Canadian National Quadrennial Report to IASPEI-IUGG2003 (Sapporo, Japan)

The Canadian Geophysical Union is pleased to present this quadrennial report on research activities in Canada at the 2003 meeting of the International Union of Geodesy & Geophysics in Sapporo, Japan.

The summaries presented are in alphabetical order as submitted by representatives at the various institutions. A copy of the report (IASPEI03.pdf) is available from

http://www.cgu-ugc.ca/cnc-iugg/report03.html

For additional information please contact the scientists concerned via the institutional representatives listed in the report.

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MARIPROBE is an umbrella for a variety of research initiatives that will support the development and application of seismological techniques to study fundamental problems relevant to resources and hazards associated with Canadian continental margins. The first phase of this program (in collaboration with the Memorial University, the Geological Survey of Canada, and University of Calgary) concerns regional investigations of two high priority areas (Grand Banks and Sable offshore basins) using deep multichannel seismic reflection and wide-angle seismic reflection/refraction profiling. For this program, we have established a joint facility between Dalhousie University and the Geological Survey of Canada that includes 23 ocean bottom seismometers (4-component) and a tuned 12-airgun (6346 in^3) source array. In 2000, a major marine program of regional seismic profiles and heat flow measurements was conducted (in collaboration with US and Danish groups) across the Grand Banks – Newfoundland Basin margin. These profiles included a survey of Ocean Drilling Program (ODP) borehole sites, which are scheduled to be drilled in Aug-Sept 2003. In 2001 and 2002, additional regional refraction seismic measurements were made across the Scotian and Flemish Cap margins in collaboration with the Geological Survey of Canada. These studies will allow us to determine if continental rifting progressed in an asymmetric fashion, including the exposure of large sections of serpentinized mantle in the transition region between continental and ocean crust, similar to what we have previously documented for the Labrador - SW Greenland margin. In addition, as part of the Flemish Cap program, a detailed study was made at the White Rose Site, Grand Banks (in collaboration with the University of Calgary and Husky Oil) in order to assess the potential of 4-component records to produce shear wave images of converted seismic phases.

LITHOPROBE. We have investigated the Proterozoic crustal structure of Labrador as part of the Eastern Canadian Shield Onshore-Offshore Transect (ECSOOT). Seismic tomography, employing both crustal refracted phases and Moho reflections, has been used to determine the 3-D velocity structure and Moho geometry beneath the Torngat Orogen. The velocity structure shows a close relationship to the tectonic provinces and the orogen is associated with an up to 50-km-deep crustal root, which narrows and flattens towards the north. Large scale shear-zones created during the oblique convergence of the Archean cratons penetrate the entire crust. Other 2-D velocity profiles were determined across Makkovik, Labradorian and Grenvillian structures, which record the progressive accretion of juvenile material to the growing Laurentian continent. We have also characterized velocity structures across the major anorogenic magmatism of the Mesoproterozoic Nain Plutonic Suite (NPS), which is host to the nickel deposits at Voisey's Bay.

Geodynamics Group (C. Beaumont): http://adder.ocean.dal.ca/
Research interests include 1) continental collision and resulting crustal deformation styles; 2) the interaction between surface processes and tectonics; 3) the development of numerical methods to model lithospheric deformation; and 4) application of geodynamic model results to current and ancient orogens.

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Seismic activities over the past 4 years within the Continental Geoscience Division of the GSC have included broad-band teleseismic, refraction/wide-angle reflection, deep-probing seismic reflection and high-resolution seismic reflection and down-hole seismic investigations.

Broad-band Teleseismic Studies of the Lithosphere: New data from multi-station broadband arrays were acquired within the Slave Province, across the Great Slave Lake Shear Zone (in collaboration with UWO), Central Baffin Island, and from 53 POLARIS stations deployed over the last 2 years in S. Ontario, SW British Columbia and in the Slave Province, NWT. Analyses of previously acquired data have been published; Western Churchill Province (Jones et al., GRL, 2002), Western Superior Province (Kay et al., GRL, 1999; Sol et al., PEPI, 2002; Kendall et al., Geol. Soc. Spec. Pub., 2002), and the Grenville Province (Rondenay et al., JGR, 1999; Rondenay et al., CJES, 1999).

Lithospheric Refraction/Wide-angle Reflection Studies: Analysis and interpretation of data from the Western Superior Province have been published or submitted for publication (Kay et al., GRL, 1999; Musacchio et al., submitted to JGR). The GSC PRS seismographs were utilized in the Celebration 2000 experiment in Europe, and more recently in Korea.

Deep Seismic Reflection Studies: Deep seismic reflection profiles were acquired in 2000 within the Slave Northern Cordillera Transect (1900 km), the Western Superior Transect (400 km), and the Grenville Province (400 km). Data interpretations have been published for the Slave Northern Cordillera (Cook et al., Snyder et al., GSA Today, 2002) and Western Superior transects (White et al., submitted to Geology).

Mining Camp Studies: Seismic surveys were acquired in mining camps for a variety of different commodities using high-resolution surface seismic reflection methods and downhole seismic imaging. The latter were conducted under the auspices of the Downhole Seismic Imaging consortium. Exploration-related surveys were carried out for base metals (Sudbury (Snyder et al., CJES, 2002), Bathurst (Bellefleur et al., submitted to Geophysics), diamonds (Victor (Attiwapiskat, Ont.), Fort-a-la-Corne, Sask.) and uranium (McArthur River, Sask.).

Energy/Environment: The GSC participated in the International Energy Agency sponsored Weyburn CO_2 Monitoring and Storage Project. 4-D multi-component surface and downhole seismic reflection data (with Colorado School of Mines, Lawrence Berkeley National Laboratory, and EnCana Resources) supplemented by downhole passive monitoring are being used to monitor the progress of the CO_2 flood within the oil reservoir.

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The Ottawa office of the Geological Survey of Canada's (GSC) National Earthquake Hazards Program (NEHP) continues to be the principal agency for monitoring earthquakes in eastern and northern Canada, for archiving seismicity and waveform data for all of Canada and for providing information on earthquakes to the media and general public. Staff also carry out seismological research. Additionally, the office houses the Comprehensive Nuclear Test Ban Treaty (CTBT) program.

NEHP is a major participant in two new initiatives, which involve collaboration with other groups within the GSC and with the academic community. The Canadian Urban Seismology Program (CUSP) is aimed at improving seismic hazard estimates and mitigating risk for Canada's urban areas in seismically active regions. An important component is the deployment of large numbers of strong motion instruments in urban areas. A pilot project is underway in Vancouver. NEHP also plays an important role in the Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity (POLARIS) project. In addition to archiving the data, staff have been involved in site selection and instrument deployments, and are using the data to improve seismic monitoring of southern Ontario and for hazard and structure related research.

The Canadian National Seismograph Network (CNSN) continues to be improved and upgraded. Many short-period, single component stations have been converted to three-component broadband stations and most of the few remaining analog stations were replaced with digital ones. The CNSN currently consists of 52 broadband and very broadband stations and 50 short-period stations. Data from 50 POLARIS stations are also received and archived by the data center. The acquisition of a mass data storage system has greatly improved the accessibility of the digital waveform archive and enabled internal and external users of the data to make large data requests via the internet. The process has been automated so that these data requests can generally be filled quickly and without the need for staff intervention.

As the reliability of automatic locations and magnitudes has improved, we have begun an earthquake notification service. Clients receive near-real-time notifications of earthquakes that might affect their infrastructure. Current subscribers include railroads and power companies.

No large earthquakes occurred in eastern Canada during the past four years but there were a few moderate earthquakes of note: 16 March 1999 Côte-Nord (mN 5.1, largest recorded earthquake in the Lower St. Lawrence seismic zone), 1 January 2000 Kipawa (mN 5.2, near the epicenter of the large, Mw 6.1, 1935 Timiskaming earthquake) and 20 April 2002 Au Sable Forks, New York (mN 5.5, widely felt in eastern Canada; POLARIS contributed a station to monitor aftershocks). Staff were involved in field investigations of large earthquakes that occurred in Turkey in 1999 (J. Adams) and El Salvador in 2001 (A. Bent).

The earthquake hazard group under the direction of J. Adams has finalized the 4^{th} generation seismic hazard model. This model will form the basis for the seismic design provisions of the 2005 National Building Code of Canada, which will be given for the new, lower probability of exceedance of 2% in 50 years.

The hazard group has formed a working group with the Institute of Seismology in Tirana, Albania in order to develop probabilistic seismic hazard maps for Albania.

To improve hazard assessments research aimed at better understanding past earthquakes and the earthquake rupture process, improving structural models and defining ground motions has been carried out. With the analysis of the 1933 Mw 7.4 Baffin Bay earthquake, A. Bent has completed the re-evaluation of the largest eastern Canadian earthquakes using modern waveform analysis techniques. A. Bent has also developed a method for determining depths of moderate earthquakes from stacked regional data and C. Woodgold has continued to refine a similar method using teleseismic data. The evaluation of depths from regional phases, such as sPmP is underway (J. Adams, V. Peci, S. Ma). Projects to use teleseismic receiver functions to model the crust and upper mantle beneath eastern Canada (A. Bent) and to determine horizontal to vertical ground motion ratios (A. Bent, E. Delahaye) are ongoing.

The test ban verification group, under the direction of D. McCormack, has continued to participate in international CTBT and related projects, developing and evaluating the global network for monitoring the nuclear test ban treaty. Seismic, infrasound, T-phase hydroacoustic and radionuclide stations are now operating in Canada as part of this network. The Canadian High Arctic Seismic Experiment (CHASME) included a two-year deployment of seismograph stations in the Arctic, which improved coverage for monitoring seismicity and provided data for research. Supplemental research by F. Darbyshire used teleseismic receiver functions and surface wave analysis to better define the structure of the crust and upper mantle beneath the Canadian high Arctic.

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Basement fault mapping with gravity and magnetic data in the Alberta Basin

Predictive exploration methods are possible due to the linear alignment of many oil and gas fields in the Phanerozoic Alberta Basin. Two fundamentally different types of crystalline-basement structure are recognized in Alberta: 1) Archean and Early Proterozoic (Hudsonian and older) ductile orogenic structures, and 2) Middle Proterozoic to Recent cratonic ones.

The influence of ancient ductile structures on the Alberta Basin largely consists of the control on Early Paleozoic depositional and drape patterns by the Precambrian erosional basement relief, which is partly related to the lithology distribution and thus to ductile ancient structures. Steep, brittle cratonic basement faults in the western Canadian platforms are much more subtle than their huge equivalents in the U.S. Cordilleran foreland. Brittle faults and fractures partly follow the older orogenic structures, but commonly cut across them. The basement-cover relationship is not 1:1. Basement control was partial, episodic, locally variable, and commonly passive and indirect, particularly where zero-offset (and seismically invisible) fractures affected fluid flow, salt dissolution and carbonate alteration. Steep, straight faults are commonly expressed as subtle potential-field lineaments, which can be gradient zones, alignments of separate local anomalies, aligned disruptions in the anomaly pattern, and so on. Many large magnetic and gravity anomalies represent the ductile, ancient, healed basement structures of little value for exploration, obscuring the desirable subtle features. Conducted for the Alberta Geological Survey, this study aimed to identify subtle potential-field lineaments in northern Alberta; similar work has been carried out by the author across the Alberta and Williston basins for other clients, contributing to oil-exploration success and strengthening the scientific experience discussed here. Subtlety of the lineaments necessitates detailed data processing, with a wide range of anomaly-enhancement techniques and display parameters. The final choice of processing steps depends on the target anomaly types, and on experimentation with various techniques. The processed and enhanced anomalies should ideally be easy to relate back to the original anomaly shapes. We avoided ill-described "black-box" techniques and relied on mathematically simple and intuitive procedures. Geosoft's Oasis montaj processing software was used.

The Bouguer gravity and total-field magnetic data were supplied by the Geological Survey of Canada. Gravity data in Alberta are comparatively sparse, yet sensitive to local vertical offsets across faults where rocks with different densities are juxtaposed. High densities in some Paleozoic sedimentary rocks just above the basement may smear out the subtle gravity signatures of basement faults. The Alberta sedimentary cover is generally considered almost non-magnetic, and the anomalies are sourced overwhelmingly in the crystalline basement. Local intra-sedimentary anomaly sources may be related to depositional concentrations of magnetic minerals in some clastic rocks, secondary magnetization of sedimentary rocks by circulating brines, etc. Bouguer gravity values decline gradually to the southwest as the Alberta Basin deepens. Because the depth to magnetic sources increases with crystalline-basement depth, the shortest-wavelength magnetic anomalies are found in northeastern Alberta, where the basement is at shallow or zero depth. Gridding of the data had to be tight enough to capture the anomaly details where the data were recorded at a close spacing, without needlessly creating enormous data files. For the gravity data, the optimal grid-cell size was chosen to be 1000 m; for the magnetic data, 400 m. Short-wavelength noise in the data, such as gridding artifacts, cultural noise or flight-line corrugation, may interfere with geologically meaningful lineaments, and is magnified when the subtle and short-wavelength anomalies are enhanced. Three noise-suppression techniques were considered: bandpass wavelength filtering, slight upward continuation, or smoothing with convolution filters. Bandpass filtering requires assuming the cut-off wavelengths, can smear anomaly separation due to non-vertical filter roll-off, and can contaminate the data by Gibbs ringing. By experimentation, upward continuation (usually by one cell size) was found to be the most effective for the gravity data in the study area, and two passes of the Hanning convolution filter for the magnetic data.

Horizontal-gradient maps reveal the anomaly texture and highlight anomaly-pattern discontinuities, by contouring the steepness of the anomaly relief's slope. Horizontal-gradient maxima occur over the steepest parts of potential-field anomalies, and minima over the flattest parts; short-wavelength anomalies are enhanced.

Vertical-derivative (vertical-gradient) maps are another tool to accentuate short-wavelength components of the anomaly field. The vertical gradient can be thought of as the rate of change of anomaly values as the data are upward continued. Though not intuitive, such maps highlight the details, discontinuities and breaks in anomaly texture. The vertical-gradient procedure was found to be effective for enhancement of magnetic anomalies. The gravity data were too sparse to benefit from such processing, which boosted the gridding artifacts.

Total-gradient (or analytic-signal) maps help to reveal the anomaly texture and highlight discontinuities and short-wavelength anomalies. Total-gradient maps are not intuitive because they incorporate the vertical derivative, but are often effective at highlighting geologically meaningful subtle and local anomalies. To highlight anomaly details, automatic gain control (AGC) boosts amplitudes in areas with smooth anomalies, without sacrificing long-wavelength information. Gain is estimated with a sliding square filter window, centered on each grid node in turn. Experimentation determines the optimal window size for each data set. A maximum gain correction is specified to prevent the procedure from blowing up in the areas of low signal. Local (as opposed to regional) AGC was found experimentally to be effective for magnetic data in the study area, but the gravity data were too sparse and lacking short-wavelength components. Inside the filter window centered at each position, the best-fit plane is calculated, which minimizes the RMS (root-mean-square) misfit with the data. The average RMS difference between the data and plane values within the window is the local signal gain. Signal at the grid node in the center of the window is the difference between the data value and the plane value at that position. The first pass over the grid determines the signal and gain for each position, and records the largest (maximum) gain encountered. In the second pass, the signal at each position is multiplied by the ratio of maximum to local gain, but not exceeding the specified maximum correction. The gained signal is then added to the original background value to obtain the final signal value.

To highlight local anomalies, the regional component of the gravity or magnetic anomaly field is commonly subtracted from the data, generating a residual map. The definition of regional vs. local anomalies is subjective. Regional-local separation can be achieved by bandpass wavelength filtering, but this procedure suffers from the shortcomings mentioned above. It is more intuitive to compute from the gridded data the best-fit smooth surface, of an optimal low order, and then remove that smooth surface as the regional component. Good results were obtained by subtracting from the data a third-order best-fit surface; gravity but not magnetic data benefited from this procedure. Shadowgrams reveal variations in the dominant anomaly wavelengths and trends between regions. This procedure treats a potential-field map as a relief, and computes the shadow pattern that would be created if this relief were illuminated by the sun from a user-specified angle. Subtle, local and short-wavelength anomalies are emphasized. Sidelighting from various "sun" azimuths acts as a directional filter, but directional bias is avoided in shadowgrams computed with a vertical sun angle, where the resulting vertical shadowgrams simulate horizontal-gradient maps. Vertical shadowgrams and horizontal-gradient maps are comparable but not identical: they are dissimilar in their nature and treatment of the data, and the differences in results are greatest with sparse data.

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The seismology group in the Department of Earth Sciences has been active in a wide range of field- and model-based seismology, associated signal processing and seismic interpretation, and theoretical work in wave propagation.

Field-based studies. Our contributions to the national Lithoprobe program are winding up as the project comes to an end. Geophysical summaries of Appalachian structure (in Lithoprobe East; *Quinlan and Hall*) are being revisited as part of the Pan-Lithoprobe synthesis on mountain building: a principal conclusion of this work is that, while the crustal reflectivity fabric - showing outwardly-vergent fabrics - is compatible with geodynamic models of continental collision, the combination of modest crustal thickness and low-grade surface rocks indicates only soft collision across Newfoundland (compatible with the arc- and microcontinent-continent collisions). Geophysical synthesis of the Proterozoic crustal structure of Labrador (Lithoprobe's Eastern Canadian Shield Onshore-Offshore Transect – ECSOOT; *Hall and Deemer*) shows similar outwardly-vergent fabrics in collisions of juvenile early Proterozoic arcs with the growing cratonic shield, but also shows a crustal root below the Torngat orogen, which has survived since the early Proterozoic, probably because of the lack of a relaxative thermal episode after the orogenic climax.

The group acquired 3500 km of multi-channel reflection data in the eastern Mediterranean in 2001 (*Hall and Aksu*), where our work is moving west from the Cyprus arc and its fore-arc basins to the junction with the Hellenic arc, with its anomalous bathymetric relief – high in the Anaximander Mountains, low in the Rhodes basin.

In 2000, we (*Hall, Deemer and Hurich*) joined with Dalhousie University, Woods Hole Oceanographic Institution, University of Wyoming and the Danish Lithosphere Centre in combined wide-angle and normal-incidence seismic surveys along three corridors across the Newfoundland margin of the N. Atlantic. The MUN group is focusing on the most southerly transect, and the correspondence of structures below the slope and rise along-strike to other corridors. The deep water margin appears to be characterized by a wide zone of continental crustal extension, followed seawards by a zone of anomalous structure (serpentinized mantle?), ending in undisputed oceanic crust.

The Centre for Earth Resources Research led a partnership of university and private sector companies in a novel, onshore-offshore transition zone seismic survey near Shoal Point, Western Newfoundland. The survey design provided for coverage of about 8 square km. centered on the PanCanadian et al. exploration well on Shoal Point with a goal of improved imaging of the top of the Cambro-Ordovician carbonate sequence that hosts the recently discovered oil on the Port-au-Port peninsula. The survey was successful in acquiring a rich dataset that provided typical 3D bin fold of 12 – 15 in bins of 25 m x 50 m. The data were processed using our Landmark ProMAX 3D processing software and Seisworks for plotting the target formation. The general deduction from the research (Rowe, MSc thesis, 2003) is that the structural setting is more complex than previously understood. It is thought that this complexity led to a drilling plan that missed the likely drilling target.

Interpretation and Modelling. Statistical approaches to wave field analysis *(Hurich)* are providing estimates of the scaling laws for crustal heterogeneity in the Abitibi and Grenville provinces. The growing understanding of the interaction between seismic waves and geologic heterogeneity is key to refining our techniques of seismic interpretation to account for realistic geologic heterogeneity. Statistical approaches to interpretation are providing detailed images of late/post orogenic intrusive complexes in the Grenville Province that have significant implications for the process of growth and collapse of the collisional orogen.

For several years we *(Hurich and Wright)* have been investigating methods of using seismic techniques to explore for massive sulfides. This work involves 2 and 3-D modeling to investigate acquisition and processing issues as well as acquisition and processing of test field data. Most recently we have evaluated the use of beam forming to detect drill targets and decrease the cost of data acquisition and the application of statistical interpretation techniques to delineate shallow mineralized intrusive systems.

Wave propagation. Our applied seismology group is focused on dealing with complex media in the context of seismic ray theory. Recent developments consist of a complete proof of Fermat's principle in anisotropic inhomogeneous elastic continua (Bona and Slawinski: Journal of Applied Geophysics) and generalization of orthogonality between rays and wavefronts in such continua (Bucataru and Slawinski, Studia Geophysica and Geodaetica). In collaborations with Department of Mathematics and Statistics at the University of Calgary (Bates, Sniatycki), this group works on inverse problems. Specifically, this work consists of seeking for detailed velocity fields by studying inverse of generalized Radon's transform using pseudodifferential operators. The outline of this work will be presented this July at the Geophysical Inversion Workshop of the Pacific Institute for Mathematical Sciences (Bates, Bona, Slawinski, Sniatycki). The pragmatic applications of the results of this group are described during week-long annual seminar to the industrial sponsors. Regular updates of codes that contain the developed algorithms are also available (Bona, Kocurko, Powojowski, Slawinski, Wheaton). A graduate textbook dealing with the scope of this group is about to appear in Elsevier Science (Seismic waves and rays in elastic media, Slawinski).

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Research into Exploration Seismic processing, imaging and inversion (Dr. R. Gerhard Pratt): These techniques are referred to generically as "waveform tomography". At the largest scale (100's of km with 1-10 Hz frequencies), collaboration with Colin Zelt and Alan Levander at Rice University has been initiated into the applicability of waveform tomography to deep crustal and upper mantle controlled source refraction seismology. A synthetic dataset has been generated and distributed (as a blind test) by the organizers of the next Commission on Controlled-Source Seismology workshop (October 2003); R.G. Pratt and D. Brenders will attend the workshop and present the results of their waveform tomography approach. On an exploration scale (10's of km with 10-100 Hz frequencies), several conference presentations and publications have been used to study the use of waveform tomography for inverting reflection seismic data; the main conclusion of this work is that such approaches are significantly enhanced by the use of wide angles and low frequencies, an unorthodox suggestion for an industry that focusses its attention on high frequency, normal incidence acquisition. At a yet smaller scale (100's of metres, with 100-2000 Hz data), Queen's has been involved in a number of crosshole experiments. Most recently this lead to a collaboration with the 2002 Mallik gas hydrate production research well program, a jointly sponsored project with partners including the Geological Survey of Canada, The Japan National Oil Corporation, The GeoForschungsZentrum Potsdam, the United States Geological Survey and several others. R.G. Pratt participated in the survey design specification, the field data acquisition and is currently working on several processing and imaging aspects of the crosshole data from the site. At the smallest scale (10's of metres with 100-500 Hz data), data from small scale, shallow seismic surveys are being processed with a view toward establishing a waveform tomographic approach for engineering problems. Collaborations are underway with Rice University (Alan Levander and Colin Zelt) and with Manitoba Hydro, which hopes to use shallow seismic methods to characterize earthen embankments used in large scale hydroelectric projects in Manitoba.

The Ar/Ar geochronology group: In an ongoing major research program, *J.K.W. Lee* continues to study Ar diffusion mechanisms in geochronologically important minerals, in order to develop a detailed understanding of the interpretation and significance of radiometric dates. With PDF A. Camacho, he is using Ar isotopes with diffusion theory to elucidate the thermal structure of the lower crust in the Bergen Arcs of Norway. Together with M.Sc. student Herbert Fournier they will also be studying Ar systematics from dry shear zones in central Australia. Other continuing projects include the development of a detailed chronology of erosional surfaces in the Andes and their role in ore deposition (with A.H. Clark, Queen's), finite-element modelling of defect-enhanced diffusion (with J. Braun, Australian National University), and applications of

Monte Carlo methods to error propagation analysis (with M. Sambridge, Australian National University).
D.A. Archibald continues his investigations of the geochronology and thermal history of the Canadian Cordillera. Current Ar/Ar studies include the tectonothermal history of SE British Columbia, with R. Price (Queen's) and BC Geological Survey.
J.A. Hanes continues with his principal research on the Western Superior LITHOPROBE Transect. The thrust of his research focuses on the determination of the post-amalgamation tectonothermal history of the Westerm Superior Province of the Canadian Shield by regional laser Ar/Ar age studies. The Ar/Ar study of the precambrian mafic dyke swarms continues and involves an M.Sc. student

LITHOPROBE Seismology (G. Musacchio in collaboration with the GSC Ottawa.): The 1997 broadband Western Superior Transect teleseismic profile has been analyzed using several techniques (S. Sol & C. J. Thomson in collaboration with the GSC Ottawa and Leeds University UK). SKS splitting and traveltime tomography results have been published, and surface-wave dispersion and polarization anomalies have been investigated. Several thought-provoking observations arise from jointly considering all these data types and are discussed in the publications and thesis of S. Sol. Results of the W. Superior Transect refraction/wide-angle reflection survey have been submitted for publication in two papers. (See also the report by D. White in the GSC Ottawa section of this document.)

Seismic modelling: (C. J. Thomson & D. Angus.): Ph.D. student D. Angus continues his development of the narrow-angle one-way seismic wave equation for three-dimensional anisotropic inhomogeneous media. Characteristic waveform effects associated with conical points (acoustic axes) for rock elasticities representative of mantle, crustal and basin-scale applications have been examined and a paper submitted for publication.

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At the time of the last report in 1999, the Geophysics group was on the rebound after the loss of our colleagues George Cumming, John Gray, Franta Hron, and Ernie Kanasewich. New colleagues Moritz Heimpel (High-Level Computational Geodynamics), Martyn Unsworth (Magnetotelluric Exploration), and Vadim Kravchinsky (Paleomagnetism) joined the faculty in 1999, 2000, and 2002, respectively. Jeff Gu, a global seismologist, was recently appointed and will arrive in 2004. An additional position that we hope to have filled by mid-2004, this will likely be in the area of environmental monitoring/near surface geophysics.

There is a wide range of research going on in solid earth Geophysics at the University of Alberta, and we strive to find a good balance between applied and basic science. Here, I will briefly overview the various research themes in progress from both current faculty and active Professors Emeriti. Additional information can be accessed through the website that has links to all the researchers, their research, and teaching.

Dr. M. Ted Evans is a Professor Emeritus since 1998. He is involved in several projects involving environmental magnetism aimed at improving our understanding of past global change. These include the natural archives residing in windblown continental deposits (loess) in China, Russia, Argentina, and the United States, as well as lacustrine sediments in Lake Baikal. The two main objectives are to systematically decode the climatic fluctuations recorded in the sediments and to address the problem of how magnetoclimatological signals are geologically encoded in the first place. For these projects, he is actively collaborating with colleagues in the ETH, Zürich, the Chinese Academy of Sciences, Beijing, Northwestern University, Xian, the Russian Academy of Sciences, Moscow, and LEMIT, La Plata, Argentina, as well as University of Alberta colleagues (N.W. Rutter, Earth and Atmospheric Sciences and V.A. Kravchinsky, Physics Department). Dr. Evans also continues his research concerning the secular variation of the geomagnetic field recorded as thermomagnetic remanence in pottery kilns that were fired in antiquity. In this context, he is an active participant in the recently-funded European program AARCH (Archaeomagnetic Applications to the Rescue of Cultural Heritage). He has most recently coauthored with F. Heller a book entitled *Environmental Magnetism: Principles and Applications of Enviromagnetics* to be published by Academic press later in 2003.

Dr. Jeff Gu currently holds a prestigious postdoctoral fellowship at the Lamont-Doherty Earth Observatory in New York and will join the faculty as an Assistant Professor at the U of Alberta in 2004. He is primarily an observational seismologist and has already worked on a variety of topics related to the upper mantle of the earth, particularly related to the discontinuities at 410-km and 670-km depths. Presently, he is working on issues related to the anisotropy of the mantle and has started new research into crustal refraction profiling.

Dr. Moritz Heimpel is an assistant professor since 1999. He conducts research in two main areas of geodynamics; the dynamics of planetary cores, and the mechanics of earthquakes and faulting. A focus of work in earthquake mechanics is to better understand how earthquake scaling is related to the tectonic environment. A primary region of study is the Western North American plate boundary region extending from the San Andreas Fault in the South to the Queen Charlotte Fault off the coast of British Columbia. The planetary dynamo project is aimed at understanding how the complex motions of liquid metal in the earth's outer core and the cores of other planets sustain the global magnetic field. Core dynamics are investigated primarily through computer simulations, based on a three-dimensional spherical convection code. Work is in progress to assemble an advanced visualization system, with the goal of enabling real-time visualization of time-dependent 3D flow and magnetic fields. This will be carried out in a visualization laboratory with a fiber optic connection that runs from the University of Alberta supercomputing facility (MACI) to the physics building.

Dr. Vadim Kravchinsky was hired in 2002 and works in a broad area of paleo and petro-magnetism and their application to solid earth and environmental studies. He was previously Director of one of the largest paleomagnetic laboratories in the former Soviet Union (1996-2001) with a team of 8 permanent researchers and technicians, equipment, and financial support (50% from academic grants, 50% from industrial agreements). Dr. Kravchinsky is in the process of applying for research and equipment grants and is taking graduate students to enlarge his research program. In particular, he hopes to construct a cryogenic magnetometer facility, the only one of its kind in Canada, that would attract a wide variety of researchers to the University for studies ranging from core orientation that will allow determination of hydrocarbon migration pathways, to high resolution stratigraphic mapping. Starting from academic programs (NSERC, CFI, Alberta Ingenuity Fund) he is actively looking for research collaboration to fit industrial needs in Alberta and Canada. He is planning to use his previous experience of dating of rocks and geological processes to study the process of kimberlite magmatism, among other projects. Dr. Kravchinsky's current research is in the areas of paleoclimate, paleoenvironment, magnetic properties of rocks and sediments, catastrophic global changes during the eruptions of flood basalts, plate tectonics, and the behavior of the outer core.

Dr. Walter Jones conducts research in three areas: electromagnetic induction in the earth, geothermics, and Earth tides and tilts. The electromagnetic induction work has included numerical modelling of 2- and 3-dimensional conductivity anomalies in the earth from small local inhomogeneities to down-going slabs as well as magnetotelluric studies in areas as geologically diverse as the Western Canada Sedimentary Basin and the region of the intersection of the Messejana Fault and Ferreira-Ficalho Overthrust in Portugal. The geothermal work has involved laboratory measurements of thermal conductivities of rocks, theoretical studies of borehole stabilization, numerical modeling of heat flow through inhomogeneous media and down-going slabs, as well as analysis of temperature data from the Western Canada Sedimentary Basin and the Jean d'Arc Sub-basin in offshore eastern Canada. The earth tilt research has included construction of both uniaxial mercury-level tiltmeters and novel biaxial mercury-level borehole tiltmeters, measurement and analysis of Earth tides in western Canada and monitoring of surface inflation associated with petroleum recovery enhancement processes. Dr. Jones has collaborated with the Geological Survey of Canada, Ottawa, and is currently working with collaborators from the University of Évora, Portugal. Dr. Jones is the current Director of the Institute for Geophysical Research and the Coordinator in the Department of Physics for the Faculty of Science Industrial Internship Program. The internship program allows 3rd year undergraduates to work for extended periods from 8 months to 16 months in a professional industrial job prior to completing their 4th year studies.

Dr. Edo Nyland is a Professor Emeritus since 1997 and is presently working towards the development of a PC based geophysical analysis package. Geophysical knowledge can be used effectively and accurately by non-specialists if the techniques they require are contained in self-checking programs that run on simple PCs. Nyland and colleagues are using Mathematica and Java to develop TerraNotes, a platform independent package of programs that uses the nature of the data the user presents to suggest methods of processing, display, or interpretation. The graphical user interface was developed with Mathematica and is being implemented in Java. Data import is as format independent as possible, while display methods use the powerful graphics tools of Mathematica and modeling uses the computational tools built into Mathematica.

Dr. Mauricio Sacchi joined the staff in 1997 and is currently an Associate Professor. His research interests are in the field of applied seismology and in particular, seismic imaging methods. He is the founder of the Signal Analysis and Imaging Group, an industry supported research initiative at the University of Alberta that focuses on the development of 3D imaging methods, inversion algorithms (Figure 4), and signal analysis techniques. Recent research encompasses the full spectrum from fundamental problems in wave propagation theory to the development of inversion algorithms to image fluid-bearing formations under massive salt bodies. The latter is a problem of great importance in hydrocarbon exploration in marine environments such as the Gulf of Mexico. Dr. Sacchi also works on multi-dimensional filtering problems, signal and image processing methods and Bayesian inference. He has recently completed a book entitled "*Information-based geophysical signal processing with applications*". He has developed and taught short courses on seismic data processing and inversion for geophysicists in the energy sector. He was elected by leading researchers at Schlumberger as one of the recipients of the Schlumberger Foundation Research Grant in 2001. He also works as a private consultant in the area of seismic inversion and de-multiple technologies.

Dr. Douglas R. Schmitt joined the U of Alberta in 1989, he is presently a full Professor and was awarded a Tier 1, Canada Research Chair in Rock Physics in late 2002. He works primarily in the field of experimental Geophysics with a focus on rock physics and its application to near surface studies and geophysical monitoring. He is currently carrying out laboratory research on the physical properties of wave propagation in anisotropic and saturated rock, on geophysical fluids under pressure and temperature, and on scattering media. Field studies focus on the evaluation of near surface properties and structures with present recent field projects related to exploration and monitoring with collaborators at sites from the Arctic to Italy on themes from gas hydrates through heavy oils to ground water. This research is assisted with equipment obtained by an infrastructural grant in 2000 that allowed him to purchase a truck-mounted seismic vibrator system and a 240-channel distributed acquisition system. He directs the 'Seismic Heavy Oil Consortium', a 5-year long project set up to examine issues related to the seismic monitoring of heavy oil and bitumen reservoirs. He also works in rock mechanics and is continues a project that employs optical interferometry to measure the elastic properties of rock. He is currently serving as an Associate Editor for the Journal of Geophysical Research and a Technical Editor for the Society of Petroleum Engineers Reservoir Evaluation and Engineering Journal, as well as the Canadian member on the Interim Scientific Measurements Panel whose mission it is to plan for shipboard laboratory and well logging measurements to be made as part of the currently forming international Integrated Ocean Drilling Program. Hi is on the AGU Executive Committee for Rock and Mineral Physics and is a member of the standing committee of the Canadian Geological Council working towards development of scientific drilling projects in Canada.

Dr. Tim Spanos is a Professor and joined the faculty in 1980. He conducts research primarily on theoretical studies on saturated porous media. In particular he has examined a variety of aspects of wave propagation and fluid flow through, and the mechanics of such materials particularly in the context of sanding of wells during heavy oil production. Some of this work related to induced pressure pulses in fluid filled rocks has motivated field studies applying his ideas to enhanced heavy oil recovery and environmental remediation; this has led to an commercial industrial start-up company that is having good success in environmental remediation of contaminated ground water sites in North America and Europe. Dr. Spanos' earlier research was primarily theoretical in nature but included some laboratory measurements of flows in porous media. He recently authored a book entitled *The Thermophysics of Porous Media* published by Chapman-Hall/CRC Press in 2001.

Dr. Martyn Unsworth is an Associate Professor since 2000. He studies electromagnetic geophysics and continental dynamics, and is presently focused on using the magnetotelluric (MT) method to understand global tectonics. As a research professor in the United States he developed an extensive research program that was active in many of the type locations for a wide range of tectonic problems. This included multidisciplinary studies of the Tibetan Plateau, the San Andreas Fault (Figure 6), the Cascadia subduction zone, the Chicxulub Impact Crater, and the East Pacific Rise. This work was supported through research grants in excess of C$4 million. A second research theme is using electromagnetic imaging in environmental applications. This has involved the development of new computer algorithms for the interpretation of controlled source electromagnetic data, and applications in environmental geophysics. Since moving to the University of Alberta, Dr. Unsworth has continued his international collaborations. The availability of research funding for geophysical instrumentation in Canada has greatly enhanced this effort. State-of-the-art MT instrumentation is being purchased with funding from CFI, ISRIP and the Alberta Ingenuity fund. Operating funds have been secured from NSERC, CFI, ISRIP and the Alberta Ingenuity Fund. These awards will be funding a study in the Canadian Cordillera, with an emphasis on seismic hazards in British Columbia. A project in Turkey will continue his study of continent-continent collisions that began in Tibet. He is also a member of the steering committee for POLARIS, a major infrastructure program recently funded by the CFI. In addition to the Canadian funding listed above, Dr. Unsworth is co-investigator on three pending National Science Foundation (NSF) proposals for studies in Taiwan, Tibet and the United States. He is also a member of an independent consortium for the environmental assessment of former nuclear weapons test sites in Alaska.

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Dr. Patrick Wu continues to use observations of the Glacial Isostatic Adjustment process to study the radial and lateral variations of rheology in the mantle and ice deglaciation history during the last 20,000 years. A new finite element model that is coupled with Poisson's equation has been developed to compute gravitationally self-consistent sealevels on a spherical, self-gravitating, visco-elastic earth since the traditional spectral approach does not handle lateral variations or nonlinear rheology well. Realistic lateral viscosity variations are obtained from scaling the velocity anomalies in seismic tomographic models. Realistic ice models are also used to model various geodetic observations such as GPS, VLBI, g-dot, tide gauge rate etc. in addition to the traditional relative sealevel data. The effects of stress relaxation induced by these deglaciation events on past and current intra-plate earthquakes or fault instability in Fennoscandia, Laurentia & Antarctica are also studied. A surprising result from these studies is that nonlinear rheology in the lower mantle appears to be compatible with secular degree 2 harmonic geoid variations in addition to observed sea level data and horizontal velocity.

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The three main axes of research at GEOTOP are:

- External geodynamics, in particular the use of tracers to reconstruct climate and environmental changes;

- Internal geodynamics, with focus on the lithosphere-asthenosphere interaction and the evolution of the continental lithosphere.

- Environmental studies, with particular interest on sources of greenhouse gases and the detection of heavy metals in lakes and reservoirs.

The external geodynamics team combines expertise in micropaleontology (deVernal), paleoceanography and stable isotopes (Hillaire-Marcel), organic geochemistry (Gélinas at Concordia), microbiology (Juniper) sedimentology (Long at the INRS), mineral geochemistry (Mucci at McGill). The team is investigating the effect of changes in oceanic circulation on climate, in particular the conditions of formation of deep water in the Arctic and sub-arctic basins in the northern Atlantic. Their studies are used for input for climate models by other Canadian teams (U. of Victoria and U. of Toronto). This team also studies then flux and the dynamics of Carbon burial along the Canadian continental margins, in relation with climate and hydrology.

In internal geodynamics, isotopic tracers, geochronometry, and geophysics are used to retrace the temporal evolution of the volume and composition of the continental crust, and its interactions with the mantle (Gariépy, Francis at McGill U., Machado, Mareschal, Stevenson). Heat flow studies by Mareschal and Jaupart (I.P.G. Paris) have shown the importance of crustal heat production in continental heat flow and the importance of continents in the Earth's energy budget. Francis, Gariépy, Mareschal, and Stevenson study the composition of meteorites and their implications for the primitive mantle composition. Petrological studies on xenoliths by Francis have shown the temporal evolution of the mantle chemistry. Stevenson and Baker (McGill U.) carry physical and numerical experiments on the petrology and physical properties of the mantle. Stevenson and David (Ministére des Ressources naturelles du Québec) have dated at 3.825~Ga a volcanic rock from Inukjuak, Québec, near Hudson Bay, Earth's oldest volcanic rock dated so far.

In environmental geochemistry, GEOTOP researchers (Lucotte and Planas) collaborate with the external geodynamics group and associates in other Montreal Universities, to address some major problems in environmental studies. A Canadian wide network studying mercury in the environment (COMERN) has its headquarters at GEOTOP.

Another major problem addressed by their team is the production of greenhouse gases by natural or artificial lakes.

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Through the years of 2001-2003, a comprehensive seismic investigation was undertaken *(Z. Hajnal)* as a major component of the multidisciplinary EXTECH-IV program, in collaboration with several government and industrial partners. The investigation included a crustal vibroseis reflection survey, a high resolution 2-D and 3-D reflection data acquisition project, as well as a variable offset, 3-D, 3- component VSP study of the McArthur River mining district in northern Saskatchewan. The remarkable seismic images outlined the complex collision tectonic history of the crust and its direct involvement in the development of the ore zones. The near-surface seismic data mapped the ore related basement unconformity and the associated complex fault system of the mining district. The investigation clearly demonstrated the feasibility of the reflection technique as an exploration tool in the Athabasca basin.

In collaboration with the international Weyburn CO_2 sequestration project, a 35,000 km^2 regional seismic reflection study is conducted (Z. Hajnal) in southern Saskatchewan. After reprocessing and synthesis of over 2000 km of high quality exploration reflection data, the new information is assembled to generate a 3-D image of the geologic environment around the Weyburn oil reservoir, one of the giant oil fields of North America. The intent is to define the lithology, sequence stratigraphy and the structural complexity of the basin fill, in conjunction with characterization of the nature and structural attitude of the underlying Paleoproterozoic crystalline basement.

As a member of the 28 European and North American institutions, a crew of the seismology laboratory partook in the Central European CELEBRATION 2000 lithospheric seismic experiment, deploying the Canadian PRS wide-angle recording systems (Z. Hajnal). The program imaged the crust of the Trans European suture zone (TESZ), the southern portion of the East European craton, the Carpathian Mountains, the Pannonian basin and the Bohemian massif. This 3-D regional investigation comprised of deployment along 14 variable length survey lines and initiation of multi-dozen explosive sources in several countries of Central Europe.

As a continuation of the CELEBRATION 2000 program, our group also participated in the ALP 2002 project (Z. Hajnal), which extended several lines of the earlier survey, across the southern margin of the Eastern Alps. This project also included, within the Pannonian basin, two 3-D survey deployments targeting tectonically relevant upper crustal anomalous zones. Utilizing the data sets of the longer profiles of the two surveys E. Takacs is investigating anomalous sub-Moho lithospheric variations within the Pannonian basin segment of the experiments.

Controlled-source Seismolgy (I. Morozov) Reprocessing of reflection records from Trans-Hudson profiles acquired by the National Lithoprobe program, with emphasis in true-amplitude and statistical characterization of the crust-mantle boundary.

In collaboration with several U. S. universities and the University of British Columbia, a pseudo-three-dimensional controlled-source wide-angle and multi-channel seismic combined with passive-source study investigation of the crust beneath the Coast Mountains (British Columbia) is in progress (project Batholiths). The objective is to constrain the volume and location of the crustal keel associated with the creation of the batholith.
Seismic experiment at the site of the planned San Andreas Fault Observatory at Depth (SAFOD) is in progress. We are participating in high-resolution imaging and characterization of the site of the planned borehole using a tripod, downhole and surface seismic array.
Analysis of the structure of the upper mantle using Russian nuclear-explosion profiles. The resulting constraints include velocity variations, reflecting boundaries, measurements of attenuation, and identification of scattering. Recently, the studies were extended to the analysis of the crustal properties using coda amplitude decays and reverberations (receiver functions).
Seismic characterization of the margin of the the Prairie Evaporite in Southern Saskatchewan. We use the available 2D (and possibly 3D) seismic data acquired by industry, to improve delineation of the margin, investigate and develop processing and interpretation techniques that would allow identification of thin salt beds and salt collapses near the dissolution edge and seismically evaluate underlying strata, with particular attention to the Precambrian basement.

Earthquake Sesismolgy (I. Morozov) Original methodology (generalization) of pre-stack depth migration of receiver functions is being developed. The method encompasses most of the existing depth-imaging schemes and is the only one to date to operate in full 3-D. It also enriches receiver-function work with numerous signal detection/enhancement approaches known in reflection seismics. The approach is being applied to several PASSCAL datasets in North America.
Seismic nuclear monitoring. Nuclear explosion datasets and data from regional seismographic networks in Eurasia are being used for the development of methods for nuclear test monitoring. These studies include analysis and modeling of the waveform of the regional phases (P, S, Lg) and development of calibration models, such as the travel-time model of Northern Eurasia derived from the Peaceful Nuclear Explosion travel times.
A comprehensive seismic processing system for both controlled- and passive-source seismic analysis is continuously being upgraded. Currently, the system includes tools for handling reflection and earthquake data, all basic processing operations, travel-time analysis, plotting, migration, and interfaces to other packages (such as Seismic UNIX and GMT). Software maintenance utilities and automated HTML documentation support is available. Graphical user interface surpassing those available in commercial systems is being created.

Simulations of Convection in the Mantle (S. Butler). Work on high-resolution computer simulations of thermal convection in the Earth's mantle is on-going. Areas of particular interest include the Earth's thermal history and the effects due to the endothermic phase transition at 660 km depth in the mantle.

J. Merriam is the Principal Investigator with the Canadian Superconducting Gravimeter Installation which houses a GWR superconducting gravimeter used for core modes research and other geodynamics projects. This instrument has a sensitivity of a nanogal and is sampled at 1 second intervals. Data is available through the Global Geodynamics Project data centre in Brussels. Merriam is also working on electrode impedances in resistivity and induced polarization and a new description for time domain IP decay.