Lithoprobe: Geoscience Studies of the Third Dimension - A Co-ordinated National Geoscience Project for the 1980s

Canadian Committee on the Dynamics and Evolution of the Lithosphere (CANDEL)

This report was written by C.E. Keen, chairman, CANDEL, from an earlier draft prepared by M.J. Berry and mainly based on documents from working groups as noted in the text. Minor changes in the final submission to *Geoscience Canada* were made by R.W. Macqueen in response to CANDEL committee members suggestions.

Summary
The Canadian Committee on the Dynamics and Evolution of the Lithosphere (CANDEL; see appendix for membership) recommends that LITHOPROBE studies be carried out in specific corridors in several parts of Canada, selected to solve key geological problems. Although the past two decades have witnessed major conceptual advances in earth science through plate tectonic models, many aspects of continental tectonics and evolution have resisted application of plate tectonic theory. Because the continents contain most of the world's known hydrocarbon and mineral resources, continental tectonics is the major challenge to earth science in the 1980s. Canada, with its vast territory and varied geology, is a natural laboratory for these studies.

LITHOPROBE involves the use of combined geological and geophysical techniques to determine the third dimension of crustal geology, by extending and relating surface geology to structure at crustal depth. A large bank of innovative techniques and concepts is available now for LITHOPROBE studies, ranging from advanced high resolution seismic techniques and deep drilling, to optimum computer-based interpretational methods and geological models of the latest plate tectonic concepts. When combined with more traditional methods, these new tools substantially improve our prospects for resolving the three-dimensional structures and evolutionary histories of key geological targets. The proposed programme is national in scope, and will involve a broad spectrum of earth scientists.

Based on regional geological/geophysical considerations, a number of LITHOPROBE transects are suggested within five regions: Appalachian Orogen/Mesozoic Passive Margin, Arctic, Eastern Cordillera, Western Cordillera and Modern Pacific Margin, and Precambrian Shield. Two areas are tentatively identified for the initial phase of the LITHOPROBE programme: onshore-offshore profiles of the northeast Newfoundland area; and the southeastern Cordillera. For each area both the surface geology and the geological/geophysical problems are well defined. Each area thus holds the promise of a high initial degree of success from the completed transects. A Precambrian corridor is of next highest priority. Key geological problems for all five regions as well as the details of methodology and costs are presented in the paper. The specific proposals were developed by CANDEL through study groups.

Studies of the depth dimension in relation to surface geological features will provide the three-dimensional geometry of major rock units and the recognition of similarities between buried geological environments which may be host to resources, and those exposed at the earth's surface. Indirect benefits include exchange of ideas and results between those engaged in the search for resources and those involved in basic research, enhanced training of Canadian geoscience students, and increased incentives to Canadian industry to develop innovative techniques and instrumentation.

An initial capital investment of about $4 million is estimated, with each corridor costing an additional $6 million on average. Five or six LITHOPROBE corridors could be completed in five years, and CANDEL considers this to be a realistic goal. Locations of LITHOPROBE corridors and methodology should be continually reviewed and assessed. The cost of the programme largely reflects the costs of high resolution seismic reflection and refraction technology, but also provides for the application of deep drilling, and of more traditional geological/geophysical measurements.

CANDEL recommends that appropriate new funds be identified by NSERC and EMR. Consideration should be given to mechanisms by which funding to these agencies can be administered to ensure coordination between studies. Disbursement should be guided by a steering committee charged with setting overall priorities, and composed of government, university and industry representatives. This committee could be supported by a series of advisory sub-committees, each similarly charged for a particular regional LITHOPROBE project.

LITHOPROBE as a programme for the 1980's can provide a focus for the government-, university-, and industry-based Canadian earth science community to cooperate on a scale never before attempted, as the scope of the problems and challenges demands. It also can concentrate the national expertise on problems of interest and significance to all Canadians.

Introduction

Objectives of the Lithosphere Programme. The Upper Mantle Project of the 1960's and the Geodynamics Project of the 1970's demonstrated the great benefits that result from coordination of national and international activities in the earth sciences. During the first decade plate tectonics was born, and in the second the hypothesis was tested extensively. The elegant simplicity of the concepts and their success in explaining the wealth of data then being collected by marine geoscientists studying the oceanic crust led to the widespread acceptance of the hypothesis at the end of the 60's. During the Geodynamics Project of the 70's the general ideas were developed and many detailed studies were undertaken either to test the hypothesis or to work out the details of plate interactions - again largely for the oceanic crust and the younger crust of the continents.

Previous studies undertaken on the older cratons with a view to testing the concepts of plate tectonics frequently have produced inconclusive results. At the same time there was a growing awareness that the hydrocarbon and mineral resources of the continents were finite and that in some cases, as for petroleum, the current rate of consumption could only continue for a short time. Continents probably formed by the accumulation of fragments of older continental crust and by the addition of oceanic crust. They may have experienced many episodes of continental separation, followed by collision and aggregation. These processes have been complex, and unlike the oceans where only the past

170 million years of earth history is recorded, only the continents contain 3700 million years of the geological record. Whereas there is appreciable knowledge, albeit incomplete, about the surface of the continents, little is known about their nature at depth. Thus it is not surprising that continental tectonics provides the major challenge to the earth sciences in the 1980's.

With this background, it is natural that the attention of the earth science community should be directed to the continents and to improving our understanding of their evolution and dynamics. In the summer of 1980, several international scientific unions (ICSU, IUGG, and IUGS; see glossary for full titles) approved a new interdisciplinary programme with the title "Dynamics and Evolution of the Lithosphere: the Framework for Earth Resources and the Reduction of Hazards" - the Lithosphere Programme.

The approved objectives of the new programme are:

- Define and explain the essential differences between continental and oceanic lithospheres.
- Measure directly the contemporary relative motions of plates and develop quantitative dynamic models of the mechanisms causing these motions.
- Test the hypothesis that the plates move as rigid units and seek explanations of intraplate tectonism and volcanism.
- Elucidate the physical and chemical processes that characterize the interactions of plates along common boundaries.
- Develop quantitative models of lithospheric evolution.

CANDEL, the Canadian Committee on the Dynamics and Evolution of the Lithosphere, was created in 1980. Its role is to develop and encourage programmes in Canada which fall within the general objectives of the international programme, to foster joint research projects and communication between the various disciplines of the earth sciences, and to promote co-operation between the pure and applied sciences. The committee consists currently of fifteen members, chosen from a broad spectrum of subdisciplines of the geoscience community, and including representatives of university, government and industry sectors (see the Appendix for members names). The parent bodies of the committee are the Canadian Geoscience Council and the Canadian National Committee of IUGG.

The LITHOPROBE Concept. With its vast territory and richly varied geology Canada has an exceptional opportunity to participate in many, if not all, aspects of the international-Lithosphere Project. In an attempt to identify a finite set of significant problems that could provide a focus for at least part of the total geoscience effort planned or underway, CANDEL has established working groups on: Continental Margins and adjacent Orogenic Belts, Arctic Tectonics and Precambrian Lithosphere, and is establishing working groups on Cratonic Sedimentary Basins, Motions and Internal Deformation of Plates, and Techniques of Exploration in the Depth Dimension. A wide range of geoscience studies are currently underway in Canada and many are directly relevant to the objectives of the Lithosphere Project. The working groups have proposed a variety of studies but, more importantly, the first three have recommended that a concerted effort be made now to study the inter-relationship between the deep structure of the lithosphere and surface geology. There is a widely held view that any real improvement in our understanding of the dynamics and evolution of the continental lithosphere can only come from detailed three dimensional studies of this kind.

CANDEL therefore recommends LITHOPROBE as a major new coordinated national project. The project involves detailed geoscience studies within corridors where important geological problems can be solved. The methodology is spearheaded by high resolution seismic techniques, to be followed by deep drilling at sites selected on the basis of seismological and geological mapping. A mix of ancillary geological and geophysical studies will provide essential supplementary data. Similar projects have been independently suggested by study groups within government and universities, and the name LITHOPROBE was coined during the Workshop on Earth Science Research in Canadian Universities (see previous article by Fyfe and Rust).

Presently there are few mechanisms for Canadian geoscientists to collaborate on high cost projects that are directed at resolving important first order geological problems. The proposed national programme will furnish the necessary incentives because it will provide a focus for the Canadian earth science community to co-operate on a scale never attempted before and to concentrate the nation's expertise on problems of significance to all Canadians.

CANDEL believes that LITHOPROBE studies are timely. There is much interest in the geological evolution of the continents as indicated by the International Lithosphere Programme, numerous projects within the International Geological Correlation Programme, and by the large-scale synthesis and compilation of North American geology/geophysics now underway as a major project to commemorate the centennial of the Geological Society of America (1988). There is a large bank of innovative techniques and concepts that is ready to be applied to the proposed programme. These range from advanced high resolution seismic reflection techniques and deep drilling expertise to optimum computer-based interpretational methods and the latest theories of plate tectonics. When combined with traditional methods these new tools will substantially improve our prospects for resolving the three-dimensional structures and evolutionary histories of the continent and its margins, and relationships to the adjacent oceanic lithosphere.

CANDEL recognizes that there is great potential for other significant Canadian contributions to the Lithosphere Programme. As yet, for example, there is no proposal dealing specifically with cratonic sedimentary basins, a topic of considerable interest to the origin and behaviour of continental lithosphere. Preliminary work on this topic is underway. Rather than delaying this report in an attempt to produce a more comprehensive geoscience programme, however, CANDEL has decided to recommend immediately that Canada initiate LITHOPROBE as a coordinated national programme. CANDEL may release further reports at a later date addressing other major geoscience research proposals, but for the present it wishes to focus attention on the third dimension of geology.

The remainder of this proposal addresses some of the key geological problems in Canada where LITHOPROBE corridors are recommended, and describes the methodology and costs of the proposed program. CANDEL is aware that the proposal needs refinement and modification. This can only occur through establishing a dialogue with a broad spectrum of the earth science community in Canada. CANDEL hopes that readers will respond with constructive criticism and suggestions for improvement and implementation of this proposal.

Some Key Geological Problems in Canada

The following discussion was extracted from working documents, prepared by the regional study groups (see selected references). It is of interest to note the common concerns in each region: the relationship of fundamental geodynamic processes and plate tectonic models to petroleum generation in sedimentary basins and to zones of mineralization in crystalline crust; the evolution of passive continental margins and their transformation to zones of subduction or accretion are examples. In the simplest terms, solution of the key geological problems in continental regions requires knowledge of the geometrical configuration of major rock units at depth so that we can recognize similarities between buried geological environments and those exposed at the earth's surface. These buried environments may be host to resources. Studies which include the depth dimension also are essential in evaluating the motion which has occurred between major geological provinces, and in the development of quantitative models for prediction of geological evolution with time.

Appalachian Orogen and Mesozoic Passive Margins. The Appalachian Orogen was formed by closure of a Paleozoic ocean basin (lapetus) which resulted in subduction, compression and perhaps accretion of exotic terrains. This phase was followed in early Mesozoic time by the initiation of extension and the formation of Triassic sedimentary basins. This lead to continental rifting, the eventual separation of continental plates in Jurassic time, and the evolution of the present continental margins. These margins are now covered by large thicknesses of sediment within which major petroleum discoveries have recently been made. These discoveries have focussed much attention on the structure and evolution of the Mesozoic passive margins. In the context of this general geological framework, it is proposed to address the following fundamental tectonic problems:

a) The deep structural evidence for the 500 million year old subduction episode which destroyed the early Paleozoic ocean that once separated opposite sides of the Appalachian orogen.

b) The relationship between the surface and deep geological characteristics of ancient island arcs and subduction zones.

c) The extent of overthrusting in the northern Appalachians compared to that in the southern Appalachians. The relative importance of strike-slip motion, as indicated by paleomagnetic evidence, compared to that of compressional tectonics, during the accretion of the orogen.

d) The mechanism(s) of ophiolite emplacement, determined from the character, surface expression and basement relationships of ophiolite slices.

e) The deep structural characteristics of late Precambrian Avalon Zone and of early Paleozoic Meguma Zone and the nature of the contact between them.

f) The deep structure beneath the Triassic rift basin in the Bay of Fundy.

g) The degree to which the pre-rift configuration of the Appalachian Orogen determined the locus of initial rifting along the contemporary Atlantic margin.

h) The geological processes involved in continental rifting. The amount of attenuation of continental crust beneath the present margin. Evidence of extensional forces during rifting, such as listric normal faults in the basement.

i) The thickness, stratigraphy and deformation of sediments within the Mesozoic continental margin basins. The relationship of crystalline crustal thickness to sedimentary basin evolution.

j) The location of the present ocean-continent transition and the nature of this boundary (i.e. sharp or diffuse).

It is proposed that LITHOPROBE transects be undertaken in two regions (see Figure 1). Each crosses the Appalachian Orogen and extends offshore across the present continental margin.

a) *Newfoundland Corridor:* Profiles 1A and 1B are selected because Northeast Newfoundland provides a well-exposed, complete section of the Appalachian Orogen. The region has the best surface exposures of rocks from the "Appalachian" lapetus ocean. It is also that part of the Appalachians geographically closest to the Caledonides with which its plate tectonic setting has been compared. Offshore (profile 1C), the Atlantic continental margin, contains all the elements of passive margins worldwide and is the site of major petroleum discoveries. It is the only region in Canada where a LITHOPROBE corridor will cross all these ancient and modern elements of continental margins.

b) *Quebec to offshore Nova Scotia:* Profile 1D is selected because the Quebec segment is already complete, and the profile may tie in with the onshore section through Maine likely to be carried out by the U.S. COCORP group.

The Arctic. Arctic Canada contains a full range of geological settings that extend north to south, from a deep-sea basin and a passive contineta1 margin through one or more orogenic belts and successor basins to platform and cratonic rocks. Over the past ten years, knowledge of these regions has advanced significantly. The Canada Basin, for example, is now known to be floored by oceanic crust and covered by as much as 5 km of sediments. The polar continental shelf appears to be composed of downfaulted blocks, partly Early Paleozoic in age, that are unconformably covered by a seaward-thickening largely Tertiary clastic wedge. The identification and age of individual structural and thermal events have been outlined within the major Early Paleozoic (Innuitian), Late Mesozoic (Columbian-Laramide) and Tertiary (Eurekan) successions. Regional aspects of basin geodynamics, chiefly within the Mackenzie Delta-Beaufort Shelf complex and Sverdrup Basin, are also beginning to be understood.

Despite this progress, our understanding of the structure and development of the geology of the Arctic remains primitive when compared to what is known about more accessible areas in southern Canada. Some key questions are:

a) History of plate dynamics associated with the early Paleozoic Innuitian Orogen. The relative roles (if any) played by subduction and strike-slip motions. The existence of displaced terranes.

b) The position of an ancestral early Paleozoic polar margin.

c) The extent and style of deformation of early Paleozoic rocks of the Antler Orogen, which is largely buried beneath the northern Yukon-Beaufort Shelf area. Its relationship to Innuitian events further east.

d) The deep structure of the geologically complex region south and east of the Beaufort Sea, which was tectonically active during Jurassic-Tertiary time. Its relationship to the timing and mode of origin of the Canada Basin, and to contemporary tectonism in the nearby northern Cordillera.

e) Basic relationships of plate tectonic motions to the structure and development of sedimentary basins of commercial interest; the MacKenzie Delta, the Sverdrup Basin, and northernmost Baffin Bay.

f) The distribution and timing of igneous activity, diapirism and organic maturation/metamorphism within these regions of commercial interest. The role of fluids in thermal metamorphism and petroleum generation.

g) The timing and plate tectonic motions which formed the present polar margin. The identification of lateral changes in margin structure and their correlation with sediment thickness, contemporary seismicity and free-air gravity peaks. The roles of shearing and rifting in margin formation. The evidence for more than one phase of opening.

h) Significance of the Nares Strait lineament and its association with the creation of Baffin Bay to the south, and the Alpha and Lomonosov Ridges to the north. The nature of the junction between these ridges and the polar margin.

i) The structural style of the basement beneath the polar margin in relation to the distribution of sediments. The changes in crustal thickness across the margin.

To maximize benefits and minimize logistical expense, it is recommended that LITHOPROBE studies be concentrated in four corridors (Figure 1). Three (2A - 2C) cross the polar margin, and these are arranged to cross structurally distinct segments of that margin. Highest priority is given to Profile 2A, which extends from the polar margin, across the Sverdrup Basin south to Melville Island and M'Clure Strait. Profile 2D, located in the geologically critical but complex region of the Yukon, should be combined with a corridor in the northern Cordillera. Studies in the first three corridors would include detailed seismic refraction profiling, with reflection studies limited to key areas. Paleomagnetic and geochronological measurements are essential. Combination of the results of these studies with industrial deep drilling results within the sedimentary basins is a further critical element in Arctic studies.

Eastern Cordillera. In general terms, the geology of the Cordillera can be related to rifting that formed the western margin of ancestral North America, subsidence and sedimentation along the resultant passive margin and, findally, its interaction with allochthonous terranes which produced the varied tectonic styles of the region. In specific terms, however, many parts of this scenario are enigmatic. The stratigraphic record of the Cordilleran prograded continental terrace wedge spans an interval from mid-Proterozoic (ca. 1500 Ma) to mid-Devonian (ca. 360 Ma). In the northern Cordillera two or three regional unconformities, perhaps associated with episodic evolution of the margin, are documented. Volcanic rocks are present locally in every system and there is much indirect evidence for basement rifting from late Proterozoic to mid-Devonian time.

The tectonic setting at initiation of Belt-Purcell sedimentation is debatable. The thick Belt-Purcell rocks are of miogeoclinal affiliation, but in Canada basal rift sequences have not been found. Possibly they are too deeply buried. Assemblages that best fit a model of rifting, rift sedimentation and volcanism followed by subsidence and sedimentation along a passive margin are the Windermere Group (late Proterozoic) and the early to mid-Paleozoic rocks. The relationship of these assemblages to basement structure provides the focus of the recommended research proposal in this area.

The following have been identified as key problems in the eastern Cordillera:

a) Nature and depth of the basement surface along and across miogeoclinal trends.

b) Age and chemistry of ancient core rocks in gneiss domes and other structures in the Omineca Crystalline Belt and their correlation with cratonic rocks.

c) Age of source rocks for rift sediments and correlation with cratonic rocks, particularly by zircon dating.

d) Chemistry and ages of dykes and volcanics, including comparisons between early rift volcanics and later volcanics in the same areas. Volcanics of Cambrian, Ordovician, Silurian and Devonian ages are present in the miogeoclinal wedge of the northern Cordillera.

e) Sedimentology of the rift sediments - sources, directions of transport, variations, etc.

f) Character of early Paleozoic sedimentation including geometry of basins overlying rifted basement.

g) Relationships of stratiform mineral deposits to sedimentation and basin tectonics.

It can be seen from the above that the ancestral passive margin was relatively energetic. Perhaps, as has been suggested, the continental terrace wedge prograded into an intermittently active back-arc basin rather than a stable expanding ocean basin. In either case, an understanding of the miogeoclinal wedge environment is fundamental to an understanding of Cordilleran tectonics. Its evolution is of great economic importance because it contains large stratiform base-metal deposits and W, Sn and Mo deposits associated with granitic plutons generated within the underlying continental basement.

It is proposed that LITHOPROBE transects be conducted across the eastern Cordillera, to determine the depths to and characteristics of basement, gross structure of the supracrustal rocks and nature of the boundaries between the Thrust and Fold, Omineca and Intermontane Belts. The preferred transects are shown on Figure 1.

3A) Southern Cordillera: Profile 3A crosses the Rocky Mountain Thrust and Fold Belt, the Southern Rocky Mountain Trench, the Omineca Crystalline Belt and part of the Intermontane Belt. Its major advantages are good accessibility, and the possibility of extending the line westward, to join the deep crustal structure profile derived during the 1980 Vancouver Island Onshore-Offshore Seismic Experiment.

3B) Northern Cordillera: Profile 3B crosses a region in which the Belt-Purcell assemblage rocks are succeeded to the south by Windermere strata. It crosses the Tintina Trench near Dawson City.

3C) Canol Road - Norman Wells to Ross River: Profile 3C is the best corridor in the Cordillera for the Thrust and Fold Belt, with excellent stratigraphy and exposure and relatively simple structure

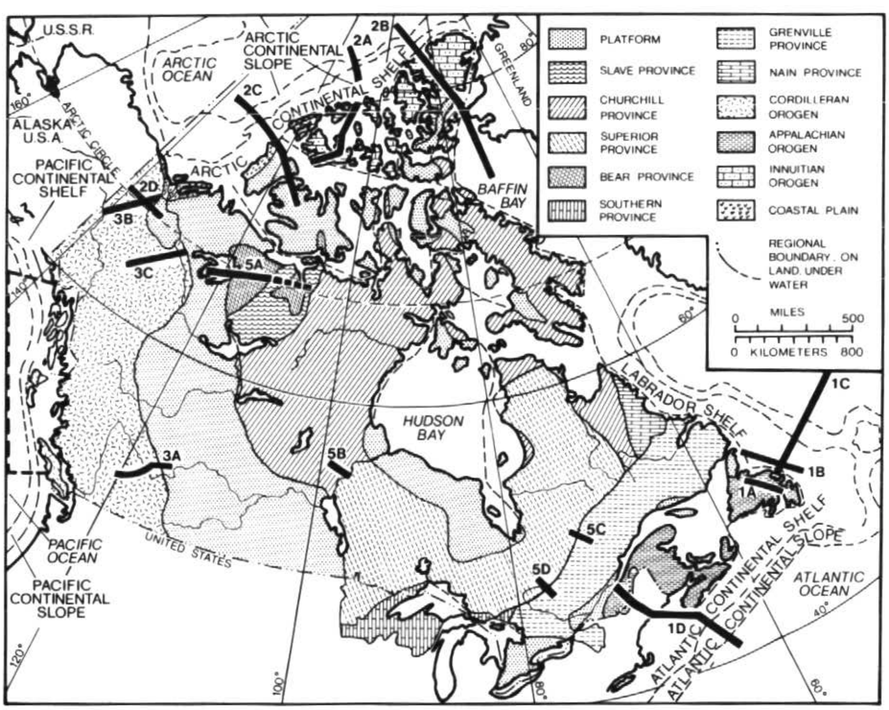

Figure 1. Location of proposed LITHOPROBE transects as discussed in text. Base map from Geology and Economic Minerals of Canada (ed. R.J.W. Douglas), Geological Survey of Canada, 1970.

in the supracrustal rocks. Unfortunately access is only available in the southern half of the corridor at this time.

Western Cordillera and Modern Pacific Margin. The modern Pacific margin includes the Insular Belt and the adjacent offshore regions of the continental shelf and slope. Although the recorded geological history of the area began during mid-Proterozoic time with rifting along the edge of the ancient craton, the history of the western Cordillera and present margin began during the Mesozoic when allochthonous crustal fragments were accreted to the ancient margin to form a collage of exotic terranes which today comprise the western Cordillera.

In general terms, the tectonic history of this region can be summarized in terms of five tectonic phases, each of which is defined by its geological effects, or in the case of the fifth, through descriptions of active processes observable by geophysical methods. Each phase requires further definition by careful geological and geophysical studies in key areas.

a) Allochthonous Phase: Identification of Paleozoic and Paleozoic-Mesozoic crustal fragments which were transported from southerly to northerly latitudes, beginning in pre-Late Triassic time and continuing until at least Early Tertiary time.

b) Suture Phase: Nature of the collision of Wrangellia with the Alexander Terrane, which occurred probably during latest Jurassic to earliest Cretaceous time; relative roles of collisional and translational tectonics.

c) Post-Suture Phase: Causes of epicontinental deposition across amalgamated terranes; nature of final suturing of amalgamated terranes with the Cordillera in mid-Cretaceous time.

d) Rift Phase: Geological processes involved in mid-Tertiary disruption of western Wrangellia in the region of Queen Charlotte Sound and Hecate Strait, which include extrusion of extensive mantle-derived volcanics, crustal attenuation aided by listric normal faults, and northward translation of Queen Charlotte Islands to their present position.

e) Modern Phase: Timing and geometry of plate motions from mid-Tertiary to present. These include: Farallon Plate convergence and subduction beneath western North America, Pacific Plate translation adjacent to Queen Charlotte Transform, Cascade-Garibaldi volcanism, rapid RFT triple junction migrations, and formation of the Winona Basin.

The northeast Pacific continental margin is the most accessible and best laboratory for studying the processes of continental acretion, plate subduction and transform motion. It is there where the complexities and varying rates of plate interaction are expressed in modern analogues such as to allow those working on more ancient terranes and orogenic belts access to the means of explaining observed effects in ancient rocks. Before such analogues can be applied however, two major research efforts are proposed:

1) It is recommended that multi-channel seismic profiles be obtained across the Pacific margin at several localities using industrial quality equipment and processing to define the structural style of the convergent and transform margin and to contribute to our understanding of the mechanisms of acretion.
2) In order to understand the plate geometry for the period between 10 and 50 Ma and thus permit reconstructions of the Tertiary margin, it is necessary to map a large area of the sea floor in the northeast Pacific in terms of magnetic, gravity and bathymetric parameters; seismic reflection profiling and sediment coring also is required. This region, west of the Alaska Panhandle, was adjacent to the British Columbia margin during the Tertiary. The precise location of possible land-based and marine LITHOPROBE transects requires further discussion. It is suggested that such studies would be a joint Canadian - U.S. program.

Precambrian Shield. Current concepts of plate tectonics are generally most successful in providing a framework for understanding the evolution of lithosphere of Cenozoic and Mesozoic age. Extension to older rocks, and in particular to those of the Precambrian Shield, is much less definite. It is worth emphasizing that much of Canada's mineral wealth is located in Precambrian rocks and these minable deposits are becoming increasingly difficult to find. Clearly, a much improved understanding of the evolution of the Precambrian lithosphere is urgently required both to provide fundamental insight into the early history of the earth, and an improved framework for the development of successful mineral exploration programmes. The vast extent of the Canadian Shield and the broad range of challenging problems demands that there be a focussing of effort on a selected set of topics if we are to acquire an order of magnitude increase in our understanding of the processes that contributed to its evolution. The following fundamental problems are suggested for study:

a) Nature of the boundaries between Shield provinces.
b) Evolution of continental lithosphere through 2 - 3 billion years of recorded history.
c) Role of fluids and volatiles in the evolution of the crust.
d) Nature of the lower continental crust and of the transition to the upper crust.
e) Nature of ore deposition in Precambrian rocks.
f) Understanding the evolution of Proterozoic orogens.
g) The potential role of the continental lithosphere as a thermal boundary layer since Precambrian time.
h) Plate tectonic motions and paleomagnetic studies in the Precambrian.

Because no single location is ideal for the investigation of all of these problems, three different regions have been selected as LITHOPROBE corridors, each of which has different advantages.

a) The Wopmay Orogen (Profile 5A). Asiak Thrust Belt in Wopmay Orogen (NW Canadian Shield) contains one of the oldest and best-exposed of all continental margins. A cooperative multidisciplinary investigation of this margin involving Earth scientists from the Precambrian Division of GSC, Memorial University of Newfoundland, McGill University, Queen's University, University of Kansas, University of California at Santa Barbara, and Viriginia Polytechnic Institute is underway. The aim is to reconstruct the margin as it was before thrusting, and to compare it with younger thrusted margins such as the Canadian Rockies and unthrusted present-day margins such as the Atlantic margin off Nova Scotia. It is anticipated that much will be learned concerning subsidence at passive margins and foreland basins, and of the mechanics of thrusting, from a comparison of relatively young margins with one formed on the thinner and less rigid Precambrian lithosphere. To complement the geological and geochronological studies now underway, there is an immediate need for seismic refraction traverses to outline major thrusts and the basement surface at depth, and detailed gravity surveys to locate the sharply-rifted edge of the underthrusted crustal margin, from which the amount of tectonic shortening in the overthrusted sedimentary prism can be deduced. The main ongoing phase of geological field work in Asiak Thrust Belt is planned for competion in 1983. The chief merit of this proposal is the close marriage of geophysics and geology in an area of the Precambrian Shield where the geology is already well understood in terms of plate tectonics. Seismic studies would be confined to refraction methods, because of the absence of access roads.

b) The Churchill-Superior boundary, in the Thompson Nickel Belt region (Profile 5B). This region is selected for a study of Precambrian province boundaries because it combines road access, previous geological and geophysical mapping and economic importance. Critical to the success of this study is how well seismic methods can delineate structural changes across near-vertical geological boundaries.

c) The Grenville Front. The origin of the Grenville Front remains a mystery. However, the Grenville Front is itself a fundamental, deep-seated geological feature, across which the crust has been shown to thicken to the southeast. The location of a Grenville Front corridor is problematic, due to the absence of detailed geological mapping and likely geological complexity in the region of previous seismological studies. Two promising alternatives are the Val d'Or - Mont Laurier section (Profile 5D), where the rocks are Archean on both sides of the front; and the Chibougamau region of Quebec adjacent to previous seismic studies (Profile 5C). A third possibility is the region of eastern Ontario near the Ottawa River.

Lithoprobe Methods

Geophysical studies provide the tools required to extend our knowledge of surface geology to depth, but they may prove meaningless when interpreted without reference to detailed geological studies within the same regions. Geologists need to be involved in the interpretation of the results, in terms of regional geology and plate tectonic models. It is of utmost importance, therefore, to develop a completely integrated approach which involves all subdisciplines from the planning to the interpretation stage. A mix of geological, geochemical and geophysical techniques will be applied to each LITHOPROBE corridor; the mix will be determined by previous work in the region and by the nature of the geological problems to be solved. By far the most expensive and innovative techniques proposed are seismic studies and deep drilling. Therefore, some aspects of these are briefly described. Some of the other geological and geophysical techniques which will form an integral part of LITHOPROBE corridors are listed in Table 1, and those which may require substantial additional resources are indicated.

Seismic Methods. Geophysical methods are spearheaded by the most advanced high resolution seismic reflection techniques. These techniques are unique in providing an approximately equal degree of resolution throughout the depth range of the crust and are the only means of determining three-dimensional crustal structure in the detail that is required for this programme. Recent VIBROSEIS surveys by the COCORP group in the U.S. have produced spectacular results across several regions of continental North America. Except for the longer receiver arrays and the longer recording times, the VIBROSEIS technique used by COCORP is essentially identical to that used by industry to explore for petroleum.

Offshore seismic reflection techniques also are proven methods of the petroleum exploration industry that have been adapted for deep crustal investigations. In 1981 scientists from the Atlantic Geoscience Centre (Energy, Mines and Resources) will participate with the LASE group in a large aperture seismic reflection survey across part of the Atlantic continental margin. The principal difference from the techniques used by industry is in the LASE group's use of extra long receiver arrays and multiple large volume air-guns for deeper penetration.

Most seismic reflection surveys do not yield accurate velocity estimates, which are necessary for reliable depth computations, so it is proposed here that regional three-dimensional seismic refraction surveys (areal coverage with close receiver spacing) be recorded across most of the targets. In recent years the Canadian COCRUST group has conducted cooperative seismic refraction surveys across a number of targets in central and western Canada, while the Pacific and Atlantic Geoscience Centres have been collecting refraction data from the continental margins using their newly-developed ocean bottom seismometers. In addition to providing the required velocity information for interpretation of reflection surveys, broad range refraction surveys will (a) be used to extrapolate laterally the results of the higher resolution surveys, (b) supply independent structural information and (c) be useful substitutes for the reflection surveys in the remote areas of Canada.

Deep Drilling. A second phase of this programme will require the drilling of deep holes (1 to 5 km depth) at critical locations, to test interpretations based on surface geology and geophysical observations. These holes will provide essential data on the changing characteristics of the rock formations with depth. Both sample analysis and extensive logging of the holes is envisaged.

At the present time CANDEL recognizes that a scientific programme of deep drilling is an expensive endeavour. To drill, core and log a 2 km hole on land costs about $0.25 million. Costs increase rapidly with increasing depth of hole and existing diamond drilling technology is limited to 3 km. Thus the holes have to be located with great care. In the first phase of the LITHOPROBE project, it is suggested that greater use be made of existing and planned industry deep holes. A wealth of core material is available from sedimentary basins, and is accessible to all geoscientists. It is further suggested that preliminary holes in crystalline crust be obtained in conjunction with Canada's scientific programme for the disposal of nuclear wastes. Additionally, it may be valuable, in some cases, if planned holes could be deepened beyond their target depth to allow study of deeper geological aspects of the area.

Once the basic geological and geophysical data have been collected in LITHOPROBE corridors, it is recommended that funds for a second phase of the project be provided for deep drilling of holes located at critical sites determined by geological and geophysical results. Sites located on the continental margins could be sampled by participation by Canada in the Ocean Margin Drilling Project, which will cost an estimated $7.5 million per year.

Participants

LITHOPROBE is proposed as a coordinated program, national in scope, that will take advantage of the research competence of university, government and industry personnel and organizations. Clearly the contribution of each group will be different but the proposed cooperative programme will provide a significant opportunity for technology transfer between groups and a potential strengthening of the geosciences in all three. Some areas of study will involve two or more groups. Fields of special expertise also can be defined, however. Industry is uniquely suited to undertake about 90% of the VIBROSEIS work, to become involved in offshore reflection surveys, in cooperative drill hole studies, and in field studies involving electromagnetic and gravity surveys. In addition, instrument construction can be contracted to industry. Universities have special capabilities in seismic refraction surveys (through

Table I: *Ancillary LITHOPROBE Techniques*

Method or Discipline	Category*	Examples of Relationship to LITHOPROBE
Electromagnetic - Magnetometer Array - Magnetotelluric - Audio-magnetotelluric	A	Together these delineate variations in electrical conductivity. Allow identification of shear zones conductive mineral concentrations, rock porosities and anisotropy. Can be used in remote areas.
Gravity, Aeromagnetic and Gradiometer Surveys	A	Integrated interpretation of deep structure. Extension of corridor results over larger region.
Heat Flow	A, B, C	Thermal regime at depth. Estimates of radioactive concentration in the crust. Estimates of thermal metamorphism and role of fluid convection in sedimentary basins.
Metallogeny	A, B, C	Predictive models of favourable environments for ore deposits. Geobarometry and geothermometry. Regional metallogenic studies in relation to major tectonic features. Stable isotope studies in relation to genesis of deposits. Comparison of Archean and contemporary volcanism.
Metamorphic Studies	A, B	Timing of metamorphic events in the Shield and orogenic belts. Relationship of metamorphism to heat flow. Relationship of degree of metamorphism to concentration of metal deposits.
Organic Geochemistry	A, B	Degree of thermal metamorphism of sediments. Models of hydrocarbon generation. Role of fluid migration in sedimentary basins.
Radiometric Geochronology	B, C	Provide baseline data on the age of geological events. Development of new dating methods for application to Precambrian rocks.
Paleomagnetic Studies	A	Basic data on directions and magnitude of plate motions. Identification of exotic terranes. Prediction of nature of plate boundaries.
Petrogenetic and Geochemical Studies	A	Effect of water, retrogressive metamorphism on physical properties of rocks. Recognition of shear zones at deep crustal levels. Mapping of compositional and textural variations along corridors.
Physical Rock Properties	A	Density, seismic velocity and magnetic properties to guide interpretation of geophysical measurements, and relate them to rock composition. Rock anisotropy as a clue to stress environment.
Stratigraphic/ Sedimentological Methods	A	Architecture of sedimentary basins. Recognition of exotic terranes. Subsidence of sedimentary basins. Depositional environments. Sedimentary facies of ancient and contemporary continental margin environments.
Structural Geology	A	Structural cross-sections as basic information for corridor selection. Palinspastic reconstructions to distinguish structural style of various phases of deformation. Measurement of crustal shortening/extension. Definition of mechanical behaviour and deformation of rocks.

*A: present high level of activity and expertise. LITHOPROBE activities require operating funds only.
B: requires major new facilities or funds to carry out research related to LITHOPROBE.
C: level of expertise not yet adequate in Canada.

COCRUST), in specialized seismic data processing and in geodynamic modelling and interpretation of results. Government has special expertise in offshore studies in regional geologic studies and compilations, and in aeromagnetic studies, and would play the prime role in funding.

Costs

The following budget (Table II) reflects the proposals available to CANDEL on May 15, 1981. It represents a realistic budget for seismological studies, an approximate budget for ancillary studies, and merely a reasonable guess at the cost of deep drilling. The figures are based on 1981 dollars, and operating costs are given on an annual basis. It should be noted that five or six corridors could be completed in a five year programme, with an additional two years needed to complete deep drilling and interpretation.

Benefits

There are two categories of benefits: direct benefits to earth scientists, and benefits to Canadians in general. They are, in most cases, difficult to separate. Some of the major benefits are as follows:

1) Enhanced knowledge of geological structure in three dimensions.
2) Recognition of buried structures, possibly resource rich, which are similar to those exposed at the earth's surface.
3) Definition of nature of motions between major geological regions.
4) Ability to define predictive models of geological evolution with time.
5) Exchange of ideas and results between those engaged in the search for resources and those involved in basic research, resulting in an increased success rate in exploration.
6) Attraction of good students to the earth sciences and their improved training.
7) Development of new expertise within some sectors of earth science, using state of the art technology.
8) Increased incentives for Canadian industry to develop innovative techniques and instrumentation.
9) Employment opportunities for earth scientists in their own country.
10) Greater recognition of Canadian geoscience on an international level, with a corresponding increase in cooperative programs.

TABLE II: *Lithoprobe Budget*

Item	Details	($ thousands) One Time Capital Costs	($ thousands) Annual Operating
		(1981 dollars)	(1981 dollars)
Seismic Refraction Recording Systems	150 portable units	$2,250	
Digital Reflection Recording System	1 system such as the DFS 5 or 6	500	
Large Air gun source	Offshore seismic surveys	250	
Computing system for seismic data processing		700	
Total Capital for National Seismic Facility		**$3,700**	
VIBROSEIS/Offshore Seismic surveys	400-800 km of reflection data/yr		$4,000
Additional industrial processing			100
Special processing	Development and implementation of new techniques		150
Refraction Survey and interpretation	1 or 2 major projects/yr.		550
Equipment Maintenance			50
Programme coordination			20
Total Operating Costs for Seismology			**$4,870**
Ancillary geological and geophysical studies	See Table I for list of methods/disciplines	$1,800	$2,000
Drilling costs	Later phase, 4 x 2 km holes/yr, diamond drilling		$1,000

Recommendations

CANDEL recommends that the coordinated national programme LITHOPROBE be funded with the following objective:

1) to map the deep structure of selected key geological structures in the major geological provinces of Canada in order to improve our understanding of their evolution and dynamics.

Principal features of LITHOPROBE will include:

2) coordinated studies bringing together geoscientists from industry, universities and government.
3) extensive application of the VIBROSEIS technique complemented by refraction surveys, to be followed by deep drilling in selected locations.
4) integration of these with other geophysical and geological studies.

CANDEL recommends that appropriate funds be identified by NSERC and EMR and that these funds be effectively combined and administered in such a way as to ensure a high degree of coordination between studies. The Government funding agency (or agencies) could be assured of this proper coordination if it were guided in its disbursement of funds by a Steering Committee composed of Industry, University and Government representatives and charged with setting over-all priorities. The Committee could be supported by a series of Subcommittees each similarly charged for a particular LITHOPROBE project, and by Sub-committees on drilling and seismological technologies.

Subject to further review, CANDEL suggests that the Newfoundland corridor and a Cordilleran corridor be selected for the first phase of the project. A Precambrian corridor also is of high priority. These recommendations are based on accessibility, and a clear definition of scientific problems which are most likely to be successfully resolved with LITHOPROBE methods. Three or four others, to be completed during a five year program, should be selected from among those shown in Figure 1. Other proposals for LITHOPROBE corridors would also be welcome at this stage and considered on their scientific merit.

We emphasize again that as a national earth science programme for the 1980's, LITHOPROBE can provide a focus for the Canadian and international earth science community to cooperate on a scale never attempted before. It also can concentrate the national expertise on problems of interest and significance to all Canadians.

Glossary

VIBROSEIS - a non-explosive method of land seismic reflection profiling.

COCORP - Consortium for Continental Reflection Profiling, based at Cornell University.

LASE - Large Aperture Seismic Experiment group composed of scientists from various U.S. oceanographic institutes, and the Atlantic Geoscience Centre.

COCRUST - Consortium for Crustal Reconnaissance Using Seismic Techniques, composed of geoscientists from Canadian universities and the Earth Physics Branch.

IUGG, IUGS - International Unions of Geodesy and Geophysics, Geological Sciences, respectively.

ICSU - International Commission of Scientific Unions.

NSERC - Natural Sciences and Engineering Research Council, Canada.

EMR - Department of Energy, Mines and Resources, Canada.

Appendix

CANDEL includes the following representatives.

C.E. Keen (chairman, CANDEL), Atlantic Geoscience Centre, Dartmouth, N.S.
H.C. Palmer (Secretary, CANDEL), University of Western Ontario, London, Ontario.
A.J. Baer, University of Ottawa, Ontario.
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H. Gabrielse, Geological Survey of Canada, Vancouver.
D.I. Gough, University of Alberta, Edmonton.
C. Hubert, Université de Montréal.
R.W. Macqueen, University of Waterloo, Ontario.
D. Oldenburg, University of British Columbia, Vancouver.
P.Y. Robin, University of Toronto, Ontario.
J. Sweeney, Earth Physics Branch, Ottawa.
C.J. Yorath, Pacific Geoscience Centre, Sidney, B.C.

A representative of the mining industry has yet to be appointed.

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