Phase 1 LITHOPROBE. A Coordinated National Geoscience Project

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Introduction

LITHOPROBE is a major new project in Canadian earth sciences to study the interrelationship between the deep structure of the lithosphere and surface geology, and thus to solve key geotectonic problems of significant interest to the university, government and industry-based geoscience community. Phase 1 LITHOPROBE now has been funded and preparation of a proposal for Phase 2 is in progress. The Lithoprobe program will be spearheaded by high resolution multichannel seismic reflection technology, the only available geophysical method with adequate resolution to help unravel complex geological structures at depth. Seismic refraction experiments, other geophysical studies, geological studies and geochemical investigations will provide essential supporting data to complement the reflection results and enable integrated interpretations in the study corridors. For further information on the Lithoprobe concept, refer to CANDEL (1981).

A large-scale research program for extending studies of geology into the third dimension has been widely discussed by Canadian earth scientists since 1981 (Fyfe and Rust, 1981; McLaren, 1981; CANDEL, 1981). In May 1982, the Canadian Geoscience Council selected LITHOPROBE as a major, coordinated multidisciplinary research effort of national scope and importance. At that time a Lithoprobe Steering Committee (LSC) was established with Dr. J.O. Wheeler, Geological Survey of Canada, as Chairman. Subsequently, correspondence and discussions took place between officials from the LSC, the Natural Sciences and Engineering Research Council (NSERC), and Department of Energy, Mines and Resources (EMR). The outgrowth of these discussions was a commitment of funds from the Earth Sciences Sector of EMR and a decision by the LSC to select two regions, Vancouver Island and the Kapuskasing Structural Zone, for study in a one-year proposal. These regions are not mentioned in the CANDEL (1981) article; the selection was made on the basis of scientific merit, overall feasibility, and information that has become available since that article was written. The author was requested to act as Principal Investigator on behalf of seven Co-investigators (M.J. Berry, W.S. Fyfe, R.D. Hyndman, E.R. Kanasewich, J.C. McGlynn, G.F. West and C.J. Yorath) to prepare a proposal for evaluation by NSERC. This proposal, "Phase 1 LITHOPROBE – A Coordinated National Geoscience Project", has been funded by NSERC in the amount of $650,000.00 as a one-year Collaborative Special Project grant for 1984-85. For the research program, summarized below, these funds will be combined with the $500,000.00 committed by EMR.

The Research Program for Phase 1 LITHOPROBE

Phase 1 LITHOPROBE includes three research components:
(1) a Vibroseis seismic reflection profile across southern Vancouver Island where preliminary studies and a major seismic refraction program have been completed;
(2) seismic refraction and preliminary reflection studies on the Kapuskasing structural zone because it has recently been identified as a region of fundamental significance for understanding the nature and evolution of Archean crust; and
(3) supporting geological, geochemical and other geophysical investigations in both these regions to enable integrated interpretations of geology and tectonics.

Vancouver Island: Background

In the region of Vancouver Island the oceanic Juan de Fuca and Explorer plates are being subducted beneath the continental America plate at convergence rates of 2 to 4 cm per year. Keen and Hyndman (1979) provide a comprehensive review. Muller (1977) has summarized the regional geology on the island; the known geology offshore is based on a range of marine geological studies (Tiffin *et al.*, 1972; Yorath, 1980) and on a 24-channel seismic reflection profile and its geological interpretation (Snavely and Wagner, 1981). On land, the main stratigraphic and structural unit is the Karmutsen Formation – a thick, Upper Triassic shield of mainly basaltic lava that separates mid-Paleozoic from Jurassic volcanic and plutonic complexes, each of which are overlain by younger sedimentary strata (Fig. 1). Along the west coast an apron of complexly deformed Upper Jurassic and Cretaceous slope and trench deposits is exposed beneath Ceno-

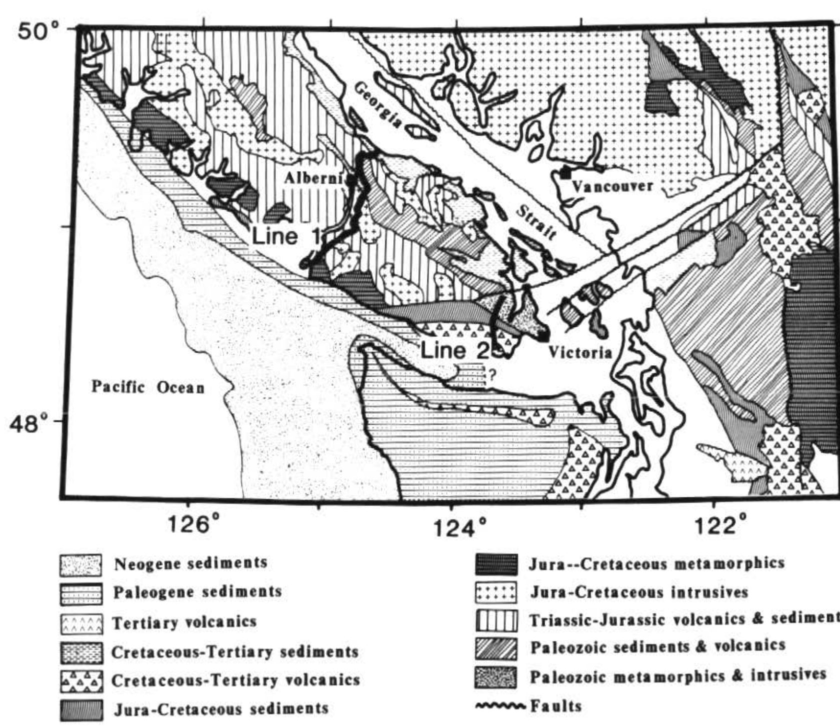

Figure 1 *Geological sketch map for southern Vancouver Island and adjacent regions (adapted from Muller, 1977 and Yorath, 1980). The thick black lines show the location of planned Vibroseis reflection profiles on the island: Line 1 – principal route; Line 2 – additional route which may be run if time and funds permit*

zoic clastic and oceanic volcanic rocks which, beneath the continental shelf and slope, are folded and thrust within a subduction complex. On the east coast the Nanaimo Group of Late Cretaceous age comprises cyclical graded sequences of conglomerate, sandstone and shale that developed within a basin between the Coast Plutonic Complex and the Insular Belt. On the basis of paleomagnetic studies, Yole and Irving (1980) have established that the Karmutsen Formation basalts originated thousands of kilometres south of adjacent parts of North America, and therefore represent accreted terranes; but there is little scientific evidence indicating the nature of the boundaries with adjacent continental rocks.

In 1980, the Vancouver Island Seismic Project (VISP) was carried out with the major objective of obtaining a seismic structural section to upper mantle depths from the oceanic Juan de Fuca plate to the inland volcanic arc of the continental America plate. Ellis *et al.* (1983) reported on the preliminary results; McMechan and Spence (1983) provided an interpretation for data recorded along the length of Vancouver Island; Clowes *et al.* (1983a) and Spence (1984) presented a more recent seismic structural section (Fig. 2a) derived from the study. The secondary objective of VISP, and one important for the choice of the Vancouver Island Vibroseis profile, was a feasibility study of seismic reflection profiling on the western part of Vancouver Island. This program was very successful, as reflections were obtained from depths corresponding to the top of the subducting lithosphere (Ellis *et al.*, 1983; Clowes *et al.*, 1983b).

A speculative tectonic interpretation (Monger *et al.*, 1984) based on the known geology and geophysics and concepts concerning regional accreted terranes is presented in Figure 2b. The heavy, dashed line shows the lower limit of geological (structural and stratigraphic) confidence. The overall tectonic style illustrated portrays a conceptual model involving a series of imbricated accreted terranes underlain by continental upper mantle and the modern descending oceanic plate. The manner of accretion of the older terranes is predicated on the principle that the contemporary processes (illustrated offshore) have been operative throughout the past 100 Ma, resulting in imbricated and vertically stacked tectonostratigraphic assemblages, each of which contains slivers of detached oceanic crust such as the Crescent formation (CR on Fig. 2b) which is known to occur offshore. However, we do not know if the basic concept is valid.

Vancouver Island: Scientific Objectives
The program embodies a unique opportunity in Canada to solve a fundamental problem in global tectonics – the processes involved in, and structural manifestations at depth of, accreting terranes – and to delineate the geometry and characteristics of a young and actively subducting oceanic plate.

There are a number of fundamental questions to which the program is directed, some of which include:
(1) Is the general seismic structural model of Figure 2a a reasonable representation of the subsurface geometry? In particular, is the large detached slab of oceanic lithosphere, velocity of 7.7 km/s, present below western Vancouver Island, as represented in Figure 2b? If so, how extensive is it?
(2) What is below the Wrangellia terrane (WR in Fig. 2b)? Has it over-ridden another accreted terrane? If so, what is the geome-

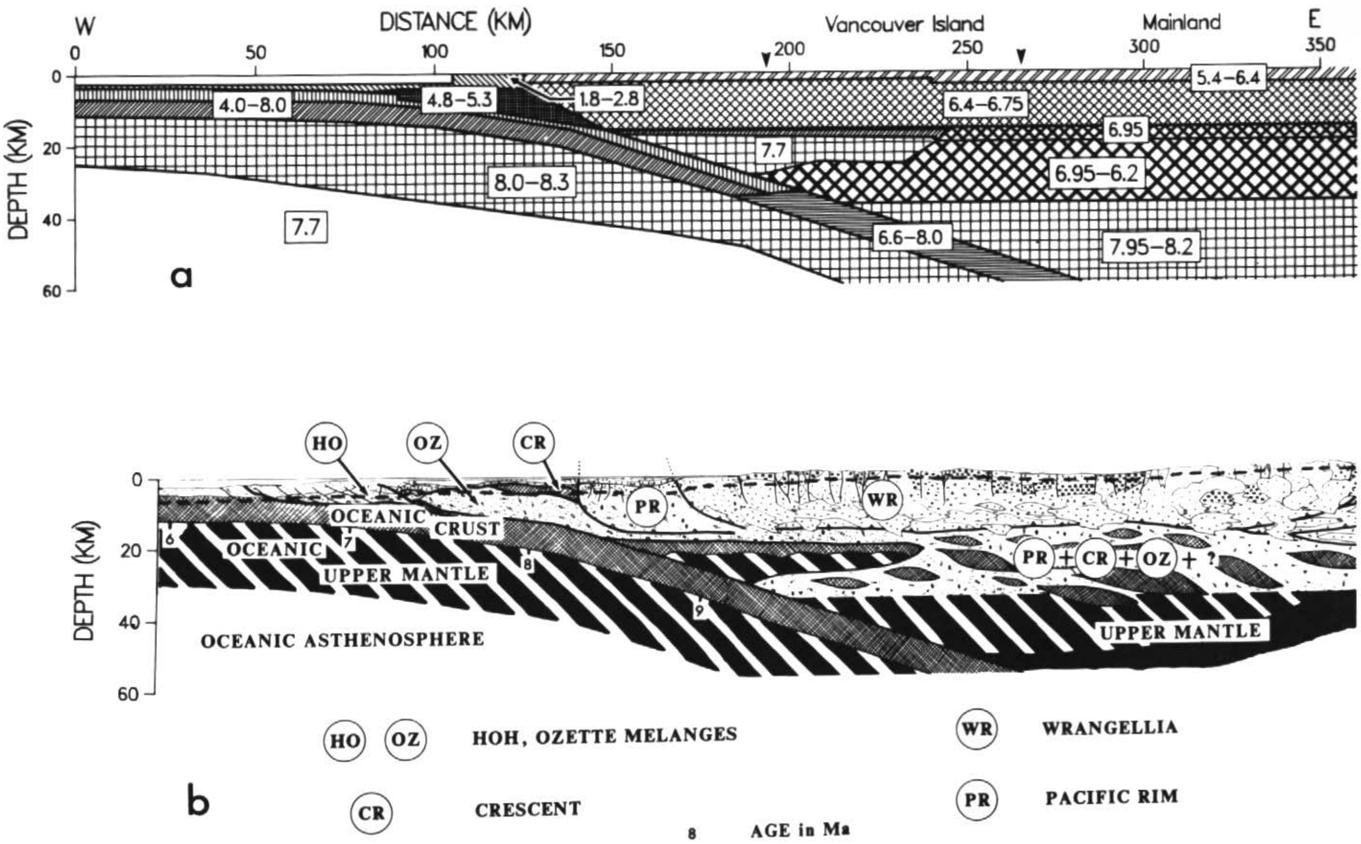

Figure 2 *(a) Seismic structure section derived from VISP refraction experiment; numbers are velocities in kilometres per second. Two numbers in one block give the velocity at the top and bottom of the block, respectively. The block below 200 km distance with velocity 7.7 km/s is interpreted as a detached segment of oceanic crust. (After Clowes* et al.*, 1983a; Spence, 1984) (b) Tectonic representation of lithospheric structure based on geology, geophysics, and concepts concerning regional accreted terranes. Heavy dashed line near upper surface represents the lower limit of geological confidence. (After Monger* et al.*, 1984)*

try of the boundary? This information would provide basic insight into how such terranes amalgamate or accrete.
(3) Are there detached segments of oceanic crust, similar to that identified as CR on Figure 2b, within the (postulated) underplated Pacific Rim complex melange (PR on Fig. 2b)? How do they occur?
(4) What are the structural and depth characteristics, i.e., shape, depth of origin and deep boundary conditions, associated with the intrusive rocks (Island Intrusions)?
(5) Of the many vertical faults identified on the surface of the Island, how many penetrate through the crust?
(6) Can the subducting oceanic plate be identified clearly and its geometrical configuration and internal structure be outlined? Can the base of the oceanic lithosphere be distinguished?

Vancouver Island: Vibroseis Reflection Survey
The Vibroseis reflection survey represents the major component of this program. With the funds available in the budget, approximately 200 km of seismic coverage will be acquired. This will enable one line to completely cross the island plus additional, shorter parallel lines, which will provide confirmation of results on the main profile and enable investigation of the depth extent of other prominent surface geological features. As shown in Figure 1, Line 1 follows a major logging road from Pachena Bay on the west coast to Port Alberni, continuing to Dunsmuir on the east coast. Decisions concerning the location of any parallel line will be made on the basis of preliminary results from Line 1. A possible choice for an additional line, which crosses the Leech River fault separating Cretaceous-Tertiary volcanics from Jura-Cretaceous metasediments, is indicated by Line 2 on Figure 1. Field equipment and parameters for the data acquisition and standard computer processing for the purposes of the initial interpretation will be similar to those used by COCORP (Schilt *et al.*, 1979).

Kapuskasing Structural Zone: Background
The nucleus of the North American continental craton is the Archean Superior Province, a vast complex of metamorphic and igneous rocks, mainly granitoid gneisses and plutons within which are preserved numerous metamorphosed and deformed volcanic and sedimentary rocks (supracrustal sequences). The Province

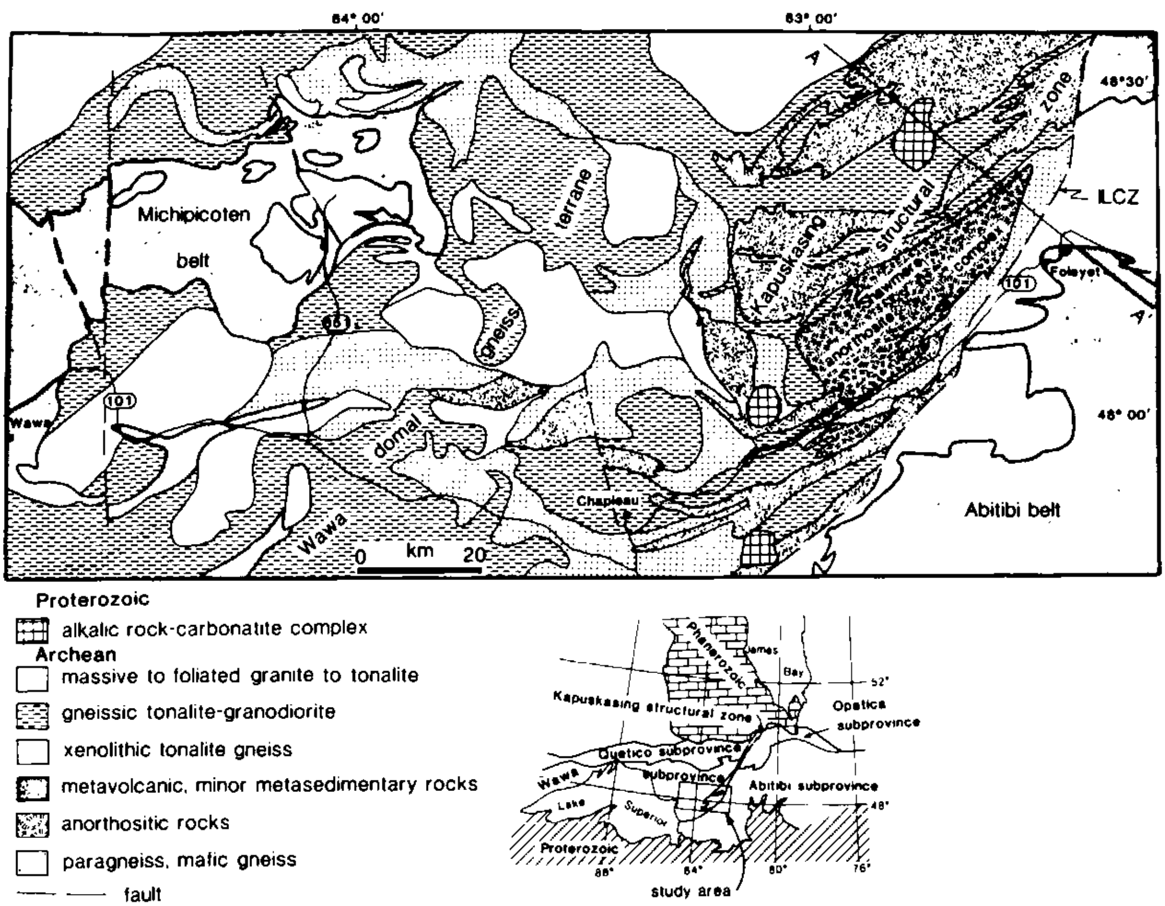

Figure 3 *Generalized geologic map of the region surrounding the Kapuskasing Structural Zone. Major lithologic features in transition from low-grade rocks of Michipicoten belt to high-grade gneiss in Kapuskasing Zone are shown. ILCZ = Ivanhoe Lake Cataclastic Zone. (From Percival and Card, 1983)*

is the largest contiguous area of Precambrian Shield rocks which have been tectonically quiescent since the close of Archean time at ~2.5 Ga. It can be divided into several sub-provinces or superbelts in which the non-granitoid component is largely metavolcanic or metasedimentary. Within the metavolcanic sub-provinces are found the characteristic metavolcanic assemblages (greenstone belts) and their associated mineral deposits for which the Province is famous.

A unique feature of the Superior Province is a structural lineament crossing the superbelt structure in a northeasterly direction from Chapleau Ontario, through Kapuskasing, and disappearing under the Phanerozoic Moose River basin – the Kapuskasing Structural Zone (KSZ; Fig. 3). The KSZ was first recognized as a regional gravity anomaly (Innes, 1960; Wilson and Brisbin, 1965); since then, many surveys and tectonic interpretations of the KSZ have been published. Recent studies by Percival (1981) and Percival and Card (1983) have shown that the high grade rocks in the central zone near Chapleau were formed at lower crustal depths (~20 km), and that there is a continuous transition in metamorphic level from low-grade greenschist facies metamorphic rocks in the Wawa greenstone belt, west of the KSZ, to upper amphibolite and granulite facies in the KSZ itself. The main faulting is along the Ivanhoe Lake cataclastic zone on the eastern margin, across which the metamorphic level decreases abruptly to greenschist facies. Percival and Card (1983) interpreted the Ivanhoe Lake cataclastic zone as a reverse or listric thrust fault which cuts the entire continental crust. Thus, the KSZ provides an oblique cross-section through the upper two-thirds of an Archean greenstone belt and of the Superior Province continental crust (Fig. 4).

Kapuskasing Structural Zone: Scientific Objectives

A substantial proportion of the mineral resources of Canada (gold, nickel, copper, zinc, silver) reside in the Archean volcanic (greenstone) belts of the Precambrian Shield. One of the significant contemporary problems of geology is to understand the nature and origin of this ancient crust. The KSZ is a golden opportunity for earth scientists interested in this fundamental problem of Archean geology. If the interpretation of the zone as an upturned, generally west dipping section through the continental crust is correct, the relatively continuous, oblique section thus exposed provides a unique opportunity to study directly middle and lower crustal levels of greenstone and gneiss belts, which are generally only known elsewhere on the basis of remotely sensed geophysical properties. Study of the KSZ thus has implications not only for the Precambrian but for continental crust in general.

Specific objectives of research on the Kapuskasing Structural Zone include

(1) Structure of the crust: establish whether the entire crust on the west flank of the KSZ has indeed been rotated into a west dipping orientation by faulting, as interpreted by Percival and Card (1983).

(2) East Margin fault zone: better definition of the Ivanhoe Lake cataclastic zone, the nature of the tectonic fabrics that have developed within and adjacent to it, and the implications these have for the nature and sequence of displacements that have occurred along the zone.

(3) Age relationships: further geochronological studies to correlate rocks across KSZ, to establish the initial ratios of components of continental crust, and to determine the cooling history of the local region.

(4) Variation along strike: the KSZ is easily traceable northeast from Chapleau to where it disappears under the Phanerozoic strata of the Moose River Basin, but it is not a uniform structure over this interval. Moreover, southwest of Chapleau even its existence is uncertain. A better knowledge of the lateral continuity and lateral variability of the KSZ is essential to understanding its origin and its regional tectonic significance.

(5) Regional pattern of deformation: whatever the basic nature and origin of the KSZ, the lack of uniformity along its strike indicates that considerable strain must have been taken up in deformation of the surrounding rocks or in numerous small faults.

(6) Sub-crustal structure: the gravity anomalies caused by dense high-grade rocks in the KSZ must be isostatically compensated in some manner. It will be important to determine how the near surface and upper crustal structure of the KSZ are related to structure of the Mohorovicic discontinuity and the upper mantle.

Kapuskasing Structural Zone: Seismic Program

A major seismic refraction study is planned for Phase 1, with the objective of providing independent estimates of the crustal velocity structure to aid in processing and interpretation of reflection surveys, to track the west-dipping mid-crust seismic velocity discontinuities as predicted by Percival and Card (1983), and to obtain the regional scale crustal structure and upper mantle velocities per objectives 1, 3 and 6. Deep reflection profiling is the key element for the detailed investigation of the KSZ and will be directed toward objectives 1, 3 and 6 above. In order to prepare for any future major reflection survey that will be technically and scientifically successful, Phase 1 LITHOPROBE includes a pilot survey to be carried out in the Chapleau area in the summer of 1984.

Supporting Geoscientific Investigations

The integration of supporting geoscientific investigations with deep seismic sounding is fundamental to the Lithoprobe concept. On Vancouver Island these should include refinement of the reconnaissance studies of the geological structure and stratigraphy along the transect, coupled with petrological studies to better define the relationship and tectonic significance of the metamorphic terranes. Additional isotopic age dating is necessary. Further studies – a combined tensor magnetotelluric-scalar audio-magne-

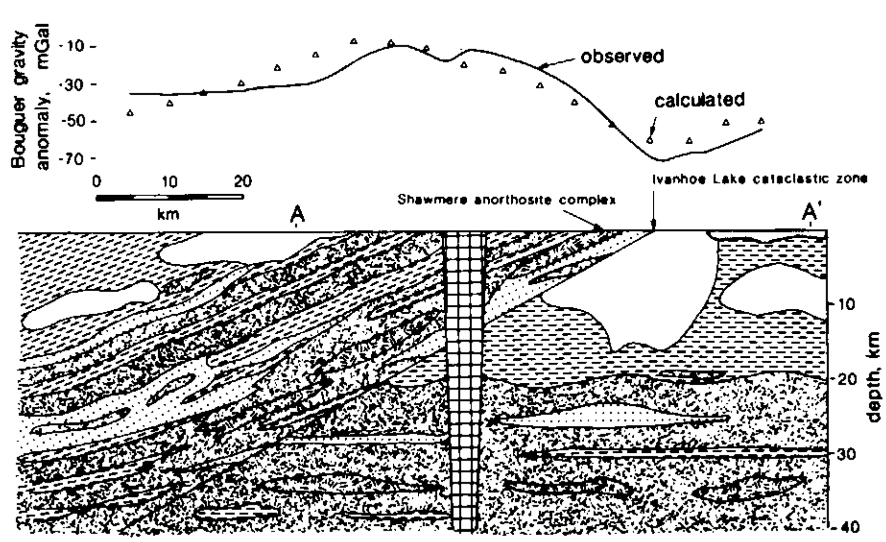

Figure 4 *Schematic cross-section showing high-grade rocks of the Kapuskasing zone thrust over low-grade rocks of the Abitibi belt, with resulting gravity anomaly. Calculated anomaly (courtesy of A.K. Goodacre) assumes mean densities in 10^3 kg/m^3 (tonalite gneiss, granite: 2.70; Kapuskasing zone: 2.82; metavolcanics: 2.90). Symbols as in Figure 3. (From Percival and Card, 1983)*

totelluric survey along the proposed Vibroseis profile, additional paleomagnetic studies, more heat flow observations, and tidal and tilt measurements – would add valuable information to be included in the integrated interpretation.

In the Kapuskasing Structural Zone geochronological and isotopic studies are necessary to provide a better basis for structural correlations across the KSZ, to obtain data on initial isotopic ratios and to determine the cooling history of the zone and compare it with adjacent parts of the Superior Province. Petrochemical and trace-element studies of rocks in the KSZ need to be carried out to determine the behaviour of geochemical elements in the lower crustal environment. Structural analysis of the East Margin fault zone should help define the nature and history of fault displacements; field work also will be required to establish the type and significance of variations along strike of the KSZ. The widespread Matachewan dykes (Watson, 1980) provide an opportunity to elucidate through detailed paleomagnetic and geochronometric studies the nature and timing of any deformation involved with the deflection of the dykes. A range of other geophysical studies – seismic velocity measurements of rock samples, magnetic susceptibility data on rock units in the region, additional gravity data, magnetotelluric programs, geomagnetic depth sounding – will provide information complementary to the seismic programs in the KSZ.

The Future – Phase 2 LITHOPROBE

Phase 1 LITHOPROBE is proceeding as the first component of the continuing overall Lithoprobe program. At the time of writing, the development of the Phase 2 proposal for submission to NSERC and EMR is progressing. The basic tenet of this major proposal will follow the concepts developed by CANDEL (1981).

From geoscientists across Canada, proposals for Phase 2 transect corridors have been prepared and forwarded to the Lithoprobe Steering Committee. These have been evaluated and incorporated into the Phase 2 submission. Other groups of specialists have met to prepare working papers on requirements for the seismic instrumentation and computer processing centre which are central to the Lithoprobe program. A Lithoprobe workshop, leading to the final preparation of the Phase 2 proposal, was held in March 1984. Geologists, geophysicists and geochemists from the university, government and industry sectors throughout Canada, aided by the perspectives of prominent foreign experts, convened in a forum that provided a broadly based input to this national proposal. LITHOPROBE, a major geoscientific research project of national scope and importance, is firmly underway.

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MS received February 9, 1984