Geophysics Program at the Department of Physics, University of Alberta

M.D. SACCHI
Chair, Department of Physics, University of Alberta

Research and training of graduate students in the area of geophysics at the University of Alberta is carried out at the Department of Physics. At present, the geophysics group is composed of 12 faculty members, 48 graduate students and 14 postdoctoral fellows. Three members of the Geophysics group also hold cross-appointments with the Department of Earth and Atmospheric Sciences. Geophysical research spans the following two wide-ranging areas: i) Applied Geophysics and, ii) Global Geophysics and Planetary Dynamics. A number of professors in the group have diverse research programs that span the two aforementioned areas. A great dose of cross-fertilization exists between applied and global geophysicists in areas such as geomechanics, induced seismicity and global seismology.

Applied Geophysics (Potter, Sacchi, Schmitt, Van der Baan, Unsworth)

This group primarily works on resource exploration and exploitation and has recently steadily advanced in areas pertaining geothermal energy research (Helmholtz-Alberta Initiative). Applied geophysics has attracted funding from oil companies and geophysical services companies and has spearheaded industrial consortia for resource geophysics such as SAIG (Signal Analysis and Imaging Group), EGG (Experimental Geophysics Group) and MUSIC (Microseismic research consortium). Additional funding comes in the form of grants from Carbon Monitoring Canada, HAI (Helmholtz-Alberta Initiative), and contracts with the Alberta Geological Survey. An important aspect of the group is its insertion in the provincial needs pertaining to the education and training of geophysicists for the oil and gas industry.

The success of our group was also achieved through many years of academically and professionally recognized high-quality undergraduate and graduate education. For instance, recently our undergrad and postgrad students have been honored with six J. Clarence Karcher awards from the Society of Exploration Geophysicists. The award is provided in recognition of significant contributions by a young geophysicist of outstanding reputation, aged less than 35 years.

The following is a brief description of current research interests of faculty members working in applied geophysics.

Dr. David Potter’s research program is in the area of nano-magnetism. One of his projects uses a combined approach involving CT scanning and sensing magnetic nanoparticles to characterize heavy oil. Another project is focused on developing magnetic nanoparticle tracers for tracking fluid paths in fractures. Dr. Potter is also investigating the use of magnetic nanoparticle contrast agents that are mixed with propellants to determine the extent of hydraulic fractures. Dr. Potter has a joint appointment with the Department of Earth and Atmospheric Sciences. He is also one of founding members of the Integrated Petroleum Geosciences (IPG) professional MSc program at the University of Alberta.

Dr. Mauricio Sacchi’s research program includes the area of statistical and transform methods for seismic data processing, waveform imaging and inversion in applied and global seismology. Dr. Sacchi directs the Signal and Imaging Group (SAIG), a consortium for advanced research in seismic data processing and imaging. The group has become recognized for developing algorithms for multi-dimensional seismic data reconstruction, de-noising and for application of sparsity promoting methods for solving seismic processing problems.

Dr. Doug Schmitt carries out field and laboratory research. Current projects in the laboratory include determination of the effects of temperature and pressure on rocks saturated with CO2 and with bitumen, on the comparison of seismic and ultrasonic measurements in fluid saturated cracked rock, and on the anisotropy of tight unconventional resources. Field studies are concentrated on scientific drilling programs. Dr. Schmitt’s team is currently completing the study of a large drilling program in Idaho, North Sweden, the Alpine Fault in New Zealand and the Koyna region of India. Dr. Schmitt’s research also spans gеomechanical modeling, stress determination and reservoir-induced seismicity.

Dr. Van der Baan’s research interests are in the intersection of signal processing for reflection and microseismic data. He is also interested in the study of geomechanical models and monitoring associated to
microseismicity. Much of Dr. Van der Baan’s research is directed by the Microseismic Industry Consortium (co-hosted with the University of Calgary), which covers all aspects of microseismic data from acquisition, processing to interpretation. Dr. Van der Baan is one of founding members of the Integrated Petroleum Geosciences (IPG) professional MSc program at the University of Alberta.

Global Geophysics and Planetary Dynamics (Currie, Dumberry, Gu, Heimpel, Kravchinsky, Sutherland, Unsworth)

Global and planetary geophysics includes studies of geodynamics and planetary dynamics, global seismology, paleo-magnetism and geomagnetic field study, plate tectonics and continental dynamics climate and environment change. This group has gathered a steady number of publications in high-impact journals such as Nature and Nature Geoscience. It is important to stress that students working in this area also do find jobs in areas associated to oil and gas exploration. Oil companies and processing contractors have hired students with backgrounds in paleomagnetism, tectonophysics and global seismology. This is quite important because it signals that graduate training on problems of academic interest is not a handicap at the time of securing a career in industry. Group members have a diverse range of interest, which I hope to capture in the following lines.

Dr. Claire Currie’s research focuses on lithosphere dynamics and convergent plate margins. Dr. Currie and her students use numerical models and geophysical observations to study the upper 300 km of the Earth. Current projects address continental tectonics, subduction zone processes and mountain-building in Western North and South America. Dr. Currie’s research program is particularly interested in understanding the relationship between mantle/lithosphere dynamics and surface observations, such as deformation, topography, basin development and magmatism.

Dr. Mathieu Dumberry’s research is focused on the dynamics of planetary interiors. This includes convective flows in spherical shell geometries, the generation and evolution of planetary magnetic fields, the rotational dynamics of planetary bodies and fluid-solid interactions at interior boundaries. The work is mainly theoretical, including numerical simulations, although a particular emphasis on trying to explain specific observations with simple models of the dynamics.

Dr. Yu (Jeff) Gu is a global seismologist interested in all aspects of 3D crustal and mantle structural studies. He is also responsible for launching the Canadian Rockies and Alberta Network (CRANE) seismic array in Alberta. Dr. Gu and collaborators at the Alberta Geological Survey have also been conducting studies in the area of induced seismicity. The group recently investigated a cluster of events near the Cordel Field, west central Alberta and its potential relationship to a nearby disposal well.

Dr. Moritz Heimpel’s main research interest is the dynamics of planetary interiors, which involves the theoretical and numerical modelling of deep flow and convection and the generation of global magnetic fields. His group pursues research that addresses current scientific problems in Earth and planetary dynamics. Specific projects have advanced our understanding of the dynamical evolution of several of solar system planets, particularly those of Mercury, Earth, Jupiter, Saturn, Uranus and Neptune, as well as exoplanets.

Dr. Vadim Kravchinsky studies magnetic properties of sedimentary rock and its implications for understanding geological, climatological

Figure 1. Geophysical survey (MT) at Volcan Uturuncu, Bolivia. Photo by Dr Martyn Unsworth.

Figure 2. Cryogenic magnetometer, Laboratory of Paleomagnetism and Petromagnetism, Department of Physics, University of Alberta. Photo by Dr. Vadim Kravchinsky.

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and environmental changes. Dr. Kravchinsky directs the laboratory for paleomagnetism and petromagnetism at the University of Alberta. The laboratory carries out scholarly and industrial research in the following areas: Magnetostratigraphy, Cyclostratigraphy, Paleomagnetic dating of igneous rocks and sediments, Paleomagnetic core re-orientation and core correlation, determining of the paleocurrent flow direction in sediments using anisotropy of magnetic susceptibility, and magneto-environmental studies. The laboratory houses a cryogenic magnetometer funded by the Canadian Foundation for Innovation and the Province of Alberta.

Dr. Bruce Sutherland’s research focuses on the dynamics of the atmosphere and oceans, particularly as they are affected by density variations. This includes the study of waves, plumes and currents. Recent work has begun to explore particles in fluid flow, including the dispersion of ash from volcanic eruptions and the transport and deposition of sediments from river plumes, turbidity currents and shoaling internal solitary waves. Dr. Sutherland has a joint appointment with the Department of Earth and Atmospheric Sciences.

Dr. Martin Unsworth has a wide range of research interests that includes magnetoelluric sensing for deep and environmental studies. His group has carried out MT sensing fieldwork at the Tibetan Plateau, Eastern Anatolia, Canadian Cordillera, Taiwan, Bolivian Puna and Mexico’s Chicxulub Impact Crater. His group has also carried out MT surveys for monitoring nuclear waste in Amchitka Island in the central Aleutian Islands. Dr. Unsworth is also the Canadian Lead, Geothermal theme, for the Helmholtz-Alberta Initiative (HAI). This program carries out structural and 3D geological and geophysical studies of parts of the Alberta Basin to understand the geothermal potential of the region. Dr. Unsworth has a joint appointment with the Department of Earth and Atmospheric Sciences.

Summary
The University of Alberta geophysics group recognizes that the success of our research program stems in large part from adopting a multidisciplinary approach incorporating ideas from physics, chemistry and Earth sciences. The group continuously fosters collaboration with scientists in the Department of Earth and Atmospheric Sciences, among other departments at the University of Alberta, and at other institutions. Through these activities and environment, the group is able to advance knowledge in Earth sciences, contribute to the education of undergraduate and graduate students, train professionals for careers in the future Alberta economy, and provide broad educational opportunities in geophysics to the wider community.

More information:
- Helmholtz-Alberta Initiative, Geothermal Energy theme: http://tinyurl.com/l2x4b8s

Acknowledgements
Thanks to all members of the geophysics research area at the Department of Physics, University of Alberta, for providing input for this article. I would also like to thank Suzette Chan for proof reading and formatting the material.

Mauricio D. Sacchi was born and raised in Buenos Aires, Argentina, where he received his Diploma in Geophysics from The National University of La Plata, Argentina, in 1988. After receiving his Ph.D. in Geophysics from UBC in 1996, he joined the Department of Physics at the University of Alberta and today, as a full professor, directs the Signal Analysis and Imaging Group, an industry sponsored initiative for advanced research in signal processing and imaging. He is also the Chair (for another year) of the Department of Physics.

Geophysical Research at UBC
FELIX J. HERRMANN, ELDAD HABER, AND DOUG OLDENBURG
Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Canada
The UBC Geophysical Inversion Facility (GIF) (http://gif.eos.ubc.ca) is a research unit at the Department of Earth, Ocean, and Atmospheric Sciences (EOAS). It is co-directed by Doug Oldenburg and Eldad Haber and our research is concerned with the development of numerical strategies and associated software needed to invert data from various types of geophysical surveys. The research is applicable to many areas in the geosciences but particularly in resource exploration, geotechnical, and environmental problems. There are two main themes of research. The first is concerned with simulating and inverting electromagnetic data in time or frequency from controlled or natural sources. Our abilities to solve full waveform time domain inverse problems provides application opportunities for different problems in resource exploration (e.g. minerals/hydrocarbons/water) and monitoring (e.g. steam in EOR or SAGD projects, or proppant in hydrofracturing). Current and immediate future research in this area includes: abilities to extract information about electrical conductivity and magnetic permeability when these properties are frequency dependent, continual improvement in numerical modelling to handle large scale EM problems involving 10’s of thousands of sources over large scale earth volumes, and coupling EM with the fluid flow in reservoir or contaminant problems. The second theme concerns the development of a new generation of potential field codes for inverting gravity and magnetic data and the development of GIFtools. This is...
a software environment for carrying out multi-types of geophysical
inversions while incorporating information from geology, petrophysics,
or other types of geophysical data. The research themes are principally
funded via two consortia involving NSERC, mining and oil companies.
There are currently 18 graduate students, 2 research associates, 4
postdoctoral fellows and 3 programmers within the GIF group.

The UBC Seismic Laboratory for Imaging and Modelling (SLIM),
https://www.slim.eos.ubc.ca/, directed by Felix J. Herrmann conducts
industry-supported interdisciplinary research in areas ranging from
seismic acquisition, processing, modelling, imaging, migration velocity
analysis, and full-waveform inversion. Our research program (see our
mind map – https://www.slim.eos.ubc.ca/Publications/Mindmap/
cmap_SLIM_html/SLIM.html), organized in the widely acclaimed
SINBAD consortium supported by 13 oil and gas majors and contractor
companies, builds on recent developments in compressive sensing
and large-scale optimization. Our research has let to major break-
throughs in areas such as randomized acquisition in marine acquisition
(Figures 1 and 2), with the introduction of random coil sampling for
marine by WesternGeco and randomized sampling on land and marine

by ConocoPhillips, and in full-waveform inversion (Figure 3), where our
batching technology has led to 4-5 fold increases in computational
efficiency, making the difference between loss or profit for a large
contractor company. Our research findings are disseminated in a wide
range of publications in the geophysical and mathematical literature
and in the form of software releases to our industrial sponsors. We
match the industrial support from SINBAD with the NSERC Collabo-
rative Research and Development grant DNOISE, which allows us to
further broaden our research program by actively involving faculty
from Mathematics and Computer Science with expertise in compres-
sive sensing, optimization, numerical linear algebra, and machine
learning. This unique interdisciplinary research program, in conjunc-
tion with our participation in the International Inversion Initiative I3 that
gives us unprecedented and exclusive access to a large $10M (17k core)
machine, puts the SLIM team with its 30 researchers in a great position
to continue its leadership role in the development and evaluation of

Figure 1. A schematic of the proposed marine acquisition with random time-
dithered sources.

Figure 2. Time-jittered acquisition with one source vessel. (a) Interferences (or
source-crosstalk) in a common-receiver gather; (b) sparsity-promoting recovery;
and (c) the corresponding difference. (d) Interferences in a common-shot gather;
(e) sparsity-promoting recovery; and (f) the corresponding difference.

Figure 3. The (a) true BG Compass model, (b) initial velocity model (prior to FWI)
and (c) final result from full waveform inversion at a cost roughly equivalent to 2 full
gradient evaluations per frequency band.

state-of-the-art acquisition, processing, and wave-equation based
inversion technology on industrial field datasets.

Aside from having two world-class research programs in exploration
geophysics, EOAS has geophysics faculty active in glaciology (Chris-
tian Schoof and Valentina Radic), mantle dynamics (Mark Jellinek),
planetary geophysics (Catherine Johnson), and seismology (Michael
Bostock). For further information consult the EOAS website
(http://www.eos.ubc.ca).

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**FOCUS ARTICLE**

**Felix J. Herrmann** received his Ph.D. degree in Engineering Physics from the Delft University of Technology (the Netherlands) in 1997. Felix was a visiting scholar at Stanford’s Mathematics Department in 1998, a post-doctoral fellow at MIT’s Earth Resources Laboratory from 1999 to 2002, and a senior Fellow at the UCLA’s Institute for Pure and Applies Mathematics in 2004. Felix is currently professor at the Department of Earth, Ocean, and Atmospheric Sciences of the University of British Columbia. Felix is director of the UBC-Seismic Laboratory for Imaging and Modeling (SLIM), which he founded in 2003. His research interests include theoretical and applied aspects of exploration seismology, compressive sensing, and large-scale optimization. Felix is the principal investigator of the industry- and NSERC-supported research programs SINBAD and DNOISE. Felix serves as a deputy editor of Geophysical Prospecting and on advisory boards of the UBC-Pacific institute for the Mathematical Sciences, the UBC-Institute for Applied Mathematics, and on the Academic Advisory Committee of the Harbin Institute of Technology (China).

**Geophysics Program at the Department of Geoscience, University of Calgary**

**D.W. Eaton**
Professor, Department of Geoscience, University of Calgary

The Department of Geoscience offers B.Sc., M.Sc. and Ph.D. programs in geophysics; by virtue of the University of Calgary’s location in Canada’s energy capital, these programs provide unparalleled access to the geophysical sector within the oil and gas industry. With 180 students majoring in geophysics, the undergraduate program is the largest in Canada. In addition, a large cohort of graduate students, postdoctoral fellows, research associates and adjunct faculty contribute to cutting-edge geophysical research in areas such as exploration, theoretical and global seismology; near-surface geophysics; planetary science; and microseismic methods. Teaching programs are both innovative and experiential, featuring access to state-of-the-art geophysical field equipment that is used each year for geophysics field school as well as for research.

**Reservoir Studies**

Geophysics, most notably 3-D time-lapse (4-D) seismology and passive seismic monitoring, plays an increasingly important role in the reservoir characterization of petroleum reservoirs. These studies include the monitoring of reservoir conditions during production of oil and gas (Figure 1). Reservoir characterization involves an integration of geology, geophysics, and reservoir engineering. The Masters degree in Reservoir Characterization (MSRC), which is jointly managed at the University of Calgary by the Department of Geoscience and the Department of Chemical and Petroleum Engineering, provides graduate students from the disciplines of geology, geophysics, and reservoir engineering with a sequence of 10 courses culminating in a capstone project in which teams of 3-5 geoscientists and engineers will do a complete characterization of a petroleum reservoir. The project involves an integrated analysis of well logs, cores, seismic data and reservoir simulation modeling.

There are three professors with research groups that are involved in reservoir monitoring of unconventional hydrocarbon production. Details of these research efforts are described in the companion article on research consortia by Professor Larry Lines in the current issue of the CSEG RECORDER. In the production of tight oil and gas, microseismic monitoring plays a key role in mapping fractures. Professor David Eaton is co-director of the Microseismic Industry Consortium, a novel, applied-research geophysical initiative dedicated to the advancement of research, education and technological innovations in passive seismic methods and their practical applications for resource development. Together with Eaton’s students and postdoctoral research, his microseismic investigations have included field acquisition using the University of Calgary’s unique downhole microseismic system, case studies, development of processing algorithms and novel interpretation techniques. In heavy oil geophysics, a group of about 12 researchers in CHORUS with Professor Lines undertake integrated studies of well log and core analysis, seismic data, and production history matching. The key link between geomodels and reservoir simulator models is made possible by rock physics. The theory of rock physics for heavy necessitates going beyond the classical rock physics theories.

![Figure 1. Seismic-time lapse monitoring over a heavy oil reservoir east of Lloydminster, Saskatchewan. Photo courtesy of Robert Stewart.](image-url)
One of the areas of great current environmental interest is the monitoring of CO₂ as part of carbon management. **Professor Don Lawton** is a Theme Lead in Carbon Management Canada (CMC). As part of CMC, Lawton and students have conducted 4-D seismic studies over several fields in Western Canada. In 2013 Professor Lawton was seconded in part to Carbon Management Canada (CMC), a research organization housed at the University of Calgary. Within CMC he holds the position as Director of the Containment and Monitoring Institute (CaMI), which is undertaking research into the monitoring of carbon capture and storage (CCS) projects as well as addressing general fluid containment issues relevant to the oil and gas industry. A major component of CaMI is the development of a field research station where small-scale injection and monitoring of fluids will be researched in a field setting. A broad range of surface and subsurface monitoring technologies will be incorporated into the site, including time-lapse multi-component surface and borehole seismic surveys. He maintains active as a researcher within CREWES into the acquisition, processing and interpretation of 3C seismic data, including near-surface S-wave acquisition using a new thumper seismic source built by CREWES.

**Theoretical and Applied Seismology**

The University of Calgary has vigorous programs in theoretical and applied seismology that are described in more detail in the companion article by Lines. **Associate Professor Kris Innanen** has expertise in anelastic seismology, perturbation methods for waves in time-varying Earth volumes, seismic inversion and seismic multiple prediction. His research program includes reflection and VSP seismic data acquisition, processing, and inversion, with application to exploration seismology and time-lapse seismic monitoring. **Professor Gary Margrave** is Director of CREWES and has a diverse research program, including innovative work on signal processing such as the Gabor Transform.

**Professor Ed Krebes** does research primarily in theoretical and computational seismology, although he has also contributed theoretically to research in electromagnetic prospecting methods. More specifically, his primary research has involved the computation of synthetic seismograms in anelastic and anisotropic media using various methods such as seismic ray theory, the finite difference method and the finite element method, and the computation of reflection and transmission coefficients in such media. He and his graduate students have also studied seismic wave propagation in subsurface media with geological interfaces that do not satisfy the usual welded contact boundary conditions. They have computed synthetic seismograms for such media and have derived mathematical formulas for P and S wave reflection and transmission coefficients for an interface with non-welded contact.

**Near-surface geophysics, tectonics and planetary studies**

Several faculty members have research programs that focus on the application of near-surface geophysics to hydrologic and environmental problems (Figure 2).

**Professor Larry Bentley** has recently worked on developing and applying methods of time-lapse electrical resistivity to problems of flow and transport in groundwater systems including the remediation of salt-affected soils. He is applying seismic refraction, electrical resistivity and ground-penetrating radar to alpine hydrologic studies in the Canadian Rocky Mountains. He is also applying normalized gamma ray logs to the hydrostratigraphic characterization of the Paskapoo Formation in Alberta. **Associate Professor Adam Pidlisecky** is focused on using advanced acquisition and inversion techniques (with emphasis on electrical methods) for improved management of groundwater resources. Central to all of his work is the idea of “decision aware geophysics” – where the geophysical workflow (acquisition, processing and interpretation) is designed to yield insights to key decision variables of relevance to end-users. His current research centers on two issues critical to long-term freshwater security: 1) Managed aquifer recharge (MAR), and 2) Saltwater intrusion. His managed aquifer recharge work has been aimed at developing a new approach to long-term monitoring, for improved operation of MAR facilities. On the saltwater intrusion front, he is running a basin scale (~50km) research project, which uses long-offset ERT to map the extent of saltwater intrusion in Monterey Bay, California.

In addition to his work on microseismic monitoring, **Professor David Eaton** has a research program focused on intraplate seismicity and deep Earth studies, including the lithosphere-asthenosphere boundary beneath continents and studies of Earth’s core. **Associate Professor Alan Hildebrand** explores small Solar System bodies and their impacts with the planets. His research into impacts has included potential-field and seismic surveys of impact craters, including the...
Chicxulub crater, to delineate impact crater structure. He has also mapped Chicxulub’s ejecta blanket around the world to constrain impact models and to better understand the environmental perturbations that ended the Cretaceous Period. He has collaboratively led several fireball investigations and has recovered meteorites across Canada from four fresh falls where pre-fall orbits could be determined. Recently Associate Professor Hildebrand and students have been measuring elastic and other physical properties of asteroid lithologies through meteorite studies, and he leads the OLA instrument science team; the OLA scanning lidar is Canada’s contribution to N.A.S.A.’s OSIRIS-REx mission to return a sample from near-Earth asteroid Bennu (Figure 3). He currently leads the Near-Earth Space Surveillance project’s international science team for Canada’s NEOSat space telescope, which is designed to search for asteroids near the Sun. Associate Professor Hildebrand is a frequent participant in science documentaries aimed at both general audiences and the classroom.

Summary

Geophysical research at the University of Calgary integrates applied and fundamental investigations over a large range of scales, from near-surface to planetary environments. These research and academic programs in geophysics at the University of Calgary are hosted by the Department of Geoscience, facilitating collaboration with experts in related fields such as petroleum geology, geochemistry and hydrogeology and providing fast and easy access to the nearby Canadian Rockies. Geophysics faculty members have also fostered close ties with research groups in other departments in the Faculty of Science and the Schulich School of Engineering at the University of Calgary as well as at other institutions around the world. This interdisciplinary breadth supports unique programs such as the Masters degree in Reservoir Characterization, with growing emphasis on geophysical research in support of sustainable unconventional resource development. State-of-the-art geophysical field equipment is used for research as well as teaching, providing hands-on experience for undergraduate and graduate students (Figure 4).

For more information, please see: Department of Geoscience: geoscience.ucalgary.ca

Professor Dave Eaton received his B.Sc. from Queen’s University in 1984, and his M.Sc. and Ph.D. from the University of Calgary in 1988 and 1992. He rejoined the University of Calgary in 2007 after an 11-year academic career at the University of Western Ontario. His postdoctoral research experience included work at Arco’s Research and Technical Services (Plano, Texas) and the Geological Survey of Canada (Ottawa). He is past-president of the Canadian Geophysical Union and Eastern Section of the Seismological Society of America and currently serves as Canadian representative for the International Association of Seismology and Physics of the Earth Interior (IASPEI). He completed his 5-year term as Head of the Department of Geoscience in July 2012.
Three examples of current graduate geophysical research projects at Carleton University, Ottawa

COMPILED BY RAYMOND CARON (raymond.caron@carleton.ca)

Editorial note: With many faculty staff away this summer on field trips, we were pleased to procure the following research notes from current graduate students at Carleton University.

Integrating airborne electromagnetic and gravity data for bedrock topography correction –
RAYMOND CARON, EARTH SCIENCE PH.D. CANDIDATE

A research collaboration between Carleton University, the Federal Government, and Sander Geophysics headed by Dr. Claire Samson, Dr. Michel Chouteau, Dr. Martin Bates, and Ph.D. Candidate Raymond Caron, is currently working on a methodology that applies the helicopter-borne transient electromagnetic (HTEM) method to measuring the thickness of glaciolacustrine overburden overlying Precambrian bedrock for the purpose of correcting airborne gravity measurements for lateral variations in overburden thickness. In Northern Ontario the Precambrian bedrock topography is largely obscured by a glacially derived overburden that changes in thickness independently of the bedrock topography. These variations in overburden thickness can on occasion result in the creation of a gravity anomaly that approaches the size and amplitude of an ore body and can be mistaken for one during interpretation.

HTEM systems that are configured to resolve a near-surface target are optimized to record the early time of an electromagnetic (EM) response from the ground. These systems are typically configured with a quick-turn off time that is often characterized by a square waveform and a lower transmitter moment that enables measurements of an EM response generated by the overburden. The response can then be inverted to determine the thickness of the overburden. In Northern Ontario the glaciolacustrine overburden is predominantly composed of Clay, Sand, and Till which have been measured in-situ to have average resistivity’s of 47.3 ± 6.7 Ω•m, 251 ± 70 Ω•m, and 123 ± 35 Ω•m, respectively (Palacky, 1992).

Figure 1 shows 1D inversions of overburden scenarios that were forward modelled with noise added. The forward modelling was done using AirBeo of the P233F EM suite developed by CSIRO. The noise was modelled following a method developed by Auken et al. in 2008. The overburden scenarios were modelled with 2, 3, and 4 layers where the bottom-most layer is a half-space used to model the bedrock and has been assigned a resistance of 10,000 Ω•m. Results of the inversions of the modelled data with noise indicates that both the thickness of the overburden and the layers of sediment can be measured within 10% of the overburden and layer thicknesses in each scenario.

References

Characterizing the location and geometry of injected CO₂ in a saline reservoir over time through the use of downhole seismic methods – KYLE HARRIS, EARTH SCIENCE PH.D. CANDIDATE

Aquistore is a CO₂ injection site located near Estevan, Saskatchewan, Canada, where captured CO₂ will be stored in a saline aquifer at a depth of approximately 3000 m. The CO₂ captured from SaskPower’s Boundary Dam Power Station will be transported via pipeline to the Aquistore injection well and storage site. It is expected that SaskPower’s Boundary Dam Power Station will capture approximately 3,000 tonnes/day of CO₂ using an amine-based system, and of this, initially up to 2,000 tonnes/day may be targeted for dedicated geologic storage. Surface and downhole (VSP) seismic surveys will be performed to monitor the location and geometry of the CO₂ plume over time to evaluate the integrity of the reservoir and caprock.

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My research is focused on the use of a novel technology, Distributed Acoustic Sensing (DAS), which employs fiber optic cables fixed down a well to use as simulated geophones at 2 cm intervals. Particularly, through my work I intend to (1) establish the feasibility of DAS to monitor CO₂ reservoirs at great depths in comparison with traditional geophone methods, (2) establish 3D VSP processing and imaging techniques to adequately characterize geometry of the CO₂ plume, and (3) perform time-lapse analysis of the CO₂ injection and plume migration. Though feasibility projects have previously been undertaken, this will be the first work to use DAS VSP technology to conduct long-term time-lapse monitoring at a carbon dioxide capture and storage site.

Identifying and characterizing the response from known volcanogenic massive sulphide (VMS) ore lenses using VSP data –
DAVE MELANSON, EARTH SCIENCE M.SC CANDIDATE

My project with the Geological Survey of Canada and Carleton University involves comparing vertical seismic profile (VSP) data with 3D finite difference modeled analogues to identify and characterize the response from known volcanogenic massive sulphide (VMS) ore lenses. For this study, multi-offset 3-component VSP data using dynamite and Vibroseis sources in three deviated wells in the Flin Flon, Manitoba, mining camp were used. Boundaries between the greenstone host rocks and the 85.5 Mt Flin Flon-Callinan-777 VMS ore system provide the strong contrasts in acoustic impedance from which seismic reflections originate. After processing, the VSP data contains observable reflections which are compared with modeled data and interpreted.

The Flin Flon mining camp has been extensively mapped, drilled, mined and targeted by geophysical surveys for decades, leading to a wealth of multidisciplinary data. Several voxel models were constructed from these data and used in 3D finite difference-modeled simulations of the VSP surveys. The number of distinct geological units used in the 3D voxel model was increased incrementally to determine the effects on seismic response of major rock units and massive sulphide ore. The outputs of this simulation method were synthetic VSP shot-gathers, which capture particle motions at receiver stations. In addition, the simulated propagation and scattering of the seismic wavefields could be visualized in 2D and 3D using the output from the simulations taken at sequential time steps. These synthetic shot-gathers were found to be directly comparable to the VSP field data. By integrating the modeled results into the interpretation process, we were able to identify and characterize a response from the mine horizon and from the ore lenses in the VSP field data.

Raymond Caron is a Ph.D. Candidate at Carleton University, Ottawa. He received a B.Sc. in Biology at Carleton University and went to work as an IT Consultant where he worked for several years for Bell Canada and the Federal Government. He then returned to Carleton and received a B.Sc. in Earth Sciences followed by a M.Sc. in Earth Sciences where he studied the application of UAS in aeromagnetic surveying. He is now working on his Ph.D. in Earth Sciences on integrating airborne electromagnetic and gravity data for bedrock topography correction. His research hobbies include advances in 3D printing and electronics.

Marine Geophysics at Dalhousie University
MLADEN NEDIMOVIĆ
Associate Professor, Dalhousie University

The current geophysical research programs at Dalhousie University are led by Christopher Beaumont, Keith Louden and Mladen Nedimović. Christopher Beaumont is a Professor in the Department of Oceanography and Canada Research Chair in Geodynamics (Tier 1). He is a globally recognized leader with a research program centered on quantitative modelling of processes associated with: 1) Extensional tectonics (formation of rifts and rifted continental margins, their sedimentary basins and associated salt and shale tectonics); 2) Formation of foreland basins and thick- and thin-skinned fold and thrust belts; 3) Orogenesis (cordilleran continental margins, continent-continent collision, formation and exhumation of ultra-high-pressure rocks, strain partitioning) and; 4) Interaction between surface processes and tectonics. Keith Louden is an Adjunct Professor in the Department of Oceanography and Mladen Nedimović is an Associate Professor in the Department of Earth Sciences and Canada Research Chair in Geophysics (Tier 2). Louden and Nedimović jointly run a large sea-going controlled source seismic program mostly focused on collecting, analyzing and interpreting multichannel seismic (MCS) and ocean bottom seismometer (OBS) data to investigate three of the Earth’s major boundaries: subduction zones, mid-ocean ridges and rifted margins. Their approach relies on applying innovative or state-of-the-art analysis to new MCS and OBS data with the goal to test leading regional scale scientific hypothesis and questions. Study areas and problems to be addressed are chosen based on both their scientific potential and interest to a broad group of earth scientists.
and general public. In this article, featured are their largest ongoing controlled source seismic projects, most of which are done in collaboration with US and French institutions.

**East Pacific Rise.** More than 1000 km$^2$ of 3D MCS data were collected for this project across the East Pacific Rise (Figure 1) on R/V Langseth in summer 2008. This was the first 3D MCS experiment carried out on an academic ship and using a multi-source and multi-streamer system, and the first such experiment over a mid-ocean ridge. The main goals are to 1) provide the first geometrically correct, complete and detailed images of a mid-ocean ridge magma plumbing system and to 2) understand how the imaged magmatic system is coupled to corresponding volcanic, hydrothermal and biological systems.

**Orphan Basin.** This experiment was carried out in 2010 on R/V Explorer and resulted in a dense 500-km-long wide angle OBS profile across the Orphan Basin. One hundred OBS were deployed with spacing from 3 to 5 km. The goals of the project are to 1) form high-resolution traveltime tomography P-wave velocity sections and layered models, 2) use these models to improve our understanding of crustal thinning across the basin, and 3) test application of advanced imaging methodology on OBS data such as prestack depth migration and waveform tomography.

**Alaska Subduction Zone.** The 2011 Alaska program on R/V Langseth acquired ~3500 km of 2D MCS data and ~800 km of OBS profiles along the western Alaska subduction zone, from the freely slipping Shumagin gap to the locked region of the western Kodiak asperity (Figure 2, right). The profiles span the entire locked zone on the megathrust, including the updip and downdip transitions to stable sliding. The primary goal is to characterize variations in the geometry and properties of the megathrust and the downgoing plate and relate them to downdip and along-strike changes in slip behavior and seismogenesis.

**Juan de Fuca Plate.** This 2D MCS/OBS experiment to characterize the evolution of the crust and shallow mantle across complete transects of the Juan de Fuca (JdF) plate, from formation at the ridge, through alteration and hydration within the plate interior, to subduction at the Cascadia margin, was carried out in 2012 on R/V Langseth (Figure 2, left). The questions to address are: 1) How does the JdF plate evolve from ridge to trench? 2) What is the relationship between the state of hydration of the JdF plate at the Cascadia trench and the Cascadia subduction zone seismicity?

**Offshore New Jersey.** The 2014 R/V Langseth high-resolution 3D MCS reflection program (Figure 3) covering 500 km$^2$ of offshore New Jersey is designed to tie clinoform geometry to facies successions and Neogene sea-level change. Objectives are to 1) establish the impact

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**Figure 1.** Ship track (white lines) of the 3D MCS program across the East Pacific Rise superimposed over multibeam bathymetry. Two source arrays and four 6-km-long streamers resulted in eight CMP lines for each sail line.

**Figure 2.** (left) Juan de Fuca Plate 2012 survey. Red lines are MCS profiles collected with an 8-km-long streamer. White and black circles are OBS locations. (right) Alaska Subduction Zone 2011 survey. Red lines are MCS profiles collected with two 8-km-long streamers towed at depths of 9 and 12 m. Triangles are OBS locations, with an 8-km-long streamer. White and black circles are OBS locations.

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Figure 3. R/V Marcus G. Langseth, owned by the US National Science Foundation and operated by the Lamont-Doherty Earth Observatory of Columbia University, is shown leaving New York in July 2014 to start work on the offshore New Jersey project.

Geophysical Research at the University of Manitoba, Department of Geological Sciences

I. FERGUSON AND A.W. FREDERIKSEN

The geophysics research group at the University of Manitoba consists of three faculty members: Dr. Ian Ferguson (Professor), Dr. Andrew Frederiksen (Associate Professor), and Dr. Wool Moon (Professor Emeritus), along with one technician and a variable number of graduate students (four as of July, 2014).

The research of Ian Ferguson and students in the electromagnetic geophysics group includes magnetotelluric (MT) imaging and tectonic interpretation of Precambrian continental lithosphere; examination of the effects of Earth resistivity on electrical power transmission; and application of electromagnetic (EM) methods in near-surface environmental and groundwater studies. The MT studies focus on Precambrian terrains in Canada and Australia, and have included studies of the Trans Hudson Orogen, Grenville Province, Western Superior province; Slave craton, Wopmay orogen and Canadian Cordillera; and Yilgarn craton and Fraser orogen in Australia. In the most recent study Ferguson and students have imaged the crust and lithospheric mantle beneath the Grenville Province in southern Ontario (Figure 1). The primary objective of the recent work in power transmission studies has been examination of the control of geological structures on ground potential rise of HVDC electrodes, e.g., the effect of the anisotropy in layered rocks in sedimentary basins. Previous near-surface studies of the electromagnetic geophysics group have included mapping paleochannel aquifers in southwestern Manitoba; delineating saltwater contamination in oil-fields in southwestern Manitoba; investigating shallow fracturing and groundwater in Precambrian shield rocks; monitoring freezing of soil; and delineating thickness and pore-water salinity of mine tailings (Figure 2). He is presently working on projects involving EM monitoring of CO2 sequestration at the Aquistore site in Saskatchewan and delineating permafrost at an anthropological site in the Canadian Arctic.

Andrew Frederiksen is a specialist in earthquake seismology, working on determining the structure of continental lithosphere from recordings of earthquake data, and so contributing to understanding the tectonic history of the Canadian Shield and the differing dynamics of the crustal and lithospheric processes involved. Figure 3 shows an example of his ongoing work in central Canada and adjacent areas of the United States, using two teleseismic methods (teleseismic tomography, which is sensitive to temperature and bulk composition, and shear-wave splitting, which is sensitive to mantle fabric) to map domains within the lithosphere of the Canadian shield, which are then related to tectonic and convective events over the past 2.6 Ga (Superior accretion, the Trans-Hudson
orogeny, extension along the Mid-Continent Rift, and the influence of the Great Meteor hotspot). Continuing work on this area is being done as part of the international/multi-institution SPREE (Superior Province Rifting Earthscope Experiment, Stein et al., 2011) project, in which instrumentation was installed along the Mid-Continent Rift axis in both Canada and the USA from 2011-2013. Dr. Frederiksen is also currently developing improved techniques for extracting structural information from teleseismic data, such as a newly-developed method for independently measuring crustal thickness, sedimentary basin thickness, and crustal P/S velocity ratio from teleseismic P waves.

Wooil Moon is retired, but remains an active researcher in the areas of satellite geophysics and remote sensing.

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References

Ian Ferguson received his B.Sc. in 1981 and his Ph.D. in 1988 from Australian National University. He came to Canada in 1988 to take up a postdoctoral fellowship at the University of Toronto and has been on faculty at the University of Manitoba since 1990, currently at the rank of Professor. From 2009 to 2014 he was also Head of the Department of Geological Sciences. His research is focused on understanding the electrical conductivity of the earth at scales ranging from the near-surface to the deep lithosphere, primarily using electromagnetic and magnetotelluric techniques, and using conductivity to obtain information about lithology, mineralogy, pore fluids and tectonic history. He also does research and consulting work involving geomagnetically-induced currents, which are a potential hazard to powerline and pipeline infrastructure.
The School of Geography and Earth Sciences (SGES) at McMaster University offers undergraduate and graduate degree (M.Sc., Ph.D) programs in Earth and Environmental Sciences. SGES currently has about 150 full-time undergraduates and about 90 graduate students in M.Sc. and Ph.D. programs. Undergraduate training in applied geophysics is offered through 3rd and 4th level courses in environmental (near-surface) geophysics, exploration geophysics, and basin analysis. Graduate courses are currently offered in exploration seismology (2D/3D seismic acquisition, processing), advanced exploration geophysics (gravity, magnetics, radiometrics, geophysical inversion modeling), geophysical basin analysis techniques (seismic stratigraphy, petrophysical interpretation), and petroleum exploration. The School has a broad array of geophysical field equipment for undergraduate and graduate instruction, including ground-penetrating radar, 24-channel seismograph, gravimeter, Overhauser magnetometer, EM conductivity and gamma spectrometer (Figure 1). Classroom training is conducted in a state-of-the-art computing laboratory with 50 PC workstations equipped with industry standard geophysical software (Geosoft Oasis, Kingdom Suite, Petrel, Vista 2D/3D) for processing, interpretation and modeling of potential field and seismic data. The laboratory also provides access to a suite of GIS and remote sensing software packages. Through support from the Imperial Oil Foundation SGES has installed a 3D visualization system, which is employed in the teaching of many undergraduate courses.

Three SGES faculty (Joe Boyce, Janok Bhattacharya, Bill Morris) employ geophysical methods in their research work, with specializations in environmental geophysics, petroleum geoscience, and exploration (resource) geophysics.

**Environmental and archaeological geophysics – JOE BOYCE (BOYCEJ@MCMASTER.CA)**

Joe Boyce and his research group apply near-surface geophysical methods (GPR, high-resolution magnetic surveys, shallow seismic, EM conductivity) to discover and investigate coastal and underwater archaeological sites and to monitor human impacts on lakes and coastal environments. This work often involves ‘data-fusing’ of two or more geophysical data types with stratigraphic information from sediment cores to document changes in Holocene environmental conditions over time. Using these techniques, Boyce and team have discovered new prehistoric (Paleo-Indian) underwater archaeological sites in the Great Lakes, documented the environmental impacts of European settlement, and developed new methods for identifying contaminants in lake sediments based in their magnetic properties. Overseas, Boyce and graduate students are employing geophysics and sedimentary archives to document changes in sea level and paleoshoreline positions to guide exploration of archaeological sites in the Mediterranean. To aid in this work, the team is currently evaluating autonomous underwater vehicles (AUV) as a new geophysical survey platform for high-resolution magnetic and multi-beam mapping of underwater archaeological sites and submerged ancient harbours.

In other recent work in Ontario, Boyce and his team are evaluating the application of multi-channel 3-D GPR for mapping and quantifying tree root biomass. GPR biomass estimates provide a new method for measuring changes in carbon sequestration in forests over time, providing important baseline information for climate models.

**Petroleum geoscience – JANOK BHATTACHARYA (BHATTAJ@MCMASTER.CA)**

Janok P. Bhattacharya has recently moved to McMaster from the University of Houston, where he served as the Robert Sheriff Professor of Sequence Stratigraphy. He now serves as the Susan Cunningham Research Chair in Geology. His research team is focused on sequence stratigraphy and reservoir characterization of fluvio-deltaic systems.

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*Figure 1. Undergraduate students collecting GPR profiles across dune at Martha’s Vineyard.*
Bhattacharya is the director of the industry-funded Quantitative Sedimentology Laboratories, which are run jointly with his colleagues at the University of Houston. Supporters include BP, Inpex, and Ecopetrol. Geophysical aspects of the program include remote sensing of unique plan-view exposures of fluvial channel belts, GPR imaging of bars and channel fills in deltaic and fluvial reservoir analogs, hyper spectral imaging of thin-bedded reservoir analogs, and seismic modeling of fluvio-deltaic systems. Bhattacharya’s present McMaster research team is focused largely on fluvio-deltaic outcrop analogs in Utah and an NSERC funded project in New Mexico, but he has also supervised 3D seismic interpretation projects in the Gulf of Mexico, Caspian Sea, and Gulf of Thailand. The New Mexico outcrop work will also be linked to an extensive subsurface database of cores, well logs and seismic data. Bhattacharya’s team is also working on the origin of thin-bedded prodeltaic reservoirs and shales.

Bhattacharya is also serving as faculty advisor for a newly formed AAPG Student Chapter and is President-elect for SEPM. In the spring of 2014, Bhattacharya led a team of McMaster graduate students to compete in the AAPG Imperial Barrel Award, which typically requires integration of geological exploration concepts in the interpretation of 2D and 3D seismic, and well-log data.

Exploration (resource) geophysics –
BILL MORRIS (MORRISWA@MCMMASTER.CA)

Bill Morris and his MAGGIC team employ gravity, magnetic and radiometric data to investigate aspects of mineral and oil resource deposits. A key element of this research involves integration of geophysical data with information derived from other data sets including: object classified imagery from various satellite systems, geomorphometric attributes from topographic data sets, contacts recorded in prior geological maps and borehole physical property variations. All of these elements are combined in the development of constrained geophysical models which are used to investigate aspects of mineral and oil deposit systems. Confirmation of the validity of the computer derived models is supported by an extensive suite of physical rock property measurements.

Morris and his group have applied these techniques of remote predictive mapping (RPM) in a number of mining camps. Work in the Bathurst, New Brunswick area have produced papers: detailing a new method for regional / residual separation of aeromagnetic data and the direct detection of zones that are remanently magnetized; a spatially variable density approach to gravity gradiometry terrain corrections; and an improved procedure for defining the edges of petrophysically defined source bodies. Studies in the Thelon basin have produced: a new map of the geology underlying the Thelon unconformity; an estimate of the location and displacement of faults that have modified the unconformity surface; and a geologically and geophysically constrained model of a doubly plunging fold structure.

In more recent work Morris is working on the NSERC funded CMIC Footprints project looking at the geophysical, geological and geochemical signatures associated with Cu porphyry, Ur unconformity and epithermal Au mineral systems. Through the development of new approaches to data integration, analysis, model construction and interrogation it is hoped will lead to new methods of mineral prospectivity.

**Figure 2.** Photos of UH-McMaster team Lidar scanning fluvial deposits of the Cretaceous Ferron Sandstone, Hanksville, Utah.

Dr. Janok P. Bhattacharya is the Susan Cunningham Research Chair in Geology in the School of Geography and Earth Sciences at McMaster University, Hamilton, Ontario, Canada. He received his B.Sc. from Memorial University of Newfoundland, and Ph.D. from McMaster. He is an AAPG Grover Murray Distinguished Educator and AAPG Distinguished Lecturer. Janok is President Elect of SEPM. He is an associate editor for the Journal of Sedimentary Research and AAPG Bulletin and has authored or co-authored over 150 abstracts and over 70 technical papers.
The research is supported by grants from government (e.g., NSERC, RDC NL, ACOA, PEEP, Turkish Research Council) and private-sector (oil and mining companies, active in the province and its offshore: e.g., Chevron Canada, Husky Energy, Hibernia MDC, Nalcor Energy, Vale). The group has eight research-active faculty, a handful of post-docs and research associates, and around 25 graduate students.

**Reservoir geophysics**

Alison Malcolm has just joined the group to occupy the Chevron Chair in Reservoir Characterisation. Her speciality is in applied seismology, especially the development of new approaches to characterising complex geology. At Memorial she will continue to work on monitoring changes in subsurface reservoirs, particularly for the offshore oil and gas developments in the region. Her group will also work on developing methods for looking for cracks and fluids in the subsurface, primarily by exploiting their nonlinear elastic responses.

**Regional geophysics**

In western Newfoundland, we are carrying out a geophysical and structural evaluation of the petroleum potential of the Carboniferous Howley Basin using reflection seismics, gravity, and MT (Calon, Farquharson, Hurich, Leitch).

Offshore Newfoundland and Labrador, we have a number of projects: interpreting reflection data of basins from various parts of the rifted margin; modelling the geodynamics of the hyper-extended Orphan Basin; and interpreting crustal structure of the margins and their conjugates from regional gravity (Deemer, Gouiza, Hall, Welford).

In the eastern Mediterranean, we have collected and interpreted 20,000 km of multi-channel reflection seismic data, across the active convergent margin of the African and Anatolian plates (Hall, Aksu, Calon) and have acquired and modelled a series of wide-angle crustal seismic profiles across the plate margin south of Cyprus (Hall, Welford).

**Field technology development**

Novel seismic sources using swept impact technology with hydraulic rock breakers are being developed and tested at various sites in the province (Hurich).

As part of a project evaluating and developing tools for vibration assisted rotary drilling, we are working on techniques for acoustic monitoring of drilling performance and evaluating and field testing vibrating drilling tools as a source for seismic while drilling (Butt, Hurich).

**Computational and mathematical geophysics**

We are at the forefront of computational geophysics, in particular, the development of computational methods for synthesizing and inverting geophysical data (Farquharson, Lelièvre). Current emphasis is on developing methods and software that work with more flexible and realistic parameterizations of Earth models. Applications are constrained and joint inversion of potential field data in the mineral exploration context, and synthesizing geophysical electromagnetic data for both mineral and hydrocarbon exploration and delineation contexts.

We (Farquharson, Hurich, Malcolm) are part of the cross-department Computational Applied Geophysics Group that also has members from the Departments of Mathematics and Physics. The interests of this Group are the development of modelling, interpretation, and inversion methods for seismic data in particular and geophysical data in general that can exploit the parallelization made possible by current high performance computer technology (multi-CPU clusters, multi-core GPUs).

Farquharson is part of the multi-disciplinary, multi-institutional Canadian Mining Innovation Council “Footprints” project that is funded by NSERC and a consortium of mineral exploration companies. The MUN geophysics component of this pan-Canadian project includes the inversion of data from and the development of integrated 3D Earth models for the three case-study mine-sites that form the focus of this project.

Modelling dynamics of vibrational modes of whole Earth continues, focussing on effects of liquid outer core and solid inner core on wobble/nutation and precession (Rochester).

Theoretical approaches to seismic wave propagation in complex media leading to enhanced ability to characterise such properties as anisotropy from field measurements continues (Slawinski).

The fluid dynamics of magma systems, from both a theoretical approach and from field observations is being pursued (Leitch).

**Paleomagnetism and rock magnetism**

Paleomagnetic study of Ediacaran rocks of the Avalon Zone of Newfoundland continues (Hodych).

**Geophysical surveys associated with mining camps**

We have several projects that are focused on adaptation and development of seismic techniques for hard rock minerals exploration. Development is mainly focused on combining borehole seismic imaging using seismic interferometry with surface seismic data, Figure 1. In addition we have been developing approaches to surface-borehole and borehole-borehole tomography. Field trials have taken place at the Voisey’s Bay massive sulphide deposit (Deemer, Hurich). Other research focussed on Voisey’s Bay, include associated studies of potential fields (Farquharson), and the fluid dynamic modelling of ore formation (Leitch).
Jeremy Hall is an applied seismologist. His current research is focused on the rifted margin off Newfoundland, and the active plate convergence zone in the eastern Mediterranean. Hall worked for Shell in Holland before joining the faculty of University of Glasgow. In mid-career, he moved to Memorial University. He has served on many national committees, especially with the Natural Sciences and Engineering Research Council of Canada. He is a former President of the Canadian Geoscience Council. He has contributed to two geological interpretation centres, the Johnson GEO CENTRE in St. John’s and the nearby Manuels River Hibernia Interpretation Centre.

Figure 1. Collecting seismic data for surface and borehole surveys at the Voisey’s Bay mine site in Labrador using an excavator mounted swept impact source.
has a legacy of inspiring some of the most influential leaders in the natural resources sector and academia. The most notable geophysical research group in the past conducted work on exploration seismology. Geophysics related research, specifically geotechnical and geomatics engineering, has a strong record at Queen’s and is currently conducted by Dr. Jean Hutchinson, Dr. Georgia Fotopoulos, Dr. Mark Diederichs, and Rob Harrap.

In July 2013, the department appointed Dr. Alexander Braun, P.Geoph. as the new Applied Geophysics professor. At present, Queen’s offers undergraduate level courses in 2nd, 3rd, and 4th year as well as graduate education opportunities in Applied Geophysics. This is complemented by the annual Geophysical Field School conducted through a collaboration with The University of Western Ontario.

Today, geophysical research at Queen’s has two major objectives, i) to give students the opportunity to conduct applied research to solve societal problems, and ii) to employ geophysics for the development of integrated geosciences and geoengineering analyses. We emphasize the integration of diverse data and knowledge to create solutions for complex geoscience targets. Specifically, research in potential field geophysics (gravity and magnetics), satellite geophysics (altimetry, synthetic aperture radar, gravimetry), and Earth system monitoring (crustal deformation, glaciers and sea ice, sea/lake level change) is currently conducted (Figure 1). This is supported by the recently upgraded computing infrastructure (High Performance Computing Linux cluster), a large software donation by Landmark/Halliburton and in-house geophysical equipment funded by departmental alumni. With a broad spectrum of research projects, ranging from magnetic mapping of Amerindian settlements in Antigua (Figure 2) to global sea level change, we will focus on two projects herein, which are the most relevant to CSEG members.

In the past, the use of “Superconducting gravimeters” was limited to a few geodetic observatories worldwide. This changed with the development of the iGrav® field operable instrument a few years ago by GWR Instruments, Inc. It is a relative gravimeter with a sensitivity of approximately 0.1 microGal or 1 nm/s². The application of such instruments for exploration geophysics was hindered by the fact that it integrates over all mass changes during a survey, including atmospheric pressure changes, tides, hydrological processes etc. Often, the signal is hidden in the environmental noise. This limitation can be overcome by measuring the vertical gravity gradient by using two instruments deployed at the surface. Our latest simulation of a fracturing experiment of a 2.5 km deep reservoir, revealed that the gravity signal at the surface is 20-30 microGal, which is clearly detectable by two instruments, despite the small fracturing induced density change in the reservoir of 0.05 g/cm³. We propose to apply this methodology to monitor fluid migration in diverse reservoirs including groundwater pumping, waste water injection and fracturing experiments. This approach has obvious synergies with microseismic monitoring and allows for improved monitoring of fluid migration patterns. Partners for this project include GWR Instruments Inc., ESG Solutions and Integrated Sustainability Consultants.

Figure 1. Revealing the crustal architecture of Greenland through gravity inversion. Image shows topography and bathymetry obtained from fused satellite altimetry and topographic survey observations.

Figure 2. Mapping Amerindian settlements on Antigua island using a Geometrics G-858 Magnetic gradiometer. Homer Montgomery (University of Texas at Dallas) and Alexander Braun (Queen’s University).
“Synthetic Aperture Radar (SAR)” from satellites provides images with spatial resolutions of up to 0.24 meter and as such supersedes the current resolution of optical imagery. In addition, the ability of SAR to extract quantitative information such as surface deformation, flow velocity and elevations makes SAR a logical tool for monitoring the ever changing Earth’s surface. We have used SAR to monitor glacial melting and land cover change and currently conduct research on rockslides and are monitoring Beaver activity in Canada by combining satellite altimetry, SAR and terrestrial and airborne LiDAR. Partners include RockSense GeoSolutions Inc. In a separate collaborative project with Environment Canada and the National Research Council - Institute of Applied Physics (CNR-IFAC), Italy, we conduct research on multi-frequency polarimetric SAR to monitor soil moisture in agricultural regions of Italy and Canada.

Further information on Geophysics@Queen’s can be obtained from Dr. Alexander Braun, Department of Geological Sciences and Geological Engineering, 36 Union St, Kingston, ON, K7L 3N6, p: 613-533-6621 e: braun@queensu.ca.

Alexander Braun is a geophysicist (Dr. phil. nat., Johann Wolfgang Goethe University, Frankfurt/Main, 1999) with expertise in theoretical seismology, geodynamics, potential fields and satellite geophysics. He is internationally known for his research using satellite altimetry, Synthetic Aperture Radar and space gravimetry to characterize and monitor Earth systems processes including glacial isostatic adjustment, vertical crustal motion, sea level, sea ice and glaciers. He is an Associate Professor of Applied Geophysics at Queen’s University, Department of Geological Sciences and Geological Engineering and previously held positions at GeoForschungsZentrum Potsdam, Ohio State University, University of Calgary and University of Texas at Dallas.

The geophysics group at the University of Saskatchewan, Sam Butler, Igor Morozov and Jim Merriam with seven graduate students, two technical support staff and emeriti, Don Gendzwill and Zoli Hajnal, are active in a number of applied geophysics projects.

Prof. Sam Butler’s research involves modelling continuum geophysical systems over length scales ranging from planetary to those of rock pores. Recently, Sam has become interested in studying flows in porous media. He has investigated effects due to thermal and compositional buoyancy and transport rates of temperature and solutes and porous media in which melting and solidification take place leading to exchange of matter between the liquid and solid matrix. Sam also investigates porous systems in which the solid matrix itself can deform in a ductile manner leading to changes in porosity resulting from externally imposed stresses. Earth’s upper mantle beneath mid-ocean ridges deforms in this manner and the formation of shear bands through compaction are a possible mechanism for extracting large volumes of melt to form ocean crust at mid-ocean ridges. Figure 1a below shows the porosity field from a model with initially uniform porosity that was subjected to a right-lateral simple shear. Magenta arrows show the flow of interstitial fluid driven by buoyancy. More recently, Sam’s group has used its expertise in porous flow modeling to enter the field of digital rock property modeling. Starting with images of rock cores taken using X-ray tomography, the pore space is extracted and meshed and the Navier-Stokes equations describing fluid flow and Laplace’s equation describing electrical current flow are solved in the pore spaces in order to determine the permeability and formation factor of core samples. An example simulation showing stream lines of fluid flow through the rock pore space is shown in Figure 1b.

Sam’s group has also developed models of freely rotating fluid drops with surface tension. An example of a result of such a simulation, side by side with an imaged dumbbell tektite is shown in Figure 2a. The real tektite was imaged using a 3D laser scanning camera by Prof. Claire Samson’s group at Carleton University. The image was then meshed and an air flow simulation over the model tektite was carried out. Colors on Figure 2b indicate airflow induced pressure variations. Finally, Sam has become interested in modeling electrical and electromagnetic applied geophysics techniques, such as VLF and magnetometric resistivity.

Three to six graduate students typically specialize in seismology (Igor Morozov’s group). Although relatively small, the seismology program is characterized by breadth and focus on...
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fundamental subjects and advanced numerical methods. The key topic is controlled-source seismology that can be subdivided into several scales of imaging. First, at the longest scale, we analysed unique ultra-long profiles (over 3000 km) using nuclear explosions to image the upper mantle of the Earth and long-range crustal profiles (about 100-200-km long) profiles for imaging the deep crust and the Moho discontinuity. At shorter scales of the “exploration” domain, our students work with 3-D/3-C datasets looking to improve the imaging and time-lapse monitoring of CO₂ injection. We have also conducted shallow refraction, reflection, rippability, and multi-channel surface-wave analysis (MASW) studies. Along with controlled-source seismic studies, we are also study passive seismic methods, particularly in view of the recent growth of micro-seismic exploration. We currently maintain two seismographs for regional seismic monitoring.

Innovative methods for seismic data processing and analysis penetrate all of the above topics. Most notable among these methods are: a new, rigorous approach to P/SV elastic impedance, a simple yet accurate method for seismic impedance inversion, a new approach to the inversion for statics in 3D, and application of receiver functions to imaging the weathering zone.

An ongoing, major methodological development offers a new view on seismic attenuation, which includes its physics, measurement, interpretation, modeling, and inversion. Seismic data processing and analysis software has also been a notable strength of our seismology program. To date, the in-house software is integrated in a powerful processing system combing nearly 300 tools for processing multicomponent seismic, potential-field, and well-log data, 3-D visualization, and a graphical user interface.

Jim Merriam focusses on electrical methods, especially induced polarization. Two graduate students are working in this area in collaboration with local mining companies. X.X. (Mary) Liang is optimizing electrode arrays for resistivity and IP surveys. Yu Han is interpreting a helicopter EM survey. The induced polarization work has resulted in a characterization of the polarization parameter space. The parameters that determine the chargeability are the ratio of intrinsic grain conductivity to host rock conductivity and a polarization index that depends on the surface resistance (the charge transfer resistance), the grain size and the host conductivity. Figure 3 is for a volume fraction of polarizable material of 0.1. Chargeability is divided into two regions, a broad plateau at the maximum chargeability for that volume fraction, separated by a transition over two decades from a region of zero chargeability. High intrinsic grain conductivity and surface resistance and small grain size favour chargeability near the maximum. Low intrinsic grain conductivity and surface resistance and large grain size favour low chargeability.

Jim Merriam has been a faculty member at the University of Saskatchewan since 1984, teaching potential fields, electromagnetics, earth physics and introductory applied geophysics, as well as graduate classes in inversion. In a forty year career he has worked on ocean tides, earth rotation, superconducting gravimetry and most recently electrical methods, especially induced polarization. Jim is currently the department head in Geological Sciences.
Geophysics at the University of Victoria

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Geophysical research at the School of Earth and Ocean Sciences, University of Victoria (UVic), is carried out by faculty, students, and an active group of adjunct faculty (many at the Pacific Geoscience Centre of the Geological Survey of Canada, PGC/GSC). Research topics are diverse, but many focus on various aspects of earthquake seismology/hazard analysis, relevant topics given UVic’s location just landward of the Cascadia subduction zone, the most seismically active region in Canada. Several representative research programs are briefly described in this article.

Geophysical Inversion: Inverse problems are ubiquitous in geophysics: A signal interacts with the earth such that observations of the signal (data) contain information regarding earth properties which are not directly accessible but can be inferred via inversion. The process is described by a model specifying the physical theory, earth system parameterization, and error statistics. Subjective assumptions on the model are often made in inversions and can have profound effects on parameter estimates and uncertainties; a more objective approach is to treat the model itself as unknown in the inversion. Professor Stan Dosso, Adjunct Jan Dettmer and their students are developing nonlinear inference methods for unknown parameterizations and error statistics via trans-dimensional (trans-D) Bayesian inversion which samples probabilistically over the number of system parameters (e.g., earth layers) and parameters of an autoregressive error model (Dettmer et al., 2012; Steininger et al., 2013). Trans-D inversion favours simple models consistent with data resolution (Bayesian parsimony), avoids linearization errors and subjective regularizations, and includes the uncertainty of the model in parameter uncertainty estimates. Figure 1 gives an example of the shear-wave velocity profile estimated via trans-D inversion of ambient seismic-noise dispersion measured on the Fraser-River Delta in Greater Vancouver, together with the resonance-amplification spectrum for earthquake-generated SH-waves predicted for this profile (in both plots colour scales represent estimated probabilities/uncertainties). Other inversion applications include telesismic receiver functions, finite-fault rupture models, controlled-source electromagnetic measurements, and seabed acoustic reflection, scattering, and reverberation data.

Subduction Geodynamics: Adjunct Professor Kelin Wang (PGC/GSC) and his students are studying the geodynamics of subduction zones, especially processes related to the generation of large earthquakes and tsunamis. Their research addresses deformation cycles of great subduction earthquakes, the mechanics of subduction faults, and the thermal structure of the subduction system including mantle wedge flow and metamorphic petrology. They develop numerical models to study fundamental physical processes and use geodetic, seismological, heat flow, and other geophysical and geological data as constraints. This research has important implications to understanding seismic and tsunami hazards in western Canada and worldwide.

Earthquake Hazard Analysis: Adjunct Professor John Cassidy (PGC/GSC) and his students are involved in all aspects of earthquake hazard analysis and mapping earth structure using passive-source seismology. Current research activities include time-varying earthquake hazard assessment (changes in the stress field caused by large earthquakes and linkages with aftershocks and fault-zone loading); mapping earthquake ruptures, including slip distribution and rupture directivity; understanding the variation in earthquake shaking (effects of soft soil, sedimentary basins, and topography); and structural mapping for hazard assessment and improved understanding of resource potential. A recent example of an important contribution highlighted by the Bulletin of the Seismological Society of America is a pair of studies that examine the effects of sedimentary basin structure on earthquake ground shaking across Greater Vancouver (Molnar et al., 2014a, 2014b). Numerical modelling with realistic deep and shallow earthquake sources show that ground shaking could be amplified by factors of 4-5
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and the duration of shaking extended by 10-20 s for sites located on the basin compared to sites away from the basin (see Figure 2). These results will contribute to improvements in earthquake building codes in the region.

Tsunami Hazard Assessment: Assistant Professor Lucinda Leonard’s main research interests concern the current tectonics of western Canada and adjacent areas. She uses GPS, seismicity, and other geophysical data to analyze crustal deformation and to assess the seismic and tsunami hazard of plate boundary and crustal faults. Recent work includes a preliminary tsunami hazard assessment of Canada (Leonard et al., 2014), and field studies of the 2012 Haida Gwaii tsunami (see Figure 3, Leonard and Bednarski, 2014). The tsunami reached up to 13 m above the state of tide on the west coast of Haida Gwaii, making it the largest tsunami of the year, globally. The tsunami was generated by thrust faulting during the second largest earthquake (magnitude 7.8) ever recorded in Canada, in a region where previous large earthquakes involved strike-slip faulting.

References


Stan Dosso received his BSc in Physics and Applied Mathematics and MSc in Physics from the University of Victoria, and PhD in Geophysics from the University of British Columbia in 1990. From 1990-95 he worked in Ocean Physics (Arctic Acoustics) at the Defence Research Establishment Pacific, and in 1995 joined the School of Earth and Ocean Sciences at the University of Victoria where he is currently a professor. His research interests centre on extracting quantitative information from geophysical/ acoustic data via probabilistic inversion methods, with specific focus on seabed geoaoustics, acoustic localization, and earthquake seismology. He is a member of the American Geophysical Union, Fellow of the Acoustical Society of America, and Past President of the Canadian Acoustical Association.

Figure 2. Left: Computed average peak ground velocity (PGV) across southwest British Columbia for realistic shallow earthquake sources. Damage to older structures begins at intensity VI. Right: Amplification of seismic shaking caused by the thick (~6 km) Georgia Basin ranges from 2-4 times across Greater Vancouver, and up to 5 times in the centre of the basin (Strait of Georgia).

Figure 3. Surveying the effects of the October 2012 tsunami on western Haida Gwaii, British Columbia.
Induced Seismicity Research Program at Western University

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Introduction

Western University has partnered with the Natural Sciences and Engineering Research Council of Canada and Industry partners TransAlta and Nanometrics in the initiation of a 5-year, $3.5 million multi-institutional collaborative research program on Induced Seismicity Processes and Hazards (2014 to 2019). Collaborating institutions include the University of Calgary, the University of Alberta, the Alberta Geological Survey and the Geological Survey of Canada (Pacific Geoscience Centre). For a full list of participants, along with a program overview and emerging program results, the reader is invited to visit the program website at www.inducedseismicity.ca.

Induced seismicity is the occurrence of earthquakes that are triggered by industrial processes including energy technologies, mining, and reservoir impoundment. The phenomenon has been recognized for more than a century, but only recently has induced seismicity become a pressing global problem - with major economic and safety implications. Improvements in hydraulic fracturing and horizontal drilling have unlocked tight reservoirs around the world, ushering in a new oil and gas boom and in the process reshaping the North American economy. The rise in the unconventional production of oil and gas has been coupled with a dramatic increase in seismicity rates in some locations. In the central United States, the rate of M3 and larger earthquakes has increased from a long-term average of 21 such earthquakes per year between 1970 and 2000, to 31 per year during 2000-2008, to 151 per year since 2008 (Ellsworth, 2013). The annual rate of events of M>3, per unit area, is now greater in Oklahoma than in California (Keranen et al., 2014). The increase in seismicity has occurred in areas of enhanced hydrocarbon production, with much of it being related to disposal at depth of production-related fluids. Some induced events have been surprisingly large (M>5.5), causing damage and significant concern (e.g. McGarr, 1991; Horton, 2012; Keranen et al., 2013).

Induced seismicity is a pressing and timely problem in western Canada, given the rapid deployment of new resource extraction technologies and the growing realization of their potential to trigger unplanned seismic events. There is a history of moderate triggered seismicity in Alberta from conventional resource activities, in particular with regards to the Strachan field (near Rocky Mountain House, Alberta), which has triggered events of M>4 (Baranova et al., 1999). In B.C., there have been several clusters of seismicity believed to be triggered by wastewater disposal, as well as a series of earthquakes of M 3 to 4 that were triggered by hydraulic fracturing in the Horn River Basin (B.C. Oil and Gas Commission, 2012). Similar clusters of triggered events have been observed in Alberta, with the most recent being a series of events of M 2 to 3 triggered by hydraulic fracturing in the Crooked Lake region. The likelihood and maximum size of events that might be triggered in various regions due to various activities is not yet known, though in general it is observed that deep disposal of fluids tends to be associated with more seismicity, and larger events, in comparison to other activities. The most extreme example of large triggered events is a series of three M–7 events that occurred near the Gazli gas field (USSR) in the 1970s and 80s, in an area that had previously been aseismic (Simpson and Leith, 1985; Grasso, 1992). It is the aim of our research program to better understand induced-seismicity processes, so that we can provide the scientific and knowledge foundation that will allow us to adequately assess the seismic hazard arising from induced seismicity.

The basic mechanism of induced seismicity is widely agreed-upon: it is caused by a change in pore fluid pressure and/or a change in the state of stress, which may cause re-activation of existing faults or fractures. However, we are not currently able to predict the likelihood or magnitude of such events from specific planned operations, because we do not have sufficient data on the complex natural rock systems, nor do we have validated predictive models (U.S. NRC, 2012). Without a validated quantitative model with which to evaluate the likelihood of induced seismicity, it is difficult to assess its significance and plan appropriate mitigation strategies to counter the risk.

A fundamental difficulty in assessing the likelihood of induced seismicity is the lack of sufficient regional information concerning the relationship between energy technologies and seismicity. In Alberta, study of this relationship has been hampered by the sparseness of regional seismic monitoring. Seismographic stations are typically spaced hundreds of km apart, and thus events are poorly located; the overall location accuracy of the national network in Alberta (as of 2013) is ~10km. This means that events cannot be confidently correlated with the structures on which they are occurring. Furthermore, the magnitude threshold for detection is high in many areas (M>3), leading to sparse statistics with inadequate resolution. Enhanced monitoring is thus a critical pre-requisite to evaluating and managing the risk, and a key platform of our research program.

The Alberta Regional Network

A backbone of the research program is improvement to regional seismographic monitoring, to provide baseline seismographic data to inform the studies. A new real-time seismographic network is being operated by Nanometrics in Alberta as of Sept. 2013, with

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funding from TransAlta; operational funding is also provided by the Brazeau Oil and Gas Operators Committee for some of the stations. The new stations, as of May 2014, are shown in Figure 1, along with regional seismicity; all stations are observatory-quality state-of-the-art three-component broadband seismographs reporting their data in real-time to the Nanometrics data centre in Ottawa, via cellular communications links. These stations augment the sparse real-time coverage by the national network operated by the Geological Survey of Canada. There are also stations operated in the region by the Alberta Geological Survey, the University of Alberta and the University of Calgary (some of which are being installed the summer of 2014), and additional stations are being added as operators join the information network. Coordination between the research partners ensures that the data from all public stations is available to maximize their research benefits, and avoids duplication of effort in placing and operating stations. Additional contributing partners are encouraged to contact the first author (gmatkinson@aol.com) if willing to support new stations in the network in a region of interest. The network provides a world-class public-domain seismographic dataset with which to characterize and understand induced seismicity; it is hoped that this network will continue to grow with time.

The Research Program
With the new network in place, we have a detection/location threshold of M1 to M2 across a broad region (varying with network density), and locate hundreds of events/year in the area, to a location accuracy of 500m to 1km. We are mining the data being collected to improve our understanding of induced seismicity processes and seismic hazards due to induced seismicity. Topics being addressed include:

- the physics of induced-seismicity fracture processes
- the relationship between resource activity parameters and induced seismicity
- the influence of stratigraphically-controlled poroelastic properties on propagation of induced seismicity
- the geomechanical characteristics of induced seismicity
- the use of advanced remote sensing techniques as a tool to map fluid injection and the associated induced seismicity
- ground motions associated with induced seismicity
- development of validated regional and local-scale probabilistic models for assessment of the hazard contributions of induced seismicity

This integrated research program will provide a knowledge-based foundation for the development of practical models to evaluate and mitigate the risk to critical infrastructure posed by energy extraction technologies. Results and publications arising from the research program will be published on the project website as they become available, and presented at a number of conference venues.

Gail Atkinson, Professor of Geophysics at University of Western Ontario, and NSERC/TransAlta/Nanometrics Industrial Research Chair in Hazards from Induced Seismicity, has devoted her career to working at the engineering-seismology interface. She has authored 180 research articles on the subjects of earthquake ground motions and seismic hazards; among these are well-known prediction equations for ground-motion amplitudes as a function of magnitude and distance that have been used earthquake hazard and risk assessments around the world. She has been responsible for seismic hazard analyses for dozens of major engineering projects, and participates in committees responsible for developing seismic design regulations for buildings and critical structures such as dams and nuclear power plants. Professor Atkinson has served as President of the Seismological Society of America (2001-2003) and President of the Canadian Geophysical Union (2011-2013), and currently serves as Chair of the Advisory Council for the Southern California Earthquake Center.

Figure 1. Seismicity of Western Alberta, showing historical seismicity from catalogues of the GSC and AGS to 2013, along with new events (small dots) recorded since beginning of the Nanometrics network (red triangles) in Sept. 2013. Dashed line is approximate location of deformation front marking the eastward limit of the Rockies.