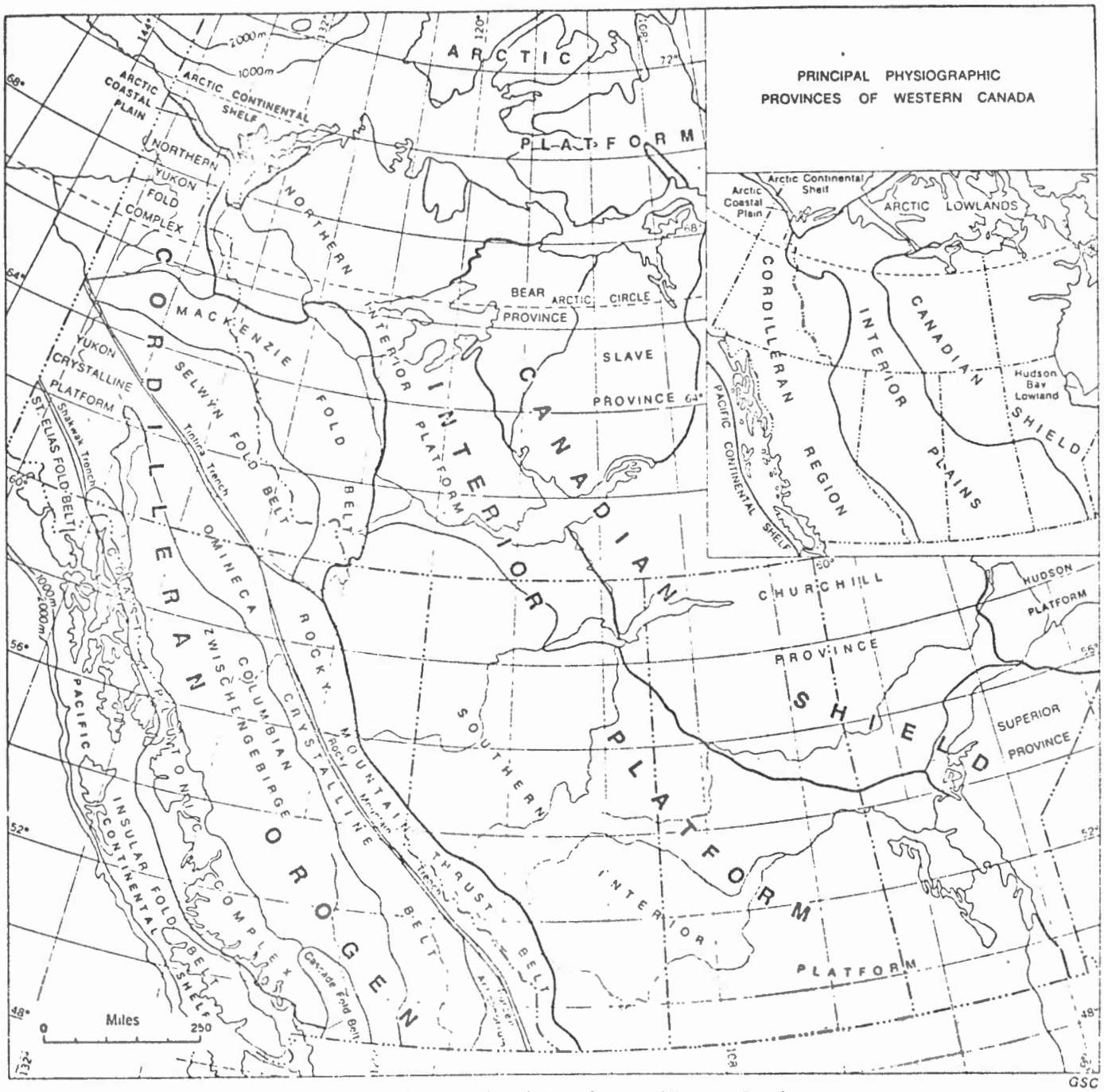

FIGURE VIII-1. Principal geological elements of Western Canada.

TIME TABLE

		Committed $K	Optional $K	Non-committed $K
1974				
	for Williston Lake explosives	7.5		
1975				
	Aidjax grant	10.		
April	Williston Lake Experiment	23.7		
Sept.	La Malbaie Experiment		3.5	
1976				
March	Tuktoyaktuk	4.		
April	Aidjex			
Sept.	La Malbaie Re-shoot		4.0	
	Reorganization of LP-BC Network			
1977				
	La Malbaie Re-shoot		4.5	
	La Malbaie Vibroseis 10 miles			40. contracting
	or			
	Alaskan Hwy			30
	or			
	Williston E-W			30
	or			
1978				
	B.C. Vancouver Island			25
	4 LP portables			80.
	6 Cassettes			50