Imaging the Fate and Transport of a Salt Spill During Remediation with Time-lapse Electrical Resistivity (Year 3 of 3)

Proposal Submitted to
Environmental Research Advisory Council
May 27, 2005

Pr. Laurence R. Bentley
Department of Geology & Geophysics
University of Calgary
Calgary, Alberta T2N 1N4
lbentley@ucalgary.ca
(403) 220-4512

1. Scope of Research

The purpose of the proposed work is to develop protocols for assessing the distribution and evolution of salt in soils and groundwater during remediation using repeated electrical surveys. Electrical resistivity imaging (ERI) and induced polarization (IP) will be used in integrated interpretations to identify areas of elevated salt concentrations and geological heterogeneities. These two types of surveys can be applied from the surface to produce three-dimensional interpretations of the subsurface. It is our intent to provide 3-D maps of the subsurface at a sequence of times over 3 years in order to monitor remediation progress of soils and groundwater containing salts from produced water spills. These maps can be used to assess remediation progress, calculate volumes of contaminated soils, track salt plume movement in groundwater, calibrate flow and transport models, aid in risk based closure assessments and demonstration that closure criteria have been met. Industry will benefit because the methods will yield detailed geometry of contaminated areas, increased assessment efficiency, provide "real-time" monitoring of remediation progress, identify problem areas for early intervention, lead to improved remediation design, reduce uncertainty and reduce risk.

Soil and water samples from drilled boreholes and groundwater monitoring wells are the principal data used in site assessment. However, these provide data at a limited number of points and the assessment between the sampling points must be interpolated. Often, key areas are missed by the sampling program or abrupt changes cause erroneous interpolations. The erroneous interpolations cause remediation design inefficiencies, increased risk of missing contaminated zones, and difficulties in demonstrating that site closure criteria have been met. Combining geophysical methods with "hard" sampling data provides a method for accurately interpolating between known values of the hard data sampling points. Surface EM surveys give only partial information about depth of anomalies and 2-D ERI surveys can contain misleading artifacts in complex settings.

We have demonstrated that 3-D ERI combined with soil and water samples can be used to define geochemical zones at a decommissioned sour gas processing plant. However, resistivity is a function of both the geology and ionic content of the water, and often it is not clear whether a particular anomaly is caused by water quality changes or geological heterogeneity. Induced polarization measures the "chargeability" of the subsurface which is a different parameter than resistivity. It has been used to differentiate changes in geology from changes in water quality that are unclear from resistivity measurements alone.

Several environmental factors (such as soil moisture and temperature) contribute to ERI and IP responses. It is our intent to identify the critical external environmental factors and develop appropriate protocols and corrections to account for them. We will also test electrode and cable alternatives. Our objective is to produce economic and practical methods that can be used by the professionals responsible for site monitoring and remediation in heterogeneous geological areas with high salt concentrations.

Repeated or time-lapse ERI and IP surveys will be conducted at an Imperial Oil Resources site undergoing active remediation of high salt concentration. We will conduct two surveys a year for three years. Surveys will be conducted in the spring and fall. Repeat surveys with different electrode and cables will be used to test alternative designs. If possible, we will test a small permanent electrode array in order to determine long-term performance. Water and soil samples and direct push EC measurements will be used for calibrating the geophysical interpretations and validating interpretations. Soil temperature and the unsaturated zone soil water pressure will be monitored to account for environmental factors.

2. Research Plan

Introduction

The project was initially funded starting March 2004. Year 1 of the program is complete and we have completed the first two repeat 3-D ERI surveys, collected 3 cores and 5 push tool electrical conductivity profiles. In addition, we have installed two tensiomenter nests for monitoring soil moisture and two multilevel thermocouple arrays to monitor soil temperature. Laboratory testing on the cores is ongoing. Year 2 funding was approved and we are now at the beginning of the Year 2 program. The start of the year 2 field program will commence with the third 3-D ERI survey being conducted in May 2005. The following is a summary of the Year 1 progress and results, the Year 2 plan that is currently in the preliminary stages of implementation and the proposed final Year 3 plan.

Background

Precise mapping of areas of elevated salt concentrations can be difficult in sites with complex geology. The proposed research will develop practical protocols for using electrical resistivity imaging (ERI) and induced polarization (IP) methods with soil and water chemistry measurements to produce accurate maps of subsurface chemistry distribution. Repeated measurements will allow the monitoring of remediation progress. Although these geophysical methods have been in use for many years, recent developments in switching technology and inversion software have made practical 2 and 3-D ERI and IP surveys[1,2]. As the concentration of salt declines due to natural attenuation or active remediation, the bulk electrical resistivity of the subsurface increases. The increasing resistivity with time can be monitored with repeat ERI surveys. We have recently shown that geochemical interpretations can be derived from ERI[3,4,5]. However, the chemistry interpretations assume homogeneous geology which is often not the case. Consequently, our intent is to use IP with ERI to reduce the ambiguities associated with geologic variations and improve our ability to map salt distributions.

In the ERI method, current is injected into the ground and voltage differences due to the current are measured. Using multiple measurements, inversion software produces an estimate of the resistivity distribution of the subsurface. The electric field produced by the current causes charge to build up along grain-fluid interfaces. The IP method measures the decay of the charge build up when the current is turned off. The results can be interpreted in terms of the subsurface distribution of “chargeability”. More complex field equipment and interpretations are sometimes used to look at the shape of the relaxation curve and these methods have been called spectral induced polarization (SIP).

ERI produces images of subsurface resistivity. However, resistivity is a function of water ionic content and geology, partially due to the effects of conductive clay or shale. Consequently, separating the effects of varying geology from varying water quality can be difficult. IP measurements are sensitive to the low-frequency properties of rocks and soils, and this capacitance-like property can be characterized by the “chargeability”. Normalized chargeability has been used to distinguish between areas that are relatively clay-free and clay-rich[6]. In one survey, salt transport has been monitored with resistivity imaging while IP was used to improve the characterization of the hydrogeologic framework[7]. In another report, peat was distinguished from an underlying clay with IP measurements, while differences in water quality were imaged with resistivity[8]. Consequently it appears feasible to develop protocols for conducting surveys that can map salt distributions and distinguish between differences in resistivity due geologic variation and water quality differences.

Several environmental factors must be accounted for during the interpretation of the surveys. Resistivity is dependent on temperature and soil moisture and IP can be affected by magnetotelluric effects and other transient electro-magnetic fields. Environmental parameters will be monitored and protocols for correcting results to account for environmental changes will be developed.

Imperial Oil Resources (IOR) is acting as the Industrial Manager and has provided a site that is undergoing active remediation of soils containing high concentration of salts. The salt plume area is approximately 2 hectares in size and is approximately 5-7m deep, making this an excellent target for high resolution ERI. Within the salt plume, several areas of hydrocarbon impact have already been remediated with on-site bioremediation. A spatially dense engineered tile drainage system has been installed with water collection sumps tied into a water disposal well. This system will mainly target soils within the top two meters of the salt plume but will be investigated for its efficacy at remediating the deeper salts which may migrate to the drainage system through moisture wicking. In addition, a phytoremediation test plot is being installed at the site. The plots will have sections of fallow, barley and halophytes. We will test for remediation progress across the different plantings. Resistivity images will add detailed information about the transient behaviour of the site, the effectiveness of shallow tile drainage systems for remediation of salt affected soils, and the ability of a shallow system to influence salts at depth. The detailed knowledge of the fate and transport can be used to develop more efficient remediation approaches.

Progress and Ongoing Work

The surveys are being carried out with the University of Calgary's Advanced Geosciences Imaging Sting resistivity unit and Swift switching box. The system has 56 electrodes installed in four, fourteen electrode cables with maximum separation distance of 12 m. Stainless steel electrodes are easier to use than the typical Cu-$CuSO_4$ electrodes used in IP surveys in order to reduce charge build-up effects. We compared of stainless steel electrodes to our in-house designed and constructed Cu-$CuSO_4$ electrodes to see if they can be used despite the anticipated additional noise. The results and other literature show that stainless steel electrodes are too noisy and require complicated correction factors. Our in-house electrodes leaked too much. We have bought two types of commercial long-life Cu-$CuSO_4$ nonpolarizable electrodes and a set of Pb-PbCl non-polarizable electrodes and will be testing them this May to make a purchase selection. Two tensionmeter nests have been installed to estimate the soil moisture profiles at the time of the surveys. Two thermocouple installations have been installed to monitor the temperature of the soil profile to two meters. These installations are being used to monitor the environmental factors that can influence the measurements. Surveys are being carried out in the spring and late summer in order to capture different temperature and hydrologic conditions and collect the data necessary for the development of appropriate correction factors.

The first survey was conducted in July 2004.The location of the surveys was based on EM-31 data provided by Imperial Oil. Another survey was conducted in November 2004. The late summer and fall were abnormally wet and the difference between the surveys indicates that we may have captured an unusual redistribution of the salt mass. We may also have witnessed a flushing of salts from the upper 2 m of the soil profile above the tile drains, but it is too early do be definitive in that interpretation Direct push EC and cores study were completed in November. Coordinates and elevations of geophysical lines were surveyed in using electronic surveying devices. We focused our study in the area of the phytoremediation plots because that will allow us to look at a wider variety of remediation contrasts. Survey markers were installed so that the geophysical survey locations can be reoccupied with precision in future surveys.

Preliminary investigations indicated that the IP capability of the Sting system was inadequate for our purposes. The University of Calgary is currently in the process of purchasing a more advanced IP system that we hope to have in hand by the end of summer. We will begin testing with that system late in Year 2 and we plan to run the first surveys in Year 3.

We have previously demonstrated that, in complex settings, 2-D surveys contain artifacts due to out of plane effects, and these artifacts can lead to poorly located images, incorrect resistivity magnitudes and erroneous interpretations[9]. Consequently, we have implemented a quasi 3-D survey geometry. Two surveys arrays were run at the site and they consisted of 10 parallel lines separated by 4 m and 5 parallel lines separated by 4 m. We are quite pleased with the survey results and the push tool EC profiles have confirmed the quality of the images. We are still analyzing some aspects of the image quality.

Three cores were collected, and selected samples are being analyzed in the laboratory. We are analyzing for electrical conductivity versus temperature, soil paste EC, 2:1 extract EC, mineralogy, grain size distribution, dry bulk density, porosity, cat ion exchange capacity, soil chemistry and SAR.

The third and fourth 3-D surveys will be conducted in spring and late summer of 2005 using the same design as it has proven very effective. Temperature, soil suction and water chemistry measurements will be conducted. We will be looking for evidence of changing groundwater and soil chemistry and the resulting correlated changes in electrical resistivity. Another purpose of these surveys is to collect data sets with a variety of environmental conditions in order to evaluate the influence of environmental factors. Using the bench marks and survey data, the geophysical survey will reoccupy the previous year's location. A direct push EC and coring survey will be conducted as part of the interpretation validation.

Processing and preliminary environmental correction factors will be generated during the winter. A report on survey design and preliminary protocols will be generated. Evidence of changing salt distribution will be compared with the geophysical results. Remediation progress will be evaluated. This report will mark the end of Phase II.

Year 3 Program

In year 3, repeat 3-D surveys will be conducted in the spring and late summer of 2006. These surveys will produce data for validating the methods and observations of changing salt distribution. Soil suction, soil and water chemistry, soil temperature and direct push data will be used to validate the geophysical results. We will also conduct a 3-D IP survey over the locations of the 3-D ERI surveys. The purpose of these surveys will be to attempt to refine our salt distribution model by identifying changes in soil types. It was our original intent to conduct this work in Year 2, but as mentioned above, our current IP system was inadequate.

The balance of 2006 will be used to synthesize the results and validate the procedures against the hard data. We will use a part of the data to calibrate the interpretation procedure. The remaining hard data will be used to test the efficacy of the integrated geophysical interpretation procedure. After validation, we will finalize the survey design, monitoring protocols and environmental correction procedures.

In December 2006, we propose to hold a workshop for environmental professionals to present the results of the research. The purpose of the workshop will be to give detailed guidance on how to implement the new methodologies. During the workshop, we will give detailed protocols on how to apply the technology in the field as well as alert potential users to the most important issues and potential pitfalls.

Related Research

We submitted a proposal to the Environment Canada PERD program to expand the scope of the project. In the proposal, we will look at the application of spontaneous potential methods (SP) to the mapping of hydrocarbon contaminated soils. The proposal was returned with a request for clarification and an invitation to resubmit it in 2005. We resubmitted the proposal and recently learned that we have obtained partial funding. We are currently designing a program to look at SP and IP methods for detecting and mapping petroleum hydrocarbon contaminated soils.

In addition, we are planning to add a numerical modeling component to our current study. This modeling project will be used to demonstrate that our results are consistent with our understanding of the physics of groundwater flow and salt transport. Although integral to this ERAC study, the modeling study will be funded from other sources

We believe that the time-lapse resistivity technology is ready for a practical demonstration. It should be deployable on a commercial basis as soon as the protocols have been developed and its effectiveness evaluated.

[1] Loke, M.H. and R.D. Barker (1996) "Practical techniques for 3-D resistivity surveys and data inversion", *Geophys. Prosp., 44*, 499-523.
[2] Loke, M.H. and R.D. Barker (1996) "Rapid least-squares inversion of apparent resistivity psuedosections by a quasi-Newton method", *Geophys. Prosp.,44*, 131-152.
[3] Wong, R.C.K., L.R. Bentley, A.W. Ndegwa, A. Chu, M. Gharibi and S.R.D. Lunn (in press) "Biodegradation of monoethanolamine in soil monitored by electrical conductivity measurement", *Can. Geotech. J.*
[4] Berthold, S., L.R. Bentley and M. Hayashi (in press) "Integrated hydrological and geophysical study of depression-focused groundwater recharge in the Canadian Prairies", *Wat. Resour. Res.*
[5] Gharibi, M., L.R. Bentley and S. Lunn (2002) "Two and three-dimensional electrical resistivity monitoring of groundwater remediation", Can Geophys Union Annual Mtg., Banff 18-21 May.
[6] Slater, L.D. and D. Lesmes (2002) "IP interpretation in environmental investigations", *Geophys., 67*, 77-88.
[7] Slater, L.D. and S.K. Sandberg (2000) "Resisitivity and induced polarization monitoring of salt transport under natural hydraulic gradients", *Geophys., 65*, 408-420.
[8] L.D. Slater, L.D. and A. Reeve (2002) "Investigating peatland stratigraphy and hydrogeology using integrated electrical geophysics", *Geophysics*, 67, 365-378.
[9] Bentley, L.R. and M. Gharibi (2004) "Two and three-dimensional electrical resistivity imaging at a heterogeneous remediation site," *Geophys., 69* (3), 674-680.

3. Deliverables

- Years 1 & 2 Annual phase completion reports
- Years 1, 2 & 3 ERAC newsletter contributions
  - 2004 ERAC Reporter, p.14-15.
  - 2004 Project Update, P-Talk, Issue 32, Nov. 2004
- Years 1, 2 & 3 One or two forum presentations per year
  - Year 1 results presented at the PTAC Soil and Groundwater Forum, Calgary March 23, 2005
- Years 2 & 3 Conference Presentation
  - Abstracts for presentation of the Year 1 results have been accepted at:
    - CGS-IAH meeting in Saskatoon 18-21 Sept. 2005.
    - AGU Spring Meeting in New Orleans 23-27 May 2005.
    - EAGS Workshop Hydrogeophysics – a tool for sustainable use of groundwater resources, Palermo, September 4 2005.
- Year 3 Final Report containing field data, analysis and recommended field and processing procedures for integrated geophysical assessment of salt contaminated soils. Included in the report will be an assessment of the remediation progress.
- Year 3 Workshop. A workshop will be presented aimed at environmental professionals. Details of the developed methodologies will be presented. A special emphasis will be placed on practical implementation of the techniques and realistic assessment of the expected outcomes of the surveys.

5. Relevant Expertise of Research Team

Dr. Laurence R. Bentley, Professor, Department of Geology & Geophysics, University of Calgary. Dr. Bentley will be the Principal Investigator (PI) for the research project. He will have responsibility for supervising the project and supervising the participating graduate student. Dr. Bentley has a B.A. in Physics from Hamilton College (1971), and M.Sc. in Geology & Geophysics from the University of Hawaii (1974). He worked for Western Geophysical Company from 1975 until 1985 as an exploration geophysicist and research geophysicist. He received his Ph.D. in Civil Engineering in 1990 from Princeton University where his work focused on groundwater flow and transport and numerical modeling. After a one year PDF at the University of Vermont, he joined the University of Calgary in 1991. He is a APEGGA registered Professional Geophysicist.

Dr. Bentley's research focuses on groundwater flow and transport and the application of geophysical techniques to groundwater studies. Dr. Bentley has a history of industrial collaborations and has worked on environmental research with AMOCO Petroleum Company, Daishawa-Marubeni International and lately with Imperial Oil Resources. The research program with AMOCO was awarded the AMOCO Progress Chairman's Award (1996). A trench and gate system was designed, constructed and tested. Over 100 reprints of papers from this study were requested and several commercial installations were constructed based on the design. Another M.Sc. student working for Komex International studied sulphur distributions around sour gas processing plant and used ^{34}S isotopes to distinguish between natural till sulphur and produced sulphur. At this particular site the isotopes were used to demonstrate that the highest concentrations of sulphate were from a natural till origin, not production. He is currently the PI for a multidisciplinary Gas Plant Remediation Project. The project is an integrated hydrogeology, geochemistry and geophysical study of a decommissioned sour gas processing plant. The current proposal builds on the successes of this study.

The following partial list of grants emphasizes geophysical and industrially oriented funding:

2005, **ERAC,** Imaging the Fate and Transport of Salts with Time-Lapse Resistivity, $65,000 (2nd of 3 years) (Sole I.)
2004, **ERAC,** Imaging the Fate and Transport of Salts with Time-Lapse Resistivity, $72,802 (1st of 3 years) (Sole I.)
2004-2007, **NSERC Discovery Grant**, Constraining Hydrogeological Models with Electrical Resistivity Imaging, $27,600/YR (4 Years) (Sole I.)
1999-2002, **Imperial Oil Resources**, 132,022 (total over 4 years), Gas Plant Remediation Project (P.I. with several Co.-I.)
1999-2002, **NSERC CRD**, $263,250 (total over 4 years), Gas Plant Remediation Project (P.I. with several Co.-I.)
1999-2002, **NSERC Operating Grant**, $25,863/YR (4 years), Constraining Hydrogeological Parameter Estimation with Electrical Resistivity Tomography (Sole I.)
1998, **NSERC Equipment Grant**, $14,500, TDR System (Co.-I. With M. Hayashi P.I.)
1998, **NSERC Equipment Grant**, $70,000, Electrical Resistivity Tomography System (Co.-I. With D. Smith P.I.)
1997, **Amoco Canada Petroleum Company**, $20,000, Passive Remediation of Organic Contaminated Groundwater (extended funding) (P.I. with J. Barker Co.-I.)
1997, **GASReP**, $35,000, Passive Remediation of Organic Contaminated Groundwater (extended funding) (P.I. with J. Barker co.-I.)

1996, **Prairie Farm Rehabilitation Administration**, $24,000, The use of Geophysical Methods in Groundwater Exploration in Albera (P.I. with K. Duckworth and D. Lawton co.-I.s.) 1996, **Daishawa-Marubeni International Ltd.**, $52,000, Fate and Transport of Black Liquor (P.I. with I. Hutcheon co.-I.).
1997-1998, **NSERC IOR**, $30,000, Fate and Transport of Black Liquor, (P.I. with I. Hutcheon co.-I).
1995, **Prairie Farm Rehbilitation Administration**, $3,000,Feasibility of Using Refraction for Groundwater Exploration in the Special Areas. (Sole I.)
1995-1998, **NSERC Operating Grant**, $23,100./YR (4 years), Characterization of Heterogeneous Porous Media. (Sole I.)
1992-1995, **NSERC Operating Grant**, $21,000./YR (3 years), Identification of Hydrogeologic Parameters. (Sole I.)
1994-1996, **NSERC IOR**, $79,950 (year 1), $66,700 (year 2), Containment and Bioremediation of Hydrocarbon Contaminated Groundwater (P.I. with J. Barker co-I.).
1994-1996, **Canadian Association of Petroleum Producers**, $40,000/YR (2 years), Passive Remediation of Organic Contaminated Groundwater. (Co-I. with P.I. Marc Bowles (my M.Sc. student) and co-I. Dr. J. Barker)
1994-1996, **GASReP**, $40,000./YR (2 years), Passive Remediation of Organic Contaminated Groundwater. (Co-I. with P.I. Marc Bowles (my M.Sc. student) and co-I. Dr. J. Barker)
1994-1996, **Amoco Canada Petroleum Company**, $40,000./YR (2 years), Passive Remediation of Organic Contaminated Groundwater (Co-I. with P.I. Marc Bowles (my M.Sc. student) and Dr. J. Barker)

The following is a partial list of relevant publications:

Berthold, S., L.R. Bentley and M. Hayashi, "Integrated hydrogeologic and geophysical study of depression-focused groundwater recharge in the Canadian prairies", *Wat. Resour. Res. 40,* W0605, doi:10.1029/2003, WR002982 (2004)
Mrklas, O., A. Chu, S. Lunn and L.R. Bentley, "Biodegradation of monoethanolamine, ethylene glycol and triethylene glycol in loboratory bioreactors, *Water, Air and Soil Pollution*, 159, 249-263 (2004).
Ndegwa, A.W., R.C.K. Wong, A. Chu, **L.R. Bentley** and S.R.D. Lunn, "Degradation of monoethanolamine in soil," *J. of Env. Eng. and Sci*, 3, 137-145 (2004).
Wong, R.C.K., **L.R. Bentley**, A.W. Ndegwa, A. Chu, M. Gharibi and S.R.D. Lunn, "Biodegratation of monoethanolamine in soil monitored by electrical conductivity measurement," *Can. Geotech. J., 41*, 1026-1037, doi: 10.1139/T04-044 (2004)
Bentley, L.R. and M. Gharibi, "Two and three-dimensional electrical resistivity imaging at a heterogeneous remediation site," *Geophys., 69* (3), 674-680.
Zou, Y. and **L.R. Bentley**, "Time-lapse well log analysis, fluid substitution and AVO," *The Leading Edge,* 22, 550-566 (2003).
Meads, L.N., **L.R. Bentley** and C.A. Mendoza, "Application of electrical resistivity imaging to the development of a geological model for a proposed Edmonton landfill site," *Can. Geotech. J., 40*, 551-558 (2003).
Bentley, L.R. and N.M. Trenholm, "The accuracy of water table elevation estimates determined from ground penetrating radar," *JEEG, 7*(1), 37-53 (2002).
Parks, K.P., **L.R. Bentley** and A.S. Crowe, ``Capturing more geological realism in stochastic simulations of rock systems with Markov statistics and simulated annealing", *J. of Sedimentary Research, 74*(4), 803-813 (2000).
Bowles, M.W., **L.R. Bentley**, B. Hoyne and D.A. Thomas, "In situ ground water remediation using the trench and gate system," *Ground Water, 38* (2), 172-181, (2000).

Fennell, J. and **L.R. Bentley**, "Distribution of sulfate and organic carbon in a prairie till setting: Natural versus industrial sources," *Wat. Resour. Res., 34* (7), 1781-1794 (1998).

Parks, K.P. and L.R. Bentley, "Enhancing data worth of EM survey in site assessment by cokriging", *Ground Water, 3*4 (4), 597-604 (1996).

Bentley, **L.R**., M. Gharibi and S.R.D. Lunn, "Time-lapse electrical resistivity monitoring of groundwater remediation", in *Proceedings of the CGS -IAH Joint Annual Meeting*, 17-19 September, Calgary, 944-951 (2001).

Leszkowicz, J.K., **L.R. Bentley**, G. Achari and S.R.D. Lunn, "Deriving Waxman-Smits parameters for estimating groundwater quality from in -situ electrical conductivity measurements", in *Proceedings of the CGS-IAH Joint Annual Meeting*, 17-19 September, Calgary, 960-966 (2001).

Zimmerman, E.P., **L.R. Bentley** and M. Haysahi, "The verification of electrical resistivity imaging in the study of saline and fresh groundwater interaction at Lydden Lake, SK", in *Proceedings of the CGS -IAH Joint Annual Meeting*, 17-19 September, Calgary, 952-958 (2001).

Bentley, L.R., J.F. Sykes, C.A. Brebbia, W.G. Gray and G.F. Pinder (editors), *Computational Methods in Water Resources, Vol. 1 Computational Methods for Subsurface Flow and Transport,* A.A. Balkema, Rotterdam, 1-588 (2000).

Bentley, L.R., J.F. Sykes, C.A. Brebbia, W.G. Gray and G.F. Pinder (editors), *Computational Methods in Water Resources, Vol. 2 Computational Methods, Surface Water Systems and Hydrology,* A.A. Balkema, Rotterdam, 591-1178 (2000).

Other evidence of Impact:

A. Director, CARA Tier 1 CIDA Project (1999-present) The main goal of the project is to create M.Sc. programs in Water Resources at the U. of San Carlos, Guatemala and UNAN, Nicaragua and to add to the M.Sc. program at UCR, Costa Rica.

B. Co-organizer for the IAH-CGS 2001 Specialty Groundwater Specialty Conference.

C. Principal organizer for XIII International Conference on Computational Methods in Water Resources 25-29 June, 2000.

D. President of the International Assoc. of Hydrogeologists, Canadian National Chapter (1996 & 1997).

E. My work on 3-D seismic surveys has been cited in the textbook, Yilmaz, O., *Seismic Data Processing*, SEG [1987] (p. 397, 398, 400).

Dr. Mehran Gharibi, Research Associate, University of Calgary. Dr. Gharibi will have responsibility for day to day operations, equipment construction, advanced analysis and computer program development. He will report to Dr. Bentley and will help supervise the graduate student assigned to the project. We expect Dr. Gharibi to devote one quarter time to the project in the first two years (requested 3 months salary) and 3 months total time in the final stages in which final protocols and the workshop will be completed.

Dr. Gharibi has a B.Sc. in Physics from the University of Shiraz (1987), and M.Sc. in Geophysics from the University of Tehran (1991). He worked for the institute of Geophysics in Iran for two years as lecturer and researcher geophysicist. During this period he conducted several research and service projects in conjunction with industrial problems in power plant and dam site selection, landslide risk analysis, groundwater exploration, and foundation stability analysis in electrical power generator building and high-rise building using refraction seismic, seismic tomography, and geo-electric techniques. He also partially involved in designing, installation and calibration of a radio telemetry seismological network around Tehran.

Later he joined the department of geophysics at the University of Uppsala in Sweden and received his Ph.D. in Electromagnetic Geophysics with emphasis on Magnetotelluric (MT) method (2000). During this period he mapped the electrical conductivity of the Scandinavian crust along a 170 km long profile using MT techniques and also developed transformation technique to improve interpretation of the Very Low Frequency (VLF) electromagnetic data. He also cooperated in designing and testing of a high frequency MT equipment (ENVIROMT) for shallow geophysics and environmental applications.

Since graduation Dr. Gharibi has been working as PDF and later research associate at the University of Calgary. His research focuses on development and application of two- and three-dimensional Electrical Resistivity Imaging techniques for shallow geophysical investigations in hydro-geological and environmental problems. Application of the developed technique on a remediation site illustrated the efficiency and success of the method in monitoring of remediation process in conjunction with the hydro-geological and geo-chemical information. Dr. Gharibi was awarded the University of Technology International (UTI) fellowship for 2002-2003.

The following is a list of his publications:

Bentley, L.R. and **Gharibi M.**, "Two and three-dimensional electrical resistivity imaging at a heterogeneous remediation site," *Geophys.*, *69* (3), 674-680

Gharibi M., Korja T. and Pedersen L.B., Electrical conductivity of the Central Scandinavian Caledonides and the underlying Precambrian basement. *Geophysical Journal International*. (in review).

Wong, R.C.K., L.R. Bentley, A.W. Ndegwa, A. Chu, **M. Gharibi** and S.R.D. Lunn, "Biodegratation of monoethanolamine in soil monitored by electrical conductivity measurement," *Can. Geotech. J.*,, *41*, 1026-1037, doi: 10.1139/T04-044 (2004)

Gharibi M., Bentley L.R. and Lunn S.R.D., 3-D Electrical Resistivity Tomography: optimizing field operation and resolution. The Canadian Society of Exploration Geophysicists (CSEG) National Convention, Calgary, Canada, Extended Abstracts, (2002).

Bentley, L.R., **Gharibi M.** and S.R.D. Lunn, "Time-lapse electrical resistivity monitoring of groundwater remediation", in *Proceedings of the CGS-IAH Joint Annual Meeting*, 17-19 September, Calgary, 944-951 (2001).

Gharibi M. and Pedersen L.B., 2000. Removal of DC-power line magnetic field effects from airborne total magnetic field measurements, *GEOPHYSICAL PROSPECTING Vol. 48, 617-627*.

Pedersen L.B. and **Gharibi M.**, 2000. Automatic 1-D inversion of magnetotelluric data: Finding the simplest possible model that fits the data, *GEOPHYSICS, Vol. 65, 773-782*.

Gharibi M. and Pedersen L.B., 1999. Transformation of VLF data into apparent resistivities and phases, *GEOPHYSICS, Vol. 64, 1393-1402*.

Gharibi, M and Pedersen, L.B., Apparent resistivity and phase estimation from magnetic filed measurements, *in preceeding of the 14th EM Workshop on Electromagnetic Induction in the Earth*, Extended Abstract, Sinaia, Romania (1998).

Gharibi M., Dynesius L. and Pedersen L.B., 1996. Rock quality detection by acoustic wave measurements. *EU project report*, Department of Geophysics, Earth Sciences, University of Uppsala, Sweden.

Graduate students.

Four graduate students will be involved in the project in the coming year.

Sarah Forté (PhD candidate) SP and integrated interpretations
Jennifer Stanners (MSc candidate) IP studies
Kevin Hayley (MSc candidate) Time-lapse processing and interpretation
Amanda Smith (MSc candidate) Numerical modelling of salt transport

4. Project Schedule

Dates	Activity	
Phase I-2004		
March-May	Survey design, electrode construction	
June	2-D reconnaissance survey + 1st 3-D surveys + EM31 & 38 survey	
July	Process and analyze results, 3-D survey design	
Sept.	3-D surveys + Push Tool EC + core	
Sept.-Dec.	Analyze survey results and compare to hard data.	
Dec.	End Phase I	Phase I Report
Phase II – 2005		
Jan.-April	Finalize analysis, update survey design	
May	3-D surveys	
Sept.	3-D surveys + Push Tool EC + core	
Sept.-Dec.	Analyze survey results	
Dec.	End Phase II	Phase II Report
Phase III – 2006		
Jan.-April	Finalize analysis, develop environmental correction protocols, calibrate geophysical interpretations	
May	3-D Surveys	
Sept.	3-D Surveys + Push Tool EC + core	
Sept.-Dec.	Synthesize results, finalize protocols, final report, workshop preparation	
Dec.	Workshop	
Dec.	End Project	Final Report

6. Budget			
Time-Lapse Electrical Resistivity Imaging			
Item	**Year 1**	**Year 2**	**Year 3**
Graduate Student	26500	26500	26500
Research Associate[1]	12375	12375	12375
Field Assistant	3300	3300	3300
Installation Materials[2]	11000	1000	1000
Direct Push Surveys	6000	6000	6000
Computer Supplies	500	400	500
Chemical Analysis[3]	3000	3000	3000
Field Expenses[4]	8702	8000	8702
ERI Maintenance[5]	1200	1200	1200
Survey Equipment Rental	225	225	225
Meetings[6]		1500	1500
Publication Costs		1500	1500
Workshop			3000
Peer Review of Final Report			5000
Total	**72802**[7]	**65000**[8]	**73802**
[1] 3 months/year @ 45000/yr + 10% benefits			
[2] Installation			
Year 1 Thermocouple arrays + hand held measuring unit			
	Measurement Unit		500
	2 arrays X 1000 ft X .5/ft		1000
	Tensiometers		500
	Misc.		1000
Permanent Array			8000
Years 2&3	Misc.		1000
[3] 20 samples X 2 sample campaigns/yr X 50/sample			
+ 1000 for soil samples		3000	
[4] Years 4 people X 2 trips X 10 days		8702	
Meals	3040	38/day-person	
Hotel	4000	50/day-person	
Car Rental	1362	454/wk	
Gasoline	300		
[5] ERI Maintenance 50/d X 24 d/yr	1200		
[6] Meetings 1 National meeting/yr	1500		
[7] The award for year 1 was for 72,802 as opposed to the requested 74,802. This budget reflects the award and changes the requested project total to 212,406.			

[8] The award for year 2 was for 65,000 as opposed to the 65,802 requested. This budget reflects the award changes and the requested project total to 211,604.

7. Peer Review and Communication of Results

Results will be communicated via national conferences and peer reviewed international journals. The results will be appropriate for the joint annual meeting of the Canadian Geotechnical Society -International Association of Hydrogeologists (Canadian National Chapter). The meeting is attended by many professional env ironmental scientists and engineers including representatives of the consulting industry and regulatory bodies.

We plan to publish the results in international journals. The journals that we would consider are *Geophysics*, *Geophysical Prospecting*, *Journal of Engineering and Environmental Geophysics*, *Canadian Geotechnical Journal*, *Ground Water* and *Water Resources Research*.

We also have budgeted for a workshop at the end of the project.

Possible reviewers of the final report:

Dr. Ron Barker
Department of Earth Sciences
The University of Birmingham
Edgbaston, Birmingham B15 2TT
United Kingdom
+44 (0)121 414 6158
R.D.Barker@bham.ac.uk
Area of Expertise: Geotechnical and Environmental Geophysics

David Lesmes:
Assistant Professor
Department of Geology and Geophysics
Boston College
Chestnut Hill, MA 02467-3809
USA
(617) 552-0839
lesmes@bc.edu
Area of Expertise: Hydrogeophysics