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# 1991 — 1995

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## Introduction

This report summarises the research carried out in Canada in the fields of geodesy and geophysics during the quadrennium 1991 - 1995. It was prepared under the direction of the Canadian National Committee for the International Union of Geodesy and Geophysics (CNC/IUGG). The CNC/IUGG is administered by the Canadian Geophysical Union, in consultation with the Canadian Meteorological and Oceanographic Society and other Canadian scientific organisations including the Canadian Association of Physicists, the Geological Association of Canada, and the Canadian Institute of Geomatics. The IUGG adhering organisation for Canada is the National Research Council of Canada.

Among other duties, the CNC/IUGG is responsible for

- collecting and reconciling the many views of the constituent Canadian scientific community on relevant issues

- identifying, representing, and promoting the capabilities and distinctive competence of the community on the international stage

- enhancing the depth and breadth of the participation of the community in the activities and events of the IUGG and related organisations

- establishing the mechanisms for communicating to the community the views of the IUGG and information about the activities of the IUGG.

The aim of this report is to communicate to both the Canadian and international scientific communities the considerable progress that has been achieved in geodesy and geophysics research in Canada over the past four years.

The report is divided into seven sections — one for each of the seven major scientific disciplines as represented by the seven sister societies of the IUGG. Each section is titled with the name of the corresponding society and was compiled by, or under the direction of, a member of the CNC/IUGG affiliated with that society.

In the interest of compiling and disseminating this report in a timely fashion, no attempt has been made to harmonise the styles of the different sections.

The full text of this report, including the extensive lists of publications and presentations, is only available electronically. The full report may be obtained via the Internet in Unix-compressed, uuencoded, printer PostScript format by retrieving the file with the following universal resource locator (URL):

<gopher://UNBMVS1.CSD.UNB.CA:1570/0EXEC%3aCANGET%20IUGG.CNC.REPORT.PS.Z.UUENC.TXT>.

The report can be made available in other formats upon request to the chairman of the CNC/IUGG.

## INTERNATIONAL ASSOCIATION OF GEODESY

Compiled by Richard B. Langley

### Natural Resources Canada
### Pacific Geoscience Centre

**Crustal Deformation Studies on Canada's West Coast**

As part of its Earthquake Hazards Program, the Geological Survey of Canada (GSC) has utilized geodetic techniques to measure the effects of accumulating elastic strain within the northern Cascadia subduction zone. Through repeated precise levelling, gravity, and horizontal control surveys, relative crustal motions of the order of several millimetres per year have been resolved in this active seismic region. Recent observations have provided the most convincing evidence that the fault zone is locked, as well as the best constraints to date for the size and location of the seismogenic portion of the thrust zone capable of producing great (M>8) earthquakes. A major research effort over the past four years has also gone into the establishment of the Western Canada Deformation Array (WCDA), a network of automated continous GPS trackers intended to provide a precise, continuous fiducial reference frame for crustal motion studies in this region. The effectiveness of this network to provide day-to-day strain information at the sub-centimetre level over distances of hundreds of kilometres has already been demonstrated. Since 1991, the Pacific Geoscience Centre of the GSC has also been involved in a pioneering cooperative project to measure centimetre displacements of the ocean floor using a combination of acoustic and GPS techniques.

**Relevant Publications:**


Dragert, H., and R.D. Hyndman, Continuous GPS monitoring of elastic strain in the northern Cascadia subduction zone, Geophys. Res. Let., Vol.22, 755-758, 1995.

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Major research in the Department of Geomatics Engineering at The University of Calgary was done in four areas: Gravity and geoid, airborne gravimetry, positioning and navigation, and system integration and multi-sensor systems.

**Gravity and geoid:** A major emphasis in geoid-related research was the optimization of spectral geoid determination methods, Li (1993). It was shown that heterogeneous noisy data and error propagation can be handled by FFT methods (Sideris and Li, 1992; Li and Sideris, 1994) and that clever application of the DFT or the fast Hartley transform (FHT) can further improve the efficiency and the memory requirements of the spectral techniques (Sideris and Li, 1992; Li and Sideris, 1992 and 1995). It was also shown explicitly that FFT methods produce identical results to numerical integration when zero-padding is properly applied (Sideris and Li, 1993). Optimized algorithms for computing the effect of the topography were also developed (Li, 1993). Sideris (1994 and 1995) showed that irregular data and grids with incomplete data can be used with (hybrid) spectral methods. Direct and indirect effects of the topography on the geoid and on airborne gravity and gradiometry were computed by the 3D FFT method in order to avoid the approximations of the 2D techniques; very promising results have been reported in Peng (1994) and Peng et al. (1995). Improvements of the 2D FFT method on the sphere by using multiple bands of data were given in Forsberg and Sideris (1993). The rigorous 1D FFT method was used to produce a geoid for Canada and part of the US by She (1993). This geoid outperformed all existing geoids, giving absolute accuracy at the level of 5 cm and sub-ppm relative accuracies (Sideris, 1993; Sideris and She, 1995). Various tests of geoids on GPS benchmarks confirmed these accuracy levels (Tziavos et al., 1992; Mainville et al., 1992; Sideris and Teskey, 1993; Tsuei et al. 1994; Mainville et al., 1994; Li et al., 1995) and also showed that the geoid can also be used to check GPS for errors (Sideris et. al., 1992a). Regional geoid determination methods are summarized in Sideris (1992 and 1994) and Schwarz and Sideris (1993). The construction of 3D gravity field models, together with the proper choice of upward and downward continuation methods, was studied by Argeseanu (1994) for the purpose of establishing a test field for checking the results of vector airborne gravimetry in rough topography (Sideris et al, 1992b). Applications of SEASAT and GEOSAT satellite altimetry have been investigated by Zhang and Blais (1993 and 1994). Zhang (1993) completed a Ph.D. thesis on the recovery of gravity information from satellite altimetry data and associated forward geopotential modeling. Satellite altimetry research using GEOSAT, ERS-1 and TOPEX data has commenced (Zhang and Sideris, 1994 and 1995) and is currently focusing on obtaining oceanic geoid and gravity by optimal combination of satellite altimetry and shipborne gravimetry data. Further research has also been done on inverse problems (Blais, 1994), multiresolution and wavelet transform applications Nie (1994); Blais et al. (1995), Li (1995).

**Airborne gravimetry:** A major emphasis during the reporting period was the development of airborne gravity systems for geodetic and geophysical tasks. Three projects are at different stages of completion. The first is the development of a GPS-aided stable platform for a scalar gravity system, done in cooperation with Sander Geophysics Ltd. Details are given in Wei et al (1991), Zhang (1993), Czompo (1993, 1994), Czompo and Ferguson (1995), and Zhang et al (1995). A thorough discussion of platform stabilization by GPS-velocity aiding is discussed in Zhang (1995). System testing is planned for the summer 1995. Second, the possibility of using an inertial strapdown system in conjunction with DGPS for vector gravimetry was explored together with Canagrav Research Ltd. The

principle of this approach is discussed in Schwarz et al (1991), a detailed error analysis is given in Wei and Schwarz (1994), and results of DGPS acceleration determination are presented in Van Dierendonck et al (1994) and Wei and Schwarz (1995). System tests are ongoing and the initial analysis will be completed in fall 1995. Third, the use of a high accuracy inertial stable platform system for both scalar and vector gravimetry was tested in cooperation with the Inertial Technology Scientific Center in Moscow, Russia and Canagrav Research Ltd. in Calgary. Results are reported in Salychev et al (1994), Salychev and Voronov (1995), Salychev and Schwarz (1995). They show that minimum wavelengths of about 3 km can be resolved with a standard deviation of about 1 mGal. The current state of airborne gravity research and some of the remaining problems are discussed in Schwarz and Wei (1994) and the contributions of this new measurement technique to geoid determination in Schwarz et al (1994) and Li and Schwarz (1995).

**Positioning and navigation:** A major part of departmental research activities was concentrated in this area.

Investigations into the performance of high performance Narrow Correlator*spacing C/A receivers for precise DGPS kinematic positioning were conducted[Cannon & Lachapelle 1992] and applications to various cases such as precisionfarming [Lachapelle et al 1994, Cannon et al 1994], hydrographic surveying[Lachapelle et al 1992, Lachapelle et 1994a, Lachapelle et al 1993], andairborne positioning [Tiemeyer et al 1994], were demonstrated. Research intothe problem of integer carrier phase ambiguity resolution on-the-fly was pursued[Lachapelle et al 1992a, Cannon et al 1993, Lachapelle et al 1993a]. Themathematical equivalence between the Ambiguity Function Method and theLeast-Squares Search Method was established [Lachapelle et al 1992b]. A new OTFmethod, namely the Fast Ambiguity Search Filter, was developed [Chen 1993, Chen& Lachapelle 1994]. The use of a multi-receiver configuration to improve theeffectiveness of ambiguity OTF was investigated with an application toaircraft-to-aircraft positioning [Lachapelle et al 1993b, 1994b]. The use ofseveral non-dedicated receivers fixed to a mobile platform to determine theattitude parameters was analysed [Lu et al 1994, Lachapelle et al 1994c,McMillan et al 1994]. Research into the estimation of the ionospheric delayusing single frequency measurements was conducted [Qiu et al 1994]. The use ofGPS to calibrate Loran-C groundwave distortions [Lachapelle & Townsend 1991,Lachapelle et al 1992c, 1993d, 1994d] and as a complement to Loran-C[Lachapelle et al 1993c] was investigated. The use of post-mission orbits andsatellite clock corrections to recover the effect of Selective Availability andobtain single point positions at the 1 m (rms) accuracy level in static andkinematic modes was investigated [Lachapelle et al 1994e, f].

Research into precise kinematic GPS algorithm development and subsequent testing in a variety of environments was conducted (Cannon et al., 1993a; Cannon and Lachapelle, 1992; Cannon et al., 1992a; Cannon et al., 1992d). Work into the use of narrow-correlator GPS technology for precise static positioning was carried out (Cannon et al., 1994c). The use of low-cost GPS receivers for cm-level positioning was investigated (Cannon et al., 1993b). Application of DGPS and kinematic methods to agriculture (Cannon et al., 1994a; Gehue et al.; 1994) as well as airborne gravimetry (Van Dierendonck et al., 1994). Investigations into the integration of GPS and INS for high accuracy positioning in land and airborne environments were conducted (Cannon, 1992; Sun et al., 1994). Research was conducted into the use of GPS for precise attitude determination in the marine environment (Lu and Cannon, 1994). Further research into aircraft attitude determination (Cannon and Haverland, 1993) including wing flexure estimation was also conducted (Cannon et al., 1994b). A land attitude determination system which intergated GPS with low-cost dead reckoning sensors was developed and tested (Cannon et al., 1992c).

Reliability in kinematic GPS positioning and navigation was another area of research.Standard covariance analysis using covariance matrices and DOPS (Dilution of Precision) have been extended to using reliability theory where the total error is computed. One part stems form the propagation of random errors, while the second is a measure of the effect that a potential bias would have on a solution. This procedure has been implemented for GPS and DGPS static and kinematic positioning. When both measurement covariance matrices for random errors and reliability measures for potential biases - fulfill the specifications, the solution is repeatable to that specification. It has been found, however, that even when the DOPS are satisfied, there are situations and configurations that cause the reliability measures not to be satisfied (i.e., outside of specs circle). In these cases the solution is not repeatable (i.e., the coordinates cannot be replicated by a separate and independent survey). Whereas, when both the covariance and reliability measures are within the specification, the coordinates are reproducible by the independent resurvey (see references for the documentation).
Three electronic books have been written over the past four years in which intelligent navigation systems being built worldwide have been documented as to the positioning technologies used, digital maps employed, and the communications technologies encorporated. As well, the specific types of systems for each sector is defined along with the intended application. A color schematic has been created for each system and the books can be read directly from a PC computer. The IVHS Navigation System Database consists of 230 systems; the Intelligent Ship Navigation Systems Database consists of 125 systems; while the Intelligent Air Navigation Systems consists of 50 systems. These books are avaliable to interested persons, universities, agencies and companies.
Mathematical and practical investigations into the positional changes at various scales that resulted from the new North American Datum (NAD83) have confirmed the appropriatedness of the National Transformation for revising geodetic positions at the federal, provincial and municipal levels [Blais, 1990; Abousalem et al., 1993].

**INS/GPS integration and multi-sensor systems:** This research area is closely related to the previous one because it deals mainly with the problem of georeferencing a primary sensor or an array of sensors (multi-spectral scanners, CCD cameras, scalar gravimeters, etc). Georeferencing requires continuous position and attitude determination of the primary sensors while in motion and usually uses the integration of INS and GPS for this purpose. The basic mathematics of the approach is discussed in Schwarz et al (1993) and the requirements for optimizing INS attitude accuracy are discussed in Liu (1992), Schwarz and Ming (1995), and Skaloud (1995). Some general implementation issues, such as ambiguity resolution on the fly and the treatment of fractal sensor noise, are discussed in Wei et al (1992), Schwarz et al (1994a), Li and Schwarz (1994), and Schwarz et al (1994b). Implementation options in airborne mode using current technology are analysed in Schwarz et al (1994) and test results for a high-accuracy system are presented in Skaloud et al (1994) and Skaloud (1995). Tests of a low-cost integrated INS/GPS are presented in Schwarz and Zhang (1994) and Zhang (1995). Tests of a helicopter system are discussed in Martell et al (1993). A major project in the area of multi-sensor system was the development of a mobile survey van which allows data acquisition within a radius of 50 m around the van, while driving with a speed of up to 60 km/h. This system was developed together with Geofit Inc., Laval, Quebec and combines an INS/GPS position and attitude system with an array of CCD cameras. The different stages of system development are described in Schwarz et al (1993), El-Sheimy and Schwarz (1993), and Schwarz et al (1994). Preliminary results are discussed in El-Sheimy and Schwarz (1994) and a more detailed analysis of a major pilot project is given in El-Sheimy and Schwarz (1995). These results show that an accuracy of about 0.25 m (RMS) in horizontal coordinates and 0.05 m (RMS) in height are achievable right now and that improvements are possible. The

possibility of replacing the INS by a GPS multi-antenna system for attitude dtermination has been explored in Schwarz et al (1992) and El-Mowafy and Schwarz (1994). Results are encouraging for low-accuracy applications. A comprehensive comparison of models and techniques for kinematic attitude determination from GPS is presented in El-Mowafy (1994). A review of inertial techniques in geodesy is given in Schwarz (1991) and their application to curvature detection problems is discussed in Martell (1991).

**Others:** Investigations related to the creosote environmental problem on the Bow River in Calgary have shown that evolutionary terrain modeling, rendering and visualization can greatly help the geoscientists in their studies [Blais et al., 1994]. Using aerial and other photographic coverage of the site over the past sixty years enables the reconstruction of the terrain and any spatial changes over the years and with modern computer technology, spatial visualization for engineering purposes can be realized.

## Publications


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## Université Laval
## Département des Sciences Géomatiques and Centre de Recherche en Géomatique

The geodesy activities carried out at the Département des sciences géomatiques and at the Centre de Recherche en Géomatique of Université Laval mainly dealt with the following topics:

The potential of GPS for dam deformation monitoring has been studied by Bélanger et al. [1991]. Important errors encountered in precise GPS positioning, needed for dam deformation, are the multipath and phase center variations. The impact of those errors in GPS positioning results has been studied by Arbour [1994] and Bourassa [1994], respectively. A method has been proposed by Santerre and Beutler [1993a, 1993b] to improve GPS height determination for small GPS networks.

GPS orbit improvement process has been addressed by Huot [1993] and Salamanca-Chaves [1993]. Alaoui [1992] and Leclerc and Alaoui [1992] made studies on tropospheric delay modelling for GPS applications.

Papers have been published on the efficiency of using a telescopic mast to improve GPS positioning in wooded and urban areas where satellites are obstructed by trees and buildings [Santerre et Roy, 1993; Santerre and Boulianne, 1995].

Kinematic positioning software has been developed at the Centre de Recherche en Géomatique [Santerre, Parrot et Roy, 1994]. The software called POSICIEL (logiCIEL de POSItionnement CInimatique) allows positioning with smoothed code measurements as well as with fixed ambiguity phase measurements (with OTF capability).

## Publications and Presentations


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Arbour, B. (1994). "Etude des effets des multitrajets sur le positionnement GPS avec les mesures de phase des ondes porteuses." Mémoire de maîtrise (M.Sc.), Département des sciences géodésiques et de Télédétection, Université Laval, 108 p.

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**University of New Brunswick**
**Department of Geodesy and Geomatics Engineering**

Researchers in the Department of Geodesy and Geomatics Engineering (formerly the Department of Surveying Engineering) of the University of New Bunswick were involved in the following projects over the past four years:

**Transfer of Positioning Technology to Chilean Geomatics Agencies • Y. Georgiadou**.
The objective was to examine the requirements for using the Global Positioning System (GPS) for densification of existing control networks related to a regionally defined geodetic datum, such as the Provisional South American Datum 1956 in Chile. Various steps involving the differential GPS data reduction were examined, and the required subsequent coordinate difference transformation was investigated. A pilot GPS project was designed and carried out in Chile. Cooperation with this project was received from the National Service for Geology and Mining, the National Geographic Institute, the Department of National Assets, universities, and leading private companies. This pilot project was designed to determine the relation between the World Geodetic System 1984 and the local datum. During the pilot campaign, the participants were introduced to rigorous procedures of GPS data collection and analysis, and several professionals were trained to conduct future projects.

**GPS Technology Activities Relevant to Developing Countries • Y. Georgiadou**.
A summary analysis was undertaken on the nature of Global Positioning System (GPS) technology and its usefulness in addressing development issues in developing countries. The project involved the identification of the needs of developing country users in research applications and activities with GPS technology, and sectoral potential uses of this

technology of interest to international development. Interviews of some key Canadian researchers working with government, industry, and academia were conducted to identify, analyse, and evaluate their views on GPS research activities that should be supported by the International Development Research Centre (IDRC) in developing countries. Recommendations were made to the geomatics program of the IDRC on research activities relevant to developing countries that should be considered for support, and on the appropriate ways to deliver this support.

**GPS for Airborne Gravimetry • A. Kleusberg**.
In airborne gravimetry, GPS can be utilized to provide position, velocity, and acceleration of the measurement unit with respect to an earth-fixed coordinate system. This project investigates the capabilities and limitations of the Global Positioning System for the separation of inertial and gravitational accelerations

**Network Differential GPS • A. Kleusberg.**
This project is concerned with the development of algorithms and software for the spatial interpolation of differential GPS correction messages. This interpolation will reduce the accuracy deterioration of DGPS over larger distances.

**Accuracy Assessment in GPS Positioning • A. Kleusberg**.
This project is concerned with the estimation of proper covariance information for GPS differential positioning results, primarily coordinates and carrier phase ambiguities. Models for spatial and temporal correlations between GPS measurements are developed to account for unmodelled error terms.

**Precise Solution of the Geodetic Boundary Value Problem • A. Kleusberg, P. Vanícek,** P. Ong, M. Najafi, P. Vajda, Z. Martinec, E.W. Grafarend, L.E. Sjöberg, B. Heck, and Sun Wenke.
Existing theories for solving the scalar boundary value problem (BVP) of geodesy, which are used in computing the geoid from observed gravity data, were formulated in an era when the accuracy of the solution was not the most pressing consideration. Thus the existing theories are inadequate for today's needs, when the users are calling for a geoid accurate to 1 cm. To re-formulate the pertinent equations to a sufficient accuracy requires adequate modelling of the effect of topographical masses, and topographical and atmospheric density. It has turned out that our limited knowledge of topographical density can be overcome if the Stokes-Helmert approach is used. The re-formulation has called for a very different and more sophisticated treatment of the geodetic BVP.

**Evaluation of Estimation Techniques for Neutral Atmosphere Propagation Delays in GPS Measurements • R.B. Langley**, A.D. van der Wal, and J. P. Collins.
The aim of the research is to determine, by analysis of actual data, the 'best' estimation techniques for the removal of neutral-atmosphere-induced errors on geodetic baselines determined using GPS. To accomplish this task, neutral atmosphere delay estimators are being included as unknown parameters in UNB's DIfferential POsitioning Program (DIPOP) package. The evaluation will be an empirical one requiring the selection of suitable data sets for testing. The analysis of these data will provide statistical evidence as to which estimation options are the most likely to give optimal results under given conditions.

DIPOP currently uses models for the neutral atmosphere delays which are driven by measurements of surface meteorological parameters or default values for these parameters. Estimating delays or corrections to modelled delays directly from GPS data, however, has shown to be a very effective tool in improving the reliability of estimates of geodetic parameters. The current version of DIPOP uses a sequential least-squares algorithm for

parameter estimation. Part of this research will involve implementing Kalman filter and square root information filter algorithms in DIPOP so that the time varying nature of the neutral atmosphere can be adequately accommodated. Statistical comparisons of each estimation technique will be performed to determine the 'best' option. Repeatability of geodetic parameters will be used as the main criterion for comparison — particularly the repeatability of height and length baseline components.

**Robust Analysis and Automatic Processing of GPS Data from the Western Canada Deformation Array • R.B. Langley**, and X. Chen.
Vancouver Island, off the coast of British Columbia, is a tectonically and seismically active region. The Juan de Fuca, Explorer, and North America Plates converge beneath the region. To assess the earthquake hazard and study tectonic movement, the Western Canada Deformation Array (WCDA) has been established by the Pacific Geoscience Centre (PGC) and has been operating continuously since July 1992. So far, data spanning 1.5 years have been processed on a daily basis. Repeatabilities of a few parts per billion have been routinely achieved for both horizontal and vertical components on baselines spanning 301 km to 630 km. The process of data reduction has been streamlined and automated using CGPS22 software on a Unix-based Sun workstation at PGC. Further developments are being undertaken to fully automate the process of daily data reductions and to facilitate analyses for deformation study. They include: (1) enhancing the software's capability in handling remaining cycle slips after automatic processing;( 2) making the user interface more friendly; (3) developing additional analysis tools such as a spectral analysis facility; (4) thoroughly testing and improving the models in CGPS22. In addition, strain analysis with all available geodetic information, will be carried out in this project.

**Estimation of Earth Rotation Parameters, Site Coordinates, and Satellite Orbits Using the IGS Epoch'92 GPS Data Sets • R.B. Langley**, and P. Li.
Global GPS data sets collected during GPS weeks 654 and 655 of the Epoch '92 campaign organized by the International GPS Service for Geodynamics (IGS) were successfully processed using an advanced version of UNB's DIPOP software dubbed DIPOP.ERP. This version runs on an IBM 9121, model 320, mainframe computer. Daily values of earth rotation parameters were determined with an accuracy of about a few tenths of a milli-arcsecond. The daily repeatabilities of baseline lengths from a few parts to ten parts in $10^9$ for most continental baselines over eight thousand kilometres in length were achieved. The daily repeatabilities for the coordinates of most of the stations ranged from a few centimetres to about ten centimetres. Comparisons with the results from other processing centres show that precise GPS satellite orbits with a mean precision of less than one metre were provided and that the mean differences between the precise and broadcast orbits, during the weeks of Epoch '92 for which data was processed, appear to be less than five metres.

**Application of the Global Positioning System to the Monitoring of Crustal Deformation in the Charlevoix Seismic Zone • R.B. Langley**, and V. de Brito Mendes.
One high-precision application of the Global Positioning System (GPS) with significant impact on the scientific community is the monitoring of crustal deformation. In addition to its high accuracy capability, the reduced costs and ease of operation make GPS more attractive than conventional terrestrial geodetic techniques or other extraterrestrial techniques, such as satellite laser ranging and very long baseline interferometry, for such monitoring.

Since 1987, GPS has been one of the techniques used to detect strain accumulation in the Charlevoix Seismic Zone (CSZ). The CSZ is defined by an area of approximately 35 km x 80 km, developing parallel to the St. Lawrence River, about 100 km northeast of

Québec City. It is historically the most seismically active zone in eastern Canada, with records of six earthquakes with magnitude 6 or greater in 1638, 1663, 1791, 1860, 1870, and 1925. The repetitive nature of large earthquakes in this zone, which may presage the occurrence of a future major earthquake, has prompted the development of a program of extensive geodetic and geophysical monitoring, which began in 1974. Precise gravity, levelling, and horizontal control surveys have been carried out to detect long-term deformation and strain accumulation. The estimate of the maximum long-term horizontal shear-strain across the CSZ based on the analysis of conventional terrestrial techniques is 0.16 μstrain/yr.

Two GPS campaigns were carried out in the CSZ, in 1987 and 1991. In 1987, four Texas Instruments TI 4100 receivers were used in a seven-day campaign. In 1991, five Ashtech XII P-code receivers were used in a five-day campaign.

A preliminary analysis of the data using a modified version of UNB's program package DIPOP 2.1 to check for data quality has been performed. The first results indicate baseline agreement of typically a few parts in $10^7$, for the 1987 campaign, and few parts in $10^8$, for the 1991 campaign. Following this preliminary analysis, efforts have been directed to the improvement of tropospheric modelling and carrier phase integer ambiguity resolution in DIPOP.

Seventeen different tropospheric mapping functions developed in the last few decades for use in the analysis of space geodetic data have been tested against raytracing through the U.S. Standard Atmosphere Supplements, 1966, and radiosonde data. In addition, repeated baselines were used to evaluate the performance of these mapping functions in the processing of GPS data. From this study, a set of new mapping functions was recommended for incorporation into DIPOP. The ambiguity resolution has been improved in DIPOP. In addition to the ionosphere-free linear combination, the narrow-lane and wide-lane combinations have been implemented. These combinations, along with a new algorithm which allows an iterative fixing of ambiguities in the L1 and L2 data, look to be very promising tools for the bias fixing. The success of this algorithm seems to be limited only by the influence of the ionosphere. This problem is currently under investigation.

**The Effect of the Ionosphere on the Global Positioning System • R.B. Langley**, and A. Komjathy.

One of the major error sources in GPS positioning is that due to ionospheric refraction which causes signal propagation delays. The disturbing influences of the temporally- and spatially-varying ionisation of the ionosphere have great impact on satellite geodesy, especially on GPS. For a better understanding of the ionospheric effect on observed pseudorange and carrier phase signals, more knowledge about the actual state of the ionosphere is needed — this is especially true when precise positions are required in low and high latitude regions of the earth. It is possible to use partially-empirical models to make predictions of transionospheric propagation delays. We are investigating the accuracy and practicability of ionospheric models for single frequency users and are comparing their use with modelling ionospheric effects using dual frequency data processing. The new IRI90 reference ionosphere model is included in the comparisons. Previous research on several ionospheric models at the Geodetic Research Laboratory was carried out solely in terms of the effect on the satellite-receiver vector. The current research investigates the behaviour of ionospheric models with respect to their effect on position solutions.

**Precise GPS Positioning for Aircraft Navigation • R.B. Langley**, A. Komjathy, and J. Cesnick.

We are currently involved in two projects applying GPS to aircraft navigation. Transport Canada Aviation, in conjunction with Cougar Helicopters Inc., has initiated an in-service trial of helicopter precision approaches using local differential GPS (LDGPS). Cougar

Helicopters, a Halifax-based commercial helicopter operator (specialising in oil rig supply, search and rescue, and medevac operations), has equipped a Sikorsky S-76A helicopter with a Trimble TNL 3100 DZUS-mounted GPS/Loran-C avionics receiver. A high power TNL-2800G landing system base station at Halifax International Airport provides DGPS signals. Simultaneously, both at the base station and the remote station, Ashtech LM-XII single frequency geodetic receivers collect data using the same antennas supplying the Trimble equipment. At UNB, we are investigating the validity of using the position solutions from the post-processed Ashtech carrier phase data as "truth." Once we have assessed the accuracy of the Ashtech results, we will use them as a benchmark against which we can assess the accuracy of the Trimble DGPS results. This trial of LDGPS is co-sponsored by the National Energy Board and the U.S. Federal Aviation Administration.

The other project with which we are involved — also with Transport Canada Aviation — is the accurate positioning of airport runway thresholds using a combination of conventional static and stop-and-go surveying. Procedures have been developed for efficiently carrying out the surveys, and Transport Canada personnel have been trained in the operation of GPS equipment, in the processing of the collected data, and in the assessment of results.

**Real-Time GPS Orbit Improvement • P. Vanícek, R.B. Langley**, and M. Santos.
The aim of this research has been to investigate the possibility of real-time, high-accuracy GPS orbit improvement; i.e., the possibility of obtaining at any time the best possible estimate of an orbit based on all observations collected up to that time. The algorithm formulated could be used by a regional/continental tracking network. The best regional orbits for all GPS satellites will be available to the subscribers of the network without having to wait days or even weeks. The availability of improved orbits with as small a delay as possible would find manifold applications in geodesy and surveying. The approach is based on a sequential updating algorithm. Tests with the orbital integrator have been carried out. The algorithm for the real time orbit improvement has been implemented. The software implementation is based upon UNB's DIPOP software package.

**Sequential Tidal Analysis • P. Vaníček,** and T. Hou.
Research has continued into the performance of the sequential tidal analysis algorithm developed at UNB. The program has been transferred into the private domain for commercialization.

**Determination of Residual Scale Error in Levelling Rods • P. Vaníček,** M. Craymer (EMR), and R.O. Castle (U.S. Geodetic Survey).
The idea behind this project is to use repeated levellings with different pairs of rods and determine residual scale errors in these rods by a series of regression analyses, local and global. The main problem is that collected levelling data are contaminated crustal motions and bench mark disturbances.

**Navigation Algorithm Using Probability Space and Non-Newtonian Dynamics • P. Vanícek**, and B. Xu.
The study has been concerned with the particular problem of determining the two-dimensional position and velocity of a vehicle, say a ship at sea. Modelling the movement of a vehicle requires either the knowledge of the forces causing the motion or the measurement of the vehicle motion in a given coordinate system. We have concentrated on kinematic modelling.

**Differential Use of Tide-Gauge Data for Vertical Crustal Movements Determination • P. Vanícek**, and G. Carrera.

For modelling linear vertical crustal movements over Canadian territory, we use the vertical velocity surface in the form of a two-dimensional algebraic polynomial. This is a known technique that allows us to combine point velocities, computed from tide gauge records, with scattered segments of relevellings and water transfers supplying the information on velocity differences. Here we concentrate on the question of how best to incorporate the point velocity values into the mathematical model. It has been repeatedly pointed out that the standard deviations of individual linear trends (point velocities) of tide-gauge records are significantly larger than the corresponding standard deviations of trend differences (velocity differences) between close-by tide gauges. This is due to a high degree of coherence between sea level variations at close-by sites; a large portion of these variations disappear when the records are differenced. This behaviour offers an alternative, and better, way of treating sea level trends: Use only one trend value as a point velocity input and difference the rest to obtain velocity differences. We show the use of regional correlation matrices and correlation coefficient confidence intervals for selecting the optimal pairing of sites, i.e., a tree diagram for optimal differencing, that gives the most precise and accurate velocity differences to be used in the modelling.

**Global Vertical Datum Establishment • P. Vanícek.**
Offshore boundary demarcation, following the United Nations Convention on the Law of the Sea, is invariably based on the behaviour of local sea level, having thus nothing to do with the vertical datum as understood in geodesy. So why do we need a global vertical datum in boundary demarcation? The only reason is to put the maritime boundaries on a sound geometrical foundation as is done elsewhere in geodesy. In this contribution, we discuss the definition of a global vertical datum, its relation to local sea level behaviour, sea surface topography, and other geodetic aspects encountered in the UNCLOS applications.

**Determination of Continental Slope Foot-Line • P. Vanícek, D. E. Wells**, Z. Ou, and T. Hou.
The goal of this project is to find a practical and automated implementation for Article 76.4(b) of the UN Convention on the Law of the Sea, which states that, *the foot of the continental slope shall be determined as the point of maximum change in the gradient at its base*. Significant progress has been made on the project during the last year. We have selected the most flexible from three equivalent techniques — a local fitting of a second-order surface — which works with regular as well as irregular data sets, to become the basis of the package we are developing. The package has been tested on real data for three different locations off Canada's east coast, and on simulated data.

**Robustness Analysis for Horizontal Geodetic Networks • P. Vanícek**, and P. Ong, in cooperation with E.J. Krakiwsky (The University of Calgary), and M. Craymer (Geodetic Survey).
This investigation addressed the problem of geodetic network analysis techniques and proposed alternatives to the standard statistical analysis techniques designed to analyse network sensitivity to gross errors and blunders. The reliability technique, introduced by Baarda and implemented by The University of Calgary, and the geometrical strength analysis, formulated by UNB, were combined into what we call robustness analysis. It was concluded that robustness analysis should be carried out side-by-side with the standard statistical analysis from which it differs fundamentally. The developed software has been tested and streamlined on simulated and real networks.

**Truncated Geoid • P. Vanícek**, and P. Vajda.
Research has been carried on into the performance of truncated geoids and their use in solving the inverse problem of gravimetry.

**Accurate Geoid for Canada • P. Vanícek, A. Kleusberg**, M. Najafi, P. Ong, P. Vajda, and Z. Martinec.
Work has continued on the completion of an accurate geoid for Canada. The completed first step consists of the revision of all the theoretical aspects of geodetic BVB. The second step consisted of the revision of numerical procedures involved in the computations. The next step will concentrate on the formulation of appropriate data averaging procedures and solution accuracy estimation.

**Horizontal Datum Transformations • P. Vanícek**, R.R. Steeves, and Y. Okia.
The aim of this project has been to formulate the theoretically most appropriate way of distinguishing between datum transformation parameters and the parameters designed to describe the existing distortions in coordinates. Development of an algorithm for estimating both kinds of parameters and their errors is being investigated.

**GPS Tides • D. Wells**, and S. DeLoach.
This project will precisely measure, in real time, a time series of heights of a floating buoy, using on-the-fly differential GPS. This time series will be evaluated to assess the ability of GPS to serve as a tide gauge.

**Integration of Hydrographic Systems • D.E. Wells, A. Kleusberg**, D. Dodd, R. Phelan, Z. Du, and H. Nanton.
Integration of high performance position, depth, and tidal data acquisition systems, with powerful real-time data processing, management, and visualization systems is feasible. Such integrated systems have many potential new applications. Several aspects of such integration are being studied in this project. A high density bathymetric data cleaning and management system was developed. Methods for assessing high density swath mapping system data quality are being investigated. The reliability of practical real-time DGPS data links has been investigated. Innovative methods for GPS carrier-phase "on the fly" ambiguity resolution were elaborated. Using these methods, real-time three-dimensional differential GPS (DGPS) positioning with an internal consistency of a few centimetres was demonstrated.

During one trial in 1993 in Kennebecasis Bay, differential GPS data was analysed in detail using on-the-fly ambiguity resolutions techniques. This provided three-dimensional antenna positions accurate to a few centimetres. The results indicate that the GPS data were mapping water level slopes at the 1 ppm level, and appears even to detect water level hydraulic effects of a few centimetres, arising from current flow over bathymetric ridges.

**Hydrographic Ground Truthing • D.E. Wells, Y.C. Lee, L. Mayer, E. Derenyi, P. Vanícek, and J. Hughes Clarke**, with C. Ware, B.G. Nickerson (Computer Science), J. Tranquilla (Electrical Engineering), and A. Hay (Memorial University of Newfoundland).
The Hydrographic Ground Truthing project (HYGRO) is aimed at studying the relationship between actual seabed characteristics (topography, texture, and composition) and acoustic measurements of these same characteristics. Careful attention has been paid to precise positioning, critical to co-registration of our data sets, and thus our ability to compare acoustic and ground truth measurements. Differential GPS and OTF DGPS are used for vessel positioning. Precise total station and digital levelling instruments are used for detailed topographic surveys for photo control, to map exposed boundaries of various sediment types, and to position representative seabed samples.

In order to handle our massive raster and vector datasets, we have taken advantage of the capabilities of the CARIS Geographic Information System (GIS) that assigns a "layer" to each dataset, allowing co-registration and quantitative comparison of similarities and differences between layers. The new CARIS tools based on our work have attracted private and public sector users, and we have been asked to process sample data sets for

both manufacturers of swath-map systems (Simrad, Krupp Atlas, Reson, Honeywell Elac, Meridata, and Navitronics) and their users (Canadian Hydrographic Service, Public Works Canada, Canadian Coast Guard, Teleglobe Canada, Atlantic Geoscience Centre, National Defence Canada, U.S. Navy, U.S. Army Corps of Engineers, and U.S. National Oceanic and Atmospheric Administration).

A second field program was begun the summer of 1993 in the Bay of Fundy. The simplicity and practicality of using Bay of Fundy tides to reveal (at low tide) what we mapped remotely (at high tide) has captured the imagination of the international ocean mapping community. Collaborators from Dartmouth, N.S.; Rimouski, Québec; Ottawa, Ontario; Washington,D.C.; Florida, Louisiana, Helsinki, Massachusetts, and Hamburg travelled to Saint John, New Brunswick, to conduct trials of acoustic mapping systems well into the new year.

The results obtained from demonstrate both the potential and the limitations of ocean mapping systems. Careful analysis of return signal waveforms from multi-transducer vertical-incidence acoustic mapping systems can distinguish seabed material types. Quester Tangent Corp., one of our industrial collaborators, has produced a commercial product, ISAH-S, which was used in 1993 to collect six channels of digital waveform data in the Bay. Several performance enhancements required of multibeam systems for hydrographic-quality surveys have been identified, e.g., improved shallow-water performance, reduced influence of measurement errors in ship's roll, and water column acoustic velocity profile.

The development of vertical-incidence seabed classification tools benefited from a second trial in August of the ISAH-S system developed by Quester Tangent Ltd. These data collected at high tide in Saint John Harbour have been compared to our low tide ground truth measurements and aided in the refinement of our classification algorithms.

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## University of Toronto
## Program in Geomatics — Department of Geography

Geodesy research at University of Toronto in the quadrennium 1991-1995 focussed on enhancing the usefulness of geodetic measurements for the monitoring of crustal movements and structural deformation.

A comprehensive review of the approaches to weight estimation in geodetic levelling (Kelly, 1991) confirms that combining the random and non-random components of variance determined by analyzing the discrepancies between the direct and the reverse measurements remains the best way of estimating the weights of the height differences over levelling lines.

An experimental study of the performance of electronic theodolites (Kingston, 1991; Wassef, 1991) shows that the tests in use overrate the accuracy, and develop alternative field tests and improved analytical procedures.

Studies into the use of GPS (El-Maghraby, 1991; Wassef and El-Maghraby, 1991; Wassef, 1992) show that the individual quality parameters are not reliable identifiers of the accuracy of GPS results but they provide powerful means of classifying individual estimates when combined in linear discriminant functions.

Discussions of the concept of hypothesis testing in the context of the monitoring of the deformation of engineering structures (Aseno, 1992; Wassef and Aseno, 1992) bring out the importance of randomizing the observations to ensure inferential validity, and question the suitability of the network-least squares approach.

An examination of the characteristic features of geodynamic networks (Wassef, 1993) brings out the inappropriateness of the tests of significance that are based on random sampling, substantiates the intuitive concern that a geodynamic network may be of little value for crustal deformation studies simply because the network is small in the number of stations, and establishes norms for the size and the testing procedure. More recent work (Wassef, 1995) addresses the implications of parameterization of undeterminable and poorly determined factors affecting GPS observations.

Continuing work includes studies in the modelling of the gravity potential and the bearing of GPS on GIS.

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Aseno, Joseph O. 1992. The design of observations for monitoring horizontal deformations of engineering structures and the analysis of subsequent data. Ph.D. thesis, University of Toronto.

El-Maghraby, Mohamed F.H. 1991. Use of geodetic methods in detecting terrain movements, with special reference to the Global Positioning System. Ph.D. thesis, University of Toronto.

Kelly, Kevin M. 1991. Weight estimation in geodetic levelling using variance components derived from analysis of variance. M.A.Sc. thesis, University of Toronto.

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## International Association of Geomagnetism and Aeronomy

Compiled by Alan G. Jones

1. Aeromagnetism
2. Geomagnetism, inclusing geomagnetic observatories
3. Electromagnetism
4. Paleomagnetism and Rock Magnetism
5. Space Physics

### 1. Aeromagnetism

Compiled by Walter Roest, Geological Survey of Canada

Aeromagnetic data processing and interpretation.

A simple user-friendly method to computationally "drape" constant elevation aeromagnetic surveys onto any specified surface has beendeveloped using a Taylor series approach (Pilkington and Roest, 1992). This results in a significant improvement in the resolving power of such surveys and allows adjacent areas flown at different elevations to be merged in a straightforward manner. Comparison between this approach and truly drape-flown surveys shows computational draping is a viable method (Pilkington et al., 1995).

W. Roest and co-workers have devised a technique for estimating the depth and position of magnetic sources without any a priori knowledge concerning their geometry (Roest et al., 1992). Their approach, using the 3-D analytic signal, is computationally cheap (only requiring derivatives of the observed magnetic field) and delineates the edges of magnetic sources irrespective of the direction in which the body is magnetized. The analytic signal has also been used to derive an observational method to evaluate the level of remanent magnetization present in a particular source body (Roest and Pilkington, 1993).

Using aeromagnetic data, susceptibility measurements and well-logs M. Pilkington and co-workers have demonstrated that continental crustal magnetization can be well-described as fractal - having the same behaviour over a range of length scales (Pilkington and Todoeschuck, 1993; 1995). Furthermore, they have shown how to incorporate this information into existing interpretation methods and have demonstrated that more accurate interpretations are obtained (Pilkington et al., 1994).

J. Ostrowski (Horler Information) under contract and in cooperation with the GSC has developed a versatile form of Werner deconvolution which can be used on aeromagnetic data collected atvarying altitudes (Ostrowski et al., 1993). This allows "draped" surveys to be processed directly with this approach, thus exploiting the high resolving power of such data. Effectively, all aeromagnetic surveys can now be interpreted with this method, irrespective of how the survey was flown.

A method originally developed for removing distortions in potential field maps has been applied (along with a simple strain analysis) to reconstruct the original shape of the Sudbury Basin, demonstrating, through the presentation of

potential field data, that it could have been circular and supporting a probable origin by impact (Roest and Pilkington, 1994). Work is now under way on applying this approach to the Kapuskasing Zone in Ontario and other areas with distributed deformation in the Canadian Shield.

Keating (1995) has succesfully used pattern recognition techniques to identify circular magnetic anomalies caused by kimberlite pipes in the Kirkland Lake region of north-eastern Ontario, Canada. Using high resolution magnetic, electromagnetic and gravity data, an integrated geophysical interpretation of the Chibougamau mining camp, northwest Quebec, Canada, wa completed (Dion et al., 1992).

In conjunction with gravity data, aeromagnetic survey data over the 65 Myr-old Chicxulub impact crater in Mexico has been processed and interpreted to provide important constraints on the size and morphology of this structure (Pilkington et al., 1994). Magnetic data suggest the presence of reversely magnetized bodies within the melt rocks and a central uplift offset from the geometric centre of the crater.

## Aeromagnetic Surveys

Approximately 300,000 sq km have been added to the regional aeromagnetic coverage of Canada available for the Geophysical Data Centre of the GSC. Surveying has taken place in three principal areas: 1) Southern Saskatchewan and Manitoba, stimulated by interest in diamond exploration; 2) Southwest Alberta/Southeast British Columbia stimulated by oil and gas exploration and 3) in the Interior Plateau of British Columbia as part of a multi-disciplinary program to stimulate mineral exploration in an area with extensive glacial and miocene and younger volcanic cover. The Manitoba, Saskatchewan and British Columbia Interior Plateau portions were flown on an 800 m by 4 km grid at 400 m mean terrain clearance, whereas the Alberta/SE BC portion was flown on a 1600 m by 5 km grid in constant elevation blocks. The surveys in Manitoba, Saskatchewan, Alberta and Southeastern BC have also provided information on the structure and divisions of the precambrian basement beneath sedimentary cover and the eastern Cordillera as a complement to the Lithoprobe Deep Seismic Reflection Program.

## Magnetic Compilation Project

In 1990, the Atlantic Geoscience Centre of the Geological Survey of Canada initiated a project to create a research-grade data base for use in investigating large-scale, regional tectonic problems of the Arctic and North Atlantic and surrounding land areas. As we near the end of this project, we estimate that we have assembled and processed about forty million magnetic data points, contributed by thirty-five organizations in fifteen countries, to develop a coherent 5-km grid throughout the study area (Verhoef et al., 1994). Contributors delivered data in a variety of forms: digital marine magnetic and aeromagnetic profiles, digital grids from previous compilations, and paper maps portraying contours or profiles along track. During the life of the project, numerous innovative computer techniques to cope with this major influx of data were designed and developed: semi-automatic error detection and correction, modelling of different classes of time-dependent magnetic field variations,

statistical cross-over analyses, interactive visualization, and grid manipulation (including levelling and adjustment). As a resource for regional studies, the new data base has already demonstrated its value by providing a departure point for a wide range of investigations performed jointly with personnel from data-contributing organizations. One of the most interesting results of the data base has been the new perspective it offers on the tectonic framework and early history of the Arctic Ocean - one of the world's most poorly known: marked disparities in the Amerasian and Eurasian Basis suggest significantly different modes of formation for these two segments of the seafloor. In the North Atlantic, the data base provides an enhanced definition of seafloor spreading anomalies, and contains interesting new evidence for ridge axis propagation and oceanic fracture zone displacements.

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## 2. Geomagnetic Surveys, Magnetic Observatories and Instrumentation

(Geological Survey of Canada, Ottawa - prepared by L.R. Newitt, D.H. Boteler, and R.L. Coles)

### i. Magnetic Observatories and Repeat Station Surveys

Instrumentation at Canadian magnetic observatories has been upgraded with the installation of the CANMOS magnetometer and data collection system. CANMOS provides faster sampling rates, increased resolution, and greater stability than was possible with the previous AMOS system. CANMOS also enables near-real-time data transmission via satellite, permitting Canada to become a major participant in INTERMAGNET, a global near-real-time observatory network. A new magnetic observatory has been established at Iqaluit, NWT, in support of the Ørsted mission.

The Canadian repeat station network consists of approximately 40 sites ar which magnetic observations are made about every four years to determine the secular variation of the magnetic field. In 1994, in addition to the normal repeat observations, a special survey was carried out to redetermine the position of the North Magnetic Pole. Its 1994 location was 78.3 degrees N, 104.0 degrees W.

### ii. Regional Modelling of the Magnetic Field

The development of a new method for modelling secular variation, by main field differences, eliminates many of the problems inherent in the previous techniques. The technique has also been extended to modelling the main field by incorporating spatial magnetic field data, including scalar data. A spherical cap harmonic analysis was performed using the new method to produce the Canadian Geomagnetic Reference Field for 1995.

A method has been developed for calculating equivalent ionospheric and induced currents over a portion of the globe using the intrinsic ability of spherical cap harmonic analysis to separate internal and external sources. A near-real-time magnetic activity modelling routine has been developed. This routine uses data obtained via INTERMAGNET and other sources, to produce hourly models of magnetic activity and ionospheric currents over Canada, and to output them graphically for remote access.

iii. Forecasting Magnetic Activity

Magnetic activity forecasts continue to be used by a broad spectrum of users. Forecasts are available in a variety of forms. These include 27-day forecasts, 4-day computer bulletin-board forecasts, and magnetic alerts . Recently, a new method of superposed epoch analysis was developed to investigate the time delay between solar events and geomagnetic disturbances.

iv. Effects of geomagnetic activity on electric power transmission

Several joint ventures are underway with Canadian electric power utilities to investigate the effects of geomagnetic disturbances on power systems. A study for the Canadian Electrical Association investigated the occurrence of dB/dt levels likely to be a problem to power systems, and a follow-on study is now examining the whole question of geomagnetic hazard to power systems. This includes an analysis of the characteristics of magnetic variations and the earth conductivity structure in order to calculate the electric fields expected during disturbances. This is then being fed into power system models to determine the expected flow of geomagnetically induced currents (GIC) throughout a number of power systems. Growth of GIC in a power system can be affected by the inductance of the power transformers but this has been hard to calculate because the inductance changes for part of each AC cycle when the GIC causes transformer saturation. However, recent work by Boteler has shown how to calculate the effective value of an inductance that is changing with time.

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## 3. Electromagnetism

Compiled by Alan G. Jones

University of Victoria, Victoria, British Columbia
(J.T. Weaver, A.K. Agarwal)

At the University of Victoria theoretical work in geo-electromagnetic induction has centred on three-dimensional numerical modelling by finite differences and two-dimensional inversion using a modelling method. Recent progress has involved the development of automatic grid generators in two and three dimensions, the use of parallel computing for both forward modelling and inversion, and an investigation of conjugate gradient techniques for solving the large system of equations generated in three-dimensional modelling.

University of Victoria, Victoria, British Columbia
(H.W. Dosso and J. Chen)
Our research has been concentrated on studying coast effect EM induction and removing this component from geomagnetic measurements in coastal sites. The resulting difference induction arrows can then be interpreted as responses of any anomalous conductors in the field site region.

University of Manitoba
(Ian Ferguson, Trevor Boyce, Yu Sheng)
The University of Manitoba participated in the 138-site magnetotelluric investigation of crustal and mantle lithosphere structure in the LITHOPROBE Trans Hudson Orogen Transect and collected an additional 15 long-period MT recordings on the transect. Modelling of the theoretical seafloor magnetotelluric response, and vertical gradient sounding analysis of magnetic field recordings from the Juan de Fuca Ridge, have been completed. In controlled-source studies, we have performed finite element modelling of the response of seafloor EM surveys for a range of hydrocarbon targets and in addition completed a number of field surveys, employing both frequency and time-domain methods, for shallow environmental targets.

Geological Survey of Canada
(A.G. Jones, D.E. Boerner, R.D. Kurtz, W. Qian)
Under Lithoprobe auspices, magnetotelluric surveys have been undertaken in Newfoundland (Lithoprobe East transect, 1991; 67 sites), Quebec (Abitibi-Grenville transect, 1992; 80 sites), Saskatchewan and Manitoba (Trans-Hudson Orogen transect, 1992 and 1994; 138 sites), and Alberta (Alberta Basement transect, 1993 and 1994; 110 sites). The analyses of these data are at varying stages of maturity, and a number of papers have already been published.
The Long period Intelligent Magnetotelluric System (LIMS) was finally completed and undertook the first successful field trials in 1992. A total of sixteen LIMS have been built, and they have already been used on a number of surveys both in Canada and the U.S. The technology was transferred to Phoenix Geophysics Ltd., who now manufactured clones for commercial sale.
Collaborative projects with the University of Washington (J. Booker) have taken place in North Dakota and the southern Appalachians. Long period measurements were made on both surveys using the LIMS systems. The North Dakota survey mapped the fine structure of the North American Central Plains (NACP) anomaly.
Modeling of passive electromagnetic responses of powerlines and pipelines has been attempted by using integral equation method. The derived solution can account for the current channelling and induction in this kinds of cultural conductors.

Ecole Polytechnique
(M.Mareschal. M.Chouteau, P. Zhang, D. Livelybrooks)
Together with colleagues at the GSC and at Univ. of Toronto, we have observed upper mantle electrical anisotropy. The direction of enhanced conductivity has recently been shown to correspond to the fast axis of seismic anisotropy. we have also developed new techniques for analysing the vertical component of the magnetic field; finally several MT surveys have beem completed over mining camps.

University of New Brunswick
(R. Kellett)
1991-1993 Investigating electrical anisotropy in the lower crust and upper mantle beneath the Archean Superior Province. Using geophysical methods including AMT and airborne magnetics to determine the geometry of Proterozoic Gabbro-anorthosite intrusions.
1993-1995 Processing C-band Synthetic Aperture Radar and airborne EM data over the Sudbury Structure. Developing a methodology for the integration of airborne and ground based EM data into a GIS.

University of British Columbia
(D.W. Oldenburg, R.G. Ellis)
Geophysical inversion studies, especially, EM tomography.

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## 4. Paleomagnetism and Rock Magnetism

Compiled by Randy Enkin, Geological Survey of Canada

Department of Earth Science, Memorial University, St. John's, Newfoundland (J.P.Hodych, G.S.Murthy)

Hodych and Bijaksana (1993) showed that remanence anisotropy can be useful in detecting and correcting paleomagnetic inclination shallowing induced by compaction in deep-sea sediments. Low temperature demagnetization experiments were used to identify internal stresses as important in remanence retention in mafic igneous rocks (Hodych 1991). Paleomagnetic studies in central Newfoundland with K.L. Buchan of the Geological Survey of Canada have shown that the Iapetus Ocean was likely closed (or nearly so) by the Silurian in Newfoundland (Hodych and Buchan 1994). Gummuluru Murthy is continuing his studies of the diabase dyke swarms from coastal Labrador. Suites of dykes exposed along the coast from Port Hope Simpson south all the way south to Belle Isle were sampled along with Charlie Gower of the Newfoundland Department of Natural Resources. Both the Lighthousecove and the Bradore magnetizations are likely remagnetizations and it seems the southeastern region of Labrador was exposed to some regional metamorphism. Ernest Deutsch and Gummuluru Murthy are collaborating with Karsten Storetvedt of the University of Bergen on the study of the Lower Paleozoic of Ireland.

Department of Geology, University of Ottawa (K.Benn)

Research over the last four years has concentrated on the use of the anisotropy of (low-field) magnetic susceptibility (AMS) as a tool to measure petrofabrics in granites and gneisses. In the Archean Opatica Gneiss Belt (Southeastern Superior Province, Canada), AMS was used to confirm orientations of regionally consistent lineations which give partial kinematics of ductile thrusting of the Opatica Belt and the Abitibi Greenstone Belt, ca. 2.7 Ga. Detailed susceptibility and magnetic mineralogy data was also presented for the mid-crustal gneisses and granites. AMS is currently being used to measure petrofabrics in Appalachian syntectonic granite plutons. In the Rose Blanche granites (Central Mobile Belt, Newfoundland), the AMS measures orogen-parallel biotite fabrics which are related to late-orogenic regional transpression. In the Canso area (Meguma Terrane, Nova Scotia), the AMS fabric pattern in granites provides an excellent criteria for syntectonic pluton emplacement during regional dextral transpression along the Meguma-Avalon terrane boundary. Applications of AMS to the study of fabric overprinting relationships, finite strains, and strain histories in granites are also being investigated.

Continental Geoscience Division, Geological Survey of Canada, Ottawa (K.L.Buchan, J.K.Park, with R.E.Ernst)

Until recently, large uncertainties in the ages that are assigned to Precambrian paleopoles have limited their use in the construction of apparent polar wander paths and the investigation of relative movement of the Precambrian terranes. However, during the past four years a new

collaborative approach to paleomagnetic and U-Pb geochronologic studies has reduced uncertainties in the dating of many paleopoles from >100my to <50my (e.g. Buchan et al. 1993). These studies have been concentrated on mafic dykes and sills, and require that (a) samples be collected for both paleomagnetism and U-Pb baddeleyite (or zircon) dating at the same locality, (b) a U-Pb age and well-defined paleopoles be obtained, and (c) a rigourous field test be carried out to ensure that the remanence is primary and therefore dated by the U-Pb age. Studies have been reported on several Early Proterozoic units in the Canadian Shield (Buchan et al. 1994) and demonstrate that there are serious problems with segments of widely-used apparent polar wander paths.

Department of Physics, University of Toronto (D.J. Dunlop, O.Ozdemir, S.Xu)

The rock magnetism group has been investigating experimental and theoretical magnetic domain structures, new theories of thermoremanent magnetization (TRM), and paleomagnetic studies of post-metamorphic uplift and cooling in the Grenville Province in Ontario. For the first time, clear closure domains have been photographed on carefully oriented magnetite crystals. Two- and three-dimensional calculations of micromagnetic structures in magnetite have traced the evolution of complex domains from simple ones as crystals grow, but have also demonstrated that simple structures do also exist in crystals as large as 1 um in size. Transitions between metastable equilibrium structures at high temperature ("transdomain TRM") have been computed with a one-dimensional model, while the thermal demagnetization and partial TRM processes have been solved analytically for domain wall motions in larger crystals. Lithotectonic domains in the Central Gneiss Belt of the Grenville Province have broadly similar uplift signatures, but uplift occurred at times differing by 50-100 Ma in the more southerly and more northerly domains. The Grenville Front Tectonic Zone has a distinct history, with widespread hydrothermal alteration and remagnetization.

Department of Geology, University of Toronto (H.C. Halls)

Paleomagnetic studies of the 2.45 Ga Matachewan dyke swarm of northern Ontario show that Proterozoic deformation of the Superior Province is more widespread than previously thought. Regional changes in paleomagnetic declination and dyke strike are positively correlated and reveal that the swarm has been distorted both within and NW of the Kapuskasing Zone (KZ) from an originally linear, radiating pattern. The new results show that the KZ is sinistrally offset and depressed progressively towards the SW. A paleomagnetic investigation of the 1883 Ma Molson dykes of Manitoba shows that older dykes are present which are estimated from APW curves to be about 2.1 Ga old. This discovery is significant because the older dykes document for the first time the opening stages of the Manikewan Ocean, the closure of which led to the Trans-Hudson Orogen at 1.8 Ga. Ferrofluid has been used to impregnate porous rocks and to render the pore volumes magnetic. AMS measurements then provide a measure of the pore shape anisotropy. The method, called Magnetic Pore Fabric Analysis, provides a new and rapid way for estimating permeability anisotropy, an important parameter in the petroleum and hydrological industries.

Department of Geology, McMaster University, Hamilton, Ontario (W.A.Morris)

Topics of research include joint paleomagnetic / aeromagnetic / seismic interpretation of the Sudbury Igneous Complex and the Grenville Front, Holocene magnetostratigraphy in the Great Lakes, and using susceptibility to

trace pollutants in Hamilton Harbour.

Department of Earth Sciences, University of Western Ontario, London, Ontario (H.C.Palmer)

The personal research of H. Currie Palmer concerns a study of the structure, paleomagnetism and anisotropy of magnetic susceptibility of early and mid-Tertiary ashflow tuffs of the Basin and Range Province exposed in southern Idaho and east central Nevada. This work is done jointly with W.D. MacDonald (SUNY, Binghamton). The object of the research is to decipher the style of deformation associated with the north Nevada Rift and with B&R extensional faulting in general. The AMS data is used to infer flow patterns and hence source went locations. Paleomagnetic research of graduate student M.G. Gala involves Late Paleozoic and Early Mesozoic rocks from the Stikine Terrane, Iskut River area, B.C., and of Precambrain rocks in the Hanson Lake block of the Trans-Hudson orogen. This research is directed towards the understanding of the tectonic history of these regions.

Department of Geology, University of Windsor (D.T.A.Symons)

Paleomagnetic methods have been used to date the genesis of epithermal Mississippi Valley-type Pb-Zn-Ba ore deposits (Gays River, Newfoundland Zinc, Pine Point and Polaris in Canada; Central Missouri and Central Tennessee in U.S.A.; Silesia in Poland) H. Pan and M.T. Lewchuk (PhD students, Univ. of Western Ontario), D.F. Sangster (Geol. Surv. Canada) and D.L. Leach (U.S. Geol. Surv.) were each involved in several of these studies. M. MacDonald (M.Sc. student, Univ. of Windsor) continues work on other deposits. Most other studies examined Cambrian or Precambrian geotectonic problems under the auspices of LITHOPROBE in the Kapuskasing Structural Zone (e.g. Callendar, Chipman Lake and Seabrook carbonanites), in the Trans-Hudson Orogen (THO) (Wathaman Batholith, Peter Lake Domain, Macoun pluton, Hanson Lake pluton, Missi conglomerate), and in the Cordillera (Aldridge Fm.). A.D. Chiasson, C.A. Lohnes, and E.A. Timmins did B.Sc. theses (Univ. of Windsor) on these rocks. M. Gala and M. Harris (Ph.D. students, Univ. of Western Ontario) continue to work on studies in the THO and Cordillera, respectively. Improvements to the data aquisition system for the automated CTF DRM420 cryogenic magnetometer give it now a sensitivity of 2x10-6 A/m.

Department of Geology, Lakehead University, Thunder Bay, Ontario (G.J.Borradaile)

The research program involves studies of strain in rocks as revealed by magnetic anisotropy, with application to tectonics in the Precambrian shield.

Institute of Earth and Planetary Physics, University of Alberta (M.E.Evans)

One primary focus has been the magnetostratigraphic investigation of the thick loess/paleosol sequence at Baoji, China. A concurrent study of the paleoclimatic information encoded in the corresponding magnetic susceptibility has also been carried out, including scrutiny of the mineral-magnetic basis for susceptibility as a climate proxy. This project involves a doctoral thesis (Y.Wang, 1991), and the active collaboration of N.W.Rutter (Department of Geology, University of Alberta), Z.L. Ding and T.S. Liu (Academica Sinica, Beijing), and F. Heller (ETH, Zurich). Work on the Permo- Carboniferous Reversed Superchron has been completed (doctoral thesis, J.-M. Maillol, 1992). Magnetostratigraphic work has also been

carried out on the last interglacial in the Yukon Territory (with J.V. Mathews, Geological Survey of Canada, Ottawa), on permafrost cores in the MacKenzie Delta (with S. Dallimore, Geological Survey of Canada, Ottawa), and on the Cretaceous/Tertiary boundary (with J.F. Lerbekmo, Department of Geology, University of Alberta / Canadian Continental Drilling Program). Archeomagnetic studies in the Mediterranean area are continuing; the work to date was summarized in an invited review to appear shortly in a special publication of the Geological Society of London.

Department of Geology, University of Lethbridge (R.W.Barendregt)

The recent flourishing of research in the areas of paleoenvironmental reconstruction and global change has underscored the need for reliable geochronological data. Our research has focussed on paleomagnetic properties as a correlation and dating tool for sediments and rocks of the Quaternary and Neogene. Remanence measurements of deposits containing proxy records of paleoclimates have been carried out in the Canadian Arctic (Barendregt et al., 1990), Canadian prairies (Barendregt et al., 1991), Canadian Cordillera (Barendregt et al., 1991), east Africa (Mahaney et al., 1989), Colombia (Helmens et al.,1995) and elsewhere. In addition to providing age constraints, the work has proven valuable as a measure of relative weathering histories, soil formation, and extent of Cordilleran and Laurentide ice in North America.

Geological Survey of Canada - Victoria (R.J.Enkin, P.J.Wynne, E.Irving)

A) Cordilleran Studies: With the recognition that plutons may have systematic tilts, study of Cretaceous displacements in the Cordilleran belts has been focussed on plutons with bathozonal tilt corrections or well-bedded rocks. Recent data confirms the large scale northward motion from the mid-Cretaceous to the Eocene, and in particular has discriminated between 3000 km displacement in the coastal belt versus 1500 km displacement in the intermontane. B) Quaternary Magnetostratigraphy (with R. Barendregt, U. Lethbridge): We have applied magnetostratigraphic study of peri- glacial deposits to a variety of settings (Arctic Islands, the Northern Cordillera, the Prairies) to correlate and date glacial events. The distribution of pre-Wisconsin glaciation in Canada is being built up and is used towards constructing better surficial maps. C) Diagenesis and Mineralization Studies: Iron oxides are easily transformed by hydrothermal events, thus providing the opportunity for paleomagnetic dating. We have studies concerning Uranium mineralization in the Athabaska basin, alteration of the Saskatchewan potash, the maturation and migration of hydrocarbons in the Canadian Rockies and Foothills, and on kimberlite properties.

Royal Roads Military College, Victoria, B.C. (J.S.Mothersill)

During the 1993 and 1994 field seasons, 16 cores were obtained from Lakes Victoria, Albert and Edward in Uganda, East Africa. Paleomagnetic measurements have been carried out on aligned samples from these cores using a Schonstadt spinner magnetometer at RRMC and on a C.T.F. System cryogenic magnetometer for those cores with low intensity of magnetization values. Palynologic analyses of the cores are being carried out at Makerere University, Uganda.

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Compiled by D. McDiarmid

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## International Association of Physical Sciences of the Oceans

Compiled by Yves Gratton

In Canada, the focus of the physical sciences of the ocean has changed during the past four years. In government laboratories, the emphasis was placed on fisheries related environmental problems: salmon on the West Coast and cod on the East Coast, and on the path of contaminants in the environment. In academic institutes, the shift was towards national and international multidisciplinary programs: global changes, large-scale ocean circulation, carbon budget, sea-ice biological production, etc. There also has been a "bloom" in numerical circulation models, climate models, ice models and remote sensing studies, with the emphasis on nutrients, eggs, larvae and contaminant distribution and transport. In general, the tendancy has been towards large, fully integrated, multidisciplinary teams and studies. Since it is impossible to cover all the research activities in Canada in such a short report, the Canadian contribution to the large national and international multidisciplinary programs will be presented.

Canadian scientists are participating in many national and international multidisciplinary programs, including the World Ocean Circulation Experiment (WOCE), the Joint Global Ocean Flux Study (JGOFS), the Northeast Water Polynya (NEW), the Saroma-Resolute Project (SARES), the Canada - US 1994 Arctic Ocean Section, the Ocean Production Enhancement Network (OPEN), the Global Ocean Ecosystems Dynamics Experiment (GLOBEC) and the Land-Ocean Interaction Zone Experiment (LOICZ). Although the Canadian contributions to the last two are still in the planning stage. A few Canadian scientists are already participating in the US -GLOBEC program.

### WOCE (World Ocean Circulation Experiment).

The objective of WOCE is to develop ocean circulation models for the purpose of climate prediction and to make the observations necessary to test them. The Canadian WOCE field oriented projects comprises sections in the Pacific and Atlantic Oceans, a surface velocity measurement program from drifters released in the North Pacific, and a full depth section across the Labrador Sea. They also occupied one of the important WOCE hydrographic sections in the Sea of Okhotsk, area of possible intermediate water formation, in 1993. Preliminary studies from this data will be presented at the Canadian Meteorological and Oceanographic (CMOS) meeting in May 1995. Some of the ocean circulation models developed in Canada include numerical models of coupled atmosphere-ocean interactions (e.g. Weaver and Hughes, 1994 ), models of the North Atlantic thermohaline circulation (Weaver et al. 1993), models of the North Atlantic interdecadal variability (Greatbatch et al. 1995), and models the North Pacific Gyre (Lee et al. 1992). Climate studies of century-scale variability (e.g. Mysak et al., 1993) were also carried out.

### JGOFS (Joint Global Ocean Flux Study).

Canadian JGOFS addresses the challenging "global warming» problem".The program attempts to determine the ocean $CO_2$ budget through three main themes: (1) gas exchange at the sea surface, (2) transformation and transport of carbon in the ocean, and (3) the burial of carbon in the sediments. Field programs are being conducted in the Northern and Equatorial Pacific Ocean, Lake Ontario, the Gulf of St. Lawrence, Nova Scotia South Shore, Labrador Sea, Northwest Atlantic, and the Arctic. Physical sciences studies are being conducted in the three themes. The physical sciences contribution to the first theme is in the area of physical transfer of $N_2$ and $O_2$ between the atmosphere and the ocean (e.g. Farmer et al., 1993; McNeil et al. 1995), while the contribution to the last theme pertains to the processes of diffusion, mixing and irrigation of the sediments (e.g. Boudreau 1994). The second theme has the largest physical sciences contribution. This

theme addresses the horizontal and vertical transport of carbon in the oceans (e.g. Anderson and Jones, 1992; Jones et al. 1994). The physical processes under study include the mesurement and the modelling of turbulence, mixing, deep water formation, upwelling and coastal jets (e.g. Denman, 1993). Studies exploring the fate of light in ocean (e.g. Hoepffner and Sathyendranath, 1992; Sathyendranath et al., 1994), with a view to understanding the implications for primary production at sea, and for interpretation of remotely-sensed data have also been carried out. Most of the JGOFS work is at the analysis stage. A Canadian-JGOFS session will be held at the Ocean Sciences Meeting in San Diego, in February 1996.

**NEW (Northeast Water).**

The general objective of the NEW project is to study the physical, geophysical and biological processes taking place in the Northeast Water Polynya. The field work was conducted under the leadership of the Alfred-Wegener-Institut für Meeresforschung on the F.S. Polarstern, in the summer of 1993. The research objective of the physical sciences was to identify the hydrodynamic mechanisms that govern nutrient and light availability in the surface waters of the polynya, at its edge and in the surrounding ice-covered waters. The preliminary results will be presented at the NEW symposium in Helsingor (Dannemark) in May 1995. A steady state nonlinear simulation of the polynya may be found in Darby et al. (1994).

**SARES (Saroma-Resolute Project).**

A Japan-Canada project was conducted on the first-year ice in Saroma-ko lagoon (Northern Hokkaido, Japan) and Resolute Passage (Northwest Territories, Canada), during the winter of 1992. The objectives of the the SARES Project were to measure the activity of the biological $CO_2$ pump under the first-year sea-ice and to characterize its main physical controls. The main difference between the two sites is that the Saroma-ko site is the southernmost area in the Northern Hemisphere with seasonal sea-ice while the Resolute Passage is one of the northernmost area with recurrent first-year sea-ice. A special issue of the Journal of Marine Systems will be devoted to the principal findings. Some preliminary results may be found in Marsden et al. (1994a, b), and Shirasawa et al. (1994). The most interesting physical observations (Marsden et al. 1994a) are the two basic high frequency structures of the flow: tidally driven pulses of finite amplitude internal waves and linear internal waves. Most of the pulses are generated by the interaction of the tidal flow with a compression ridge.

**Canada - US Arctic Ocean Section**.

There is a growing international concern that the Arctic has been polluted by a variety of contaminants. We know neither the regional nor the global consequences of a changing or a polluted Arctic, the major reason being the lack of measurements upon which analyses and models can be based. The objective of the Canada - US 1994 Arctic Ocean Section was to increase the observational base necessary for understanding the role of the Arctic in global change. From July 17 to September 9, 1994, mesurements were gathered along a section from the Norwegian Sea to the Bering Strait, on the USCGC Polar Sea and the CCGS Louis L. St-Laurent. The mesurements included (1) physical properties of the ocean and of the ice cover, (2) biological parameters, (3) geological observations, (4) contaminant distribution, and (5) atmospheric and upper ocean chemistry and physics relevant to climate studies.

**OPEN (Ocean Production Enhancement Network).**

OPEN is a Canadian action plan designed to promote the collaboration between Canadian marine scientists. OPEN's objective is to study the processes that control the survival, growth, reproduction and distribution of fish and shellfish in general and of Altantic cod and scallops, in particular. The importance of currents on the sockeye salmon

migration patterns was also studied by the West Coast team (Thomson et al. 1994). The physical module, "Coastal Ocean Dynamics", was mostly involved with field work and numerical modelling of Eastern Canada coastal regions. The study regions include the Newfoundland coast (de Young and Sanderson, 1994; de Young et al., 1995), Baie des Chaleurs (Bonardelli et al., 1993; Gan et al., 1995; Le Quéré 1992) and the Scotian Shelf. The first succesfull, real-time larvae-tracking numerical model-data assimilation experiment was performed in Emerald basin (Scotian Shelf) and is discussed in Bowen et al. (1993).

**Other regional models**

The Canadian contributions to the physical sciences of the ocean over the period 1991-1994 were not restricted to the international programs. Since a large number of numerical circulation models appeared over the past four years, a few regional models are considered in order to complete the coverage of Canadian waters.

Numerical models, including data assimilation, account for a large part of recent research projects. The availability of cheap, powerful computers, the need to look at more realistic coastlines and bathymetry, and the urge to solve «the nonlinear problem», especially for the long-term atmosphere-ocean climate interactions, water quality evaluation and emergency reponse purposes, are responsibble for this bloom. On the West Coast, the modelling effort covered individual inlets (e.g. Stacey and Pond, 1992; Stronach et al., 1993), as well as the Vancouver Island Shelf (Walters and Foreman, 1992) and the North Coast of British Columbia (Foreman et al., 1993). One of the promising future applications is the removal of tidal currents from ship-mounted acoutic Doppler measurements (Foreman and Freeland, 1991). Wang et al. (1994a, b) and more recently Saucier and Dionne (1995) studied the circulation and the interannual variability of the sea-ice response to atmospheric climate forcing and runoff in Hudson Bay. These studies were motivated by the question of cumulative impacts of the Hudson and James Bays hydro-electric projects. On the East Coast, a 3-D circulation model for the Gulf of Maine Region is being developed at the Bedford Institute of Oceanography (BIO) by J. Loder and D.A. Greenberg. The objective is to study the fate of polluants and the distribution of fish eggs and larvae. A set of circulation and ice models (and studies) for the Labrador Sea and Coast, as well as the Baffin Island Coast, are also being developped at the Bedford Institute, the Northwest Atlantic Fisheries Centre and Memorial University. Finally, the modelling wave reached the St. Lawrence system where Chassé et al. (1993) modelled the barotropic tides in the estuary while Chassé (1994) developped a full 3-D baroclinic model. Toro (1992) developped a 3-D diagnostic model for the buoyancy driven seasonal circulation in the Gulf of St. Lawrence.

Canadian scientists have been active in many other branches of the physical sciences of the ocean: remote sensing, turbulence, double diffusion, waves, fronts, other climatic studies, air-sea interactions, physical-biological interactions, sediment transport. They also have contributed to the study of many bodies of water, in addition to Canadian waters. It is simply just not possible to present every study in a five page report. Therefore, this report was restricted to the large national and international programs because that is where most of the canadian research funds were allocated.

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## International Association of Hydrological Sciences

Compiled by H. Gerry Jones

### 1) Directions in Canadian Hydrology 1990-1994: An overview

In the period covered by the present quadrennial report (1990-94) Canadian Hydrologists have faced many challenges. At the beginning of the decade a synopsis on the state of Canadian Hydrological Science (NRC/ACH 1991) defined the effects of a changing World on Canadian Water resources and the difficulties in adapting hydrological research to rapid social and environmental change. The report recognised that a major challenge concerns the necessity to produce "*the kind of information needed for making and defending intelligent decisions, and then making it available*" i.e. in a form that can be used by the public, policy makers and political leaders to promote and legislate the conservation and protection of both the resource and the Canadian environment.

To this end, Canadian Hydrologists addressed themselves to major environmental issues concerning Canada such as Global warming and climate change, surface-atmosphere exchange and the redistribution of airborne toxic compounds in terrestrial and aquatic ecosystems, land-use changes, and habitat destruction. Workers in both fundamental and applied hydrological research responded to the problems posed by these changes by the study of small and large-scale hydrological processes often within the framework of more wide-ranging interdisciplinary programs. The latter search for the relationships between hydrological pathways and biogeochemical cycling that permit the development of distributed models for ecosystem dynamics and change.

Participation of Canadian hydrologists in four working groups of the International Hydrological Programme (IHP-IV; 1990-1995; Projects H-3-2, H-5-3, M-4-3 and E-1-1) and major international programs such as the Global Energy and Water Cycle Experiment (GEWEX; McBean, 1992) and Boreal Ecosystem-Atmosphere Study (BOREAS; Hall et al, 1993) reflect the direction taken in recent years. Much of the research is focused on studies in the North (e.g GEWEX, the Mackenzie Basin; BOREAS, northern Saskatchewan and northern Manitoba). Research into the role of snow and ice in Arctic and subarctic hydrology is thus become one of the major concerns of Canadian workers (Prowse and Ommanney, 1990; Gray and Prowse, 1993). In the case of GEWEX, for example, a particular effort to model the water and energy balances of the Canadian Arctic basin at spatial scales of 100 $km^2$ and temporal scales of one month is being made.

The necessity of linking hydrological processes and northern ecosystem dynamics has resulted in innovated approaches to the study of northern hydrology. Much of this work is reported on an ongoing basis in the Northern Research Basin (NRB) workshops and symposia where Canadians have shown leadership and strong participation. The NRB, formed in 1975 by the IHP national committees of Canada, Denmark, Finland, Norway, Sweden, U.S.A., and the former Soviet Union, held a very successful meeting in the Yukon and the Northwest Territories in 1992 (NRB, 1992) and another at Svalbard in 1994 (in press). Examples of new directions in Canadian hydrology from the 1992 NRB meeting are the application of fractal geometry to snowmelt, the role of wind-blown snow in the nutrient cycling of cold ecosystems, and the ecological repercussions of river ice (NRB, 1992).
In spite of the increasing emphasis on the Canadian North, a significant part of hydrological research is still to be found in the southern half of the country. Much of the work concerns the impact of high levels of pollution on biological productivity and species

diversity. Studies are interdisciplinary and consist of integrated projects on hydrological pathways, geochemical mechanisms and population dynamics of well-defined catchment areas (e.g. acid deposition and aquatic ecology; FPCCRM, 1990).

These research efforts have not, however, been without difficulty as the organization of scientific hydrology in Canada went through important changes during the 1990-94 period. The demise of the Associated Committee for Hydrology (ACH), which handled the international obligations of the Canadian scientific community towards IAHS, occurred in 1991. This lead to a regroupment of hydrologists which became the basis of the Hydrology Section of the Canadian Geophysical Union (CGU-HS), formed at the CGU General Meeting at Banff, Alberta, in 1993, and the Canadian Society of Hydrological Sciences (CSHS) of the Canadian Water Resources Association (CWRA) formed in 1992.

In addition to the CGU-HS annual meetings, CSHS and NRB symposia, other conferences and workshops held by CWRA, the Hydrological Special Interest Group of the Canadian Meteorological and Oceanographic Society (CMOS), the Canadian Global Change Program (CGCP), the Canadian Chapter of the International Association of Hydrogeologists (IAH) and the Government of Canada (e.g. Environment Canada) all provide a forum for the dissemination of information of knowledge in many fields of hydrological research and water management.

New directions in hydrological research in 1990-1994 include hydrological models of the Mackenzie River, streamflow measurements in ice-covered rivers, the estimation of evapotranspiration using surface temperature data from NOAA AVHRR observations, the presence of complex subglacial drainage containing high and low-pressure systems not previously described, and new knowledge on the role of active layer depth, water table elevation, and soil moisture on the routing of runoff in tundra soils (CGU, 1993; CGU, 1994).

Finally, in 1994, the CGU-HS Bureau formed the interim Canadian National Committee for IAHS (CNC/IAHS) made up of members from CGU-HS, CSHS (CWRA), IAH, and CMOS. The secretariat is located at the National Hydrology Research Institute (NHRI) in Saskatoon. The interim committee is in the process of defining the terms of reference, regulations and procedures for the future CNC/IAHS so that it may better represent all of Canadian scientific hydrology particularly at the international level.

## 2) Reports of the Canadian representatives for IAHS commissions and committees

The International Commission on Continental Erosion

Work on terrestrial erosion and sedimentation may be classified into four major themes. Traditional preoccupations with natural surface erosion, and with erosion induced by forestry and agricultural activities, are being extended to provide a distributed view of the drainage basin by linking functional models of erosion to GIS-based models of land surface attributes (e.g., Martz and deJong, 1991). At the same time, it is now firmly recognised that in most of the relatively undisturbed Canadian landscape, the bulk of fluvially mobilised sediment derives, not from the land surface, but from the streambanks of the rivers themselves (see review by Ashmore, 1993). Accordingly, the sediment balance of river reaches is receiving major attention (Goff and Ashmore, 1994; Martin and Church, 1995). The approach, based on surveys and sediment continuity, promises results for the bed sediments of rivers that are far more economical to obtain than traditional hydraulic measurements. The extension of this technique to study major alluvial deposits (and thereby to connect sediment transfers firmly with geomorphology) has received a

major technical acceleration from the deployment of ground penetrating radar to view the three-dimensional structure of surficial materials (e.g., Moorman et al., 1991). Hickin (1993) has contributed a recent critical review of sedimentary studies. Studies of fluvial sediment transport mechanics have focused upon turbulent sediment entrainment and movement, and upon the statistics of sediment grain displacements (see review in Robert, 1993). At the same time, there has been a significant increase in interest in aeolian sediment movement in the northern, continental environment (mcKenna Neuman, 1993).

For about two decades, the Water Survey of Canada maintained a program of routine measurements of suspended sediment transport in a number of Canadian rivers. Fiscal constraint has forced a major reduction in this program, but a series of useful station summaries is being published which define magnitude and frequency of sediment transport. The initiative for routine measurements of sediment transfer appears now to be passing to land use agencies - primarily provincial - interested in forestry and agricultural effects.

The International Commission on Snow and Ice

The past four years has seen the production of comprehensive state-of-the-science reviews and future-research needs in the fields of floating ice, snow, ground waters, permafrost, and glacier hydrology in Canada (Gerard, Marsh, van Everdingen, Woo, and Young; respective contributions in Prowse and Ommanney, 1990). Most of the new advances in snow hydrology have been in the study of melt processes. Marsh (1991) summarized the physics and thermodynamics of water flux within melting snow covers. On a larger scale, Shook et al (1993) studied the melting of snow covers through the use of fractal geometry, while fractal analysis was also applied by Pomeroy and Schmidt (1993) to the evolution of intercepted snow. In the field of hydrogeochemistry, new relationships between the nutrient content of snow meltwaters and the microbiological productivity of snow algae were examined by Jones (1991). Pomeroy et al (1991) also studied the redistribution of nutrients by landscape form and the effects of wind on the chemical composition of snow crystals. New formulations for the subsequent flux of meltwater into the permafrost active layer were also developed using simplified thermal and hydrological parameters (Xia and Woo, 1993).

Significant new steps in glacier hydrology were made during 1990-1994. Gratton et al. (1994) modelled the energy terms controlling surface melt by devising methods to map terrain irradiance in glacier basins from satellites. Other studies included the calculation of hydraulic properties of the internal flow system from measurements of basal water pressure (e.g., Stone and Clarke, 1993), and methods to obtain reliable time-series measurements of glacial runoff (Kite, 1994).
In the field of floating ice, further refinements have been made in numerical modelling of river ice jams (e.g., Beltaos, 1993) but this field has also broadened into river ecology through such review papers as Scrimgeour et al. (1994) and by the publication of a state of the science review on environmental aspects (biology, hydrology, chemistry, etc.) of river ice (Prowse and Gridley, 1994).

The International Commission on Water Quality

During the last four years, major water quality research and monitoring programs have taken place throughout Canada. The largest of these all involve an ecosystem approach to water quality issues. The most complex has been in the Great Lakes where the programme has dealt with remedial action plans for the most polluted nearshore sites, with plans for management of the open lakes, with the problem of contaminated sediments, and with the role of the atmosphere and groundwater on water quality (Government of. Canada, 1991).

The main issues have been related to toxic chemicals but most recently with the impact on water quality of exotic species such as the zebra mussel. Similar programmes have taken place in the St.Lawrence River and in western Canada in the Athabasca and Fraser River basins. In the case of the last two, the focus has been on the impact of pulp and paper mills (Carey and Hall, 1992). In Eastern Canada, similar approaches have been taken to the most polluted coastal harbours and bays. In the Arctic and sub-Arctic, the last four years have seen extensive research and monitoring on the fate of atmospherical deposited toxic chemicals in freshwater ecosystems (Government of Canada, 1992),. It has been shown that flocculation is an important factor in sediment and contaminant transport (Droppo and Ongley, 1994). Research on numerous rivers in Ontario as well as the St. Lawrence, Fraser and Mackenzie Rivers has demonstrated that, irrespective of river size and location, fine-grained suspended sediment moves preferentially as flocculated particles.

These programs involved government and university scientists as well as contractors and consultants. Canada continues to conduct major water quality groundwater program from federal institutes and universities but emphasis has shifted to the development of in situ remedial techniques for polluted groundwater. In terms of acid rain, there is a renewed interest in the role of nitrogen. Other stressors on water quality and aquatic ecosystem health that are seeing a new and renewed interest include the impacts of ultraviolet light, climate change and long-range atmospheric transport and deposition of metals, particularly mercury.

The International Committee on Remote Sensing and Data Transmission

Remote sensing projects in Canada relevant to hydrology primarily involve passive and active microwave sensors. The Climate Research Branch of AES has developed, and now uses operationally, SSM/I based algorithms to map snowcover state over the open prairie of western Canada (Goodison, 1989). Work is in progress to adapt the procedure for boreal forest and tundra environments. Active sensor research has been strongly influenced by the impending launch of RADARSAT, scheduled for late summer 1995. The Canada Centre for Remote Sensing along with investigators at NHRI and the Universities of Waterloo, Sherbrooke and Quebec have explored the mapping of snow properties and soil moisture using airborne and ERS-1 radar images. Mapping of snowcovered area during melt appears practical (Donald et al. 1993). Also glacier extent and snow-line mapping using a multi-sensor approach. Soil moisture mapping appears to be feasible to some extent using C-band for bare ground and possibly for pasture fields (Pietroniro et al. 1993; Brown et al, 1993). Models under development to use the new data sets include CANTEL, HYDROTEL, SLURP and WATFLOOD (Kouwen et al. 1993). All are distributed or semi-distributed and use landcover data derived from LANDSAT-TM or SPOT imagery to address within-basin heterogeneity.

The International Committee on Tracers

The International Committee on Tracers (ITC) has compiled a data base of tracer scientists and the use of tracers in hydrology, which was distributed and analyzed at NHRI, Saskatoon. The data base includes approximately 300 scientists world-wide and is being used by the President of ICT to disseminate information on tracer methods and to plan for future needs of the tracer community.

Tracers are widely used in hydrological investigations in Canada, ranging from the use of naturally occurring isotopes in precipitation, surface and ground waters, and ice cores to the use of artificial dye and salt tracers. Recent examples of studies include: the dating of ground water using $^{3}H/^{3}He$ (Solomon et al. 1991), runoff generation and water balance

using $^{18}O$ and $^{2}H$ (Gibson et al. 1993 a,b) paleohydrology of ground waters using $^{18}O$ (Remenda et al. 1994), and stream discharge measurements by automatic conductivty analyses (Kite, 1994).

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The quadrennial reports of The International Committee on Atmosphere-Soil-Vegetation Relations (ICASVR), The International Commission on Water Resource Systems (ICWRS), The International Commission on Surface Water (ICSW), and The International Commission on Groundwater (ICGW) were not available at the time of publication.

## International Association of Volcanology and Chemistry of the Earth's Interior

Compiled by P. Metcalfe

### Summary

Volcanological research in Canada has continued in its popularity over the course of the last year. The report presents an overview of current activities in Canada.

### Introduction

Volcanology in Canada has undergone a rapid increase over the course of the last twenty years, to the extent that nearly every large earth science department includes volcanology, in some form, in its curriculum. The discovery, in the Canadian Cordillera, of volcanoes active during the Holocene closed the circum-Pacific "Ring of Fire" and opened up a new field of research in an area where much work remains to be done. During the past two years, the interest in all aspects of igneous processes has acquired new momentum as a result of the presence of diamond-bearing pipes in the Canadian Shield, an occurrence long suspected, but which has only recently been widely publicized.

On May 22nd, 1974, the Volcanology Subcommittee of the Associate Committee on Geodesy and Geophysics (Canada's liaison with the International Union of Geodesy and Geophysics or IUGG) was replaced by the newly formed Volcanology Division of the Geological Association of Canada. This division was renamed the Volcanology and Igneous Petrology Division in 1993, to reflect its broad disciplinary base. The division publishes a newsletter thrice annually and sponsors field trips short courses, symposia and workshops, both independently and under the auspices of its parent body. Membership in the division is presently greater than 100.

The executive of the Volcanology and Igneous Petrology Division is as follows:

Chairman: Catherine J. Hickson
Geological Survey of Canada, Vancouver, British Columbia

Vice-Chairman: Tom Pearce
Queen's University, Kingston, Ontario

Secretary-Treasurer: Paul Metcalfe
Geological Survey of Canada, Vancouver, British Columbia

Councillor on Research: Kelly Russell
University of British Columbia, Vancouver, British Columbia

Past Chairman: Les Coleman
University of Saskatchewan, Saskatoon

Councillor, East: John Stix
Universite de Montreal, Montreal, Quebec

Councillor, Central: Tony Fowler
University of Ottawa, Ottawa, Ontario

Councillor, West: Stephen Juras
Westmin, Campbell River, British Columbia

Councillor, Student: Shirley Peloquin
Universite de Montreal, Montreal, Quebec

## Current Activities

Activities in Canada of a volcanological nature are numerous and diverse. No report of this nature can do justice to them all. Accordingly thay have been grouped on a somewhat arbitrary basis partly by geological age and province and partly by specialty.

### The Modern Regime

Under this heading are included activities that can be related directly to the present era of plate tectonic movements. Not surprisingly, these studies in Canada are centred on the east and west coasts. On the west coast, the presence of volcanoes which have been active during the Holocene has focused studies, carried out by the Geological Survey of Canada, on volcanic hazards. In addition, petrological studies have been carried out on basaltic subaerial and ice-contact volcanic rocks in northern, northwestern and east central British Columbia and in the Yukon Territory, by the Geological Survey of Canada, McGill University, Carleton University and the University of British Columbia. Studies are being carried out at the Universite de Montreal on the seismic properties of mantle xenoliths. Mapping and petrological of Eocene volcanic rocks in the Intermontane Belt is being carried out by the Geological Survey of Canada and by the Geological Survey Branch of British Columbia. These rocks host epithermal gold-bearing mineralization. In northwestern B.C., the Mineral Deposit Research Unit at the University of British Columbia is concluding a study of the Hazelton Group volcanic rocks which are related to much of the gold-bearing mineralization in the "Golden Triangle".

On the east coast, studies are focused on older volcanic products. The Atlantic Geoscience Centre (Geological Survey of Canada) is conducting studies modelling the processes of rifting and comparing these with the distribution of Cretaceous volcanic rocks. Complementary studies are taking place on occurrences of Cretaceous volcanic products in the Arctic Islands (Geological Survey of Canada, St. Mary's University and the Universities of Dalhousie and Calgary).

### The Early Geosynclines

Volcanic rocks of Palaeozoic and Proterozoic geosynclines which have many of the attributes of plate-generated volcanism of more recent times are more difficult to interpret in terms of the modern concepts because of their remoteness from known plate movements. The Appalachian Geosyncline has been attributed to a former opening and closing of the Atlantic Ocean. Research is continuing on boninite and peridotite magmatism in the Bay of Islands ophiolite complex (Geological Survey of Canada, Laval and Memorial

Universities). Several studies of the Palaeozoic magmatism in Appalachia are proceeding at Memorial University of Newfoundland, University of Western Ontario, Universite de Quebec a Montreal, University of Ottawa, Geological Survey of Canada and the Nova Scotia Department of Mines and Energy. The Avalon Zone is a subject of research at Acadia University and the University of Dalhousie. The Proterozoic magmatism of the Nain Complex has produced publications from the Newfoundland Department of Mines and Energy, the Geological Survey of Canada, Windsor University and the Geological Survey of Newfoundland and Labrador.

Volcanism in some of the major Proterozoic geosynclines; Circum-Ungava, Coronation and Grenville has been and continues to be of prime interest. Former work by the Geological Survey of Canada and the Quebec Department of Natural Resources in the Circum-Ungava Geosyncline indicated that the volcanic rocks were mainly oceanic in character and that calc-alkaline rocks, the hallmark of subduction zones, were essentially lacking. The Geological Survey of Canada and McGill University are presently active in this research field. The Grenville Province is under study by researchers from the Ontario Geological Survey, University of Dalhousie, University of Toronto and Universite de Montreal.

## Archean Greenstone Belts

Archaean greenstone belts are characteristically composed of thick sequences of predominantly subaqueous mafic to felsic volcanic cycles, with variable thicknesses of interbedded and overlying clastic sedimentary rocks. They are chemically analogous to modern island arcs but thair tectonic setting and structural style are unique. Fragmentary evidence suggests that they may have been deposited in part on a continental crust. Some workers believe that they were formed by a primitive type of plate tectonics.

Geochemical and stratigraphic studies have been carried out on many of these belts and are ongoing at the University of Manitoba, the University of Toronto, the Ontario Geological Survey and the Quebec Department of Natural Resources. The Abitibi Greenstone Belt has received the most attention in the past year, producing publications from the Universite de Quebec a Montreal, Universite de Quebec a Chicoutimi, University of Toronto, University of Western Ontario, McMaster University and Queen's University. The University of Saskatchewan, Saskatchewan Geological Survey, Royal Ontario Museum and St. Mary's University have all been active in such studies.

## Volcanism of the Stable Crustal Platforms

Plateau basalts are the principal representatives of this type of volcanism. In Canada, the major provinces are the Coppermine River, the Keweenawan, the Seal Lake and the Natkusiak, all of Proterozoic age and basalts of Miocene age in central British Columbia. Although known to be related to tensional faults, the place of these basalts in the global tectonic system is still obscure. All have received past study and the Miocene lavas of British Columbia are currently under study by the Geological Survey of Canada.

## Coordinated Studies of the Continental Lithosphere; the Lithoprobe SNORCLE Transects

A group of Canadian petrologists has initiated a number of individual projects under the Lithoprobe Supporting Geosciences Program to provide petrological constraints for the SNORCLE geophysical transects. The 3 proposed SNORCLE Transects will provide new insight to the structure of both ancient and modern orogenic belts. The detailed petrological studies focus on xenoliths brought to the earth's surface in Tertiary and Quaternary volcanoes (B.C., Yukon) and Cretaceous kimberlites (N.W.T.) for "petrological imaging" of the composition and structure of the subcontinental lithosphere along the transects. In the Northern Cordillera, the volcanic rocks both parallel and cross-cut the proposed transects and also cross-cut several terrane and major structural boundaries.

The group has met twice in the past 14 months (1994 Spring Lithoprobe Transect workshop in Edmonton; 1995 Annual GAC-MAC meeting in Victoria) to discuss specific research interests and coordinate the sharing of existing and future xenolith collections. Organizations involved in this research are the University of Victoria (Crustal and mantle xenoliths brought up in kimberlites within the Slave Province), Universite de Quebec a Montreal (Geochemistry and radiogenic isotopes of xenoliths), Carleton University (U-Pb dating of crustal xenoliths from the Slave Province and the Cordillera); St. Mary's University (Geochemistry of lower crustal and mantle xenoliths); University of British Columbia (Reactions between crustal xenoliths and lavas in the Cordillera); McGill University (Geochemistry of mantle xenoliths and lavas in the Cordillera); Pacific Geoscience Centre (Physical properties of crustal and mantle xenoliths in the Cordillera; University of Calgary (Thermobarometry of mantle xenoliths and lithospheric magma storage in the Cordillera); Universite de Montreal (Physical properties of mantle xenoliths from Cordillera and Slave Province).

## Economic Geology

Concepts relating ore deposits and volcanism have developed rapidly in recent years and have expanded to include a great diversity of ore deposits. The study of volcanic stratigraphy has become a vital adjunct at all levels of mineral exploration. The volcanic belts of principal current interest in Canada are the Mesozoic volcanic and subvolcanic assemblages of the Cordillera, the Palaeozoic volcanic rocks of the Appalachians and the Archaean greenstone belts. In the Cordillera, much of the work is related to subvolcanic phases, such as porphyry copper and epithermal deposits, but massive sulphide deposits are also a focus of study at the University of British Columbia. In the Appalachians and the Archaean studies are primarily directed at stratigraphic ores, and interest is also focused on the Sudbury ore-forming environment (Geological Survey of Canada and Ontario Geological Survey). Ongoing palaeomagnetic and geochronology studies at a number of laboratories in Canada are contributing indirectly to volcanology by helping to formulate a tectonic framework for past volcanic events. Experimental petrology studies are being conducted at the Universities of New Brunswick and Alberta. Most importantly, new methods of manipulation of igneous geochemical data have been modified to allow for alteration processes; studies in this field are ongoing at several institutes, including the Mineral Deposit Research Unit at the University of British Columbia.

## International Association of Seismology and Physics of the Earth's Interior

Compiled by Peter W. Basham

### LITHOPROBE

LITHOPROBE is Canada's national, collaborative earth science research project, established to develop a comprehensive understanding of how the North American continent has evolved. Ten transects, or study areas, have been chosen to investigate pivotal geological features to their deep lithospheric roots. They span the country from the Pacific to the Atlantic Oceans and from the U.S. border to the Yukon and Northwest Territories, and geological time from four billion years ago to the present. A multidisciplinary geoscientific approach has been found to be essential in developing complete interpretations and outstanding scientific results. From the geophysical perspective, the project is spearheaded by seismic reflection experiments and includes complementary seismic refraction/wide-angle reflection, magnetotelluric (and some other electromagnetic procedures), gravity, magnetic, heat flow, paleomagnetic, physical property and geodynamical modeling studies.

For LITHOPROBE in the last quadrennium, the most important development was the response of our principal funding agency, the Natural Sciences and Engineering Research Council of Canada (NSERC), to the submission and evaluation in 1993 of LITHOPROBE Phase IV Proposal -- Studies of the Evolution of a Continent, our proposal for the continuation of the project. The LITHOPROBE community of scientists was very gratified with the acceptance of both the 5-year program and the proposal for a further 5 years of support during which the project would be brought to its planned conclusion. This acceptance was strongly supported by the second primary funding agency for the project, the Geological Survey of Canada.

During the period 1991-94, a number of seismic reflection surveys were carried out across the continent. Studies in the Trans-Hudson Orogen and Alberta Basement transects are examining the history and processes of Precambrian continental assembly of western North America. In the Trans-Hudson Orogen transect, about 2000 km of high quality data have been obtained across and along the orogen in Manitoba and Saskatchewan. With the participation of many oil and gas companies, about 1140 km of new reflection data were acquired on the western Canada sedimentary basin of Alberta, producing excellent images of both the sediments and underlying Precambrian crust. As part of our Eastern Canadian Shield Onshore-Offshore Transect in Labrador and Quebec where a series of Proterozoic orogenic belts stitch together three Archean cratons, 1250 km of marine seismic reflection data were recorded across Ungava Bay, around northern Labrador and off the southeast coast of Labrador. To augment data acquired in an earlier stage of studies in the Abitibi-Grenville transect, investigating the Archean Abitibi greenstone belt and Mesoproterozoic Grenville orogen, 900 km of reflection profiles were acquired across the northern Abitibi and Opatica belts and along two crossings of the Grenville. A significant LITHOPROBE contribution has been the demonstration of the applicability of the seismic reflection technique to exploration problems in the mining industry.

A combined onshore-offshore seismic refraction/wide-angle reflection (R/WAR) survey was carried out in our Lithoprobe East transect, examining the Paleozoic orogenic belt of the Appalachians on and around Newfoundland. Other extensive R/WAR surveys were carried out in the region of the Abitibi-Grenville transect in Ontario and Quebec, and the Trans-Hudson Orogen transect in Saskatchewan and Manitoba where we recorded strong first arrivals to 730 km offset. Our unique +Deep Probe+ experiment, an expanding R/WAR survey with north-south offset distances to greater than 2000 km to enable arrivals from as deep as the 410 km discontinuity and centred below the Archean Hearne craton of southeastern Alberta, is planned for 1995. During the quadrennium, large magnetotelluric surveys, to determine the conductivity structure of the crust and upper mantle and its relation to physical properties determined by other studies, have been carried out in the following transects: Lithoprobe East, Abitibi-Grenville, Trans-Hudson Orogen and Alberta Basement. In regions of exposed crystalline rock near mining interests, higher frequency controlled source electromagnetic experiments also were carried out. Use of gravity and aeromagnetic maps, paleomagnetic studies, heat flow studies, physical properties measurements and geodynamic have all been active during the last four years.

During the past four years, more than 400 contributions from all disciplines have been added to the LITHOPROBE Publication List, which is available from the LITHOPROBE Secretariat (Geological Sciences Centre, 6339 Stores Road, University of British Columbia, Vancouver, B.C. V6T 1Z4; clowes@lithoprobe.ubc.ca) and on the World Wide Web network (http://www.geop.ubc.ca/./Lithoprobe/lithopb.html). These have been separated into contributions relating to individual transects, geophysical data processing and general crustal studies, but not according to discipline. A few general articles relating to the project and a special seismological publication for which LITHOPROBE was a principal sponsor are in the bibliography below.

## UNIVERSITY OF BRITISH COLUMBIA

R.M. Clowes and R.M. Ellis with their crustal studies research group have continued the analysis of several seismic R/WAR data sets: the crustal structure and its tectonic implications of the Hecate sub-basin of the Queen Charlotte sedimentary basin; structure within a triangular array within the southern Canadian Cordillera; a profile within the Coast Belt of southern British Columbia and two crossing profiles from the northern Yukon-Mackenzie Delta region of northwestern Canada; the west coast of Vancouver Island to determine velocity structure below the continental shelf; a profile in the Trans-Hudson Orogen of western Canada; data recorded in northwestern British Columbia from the airgun source; and a reflection survey in southeastern Alaska as part of the U.S.-funded ACCRETE project.

R.M. Ellis and his students have continued their studies of the lithosphere using teleseismic sources: a receiver function study across the Juan de Fuca-North America plate margin with a primary result being the imaging of the dipping subducting plate to near 65 km as well as shallower structures; a similar data set across the Explorer-North America plate for a comparative analysis of the two interaction zones; the combined use of

receiver function and tomographic techniques to image the lithosphere in the Trans-Hudson Orogen, a region of very complex structure.

R.M. Clowes with his students and postdoctoral fellows have continued a number of research projects using multichannel seismic reflection and other data: the northern Cascadia subduction zone through an integrated geophysical modeling study involving gravity and magnetic data constrained by geology, seismic refraction and reflection interpretations and physical properties data; analysis and interpretation of 230 km of marine reflection data recorded across the northern Juan de Fuca plate; reprocessing and reinterpretation of LITHOPROBE reflection data from the southern Canadian Cordillera in British Columbia and the Trans-Hudson Orogen in Saskatchewan; reprocessing and interpretation of a reflection profile across the Fraser fault, a crustal-scale strike-slip fault system; analysis of data recorded near the Mt. Cayley volcanic centre, part of the Garibaldi-Cascades volcanic belt, and reanalysis of crustal and upper mantle reflections from below the southwestern Coast belt northwest of Vancouver; the central and eastern Coast belt north of Vancouver in a region of mining interest; and reflection data along a line crossing the Paleoproterozoic western Trans-Hudson Orogen and extending into the Archean Hearne craton.

M.G. Bostock has commenced a series of projects with the aim of acquiring a better understanding of the upper mantle beneath Canada at a range of scales. With J.C. VanDecar (Carnegie Institute of Washington) he has inverted P-wave teleseismic traveltime residuals to delineate mantle structure of the Cascadia subduction zone. With J.F. Cassidy (Geological Survey of Canada) he has investigated upper mantle anisotropy using the broadband stations of the Canadian National Seismic Network, and variations in depth to the upper mantle discontinuities and overlying velocity structure over Canada.
A study to monitor detailed variations in mantle structure across the northern Cordillera through to the Slave province as part of the Lithoprobe SNORCLE transect is currently underway.

B. A. Buffett continues to work on a number of problems related to the structure and dynamics of Earth's interior. With J.R. Lister (University of Cambridge), he has investigated the relative importance of thermal and compositional convection in the dynamo problem. Studies with P.M. Mathews (Harvard-Smithsonian Center for Astrophysics) continue on the tidal deformation of a rotating, spheriodal Earth. A new investigation with J. Douglass addresses the interseismic deformation above a subduction zone. Other studies currently in progress include the magnetic damping of inner-core oscillations, the effects of a heterogeneous lower mantle on the flow and magnetic field at the top of the core, and the formation of gas hydrates in porous media.

R.D. Russell, K.E. Butler and A.W. Kepic have been continuing their research on methods of seismoelectric exploration. There are at least four phenomena of interest: modulation by seismic stress of the resistivity of a volume of earth through which telluric currents flow, seismically induced electrokinetic effects, piezoelectric effect of quartz veins, and generation of radio-frequency impulsive responses in sulphide-rich rocks. Regardless of the conversion mechanism, the methods use a seismic source, and electric or magnetic receivers. Data from different shotpoints can be used to locate or

delineate the target. They have made detailed studies of the electrokinetic effect on an unimproved dirt road within the Malcolm Knapp Reserach Forest at Haney, near Vancouver, Canada. The road fill consists of a permeable, organic-rich soil which overlies a highly impermeable, silty glacial till. Using a sledgehammer source and grounded dipole receivers, they have observed that electric currents are generated when the seismic wave impinges upon the boundary at the base of the till. Four boreholes confirmed the interpretation. Among several studies of sulphides in underground mines, the most productive have been those at the Lynx Mine on Vancouver Island. By placing shotpoints around a target, it has been shown that a credible psuedo-tomographic representation of the orebody can be constructed. The latest experiment, made with a data acquisition capable of observing electromagnetic signal components to approximately 5 MHz, showed that the arrivals are rich in frequencies up to 2.5 MHz, and contain a characteristic band centered around 1.3 MHz.

## QUEEN'S UNIVERSITY

C.J. Thomson and students have focussed their current activities in three areas: (i) surface waves in anisotropic media using a new anisotropic reflection-matrix program to investigate the excitation and propagation of surface waves in laterally-homogeneous and slowly laterally-varying media. As with body waves, new effects such as phasefront folding and mode coupling arise from the anisotropy. (ii) The same reflection-matrix technique is being adapted for the modelling and interpretation of broadband teleseismic body waves. The aim is to understand what constraints can be placed on a multilayered anisotropic near-receiver structure by teleseismic data. (iii) Studies on the folding and coupling of quasi-shear body waves are being extended to 3D anisotropic structure, with emphasis on subduction-zone applications. A 3D anisotropic one-way wave-equation (finite difference) technique is being developed.

## GEOLOGICAL SURVEY OF CANADA

(a) Crustal Seismology

In the Continental Geoscience Division, I. Asudeh has been involved in design, acquistion and interpretation of crustal refraction profiles from Trans Hudson orogen (northern Saskatchewan and Manitoba) and New Brunswick Appalachians. D. Eaton has been Involved in acquisition, processing and interpretation of deep seismic reflection data from central Alberta, the Grenville province in eastern Quebec and the Peace River Arch region of northern Alberta. He is also developing new techniques for true-amplitude processing and new algorithms to model seismic scattering in 3-D heterogeneous media using the Born approximation and finite-difference techniques. These methods are being applied to model the scattering response of ore bodies in structurally complex settings. New techniques are being developed for borehole seismic imaging of near vertical structures, in collaboration with industry.

D.A.Forsyth and colleagues, including COCORP, are working with Ontario Hydro who have supported work to license, acquire, process and interpret

reflection seismic data from Lake Huron. They are continuing interpretation of deep reflection data from lakes Ontario, Erie and Lithoprobe data from the northern Central Metasedimentary Belt; and interpretation of wide-angle crustal data from the northeastern Sverdrup Basin and continental margin. Forsyth is also involved in the acquisition, processing and interpretation of new, higher resolution aeromagnetic data from the Canadian polar margin; and in the acquisition of long range wide-angle seismic data across the Appalachian Orogen of Nova Scotia, New Brunswick and the Quebec Gaspe from a source provided by a shock test in the navy's new Canadian Frigate program.

B. Milkereit and colleagues are involved in acquisition, processing and interpretation of high resolution 2-D seismic data, borehole geophysical surveys and physical property studies at base metal mining camps in northern Ontario and Quebec. He is designing the first-ever 3-D seismic surveys for mineral exploration in Canada, in close cooperation with industry.

B. Roberts is reprocessing seismic reflection data from the Huronian segment of the Southern Province, and continuing to process and interpret data from Newfoundland (Lithoprobe East). D. White is involved in acquisition, processing and interpretation of deep seismic reflection data and crustal refraction profiles from the Paleoproterozoic Trans Hudson orogen of northern Saskatchewan and Manitoba, including high resolution profiling in the Thompson nickel belt. He is developing new algorithms to position dipping reflectors correctly in three dimensions for crooked-line 2-D profiles. J. Wu is involved in processing and interpretation of 2-D high-resolution seismic reflection profiles and borehole geophysical measurements from the Sudbury Impact Structure and the Thompson nickel belt; and developing new techniques for processing seismic reflection data acquired in a hard rock environment.

At the Atlantic Geoscience Centre, C.E. Keen, H.R. Jackson, I.D. Reid, S.P. Srivastava, F. Marillier and colleagues has been active in geodynamic studies of rifted continental margin and rift basin formation and evolution. These studies encompass the following: (i) finite element-based dynamical models of extension of the lithosphere; (ii) studies, based on observations of crustal thinning and subsidence, of the kinematics of continental margin extension off eastern Canada and the conjugate European margins; and (iii) predictions of the volume and compostion of magmas generated through decompression melting; and (iv) numerical modelling of the rift-generated small scale convection in the asthenosphere below rifts.

Extensive wide-angle seismic studies were carried out around Newfoundland (Part of LITHOPROBE EAST), in northern Baffin Bay, and in the Canada Basin, Arctic Ocean. A deep seismic reflection survey was undertaken (in collaboration with IFREMER, France) in the Flemish Cap region. Analysis and interpretation (with Dalhousie University) of the combined reflection/refraction transect of the Labrador Sea and its conjugate margins was completed; as was interpretion of continental margin structures across the Grand Banks from wide angle seismic data and across the Nova Scotian margin from vertical incidence data. These margin studies have allowed delineation of the structure of non volcanic margins, including the presence of very thin crust against the margin and the probable presence of serpentinised mantle. Off Nova Scotia the transition from volcanic to non-volcanic margin has illuminated the role of volcanism. The Baffin Bay work supports the conclusion that significant motion has taken place between Greenland and North America.

The crust under the central Newfoundland Appalachians is substantially thinner than under its margins, and it is underlain by a layered upper mantle.

(b) Earthquake Seismology

The upgrade of the Canadian National Seismograph Network (CNSN) is well underway. As of 1 May 1995 the CNSN consisted of 22 broadband or very broadband and 16 short-period stations. During the next year, 3 additional broadband stations will be added and the remaining short-period stations comprising the dense networks in eastern and western Canada will be converted to CNSN format. Network data can be easily accessed by the external seismological community through an internet-email based retrieval system.

A.L. Bent has been systematically re-examining and applying modern waveform analysis techniques to early instrumental (pre-WWSSN) earthquakes in eastern Canada in an effort to better understand their source characteristics.
In a recent study of the 1929 Grand Banks earthquake (Ms 7.2), she showed that the source mechanism was not a single force (landslide) as had been suggested, but a double couple (earthquake) consisting of several strike-slip subevents.

R.A.W. Haddon has focused his attention on modeling strong motion records and the use of empirical Green's functions as tools for gaining insight into the details of the earthquake rupture process. He found that the unusually high levels of high-frequency ground motion for the 25 November 1988 Saguenay earthquake (mb 6.0) were a result of source directivity rather than high stress drop.

The Ms 6.3 earthquake that occurred in the Ungava Peninsula on 25 December 1989 was unique in that it produced the first known surface rupture from an eastern North American earthquake. Field observations under the direction of J. Adams and a waveform analysis study by Bent both found evidence for a complex rupture consisting of both thrust and strike-slip faulting.

In western Canada, the Cascadia subduction zone has been of particular interest because of its potential for a catastrophic earthquake. J.F. Cassidy and R.M. Ellis (UBC) have employed receiver function analysis to determine the shear wave velocity structure of various segments of the zone. H. Dragert, R.D. Hyndman, K. Wang and colleagues have synthesized heat flow and geodetic data to map the location of the locked portion of the subduction zone. J.J. Clague and colleagues have found evidence from buried marsh surfaces and sand layers for previous Cascadia subduction earthquakes on the west coast of Vancouver Island.

Cassidy has also been studying the source characteristics of large west coast earthquakes, of which the 6 April 1992 (Ms 6.8) offshore earthquake is an example. Employing a variety of modeling techniques he has been able to work out a detailed picture of the slip distribution of this earthquake.

J. Adams, D.H. Weichert and colleagues have produced the fourth generation of seismic hazard maps of Canada. New techniques have been

employed to develop ground motion estimates that can be used to produce uniform hazard spaectra. These hazard maps and associated changes to the seismic provisions of the National Building Code will be issued for trial use by the engineering community in 1995. Revisions as necessary will be carried out in about 1997 to produce new seismic zoning maps for the year 2000 building code.

R.G. North, P.W. Basham and colleagues have continued to make the Canadian seismological contributions to the Comprehensive Test Ban monitoring system. Basham and North represent Canada in the Geneva discussions; North and colleagues have developed a substantial Canadian contribution to the experimental international seismic monitoring system, GSETT-3.

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