ALLOCATION REPORT OF THE SOLID EARTH SCIENCES GRANT SELECTION COMMITTEE (COMMITTEE 08)

The Solid Earth Sciences Grant Selection Committee is responsible for reviewing and adjudicating research into the solid surface and the interior of the earth, as well as the record of Earth history. Hence, the fields of igneous, metamorphic and sedimentary petrology (and sedimentology), geochemistry, mineralogy and crystallography, isotope geochemistry and geochronology, structural geology and tectonics, mineral deposits geology, geophysics and paleontology fall within the terms of reference of the committee. A total of 287 grantees is currently (1994-95) supported in this field.

The impact of Canadian research in solid Earth sciences has been, and is currently, substantial. Table 1 summarizes the results of a survey of the research papers published over the period 1989-93 in the top international journals, as identified by the members of the Solid Earth Sciences Grant Selection Committee in 1994. This shows that Canadian researchers ranked first in numbers of papers published, relative to GERD, in 7 of 15, and ranked second in another 7, of these rigorously reviewed journals. Thus, Canadian solid Earth scientists have a disproportionately high impact in terms of the numbers of high-quality refereed papers in the top journals published annually.

A survey of 34 of the top researchers in Solid Earth Sciences (selected on the basis of their impact on the discipline and their international stature, rather than grant size) reveals that, on average, this group obtained a doctorate in 1969 and have had 20 years of NSERC support. They average a total of $248,360 in annual research funding, including $69,896 in the form of a Research Grant (leverage ratio = 3.5). They have educated a total of 22 graduate students and have worked with 4 post-doctoral fellows dur-

Table 1. Percentage of the total number of first-authored papers by members of G-7 countries and Australia (1989-93) in top international journals in solid Earth sciences

Journal	Canada	Australia	France	Germany	Italy	Japan	UK	USA
Amer Mineralogist	**1.09**	*1.04*	0.14	0.17	0.18	0.04	0.28	0.40
Econ Geol	*2.58*	**3.89**	0.10	0.13	0.08	0.02	0.16	0.24
Geochim Cos Acta	**1.07**	0.98	0.22	0.11	0.04	0.04	0.26	0.40
Geology	**1.66**	*1.50*	0.20	0.06	0.00	0.02	0.32	0.40
Geophys Res Lett	**0.48**	0.41	0.25	0.15	0.13	0.09	0.19	0.43
Geophysics	**1.53**	*0.64*	0.19	0.07	0.12	0.01	0.20	0.37
Geophys J Intern	*1.10*	**1.79**	0.36	0.22	0.30	0.08	0.69	0.16
J Geo Res (Solid)	**0.67**	0.41	0.27	0.05	0.07	0.05	0.23	*0.48*
J Metam Geology	*1.07*	**4.18**	0.22	0.14	0.20	0.08	0.39	0.18
J Petrology	*1.18*	**2.06**	0.29	0.15	0.19	0.02	0.79	0.26
J Sedim Petrology	**1.73**	*0.89*	0.05	0.04	0.17	0.00	0.34	0.40
J Struct Geology	*0.98*	**2.22**	0.39	0.07	0.02	0.05	0.65	0.26
Mineral Deposita	*1.26*	**2.03**	0.31	0.43	0.21	0.04	0.19	0.05
Palaeontology	0.69	*0.77*	0.21	0.07	0.05	0.02	**2.49**	0.07
Precamb Research	*1.82*	**3.66**	0.20	0.12	0.02	0.01	0.37	0.13

Note: Data are normalized to GERD. Figures in bold are first rank; and, italics are second in rank.***

**GERD = Gross Expenditure of Research and Development in $PPP billion (Purchasing Power Parity) for 1990 (latest year of complete data) from Main Science & Technology Indicators, OECD Paris, 1993, Part 2.*

*** The same result is obtained if population is used for normalization* ing their university careers. They are editors or associate editors of two journals, and have published 77 refereed journal articles.

A survey of a random sample of 38 of the established researchers in Solid Earth Sciences (including middle- to late-career scientists with established and stable research programs, but excluding those in the top group) reveals that, on average, this group obtained a doctorate in 1974 and have had 17 years of NSERC support. They average a total of \$104,700 in research support annually, including \$32,953 in the form of a Research Grant (leverage ratio = 3.1). They have educated a total of 14 graduate students and have worked with 1 post-doctoral fellow during their university careers. They are editors or associate editors of one journal, and have published 44 refereed journal articles.

Quality of Research in Canada

Canadian solid Earth scientists have made important contributions to our understanding in all areas that come under the purview of the Committee, including Earth material science, geochronology, the composition, structure and dynamics of the deep mantle and core, the evolution of the global mosaic of plates that constitutes the Earth's lithosphere, and the origin and evolution of the continents and oceans, with their sedimentary cover and mineral deposits. In this review, we examine the stature of solid Earth sciences research with reference to five broad disciplinary groupings, emphasizing the integrated systems approach currently being adopted by most researchers across the country.

Geochemistry. Mineralogy and Petrology

Geochemistry. Canadians stand at the forefront in knowledge of crustal and mantle evolution studies using stable and radiogenic isotopic tracers and trace-, minor-, and major-element geochemistry allied to sophisticated field mapping and sampling programs. In isotope studies, improvements in mass spectrometry have reduced the limits of detection by more than two orders of magnitude. Work on the geochemistry of stable isotopes began very early in Canada with the pioneering studies of H. Thode at McMaster, with whom S. Epstein (a McGill graduate) worked for a short period before leaving to work with Harold Urea at Chicago. Thode built some of the first mass spectrometers for geochemical research and is the father of sulphur isotope systematics. Epstein is now widely regarded as the father of the general field of stable isotope geochemistry. The first multi-collector solid source mass spectrometer (a Finnigan-MAT 261) in North America was set up at Carleton in 1981 to measure the radiogenic isotopes of Pb, Sr, Rb and Nd in the static mode. The development of this branch of geochemistry to trace fluid sources has had a major impact on low-temperature geochemistry and mineral-deposits research in the last decade. Fundamental work has been carried out in the laboratories of K.T. Kyser and R. Kerrich at Saskatchewan, F.J. Longstaffe at Western, H.R Krouse at Calgary, J. Veizer at Ottawa, H.P. Schwarcz at McMaster, P. Fritz at Waterloo, and others. Krouse is a world leader in sulphur isotope geochemistry. The application of stable hydrogen, carbon and oxygen isotope methods to archeology and speleology has been vigorously developed at McMaster by Schwarcz and D.C. Ford. Longstaffe has pioneered stable isotope analysis of diagenetic silicate minerals and their interpretation in terms of large-scale paleofluid movement and evolution in sedimentary basins. Kyser has been at the cutting edge in the development of laser sampling methods for stable isotope analysis, an approach that will likely become the standard method in the near future. These researchers rank alongside the other international leaders in this vigorous area of study, such as R. Clayton at Chicago, H. Taylor at CalTech, S. Sheppard at Lyon, S. Savin at Northwestern, J. O'Neil at Michigan, J. Valley at Wisconsin and J. Hoefs at Gottingen. Major advances in the geochemistry of element fluxes and cycles within the Earth have been made using trace elements and radiogenic isotopes by Fyfe and J. Veizer (Ottawa), which are having profound implications for the understanding of atmospheric, oceanic, crustal and mantle processes. The recent introduction of laser sampling to ICP-MS analysis, in which Canada is a world leader (Memorial, Kerrich and Kyser at Saskatchewan, J.N. Ludden at Montreal), is set to revolutionize mineral analyses by this method and open up a whole new level of data for interpretation. The possibility of isotopic analyses by this method has been demonstrated

The application of geochemical methods to geochronology is very strong in Canada With respect to the U/Pb isotopic systems, the development of super-clean laboratory techniques, analyses of single grains, and extension of the method to new minerals including some previously out of reach because of low isotopic concentrations (e.g., titanite, baddeleyite, monazite), all of which were developed in Canada, has had an immeasurable impact on the understanding of crustal evolution and indirectly on crustal and mantle processes. Dating to an accuracy of ±3 Ma for rocks older than 1000 Ma is now routine for many samples. Canadian expertise in U/Pb geochronology is recognized worldwide, and T.E. Krogh (ROM, Toronto) is the world leader in developing new and improved techniques. The results of work by Krogh and others have led to a quantum leap in understanding the geological evolution of the Precambrian and a marked improvement in the much better

FRANK HAWTHORNE (Manitoba, Geological Sciences) ranks in the top five active mineralogists in the world. He specializes in x-ray crystallography and crystal chemistry, with primary interest in the structural topology and electronic structure of minerals, and the controls that these exert on the chemistry and behaviour of minerals in geological processes. Seminal contributions include the crystal chemistry of amphiboles, staurolite and other minerals important in metamorphic rocks, structural topology of complex minerals, role of light elements in minerals, and mineral spectroscopy. His current scientific productivity (quality and quantity) is astonishing, possibly exceeding that of all contemporary Earth scientists worldwide. Recent awards include a Canada Council Killam Research Fellowship (1992-93), the Gold Medal of University of Pavia (1992), and the Willet G Miller Medal of the Royal Society of Canada (1993).

known Phanerozoic. For example, recent studies by Krogh have produced the first unequivocal evidence for magmatic underplating in Archean crust, previously an unsubstantiated hypothesis, and provided important new information on the identification of the long-sought impact crater hypothesized for the Cretaceous/Tertiary boundary event. His laboratory has been the training ground for the new generation of U/Pb geochronologists worldwide, including five who are running active laboratories in Canada. Ar/Ar geochronology is carried out in several laboratories in Canada (Toronto, Queen's, Dalhousie, UBC), with D. York at Toronto being renowned for his systematic development of improvements to the technique, particularly the recent introduction of laser sampling, which is now the method of choice for most applications. His group has recently published another breakthrough by reducing the lower age of Ar/Ar dating so that it overlaps with the upper age limit for radiocarbon dating. A profoundly important Canadian contribution has also been made to radiocarbon dating, a technique used worldwide for dating archeological and geological materials/events to about 40 Ka. Research groups at Toronto (E.A. Litherland) and McMaster (led by D.E. Nelson (Simon Fraser)) independently pioneered the development of the tandem accelerator mass spectrometer for directly measuring the abundances of rare radioactive isotopes in very small samples, and this approach has been adopted worldwide. The range of nuclides measured with this technique is increasing rapidly, and the Isotrace Laboratory at Toronto is a centre of this development.

Mineralogy. Canadians excel in Earth material studies. F.C. Hawthorne (Manitoba) is a world authority on the crystal chemistry of amphiboles and has made seminal contributions to the understanding of structural topology and bonding in minerals. His laboratory is an important centre for x-ray structure analysis of new minerals and Rietveld structure refinement of fine-grained natural and synthetic materials. ME. Fleet (Western) and S. Chryssoulis (Amtel) were the first to map the distribution of lattice-bound gold in ore minerals by secondary ion mass spectrometry using facilities at Surface Science Western, the foremost facility in North America for studying the surface chemistry of minerals and related materials. G.M. Bancroft (Western) has made major advances in understanding the role of iron in minerals through Mossbauer spectroscopy and the electronic structure of minerals through x-ray photoelectron spectroscopy and very recently (with Fleet) through x-ray absorption spectroscopy (XAS). This excellence in Canadian universities is complemented by a world-ranking group of applied mineralogists at CANMET and GSC, ably led by L.J. Cabri and W. Petruk.

Igneous and Metamorphic Petrology. The multi-anvil device at Alberta provides a focus for high-pressure experimental petrologists in Canada. Important contributions to mantle petrology have been made by several Canadian petrologists including J.G. Malpas (Memorial), and R.H. Mitchell (Lakehead) is one of the world's foremost authorities on deep mantle alkaline rocks. Mitchell's pioneering research and books have increased our understanding of the formation of diamonds in kimberlites and lamproites, lithologies that have recently become the focus of intense exploration activity in northern Canada. In the crustal realm, P. Cerny (Manitoba) is distinguished for his work on the mineralogy and petrogenesis of granitic pegmatites, and there is a growing body of expertise in groundbreaking numerical modelling of magma chamber processes.

Canada has a history of fundamental contributions to metamorphic petrology. R. Kretz (Ottawa), W.S. Fyfe (Western Ontario) and G.M. Anderson (Toronto) were among those who developed the rigorous equilibrium thermodynamic theory for application to metamorphic rocks, and the experimental studies of H.J. Greenwood (UBC) and G.B. Skippen (Carleton) laid the foundations for our present understanding of the role of fluids in metamorphic processes. E.D. Ghent (Calgary) developed techniques based on mineral chemistry for geothermobarometry and has now established one of the top schools in North America in this field R. Berman (UBC and GSC) has produced an internally-consistent data base for use in geothermobarometry, one of only two available worldwide, together with computer code that is receiving widespread international use. Field studies in metamorphic belts in the Canadian Shield and elsewhere have made good use of these developments and of others, such as D.M. Carmichael's (Queen's) bathograd method for mapping the distribution of metamorphic paleopressures in the field.

Geophysics

Canada has for many years been a world leader in the application of geophysics and geophysical techniques to understanding the Earth in the pure and applied aspects. The technical service industries receive significant research support and depend for their scientific personnel on Canadian universities. Occasionally, the influence is so direct that a new firm is created (e.g., ITA of Calgary by D.W. Oldenburg and others from UBC). Particularly outstanding is the industry-university cooperation engendered recently by the CREWES project (Consortium for Research in Elastic Wave Exploration Seismology) at Calgary (which was awarded the 1993 Achievement Award of the Association of Professional Engineers, Geologists and Geophysicists of

WILLIAM FYFE (Western, Earth Sciences) is a renowned geochemist and one of the best-known geologists anywhere in the world. He was among the pioneers in the application of thermodynamics to metamorphic rocks and was co-author of a book on the subject in the sixties that fundamentally changed our approach to the study of metamorphism and subsolidus chemical processes in general. His early laboratory experiments led to the present understanding of the role of fluids in the Earth's crust, particularly with respect to metamorphic reactions and the formation of ore deposits. Recent research has focused also on the application of geochemistry to the environment, and he has tackled problems as diverse as the geochemistry of coals, element cycling in major river systems, and biological mediation of metals. His graduate students (totalling about 70) have been one of his major contributions. He was elected FRSC in 1980, he is the recipient of numerous foreign awards and distinctions (including FRS), and is currently President of the International Union of Geological Sciences (1992-6)

Alberta), but there are many other examples of important university research input to exploration seismology (e.g., E.R Kanasewich, Alberta), not to mention the world of those adapting petroleum style reflection seismology for investigation of crustal geology or other unusual environments (e.g., F.A. Cook (Calgary), R.M. Clowes (UBC), G.F. West (Toronto), J. Hall (Memorial), R.F. Mereu (Western), and others), mainly working in conjunction with Project LITHO-PROBE, where new methods of data acquisition and software development are being used to enhance the high resolution images of deep structures. In Canadian mining geophysics, there has been a long history of university researchers moving to industry as their career progressed, often to start a new enterprise. Three examples of such startups, where the principals were young NSERC supported researchers, are Lamontagne Geophysics, Sensors and Software/A-cubed, and Petros Eikon.

Electromagnetic methods have been a particular Canadian specialty, with fundamental research contributed by West and R.N. Edwards (Toronto). Also, using mainly the magnetotelluric EM method, the electrical properties of the crust and upper mantle are being probed much more effectively than heretofore (e.g., M. Mareschal (Ecole Polytechnique) and L Gough (formerly of Alberta). E.A. Irving (formerly Victoria and GSC) is world famous for his world on global compilations and Cordilleran paleomagnetism, and D.J. Dunlop (Toronto) is renowned for his fundamental work on rock magnetism. Terrestrial heat flow studies were pioneered in Canada by A.E. Beck (Western) and techniques developed in his laboratory are in use around the world. A strong heat flow group exists at the Pacific Geoscience Centre (R.D. Hyndman and others), applying geothermal knowledge as well as other techniques to solving tectonic problems. Significant advances in knowledge of the Earth's core dynamics have been made by M.G. Rochester (Memorial), L. Mansinha (Western), and others working with the superconducting gravimeter installed at the Absolute Gravity Station near Ottawa. W.R. Peltier (Toronto) leads a group focused on the important problem of the impact of mantle phase transitions on convective mixing. This work also involves the application of unique models of the deep circulation based upon seismic tomographic imaging, and has high international impact. Another aspect of this program involves the inference of mantle viscosity on the basis of the analyses of the postglacial rebound process.

Geodynamics and Geodesy

Canadians have a history of fundamental contributions to all aspects of geodynamics. The late J. Tuzo Wilson (Toronto) was one of the founding fathers of the theory of plate tectonics, and the cycle of lithosphere generation - seafloor spreading - subduction is popularly known as the Wilson Cycle. The paradigm shift from static estimates of total strain to dynamic estimations of kinematic vectors has influenced all aspects of geodynamics. Progress in understanding the structural evolution of the Canadian Cordillera has been led by R.A. Price (Queen's), and H. Williams (Memorial) and P.F. Williams (New Brunswick) lead research into Appalachian tectonics. There has been enormous progress in understanding the tectonics of our Precambrian Shield terrains. The original and highly proclaimed tectonic syntheses of Proterozoic orogenic belts by P.F. Hoffman (formerly Victoria and GSC) have caught the attention of geologists worldwide, and the geochronological work of D. Davis (ROM, Toronto) on the assembly of Archean granite greenstone belts of the southern Superior Province has also been particularly noteworthy. More generally, C. Beaumont (Dalhousie) is a world leader in geodynamic modelling, and with C.E. Keen (Atlantic Geoscience Centre) gives Canada particular strength in the application of numerical modelling to basin analysis and orogenesis.

Canadian geodesists have been very heavily involved in the development of the Global Positioning System into the precise tool that it is now. The early work of D. Wells and others at New Brunswick, G. Lachapelle and others at Calgary, the Geodetic Survey of Canada, and the private sector received worldwide recognition. Now, one of the six computing centres that make up the International GPS Service (IGS) for geodynamic studies around the world, organized by the International Association of Geodesy, is located in Ottawa. A modem global theory of postglacial rebound and relative sea level change has been developed by Peltier (Toronto), and the predictions of this theory are now being employed by the international geodetic community to target their observational programs.

SUSAN KIEFFER (UBC, Geological Sciences) has established the field of geological fluid dynamics, the study of fluid Earth materials. Using approximate numerical solutions of the full Navier-Stokes equations, she has developed models for explosive volcanic effusions, meteorite impact mechanics, and geyser eruptions. She also studies planetary volcanism and river hydraulics at high Froude number. She moved recently to the Chair at UBC, following a distinguished academic career in the USA. Dr. Kieffer was awarded the Day Medal of the GSA (1992), the Spendiarov Award from the (then) USSR Academy of Sciences, and is a Fellow of the American Academy of Arts and Sciences.

DAVID DUNLOP (Toronto, Physics) is Canada's foremost expert on rock magnetism and ranks among the elite researchers in this field worldwide. His research centres on field studies aimed at the elucidation of complex chemical, viscous and thermal remnant magnetism of plate margins, ancient orogens and the deep crust, supplemented by innovative experiments on tuck magnetism and theoretical calculations. He is extraordinarily productive, and his flow of publications to the world's prominent geophysical journals continually expands frontiers in his field. His research students are highly regarded members of faculties in Canada, USA, UK, Germany, Japan and Venezuela. Dr. Dunlop was a Canada Council Killam Research Fellow (1983-85), he was elected FRSC in 1990, and is the immediate past-president of the Geomagnetism and Paleomagnetism Section of AGU.

Sedimentary Geology

Canadian contributions to the field of sedimentology and stratigraphy have been fundamental and out of all proportion to the numbers of active scientists involved, and Canadian paleontologists have been widely recognized for their world in unravelling the development of faunas and floras of the extensive Phanerozoic formations exposed throughout the continent.

Canadian sedimentologists, led by R.G. Walker (McMaster), N.P. James (Queen's) and A.D. Miall (Toronto), have gained an intemational reputation for work on facies models. In the last few years, the research emphasis has switched to sequence stratigraphy, a new paradigm for interpreting the environment of deposition of sequences of strata. Together with colleagues in the petroleum industry (e.g., D. James) and at the Institute for Sedimentary and Petroleum Geology (ISPG, e.g., A. Embry, D. Leckie), they are carrying out leading-edge research, which involves a reinterpretation of Canada's hydrocarbon- and coal-rich basins and is of great economic importance. Canadians have also led in diagenetic studies of sandstones and clays (e.g., F.J. Longstaffe, Western, and others), coal (R.M. Bustin, UBC), and carbonates (N.D. James, B. Jones, Alberta, and associates in industry and at the ISPG). N.C. Wardlaw (Calgary) has advanced our understanding of fundamental reservoir properties, such as porosity and permeability.

The study of the biostratigraphic potential of late Precambrian biota by H. Hofmann (Montreal) and G.M. Narbonne (Queen's), and of late Precambrian reef biotas by Narbonne and James (Queen's), are second to none in the world. Research on the relationship between organismal activity (traces), sediments, and sedimentary environments by S.G. Pemberton (Alberta) is on par with the top 34 workers in North America. Studies of trilobites and conodonts by B.D.E. Chatterton (Alberta) and graptolites by A. Lenz (Western) in Arctic Canada permit much refined biostratigraphy and a better understanding of their evolution and biogeography, and of Lower Paleozoic mass extinction events. P. Copper (Laurentian) remains the world authority on Ordovician - Devonian atrypid brachiopods, and his reef studies are becoming increasingly recognized. C.R. Barnes (Victoria) and a large group trained under him are unrivalled in their study of Lower Paleozoic conodonts and their paleoecology. C.W. Steam (McGill) remains the world authority on stromatoporoids, and his studies of modern and fossil reefs are internationally recognized.

Mineral Deposits Geology

Canada, with its large area and diverse geology, hosts a great variety of mineral deposits. Indeed, Canada is probably more reliant on its geological resources than any other developed country in the world. The resource industries contribute almost $28 billion to Canada's positive trade balance and are responsible for 45% of total exports. The minerals industry alone contributes $17 billion of this revenue. Canada has a strong leadership role in this area.

Besides being economically important, ores are fascinating indicators and tracers of many geological processes. Canadian geologists and geophysicists in universities, industry, and the GSC are world leaders in deciphering the many ways in which ores have formed and in developing ways for exploring and investigating them. This is a most exciting and rapidly advancing subject area and has led to great improvements in the technology of ore exploration. It has also been an area of exceptional synergy, with cooperation between scientists in many fields and synthesis of a wide variety of information. A.D. Naldrett (Toronto) is a world authority on magmatic sulphide and platinum-group element deposits and on the petrology and geochemistry of the huge igneous complexes associated with them, including the famous Sudbury complex. R. Kerrich (Saskatchewan) and W.S. Fyfe (Western) promoted the connection

Table 2. representative annual budgets required by top researchers in solid Earth sciences specializing in laboratory-, field-based and theoretical studies

Category	Item	Laboratory based			Field Based			Theoretical		
		No.	Unit Cost	Total Cost	No.	Unit Cost	Total Cost	No.	Unit Cost	Total Cost
Personnel	Undergrads	1	4000	4000	1	4000	4000	1	4000	4000
	Grads	5	15000	75000	6	15000	90000	4	15000	60000
	PDFs	2	27500	55000	1	27500	27500	3	27500	82500
	Technicians	1	30000	30000	1	30000	30000	1	35000	35000
	Res Assts [1]				4	7500	30000	1	30000	30000
Equipment	Capital [2]			30000			10000			10000
	Maintenance			20000			5000			
Materials [3]				50000			30000			25000
Travel	Field Work [4]			10000			45000			10000
	Conference			10000			10000			10000
Others	Computing			10000			5000			15000
Totals:				**$294,000**			**$286,500**			**$281,500**

[1] *Field-based research requires student assistants for individual field projects*

[2] *Items costing less than $7000*

[3] *Materials includes materials, supplies, analytical costs, publication costs*

[4] *Field work includes laboratory visits but does not include access to remote regions*

between shear zones and gold deposits, and they pioneered sophisticated modern methods of geochemistry to investigate them. R. Hutchinson (formerly of Western) pioneered the modern understanding of volcanogenic massive sulphide deposits, and S.D. Scott (Toronto) and J.M. Franklin (GSC) are recognized worldwide for their work on seafloor massive sulphides. D. Sangster (GSC) has added to Canada's prominence in this area with his widely-recognized work on the sulphur isotope systematics of such deposits. Scott and M.E. Fleet (Western) are world leaders in geochemical experimentation on ore-mineral systems. A. Williams-Jones (McGill) has established a dynamic laboratory program examining the role of fluids in ore formation, tackling, in particular, deposits of the high-technology metals.

The evolution of sedimentary basins is an important aspect in the development and preservation of hydrocarbons and certain ore deposits, such as those of potash, uranium, lead-zinc, and kaolin. F.J. Longstaffe (Western) and others have received international acclaim for their work in unravelling the pressure, temperature, and history of fluid-flow events in mineralized basins. In western Canada, there is increased emphasis on enhancing the recovery of known reserves of hydrocarbons, and this will require the further integration of geological and engineering knowledge of water-oil-gas movement in the subsurface to achieve greater efficiencies. For example, I.E. Hutcheon (Calgary) and Longstaffe are acknowledged experts in the nature of rock-water interactions during steam recovery of oil sands and heavy oil and continue to work closely with industrial partners on *in situ* exploitation of these world-class resources.

Costs of Research

The requirements and modus operandi of research in Earth sciences are especially stringent. The discipline requires extensive and expensive field programs, often in adverse and remote environments and sometimes requiring large, expensive platforms. Canada is internationally known for its highly-productive field-based research programs. Canadians have also been world leaders in the transition from descriptive to analytical Earth sciences. This has required substantial funding for new field instruments. Furthermore, the analytical facilities that are necessary to study collections from the field are very sophisticated and costly. Finally, realistic modelling of Earth systems requires the fastest and often the largest computing facilities available. The Earth sciences are therefore a very costly enterprise, and one where the skills of individual researchers are often very broad.

Information on the Price Index for Research Grant expenditures (NSERC Cost of Research Report (COR) Table 1) shows that solid Earth scientists used the bulk of their grants for laboratory costs (materials), technical assistance (other salary) and for travel, the latter including field work. This distribution of expenditures supports the claim that the main burden on solid Earth sciences is for field and laboratory support Table 3 (COR) shows that the inflation in the Price Indices is the lowest for materials and somewhat low for travel, placing solid Earth sciences lower in the rankings of the committees in Table 5 of COR because of the emphasis on these two categories. However, the price index for travel is derived from the Statistics Canada transportation and travel price index, which does a poor job of assessing changing costs of field work in remote regions of North America and the world. Researchers in other disciplines have used more of their funds to support students and post-doctoral fellows, where the inflation rate has been much higher, and this has placed them higher in the rankings.

Among the top researchers, solid Earth scientists have had the third highest increase in the size of their Research Grants (COR Table 10), only lower than two of the engineering committees. This is a clear reflection of the increasing activity and stature of the top solid Earth scientists over the past decade as well as the increasing sophistication of many areas of research in this discipline.

Representative annual budgets (all sources, but excluding major equipment) required by top researchers in solid Earth sciences to compete successfully and to realize their full potential are shown in Table 2. The representative researchers have a Research Grant of $70,000 per annum, giving an average leverage ratio of ca. 4.1.

Vision Statement

Earth sciences are experiencing a period of profound change as the quantum advances of the last two decades, including new and improved analytical techniques, new

RAYMOND PRICE (Queen's, Geological Sciences) is one of Canada's most distinguished structural geologists and scientific administrators (Director General of the Geological Survey of Canada, 1982-87). His field and theoretical work and structural syntheses have made him the leading expert on the structure of the Canadian Rockies and one of the world authorities on foreland fold and thrust belts and gravity tectonics. Among his numerous honours, he was elected FRSC in 1972, he is a Foreign Associate of the U.S. Academy of Sciences, and he has served as President of the ICSU Commission on the Lithosphere (1980-1985) and President of the Geological Society of America (1989-1990).

CHRISTOPHER BEAUMONT (Dalhousie, Oceanography) researches tectonophysics through numerical modelling, with emphasis on problems involving the interactions between lithospheric dynamics and sedimentation/erosion processes. He has made important contributions to the evolution of sedimentary basins and maturation of hydrocarbons within them, interaction of subduction zones with continental platforms via tilting and submergence, and dynamic effects of erosion on mountain building. He was a Steacie Fellow in 1981-82. In an international context his contributions are on a par with those of Tony Watts, now at Oxford University but previously with Lamont-Doherty Earth Observatory (Columbia University).

methods of data analysis and processing, new conceptual paradigms and an unparalleled degree of cross-disciplinary cooperation and integration, world their way through the system. The boundaries of our discipline have been substantially broadened and deepened in the last ten years, and at the same time there have been enormously fertile cross-linkages established, both within Earth sciences and between Earth sciences and other sciences. Research is conducted in a different environment to that of five years ago; we have access to a broader range of instruments with substantially improved potential, and the questions we are asking today are dramatically different from those we asked only a short time ago.

There is a rapidly developing trend for more integrated studies in solid Earth sciences (*e.g.*, petrology/geochronology/stable isotope geochemistry/digital mapping; stratigraphy/deep Earth processes/plate tectonics/surficial sedimentary processes; and electromagnetic methods/geochemistry). High precision geochronology, for example, is revolutionizing our understanding of Archean geology. The long-term trend in mineralogy is for increasing sophistication in theory and instrumentation, with strong coupling and interaction with chemistry and materials science. Growth areas include the structure and reactivity of mineral surfaces and synchrotron radiation studies (x-ray absorption spectroscopy and diffraction). We are underrepresented in high-pressure mineralogy and require a diamond anvil cell laboratory to complement the excellent multi-anvil facility at the University of Alberta. The latter is a national facility and, in view of the expense of modern research equipment, a possible model for further expansion of laboratory facilities in Canadian universities. Very high-pressure laboratory studies would naturally tie in with geophysical investigation of whole Earth structure. There is an urgent need in mineralogy/petrology/geochemistry for *in situ* analysis of elements present at ultratrace levels, stable isotopes and radiogenic isotopes. The LA-ICP-MS facilities at Memorial, Saskatchewan and Montreal are on the leading edge of research into *in situ* trace element analysis. The impending installation of a SHRIMP at the GSC will open up many opportunities for research into *in situ* isotope geochemistry. We anticipate an explosion of information on the composition of Earth fluids and their role in rock-forming processes from our well equipped stable isotope laboratories, from fluid-inclusion studies, and through inferences from mineral compositions. There will be an increase in field-based investigations linked to metallogeny and Earth structure (*e.g.*, large-scale tectonics, mountain building, orogenic processes, plate tectonics). Structural geologists, who previously adopted sophisticated laboratory techniques of materials analysis, stress the need for detailed field observations to advance understanding of regional tectonics. Numerical modelling of Earth-scale nonlinear problems relating to many diverse aspects of solid Earth sciences (*e.g.*, core-mantle boundary, basin analysis, volcanism, and impact geology) will continue to grow in importance with the emergence of new solutions and increase in size of data bases and computational capacity. In sedimentary geology, there will be adoption of new allostratigraphic concepts (subdivision of the geological record using bounding discontinuities) for objectively subdividing the geological record. Traditional strengths in taxonomic paleontology will continue, since careful and detailed taxonomy is essential for understanding the history of life.

LITHOPROBE has a full program for the next five years (phase IV) and will continue to yield fundamental information on mid- and deep-crustal structures. Probing deeper into the sub-continental mantle, one important objective is to see if continental shield areas have keels of depleted mantle rocks to depths of 400 km. Mineral deposits research will increasingly investigate the role of fluids in forming ore deposits. There is clearly a need to develop ore deposit models that focus more closely on possible exploration targets. There is great potential for collaborative research projects funded by MITEC (Mineral Industry Technology Council) and for research into deposits of the emerging high-technology metals (*e.g.*, rare earth and high field strength elements). Hopefully, Canada will have a significant diamond mining industry in the near future. The present "diamond rush" in the Northwest Territories has resulted in a wealth of new information on the petrology and geochemistry of the upper mantle that should energize these areas for years to come. Canada's future contribution to ODP is in doubt; loss of access to this research platform would have serious consequences for offshore research by Canadians.

These new results will find applications that will benefit the country in many ways. The development of natural resources of all kinds (industrial minerals, ores, petroleum, coal, water) has always been a primary motivation for solid Earth science studies and will remain so for the foreseeable future. The resource industries of Canada are still our strongest asset in the international marketplace, and they are key to our nation's capacity for wealth generation [1]. Moreover, Canadian expertise in the understanding and development of natural resources is widely respected. Canadian Earth scientists and resource companies are deeply involved in natural resource development in former East-Block countries and the Third World, especially Russia,

NOEL JAMES (Queen's, Geological Sciences) researches the sedimentology and diagenesis of carbonate sediments and rocks. He has made outstanding contributions to our understanding of Proterozoic/Early Paleozoic limestones and modern shallow- and deep-water carbonates. After the grand pioneers of carbonate studies (Bathurst in the UK and Ginsburg in the USA) there is no researcher in the world today who is better known for the breadth of his research and scholarship on carbonate sediments and rocks. His articles reviewing carbonate facies have become classics that have deeply influenced research on carbonates and the way the subject is taught to students. His strength lies in field and petrographic studies and the breadth of his knowledge and research experience, which includes both ancient and modern carbonates. Worldwide, Dr. James has only one equal, Lynton Land of the University of Texas. Dr. James has received two Outstanding Paper Awards from the Society of Economic Geologists and Paleontologists (1976 and 1983). He was a Steacie Memorial Fellow (1984 86), he was elected FRSC in 1989, and he is currently President of the Society for Sedimentary Geology.

China and South America. This represents a very visible expression of Canadian science and technology in the world.

Canadian solid Earth scientists have figured prominently in the understanding and exploration of deposits of metalliferous ores and natural fuels and will continue to do so in the future. The solid Earth sciences community of Canada recognizes the difficulty of developing a strategic science policy based, in part, on the fortunes of industries (mining, oil and gas) that are cyclical in nature. However, we note the present strong demand for gas, with increased exploration activity for both oil and gas in 1994, as well as a general firming of metals prices. As a result of the present long recession, the natural resource industries in Canada are lacking the numbers of young and mid-career Earth science professionals required by a new phase of expansion and growth, and it will be essential to provide state-of-the-art facilities for the training of these scientists. A new generation of exploration science and technologies will be developed for resources that are increasingly more difficult to find. For example, there is a large gap between the exploration depths attainable by conventional geophysical techniques and the depths to which ores can be mined economically. New discoveries of giant orebodies are urgently required to sustain productivity and commercial viability in the mining industry. Similarly, much more research is needed on hydrothermal rock-water interactions to exploit the oil sands efficiently.

Environmental aspects of the development of natural resources have come to the forefront in recent years. Solid Earth scientists are well positioned to address these concerns by documenting contamination and researching effective remediation. Although there is a separate committee for environmental Earth sciences, solid Earth sciences have much to contribute. We have a sophisticated understanding of the rocks and mineral materials involved and of their interaction with the environment, as well as of the movement of fluids through rocks and unconsolidated surficial deposits. Solid Earth scientists are breaking new ground in the surface science of mineral materials and its application to attenuation of contamination by sulphides. We have extensive experience in the materials aspects and geology of high-level nuclear waste disposal. Exploitation of Canada's huge reserves of uranium ores ultimately hinges on the safe development of nuclear technology. Research and training in solid Earth sciences is essential for the economic and safe development of our natural resources.

The transfer of Canadian Earth science and technology to underdeveloped countries has humanitarian, commercial, self-image and foreign policy ramifications. The training of foreign students has always been an important component of Earth science graduate programs in Canada However, it is unfortunate that the policy of differential fees for overseas students in some Provinces has had a stifling effect on our ability to train scientists from underdeveloped countries.

The Introduction to this Allocation Report emphasizes the fact that the sheer size of Canada's landmass and oceanic jurisdiction necessitates an active and internationally competitive Earth sciences community. The size and natural beauty of Canada are part of our national identity. Documentation and understanding are essential for the preservation of this heritage and its harmonious development for habitation, tourism and natural resources. At the same time, the search for a fuller understanding of the constitution and functioning of the Earth necessitates work outside Canada and requires the involvement of Earth scientists in international collaborative programs, an activity that is increasing substantially. Canadian researchers have developed the networks world-wide to make this involvement effective.

The close working relationship between and interdependence of the two Earth sciences Grant selection Committees (08 and 09) will continue into the foreseeable future. We are clearly firmly bonded in respect to surficial processes, geochemistry and geochemical facilities, remote sensing, rocks as a platform for human life, the interaction of the solid Earth with the biosphere, hydrosphere and atmosphere, planetary processes, and so on. Large parts of the current undergraduate and graduate curricula in Earth sciences are common, and students of geology are uniquely able to appreciate the evolution and environments of life forms over the span of geological time. However, we anticipate major, perhaps radical, changes to traditional undergraduate and graduate teaching programs. Geochemistry is rapidly bridging chemistry and Earth science. Our teaching programs in Earth sciences will see a greater input of knowledge from chemistry, cell biology, and physics.

Summary

The solid Earth sciences research community in Canada is healthy and vigorous. With respect to productivity in top journals, solid Earth sciences in Canada compares very favourably with all other disciplines within the purview of NSERC Grant Selection Committees and, on a per capita basis, Canadians make a larger contribution to published research in solid Earth sciences than any other G-7 country. Earth resource industries remain extremely important for Canada's economy, and the solid Earth sciences continue

LITHOPROBE (An NSERC Collaborative Special Project). A significant feature of Canadian research on the lithosphere is the continuing megaproject LITHOPROBE: a national collaborative, multi-disciplinary research project created to answer fundamental questions on the nature and evolution of the outer shell of the solid Earth. Directed by R.M. Clowes at UBC, teams of Canada's best geophysicists (including C. Beaumont, Dalhousie, F.J. Cook, Calgary, E.A Kanasewich, Alberta, m. Mareschal, Ecole Polytechnique, and G.F. West, Toronto, as well as Clowes himself), geologists and geochemists (including J.N. Ludden, Montreal, B.E. Nesbitt, Alberta, T.E. Krogh, Toronto & ROM, P.F. Williams, New Brunswick, R. Kerrich and T.K. Kyser, Saskatchewan, and numerous others) are focusing their knowledge and expertise on major geotectonic problems, thereby enhancing the scientific studies well beyond the level of individual contributions. The project has drawn together scientists from the universities, GSC, provincial and territorial geological surveys and industry (both mining and petroleum), and this has had a very unifying effect on the solid Earth sciences. LITHOPROBE has been spectacularly successful in leveraging funds from government and the private sector for the work it is performing. Since 1987, there have been $15.5 million in direct and nearly $12 million in indirect contributions to this project.

to provide essential scientific and technological support for them. Solid Earth scientists in Canada work closely with governments and the private sector and correspondingly have a very high average leverage ratio for grant funding. Finally, although this report profiles established scientists in the discipline, solid Earth sciences has an excellent cadre of younger scientists, and this will guarantee the continuing strength of our discipline.

Reference

1. National Advisory Board on Science and Technology. Committee on the Competitiveness of the Resource Industries, 1993.

OCEAN DRILLING PROGRAM (ODP). Funded principally by twenty member countries with minor contributions from the private sector, ODP supports worldwide multi-disciplinary research of oceanic crust and the overlying sedimentary cover. Canadian participation has ensured that some of this research has been carried out in waters under Canadian jurisdiction and in areas of interest to Canadians. The pioneering work by S.D. Scott (Toronto) and J.M. Franklin (GSC) on the formation of seafloor hydrothermal sulphide deposits has provided real-time evidence of modem analogues of Archean sulphide deposits. Studies of the igneous components of ocean crust and of basalt-sea water interaction along ridges and transform fault systems by J.C. Malpas (Memorial), J.N. Ludden (Montreal), and others have added substantially to our understanding of the formation and in situ metamorphism of ocean crust. R.D. Hyndman (EMR and Victoria) and others have produced exciting new information on the role of fluids in subduction zones, including seismically-imaged methane clathrates from the Cascadia margin off British Columbia and the role of fluids in active accretionary thrust wedges. In addition, ODP has a history of making novel contributions to the understanding of sedimentation on the continental slopes, Quaternary geology and biostratigraphic.