geophysics

Colorado School of Mines

geophysics

Spring 2015
Colorado School of Mines

GREETINGS

Look for Us at SEG!

As of this printing, we are still finalizing the details of the annual department alumni luncheon at SEG. Please see Michelle Szobody at the CSM booth in the exhibit hall, or contact her at *mszobody@mines.edu*.

On the front cover: Emily Hart, Class of 2015, collects field data near Mount St. Helens for iMUSH, a collaborative research project funded by the National Science Foundation (NSF). Read more about Emily's experience on page 20.

From the Department Head

Greetings from the Department of Geophysics! We're glad this newsletter has found its way into your hands; we know you'll find it to be interesting and enjoyable. Our aim is to convey through short articles and great photos both the life and the spirit of geophysics programs at Mines. Last fall, numerous individuals and groups in the Department were showered with awards from the Society of Exploration Geophysicists — you'll find the details inside! This spring, Phil Romig, former department head in Geophysics, celebrated 50 (!) years of service at CSM. This is a very interesting time in our department. We are blessed to have an outstanding group of about 150 undergraduates and just under 100 grad students. A group of the undergraduates have written papers concerning "Grand Challenge" problems whose ultimate solution is likely to include the applications of geophysics. The women in Geophysics revitalized their networking and mentoring program and renamed it the Society of Women in Geophysics (SWIG). After a long period of rock-solid faculty stability, the department is in a period of unprecedented turnover. Professor Hale announced his plans to retire in June 2015. CSM has announced that in the C.H. Green Chair, Professor Hale will be succeeded by Professor Paul Sava — both are faculty members of our Center for Wave Phenomena. Professor Davis, Director of the Reservoir Characterization Project, has announced his plans to retire in June 2016 — a search for his successor is underway. We were hard hit by the sudden, unexpected passing of Professor Mike Batzle in January. So we are also involved in a search for his successor. These searches amount to a significant "reinventing" of the department along lines that will become defined by the new talent we choose for the faculty. One of those newcomers to the faculty is Whitney Trainor-Guitton, who is joining us this fall. Pretty exciting!!!

Terry

Colorado School of Mines has named Dr. Paul C. Sava to be the next Charles Henry Green Chair of Exploration Geophysics. Three people have previously held this chair -- Professors Ed White, Ken Larner, and Dave Hale. Larner, Hale and Sava all serve on the faculty of the Center for Wave Phenomena (CWP), and Paul is CWP's current Director. Paul earned his undergraduate Engineering degree from the University of Bucharest, and his M.Sc. and Ph.D. in Geophysics from Stanford University. He

joined the CSM faculty in 2006. The Society of Exploration Geophysicists (SEG) awarded him the Reginald Fessenden Award in 2007 for his contributions to the field of wave-equation imaging. He is currently serving as Education Officer on the Board of the European Association of Geoscientists and Engineers (EAGE). Dave hands the baton to Paul on June 1st. Paul (left) is pictured with Prof. Emeritus Ken Larner and Prof. Dave Hale. *Congratulations, Paul!*

GREETINGS

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Happy Trails, Dave Hale!

Ken Larner, Professor Emeritus

At the end of the 2015 Spring semester, Dave Hale, will be retiring from his position as Charles Henry Green Professor of Exploration Geophysics in the CSM Department of Geophysics. Retiring and Dave Hale? These simply don't go together – and they won't. He's just too young, too energetic, and too creative for that; but these assessments will hold as well for him for a couple of decades into the future. Perhaps "stepping down," but the word "down" has also never applied to him. Dave is "moving over," not for the first time in his career, a career that has had him toggling between industry and academia.

Leaving aside the years from kindergarten through high school, after receiving a B.S. degree in physics from Texas A&M University in 1977 Dave stumbled into geophysics taking a field position in Venezuela, with Western Geophysical Company. It wasn't a year before he was ready for a different perspective on geophysics, transferring to Western Geophysical's research group in Houston. The fit in research was a natural one for him, which meant that it wasn't long

till Dave applied for and was accepted into the Stanford Exploration Project as a Ph.D. student. A few years afterward, he was a senior research geophysicist for Chevron before returning to CSM as associate professor of geophysics, where his arrival gave an immense boost to the future of the Center for Wave Phenomena (CWP) from 1988 till 1992. Then, after four years he returned to industry, where he served as chief geophysicist and software developer for Advance Geophysical, and as a senior research fellow for Landmark Graphics. In 2005, he returned to Mines as the C.H. Green Professor of Exploration Geophysics and till now has taught geophysics and computer science, all the while hanging out – actively (how else?) -- as faculty advisor for the Mines swimming and diving team.

Amidst all this shuffling back-and-forth between academia and industry (well, not really shuffling, since shuffling is an activity never observed in Dave), starting with his Ph.D. thesis "Dip-moveout by Fourier Transform" he has provided the exploration geophysics world with a remarkable number of breakthrough advances in the theoretical and computational exploration seismic method. These include dip-moveout processing of seismic data for which he received the Virgil Kauffman Gold Medal from the SEG in 1989 and which led to his serving as editor of DMO Processing, volume 16 of the SEG Geophysics reprint series and offering SEG's first continuing education course in DMO

DAVE HALE

processing. His paper "Imaging salt with seismic turning waves", demonstrating imaging of salt-dome flanks having dip that exceeds 90 degrees, earned Dave the SEG award for Best Paper in Geophysics in 1992, and for his paper "Atomic meshing of seismic images" he received Best Paper Presented at the Annual Meeting in 2002. This past year, Dave toured the world delivering the 2014 SEG/AAPG Distinguished Lecture, "3D seismic image processing for interpretation of faults and horizons".

Does this summary cover all of Dave's published and presented research? Certainly not. To list Dave's biography, including schooling, employment, scientific contributions, awards and honors for presentations, writing, and scientific contributions would unduly burden this article.

Dave has done large things in his career, and he can expect larger going into the future. Not for recognition; that element isn't there in him. Likely, he'll make time and space for a return to playing bluegrass banjo. Whatever he does, Dave will be doing it swimmingly (he knows no other way), even if that includes a return to hiking the 475-mile Colorado Trail. Can he also take on that challenge swimmingly? He's capable.

Dave promises not to drift too far from Golden, minimizing occasions for us to miss him.

For more insights about Dave, check out the following links:

Interview in the CSEG Recorder:
 http://csegrecorder.com/interviews/view/interview-with-dave-hale

YouTube video talk "My Kind of Crazy: Mines the Best Parts" that Dave gave at the CSM Luncheon during the 2014 SEG Meeting
  https://www.youtube.com/watch?v=HtDWx3iMeLw

Michael L. Batzle
Endowed SEG Student Scholarship

Ludmila Adam and Ronny Hofmann

Sometimes those who inspire us leave us too soon, departing before they had a chance to accomplish all the things they looked forward to doing. This was the case for Dr. Michael L. Batzle, better known as Mike or Batz, who left us all too soon on 9 January 2015. Mike's most cited contributions to geophysics were in rock physics (which he termed "squeezing rocks") and acoustic-fluids research, for which he and Zee Wang received the SEG Virgil Kauffman Gold Medal for their work on seismic properties of pore fluids. In 1994, Mike moved from ARCO to academia, establishing the Center for Rock Abuse at Colorado School of Mines and codirecting the Fluids and DHI Consortium with De-Hua Han.

Mike's legacy started in the classroom; he loved to teach. In the laboratory, he showed that the only way to learn is by giving students the chance to do things by themselves. He was a patient mentor and did not criticize, even if you broke the fifth strain gauge in the lab or yet again the wiring to the geophone.

Mike's close connections with his students arose from his humbleness and humor; he was always just one of the troops. Mike found the perfect balance between "fearless leader" and colleague — even though he had a far deeper understanding of the subject matter. He gave freedom to his graduate students to explore and sometime fail, but he was there for them at each step of their journey. As frustrating as lab work can be, we cherish our years in the laboratory with Batz.

Although not as well known, Mike's legacy extended beyond teaching rock physics and petrophysics in the classroom: He organized and led the Geophysics Field Camp at Colorado School of Mines. Everyone who knew Mike knows that he had a passion for rocks, and the field camp included geologic fieldwork and valuable hands-on experience acquiring (electro)magnetic, seismic, and gravimetry data. During this time, Mike kept up the spirit of the troops and found time to reach out to the local communities.

As former students of Mike's, we benefited tremendously from his knowledge, experience, and wisdom and from his teaching philosophy that focused on the students. Mike will be sorely missed, not just as a mentor but also as a good friend, and we are pleased that SEG has initiated the Michael L. Batzle Endowed SEG Student Scholarship to support future geophysics students and keep Mike's legacy growing. For those of you who did not have the privilege to hear this from Mike directly, we end with a quote from an interview he gave to the Canadian SEG (Chopra, 2006): "What you got to do is figure out what you think is interesting and pretty much design your path around that. My basic theory of life is that life is going to be pretty much whatever you make of it yourself."

We will. And thank you, Mike!

Thank you to the SEG for permission to use this article. Please see page 43 for full citation.

Note: We thank those who have contributed to the Michael L. Batzle Endowed SEG Student Scholarship. If you are considering a contribution to the scholarship, please visit www.seg.org/donate.

"I think geophysics is like a candy store…" Mike Batzle

Dr. Mike Batzle passed away on January 9, 2015. As a geophysicist, it is a great loss to our profession, as Mike was a wealth of knowledge on many topics and was a pioneer in laboratory measurements of fluids and rock properties. On a personal level, it is an even greater loss, as Mike brought a personality, sense of humor, and humility to an industry that is, at times, in desperate need of it.

Mike was probably one of the most humble people you could possibly meet in life, let alone as a geophysicist. At the Green Center at Colorado School of Mines (CSM), where Mike had taught since his 'retirement' from ARCO in 1994, he would introduce himself to new students as "the janitor they keep locked in the basement". I thought he was serious until someone told me he was a PhD Geophysicist from MIT, a Virgil Kauffman Gold Medal award winner from the SEG, and one of the fathers of the Batzle-Wang fluid properties equation. This was a man who dressed for the lab, so much so that while at ARCO, people thought he would show up naked for casual Friday. Dr. Batzle was a consummate workaholic who lived most of his life in his lab, in the classroom, and in the field. He gave so much to the discipline of geophysics, but especially to his students at CSM and around the world.

The science of geophysics is not the same without him.

– *Kurtis Wikel, CSEG Director of Education and former student of Mike Batzle*

MIKE BATZLE

To read Mike's interview in the CSEG *Recorder,* go to http://csegrecorder.com/interviews/view/interview-with-mike-batzle. *Thank you to the CSEG for permission to use this article. Please see page 43 for full citations.*

The SEG bestowed on Norm Bleistein its highest award — the Maurice Ewing Medal. The citation for Norm's award was written by Zhaobo (Joe) Meng, a geophysicist and mathematician who is founder and CEO of In-Depth Geophysical Inc. In the citation Joe gives this brief version of Norm's bio: "Norm received a Ph.D. in mathematics from the Courant Institute for Mathematical Sciences at New York University in 1965. After a year of postdoctoral study there and three years as an assistant professor of applied mathematics at MIT, he moved to the University of Denver in 1969, where he advanced to full professor. In 1983, Norm, along with Jack Cohen, John DeSanto, and Frank Hagin, moved to the mathematics department at Colorado School of Mines (CSM). In 1984, they founded at CSM the Center for Wave Phenomena (CWP) and the Consortium Project on Seismic Inverse Methods, where Norm served as director until 1996." Joe's citation not only describes Norm's important pioneering contributions, both mathematical and geophysical, to the fields of seismic imaging, migration and inversion, but also highlights the human side of Norm that we all love so much: "Norm has always kept a special place in his big heart for all people and various cultures. He has helped many mathematicians to improve their careers . . . ." Appropriately, the punchline of Joe's citation is, "With the Maurice Ewing Medal, the Society of Exploration Geophysicists honors Norman Bleistein not only as an exceptional applied mathematician who has made seminal contributions to the science and practice of geophysics but also as a passionate colleague and mentor to many practicing geophysicists around the world." The entire citation for Norm's award, and others, can be found at http://www.seg.org/documents/9274369/10134793/H%26A_OP14.pdf .

CSM's Reservoir Characterization Project, directed by Tom Davis and co-directed by Bob Benson, received SEG's Distinguished Achievement Award. On its website, SEG notes, "The Distinguished Achievement Award shall be given from time to time to a company, institution, or other organization for a specific technical contribution or contributions that have, in the opinion of the Honors and Awards Committee and the Board of Directors, substantially advanced the science of exploration geophysics." In their award citation, authors Sue Jackson and John O'Brien say, "As an industry-funded research consortium

at Colorado School of Mines, the Reservoir Characterization Project (RCP) has pioneered substantial advances in reservoir characterization through application of multicomponent and time-lapse (4D) seismic technologies. RCP has been an outstanding and consistent voice in the industry, advocating the application of shear-wave seismology . . . This has spurred development of shear-wave acquisition and processing capabilities by service providers, has created real data sets for student research, and has furnished case studies to advance the science and practice of shear-wave imaging and interpretation." They also note that RCP "has a track record of producing some of the most sought-after graduates in the industry." (http://www.seg.org/documents/9274369/10134793/H%26A_OP14.pdf) .

The Presidential Award of SEG is not often given. However this past year President Don Steeples elected to bestow the award on John Stockwell. Chris Liner (with Ted Bakamjian and Isaac Farley) wrote the citation for this award, noting that "John is something of a Renaissance man with a love of classic textbooks and a deep interest in the history of geophysics. His efforts to bring this knowledge to the SEG Wiki are nothing short of remarkable. As of 16 July 2014, there had been 14,409 edits to the SEG Wiki since it was launched. John contributed about 4,800 of those, meaning he is responsible for one-third of the total edits to the Wiki . . . . For his truly exceptional work on the fledgling SEG Wiki, the Society very gratefully bestows on John the Presidential Award for 2014. (http://www.seg.org/documents/9274369/10134793/H%26A_OP14.pdf) .

The SEG gave a Special Commendation for the SEG Advanced Modeling Corporation (SEAM). Among those recognized for this work were CSM's Ken Larner and Walt Lynn. In conveying this award, it was noted, "The SEG Advanced Modeling Corporation (SEAM) has uniquely advanced the science of geophysics within the new paradigm of cooperative research. By sharing the very high costs of model design and data simulation, SEAM has successfully provided forums for industry leaders to discuss geophysical and geologic challenges with great current relevance. It also has advanced the art of modeling and scientific computation by stimulating research and development and has delivered data sets for industry benchmarks and educational learning and outreach." (http://www.seg.org/documents/9274369/10134793/H%26A_OP14.pdf) .

Ivan Vasconcelos, former student of Ilya Tsvankin in the Center for Wave Phenomena, received SEG's J. Clarence Karcher Award. The SEG website notes, " . . . the J. Clarence Karcher Award is given in recognition of significant contributions to the science and technology of exploration geophysics by a young geophysicist of outstanding abilities who, in the unanimous opinion of the Honors and Awards Committee and the Board of Directors, merits such recognition. Recipients must be less than 35 years of age . . . ." In the citation for Ivan, Roel Snieder, Filippo Broggini and co-authors observed, "Ivan is an exceptional person from both professional and personal points of view. His skills in the physics and mathematics of wave propagation and imaging, his creativity, his insatiable curiosity, his ability to make theory applicable to practical problems, and his wonderful personality make him one of the strongest geophysicists in his age group." (http://www.seg.org/documents/9274369/10134793/H%26A_OP14.pdf).

2014-15 Faculty Accolades:

- **Jeff Andrews-Hanna** was the primary author of "Structure and evolution of the lunar Procellarum region as revealed by GRAIL", Jeff Andrews-Hanna, et. al., that made the October 2, 2014 cover of *Nature.*

- **Tom Davis** co-authored a paper that won Best Paper Award at the GeoConvention in Calgary, and a paper he presented at the SEG annual meeting was selected among the top 30 out of approximately 1000 papers at the conference. Tom was also invited to apply for the ENI Award – New Frontiers of Hydrocarbons – Upstream Prize.

- **Dave Hale** was named Fall 2014 SEG/AAPG Distinguished Lecturer: "3D seismic image processing for interpretation of faults and horizons". He spoke at 27 venues worldwide. Dave was also granted an honorary membership in the Geophysical Society of Houston.

- **Yaoguo Li** has been invited to give an EAGE lecture tour: "Gravity and Magnetic Methods for Oil & Gas and Mineral Exploration and Production.

- **Ed Nissen** gave the plenary lecture at the annual meeting of the Southern California Earthquake Center (SCEC), an important meeting of the international earthquake community that attracts more than 500 attendees.

- **Andre Revil** received the 1st Nishida Prize for Promotion of Geoscience, Japan. Andre also published a new book with **Paul Sava**: *The Seismoelectric Method: Theory and Application.* A. Revil, A. Jardani, P. Sava, A. Haas - 2015.

- **Paul Sava** co-authored a paper with CWP PhD student Yuting Duan, "Converted-waves imaging condition for elastic reverse-time migration," ranked in the top 30 papers presented during the 2014 SEG Annual Meeting in Denver, Colorado.

- **Roel Snieder** received a 2014 Research Award from the Alexander von Humboldt Foundation valued at 60,000 Euros. He was also selectedas a Distinguished Lecturer for the European Association of Geoscientists and Engineers (EAGE). **Roel and CWP alumnus, Kasper van Wijk,** published the third edition of *A Guided Tour of Mathematical Methods for the Physical Sciences.* Kasper is currently a faculty member in the Physics Department at the University of Auckland, New Zealand

- **Andrei Swidinsky** was invited to make an E-recording of a paper he presented at the 2014 European Association of Geoscientists and Engineers annual meeting in Amsterdam.

Sue Jackson and Renie Herrin Join RCP

Last fall the Reservoir Characterization Project welcomed staff members, Sue Jackson (left) and Renie Herrin (right). Sue serves as the RCP Project Manager while Renie serves as the RCP Administrator.

Alfred H. Balch Sr., 86, of Golden, Colorado, died peacefully on Friday, May 23, 2014, at Collier Hospice Center after an extended battle with pancreatic cancer, surrounded by his loving family. He is survived by his wife of 61 years, Manie B. Balch; his three children Susan Balch Clapham (David) of Wellesley, Massachusetts, Alfred H. Balch Jr (Sharon), of Salt Lake City, Utah, and Christopher C. Balch (Jeanie) of Louisville, Colorado, as well as grandchildren Katharine, Rebekah, Julia and Charlotte Clapham, and Michael, Christopher, Elizabeth, Louisa and John Balch. He was preceded in death by a grandson, Benjamin Clapham. Born in Manhattan, Kansas, to Katharine and Walter Balch, Dr. Balch spent most of his youth in California. After graduating from Stanford with a degree in geology in 1950, he joined the U.S. Navy and served for three years on destroyers during the Korean War. He began his professional career in the oil industry with Phillips Petroleum, returning to graduate school at the Colorado School of Mines in 1957 and received his doctorate in geophysics in 1964. After a career as a research geophysicist in oil exploration, he became a research professor at the Colorado School of Mines in 1986 and retired in 1998 to pursue his love of the Colorado outdoors -- bicycling and skiing and passionately following the vicissitudes of the Denver Broncos.

Dr. Balch met the love of his life, Manie, on a blind date while stationed in California, married her after a whirlwind courtship and celebrated their 61st anniversary earlier this May. An active father and community volunteer, he helped to bring a Little League organization to Littleton, Colorado, where he also coached a number of soccer teams. An Eagle Scout himself, he was active with the local Boy Scouts for many years.

Among the many honors received during his long professional career, Dr. Balch was particularly proud of being awarded a Fulbright Professorship to lecture and teach at Moscow State University. He was a recipient of the Hagedoorn Award of the European Association of Exploration Geophysicists, served as a national officer of the Society of Exploration Geophysicists, and authored one of the pioneering textbooks on vertical seismic profiling. At the invitation of the U.S. Geological Survey, Dr. Balch established a seismic stratigraphic research group within the organization during the 1980s. He became interested in using seismic profiling techniques to map underground structures such as abandoned mining shafts and tunnels, and received recognition from the Republic of Korea (South Korea) for his scientific contributions.

Electromagnetic Resource Exploration Group

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Electromagnetic Resource Exploration Group

Powerline Effects of Airborne Electromagnetic Data

Benjamin R. Bloss, PhD student; Andrei Swidinsky, Assistant Professor

ELECTROMAGNETICS

During late 2012 and early 2013, the USGS contracted a time-domain airborne electromagnetic (AEM) survey in Winneshiek County, Iowa and Fillmore County, Minnesota, within The Upper Iowa River Watershed. The scope of this survey was two-fold: to map out the structure within the Precambrian basement which may be related to the development of the Midcontinent rift, and to map out the Phanerozoic sedimentary cover for water resource management. Unfortunately, this area had a power line approximately every 1.6 km, which caused substantial contamination in the data. The data affected by these power lines spans an average width of 1.5 km, with late times being affected more, which correlate with longer frequencies and deeper investigations (figure 1).

Because of this trapezoidal shape in affected data (figure 2) a two-step culling process was used: the first step removed whole soundings if the early times were affected and the second step removed only affected late time data. The USGS estimate that as much as 40% of this data set is contaminated by cultural noise. Decay curves with higher amplitudes correlate with more conductive media and will produce false conductors in inverted models. Ultimately, the required culling of the late time data lead to a depth of investigation that was not quite deep enough to image the Precambrian basement
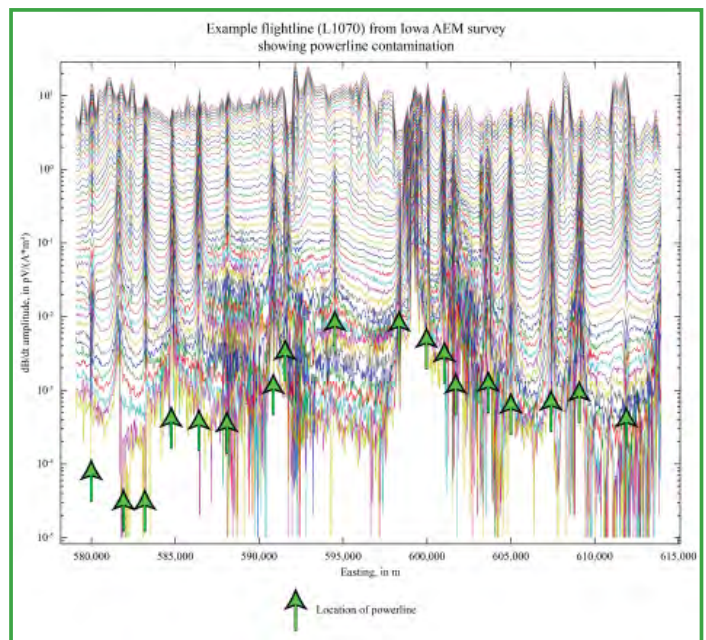

Figure 1 – dB/dt amplitude for each time-gate for line L1070 from Decorah, Iowa AEM survey. Green arrows indicate cultural contamination, most likely from powerlines.
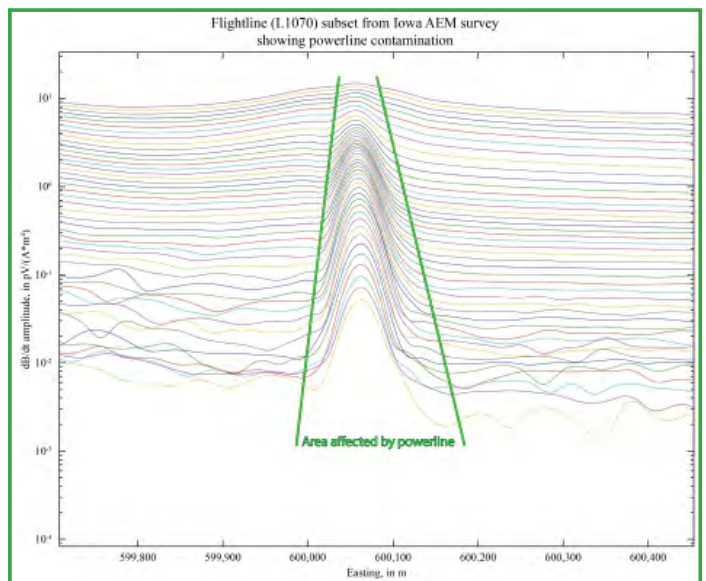

Figure 2 – Zoomed in region of powerline contamination for all time gates. Green lines show trapezoidal area affected. Note this is a 'small' powerline – or only affects the data on a small spatial scale.

directly; however the deepest sedimentary layer in the stratigraphic column was used as a proxy to estimate the depth to basement.

My graduate work is to identify the mechanism causing this powerline contamination, and hopefully develop a scheme to remove these effects allowing the contaminated data to be used. This project is in its infancy, but currently I am working on classifying

Figure 3 – Several general types of powerlines.

and cataloguing the various responses for different types of powerlines (for example, single wire distribution lines or large multi-wire transmission lines, figure 3) using a ground based time-domain system. We speculate that the contamination is from several sources, but the primary source is galvanic coupling which creates ground return loops containing inductors (L) and resistors (R) (see figure 4, courtesy of Esben Auken).
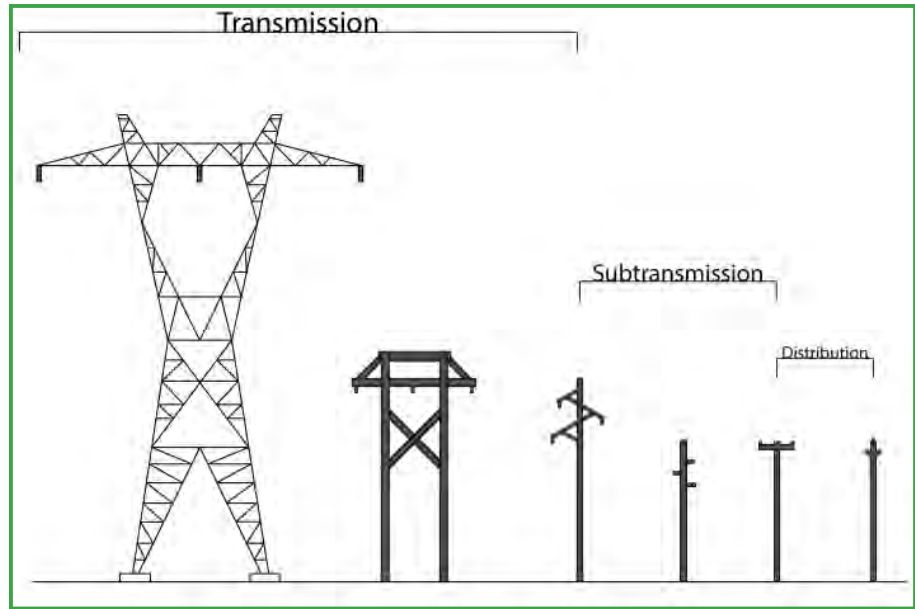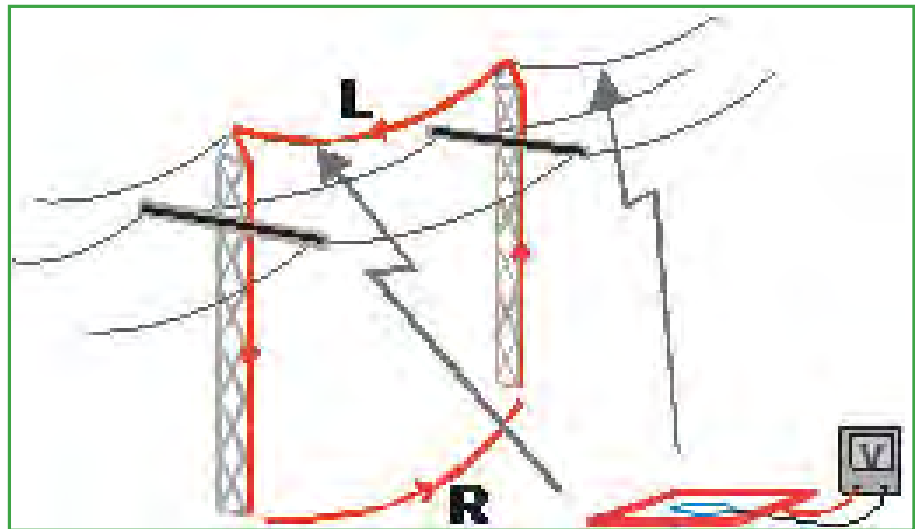
Figure 4 – Galvanic coupling. This galvanic return path contains both inductors (L) and resistors (R).

Reservoir Characterization Project

RCP in Argentina...Kyla Bishop, MS student

In April of 2014 Wintershall, a subsidiary of BASF – the largest German chemical company, brought a project to the RCP group looking at optimizing well locations in the Vaca Muerta Formation of central Argentina. The company is looking to drill several wells over the course of the next few years in order to improve technical understanding of how this reservoir ticks, and where to place horizontal wells in the future. This is the first time that RCP is venturing outside of North America, and the first time that RCP is looking at such an early stage unconventional resource. Jorge Fernandez-Concheso and I were offered the opportunity to look at this complex system as part of our master's degree research, and to kick the project off.

The high pressures in the Vaca Muerta, the tight carbonate rocks that make up the Formation, and the relative lack of historical data for the petroleum system mean that we are at an early stage of trying to understand how best to produce from this rock. Our work started with Jorge heading to Wintershall's headquarters in Kassel, Germany to spend his summer working on the data and tapping into the work that the Geomechanics team there has already done.

The key to our success in this project will be the integration of our two approaches. Jorge is trying to locate sweet spots from a geophysical perspective, using seismic inversion and attribute analysis to try and find those zones, which seem to exhibit favorable mechanical behavior. I am looking to define what constitutes the best mechanical properties for the development of those fracture systems, doing so from a geologic perspective using wireline logs, and image logs in particular, to characterize the distribution and nature of fractures at the reservoir level. Together, these two components define how we predict where complex fracture systems can be developed, then go about predicting those locations.

Jorge and I are exploring concepts in geoscience that we find interesting, the questions of how we quantify our observations, and move beyond correlation to try and establish causal relationships. Ultimately though, our work will be available to Wintershall, and all RCP sponsors, in order to offer insight into what works and doesn't work for building an integrated project at this stage of development. Jorge and I are working on our own topics but with frequent discussion, so that our projects can benefit from the other's expertise and findings. As we move forward in this endeavor, we in close collaboration with Wintershall's offices in Buenos Aires, Argentina and Kassel in order to tap into their technical experience and ensure that our project can provide the greatest value. Finding our own 'sweet spots', of what time is best to hold a conference call that spans 3 continents, interacting with our multinational team (Canadians, Venezuelans, Germans, and Argentines) and trying to coordinate travel and face-to-face collaboration in the form of workshops (Argentina in February!) and internships, is how we're gong to make this project exceptional.
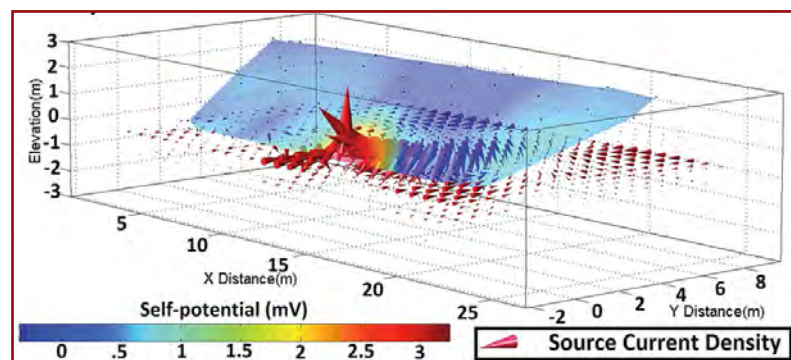
HYDROGEOPHYSICS AND POROUS MEDIA

A New Technique to Detect and Monitor Focused Seepage and Internal Erosion in Earth Dams and Embankments

André Revil, Associate Professor and Justin Rittgers, PhD Candidate

Earthen levees and dams constitute a major category of modern-day aging infrastructure that offers critical functionalities, including flood protection, fresh water transport and supply, and energy production. In the Netherlands (42,000 km2), approximately 25 percent of the country is below sea-level and 65 percent would be flooded or susceptible to regular flooding in the absence of current levels of protection from the sea and rivers. Protection is provided by 3,200 km of dikes, dams and levees along the main water bodies, and 14,000 km of dikes and levees along smaller waters. The high levels of economic and social risk associated with dam and levee failure creates a need for early and more precise remote detection, imaging, and monitoring of poorly performing and elevated risk sections of earthen embankments. This has motivated a recent work successfully published in Geophysical Journal International (Rittgers et al., 2015) by the group of hydrogeophysics hosted by the department of Geophysics of the Colorado School of Mines. We developed a passive seismic monitoring of embankments and dams by introducing a novel 4D acoustic emissions source localization algorithm. This technique is used to find the location of discrete acoustic emissions events. In turn, this information is used to constrain

Final flow model determined form the combination of passive seismic and electrical field data. The flow model is consistent with the observed location of the seepage through the dam.

the self-potential inversion process. Self-potential signals are passively recorded electrical field fluctuation associated with the flow of water in porous media (a so-called electrokinetic effect). Assuming that both passive techniques are sensitive to concentrated seepage and internal erosion processes that precede levee failures, we develop a new technique to monitor focused flow in dams and embankments. We apply this approach to passive seismic and self-potential monitoring data recorded during a 7-day full-scale levee embankment failure experiment referred to as the "IJkdijk" test (pronounced "ike-dike," and Dutch for "calibration levee"). We believe that this new approach could be used to characterize many types of hydromechanical disturbances at different scales affecting the upper crust of our planet.
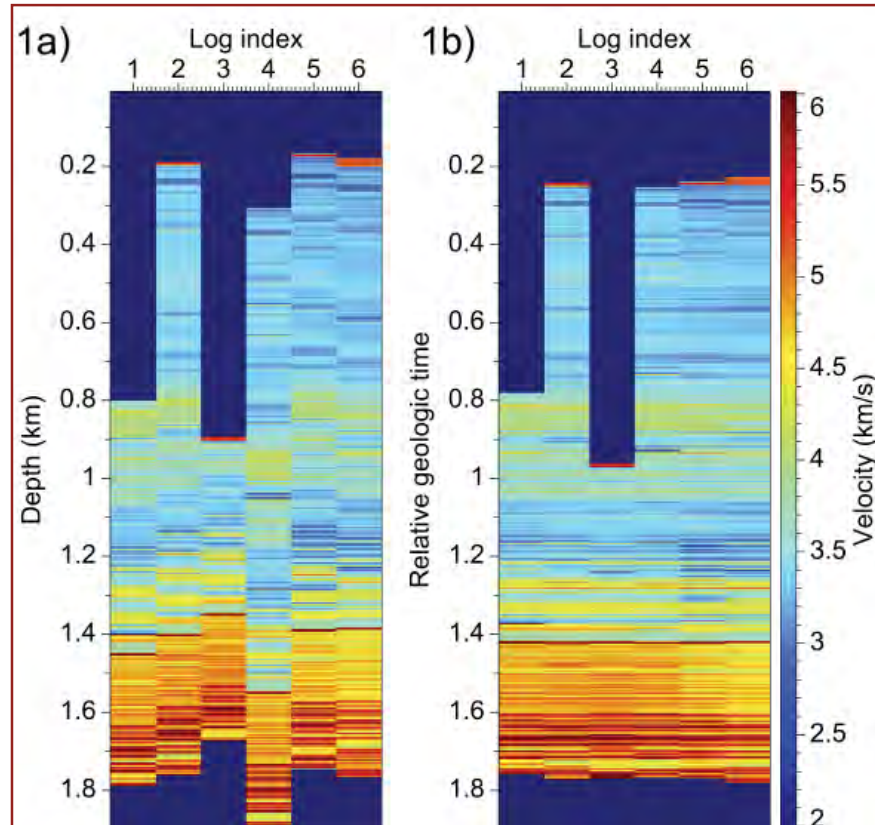
Reference: Rittgers J. B., A. Revil, T. Planès, M. A. Mooney, and A.R. Koelewijn, 4D imaging of seepage in earthen embankments with time-lapse inversion of self-potential data constrained by acoustic emissions localization, Geophysical Journal International, 200, 758-772, doi: 10.1093/gji/ggu432, 2015.

HYDROGEOPHYSICS

Center for Wave Phenomena

"Simultaneous Correlation of Multiple Well Logs"
Loralee Wheeler, MS 2015

Well log correlation is an important step in geological and geophysical interpretation, but as the number of wells increases, so does the complexity of the correlation process. Several methods for multiple well log correlation exist, but these methods do not require consistency over all pairwise correlations. We have developed a new method for automatic and simultaneous well log correlation that provides a globally optimal alignment of all logs, and in addition, is relatively insensitive to large measurement errors common in well logs.

First, for any number of well logs, we use a new variant of the dynamic warping method, requiring no prior geologic information, to find for each pair of logs a set of corresponding depths. Depths in one log may have one or more corresponding depths in another log, and many such pairs of corresponding depths can be found for any pair of well logs. A single pair of such corresponding depths implies that the sediments at those depths were deposited at the same geologic time.

Using these sets of corresponding depths, we compute a relative geologic time (RGT) for each sample in each well log, which allows us to map the logs from depth to geologic time. An example of this mapping is illustrated in Figure 1, where we use the phrase "relative geologic time" to indicate that the geologic time scale used here is arbitrary. We know only that sediments with greater RGT were deposited before those with lesser RGT. For each RGT in Figure 1b, we have a set of six corresponding depths, one for each well log.

CWP

"Elastic Migration with Converted Waves"

Yuting Duan, PhD student

Elastic migration with multi-component seismic data can provide additional subsurface structural information, for example, fracture distributions and solid-related properties. In elastic media, source and receiver wavefields are constructed using elastic (vector) wave equations. Multi-component wavefields allow for a variety of imaging conditions. A simple imaging condition for multi-component wavefields is the crosscorrelation of components of the placement vectors in source and receiver wavefields. Polarity changes in converted-wave images constructed by elastic reverse-time migration causes destructive interference after stacking over the experiments of a seismic survey.

Under the guidance of my advisor Paul Sava, I derived a simple imaging condition for converted waves imaging designed to correct the image polarity and reveal the conversion strength from one wave mode to another. Our imaging condition exploits pure P- and S-modes obtained by Helmholtz decomposition. Instead of correlating components of the vector S-mode with the scalar P-mode, we exploit the entire S wavefield at once to produce a unique image. We generate PS and SP image using geometrical relationships between the propagation directions for the P and S wavefields, the reflector orientation, and the S-mode polarization direction. Compared to alternative methods for correcting PS and SP images polarity reversal, our imaging condition is simple and robust and does not add significantly to the cost of elastic reverse-time migration.

We also applied this new imaging condition to elastic migration using water-column multiples in OBS (Ocean Bottom seismic) data. We first separate receiver-side water-column multiples from primaries in recorded OBS data, and then use mirror imaging to migrate the multiples. The elastic images provide complementary information about the subsurface structures, and can be used to perform more accurate petrophysical analysis, compared to more conventional images obtained from acoustic data.
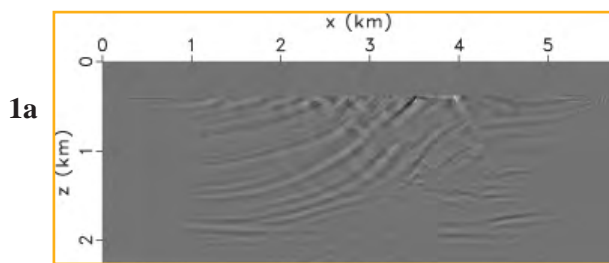

1a

Figure 1(a) and 1(b): PS stack images obtained using (a) the conventional and (b) the new imaging condition.
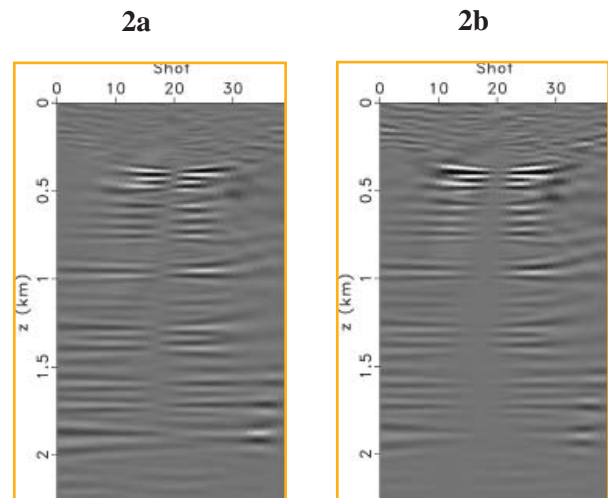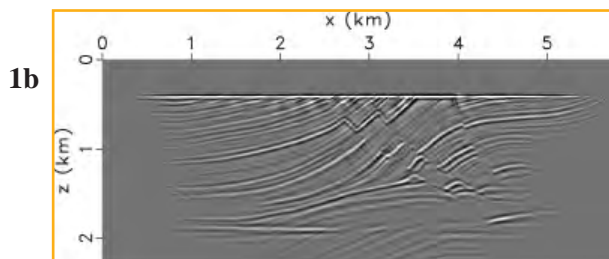
1b

2a

2b

Figure 2(a) and 2(b): PS common image gather at x = 2 km obtained from (a) the conventional imaging condition and (b) our new imaging condition.

CWP

The Fulfillment of Field Camp
Tiffany Lane, Class of 2014

2014 Geophysics Field Camp - Pagosa Springs, Colorado

The experience that I had at field camp was a very important piece of the curriculum that I had at the Colorado School of Mines. The processes used in Geophysics and geophysical investigation of the Earth had seemed abstract to me before going to field camp. As students, my colleagues and I spent countless hours in the classroom learning advanced math and physics and how it applied to the theories and applications of geophysical methods. We had taken geology courses to learn about the structure of the earth and sedimentary processes. However, after using gravity and magnetic methods to understand these processes and using acoustic waves to understand different structures, it was still difficult to picture how it would really work in practice.


When we arrived in Pagosa Springs in southern Colorado, we spent a few days learning and understanding the geology of the area. We explored "the dome", also known as the Archuletta anticline, for surface features that indicated where hot water was flowing. "Where was the water coming from?", this was our main purpose of being in Pagosa. This question has been asked by many students and faculty that have come through this area in the years past. Our task was to attempt to answer this question using everything that we've learned in our studies at Mines. Geology, physics, math and geophysical methods all came into play in attempting to answer our question.

After time well spent investigating the geology of the area, we dove right into geophysics. Some of these methods we had practiced before at the school, but some of the methods,

such as seismic, we were seeing for the first time. Spending time in the "doghouse" and seeing raw data being recorded, seeing the vibroseis truck in action was an experience that I would never forget. I am so thankful to the companies and the professionals who donated their time and equipment to help us acquire seismic data.
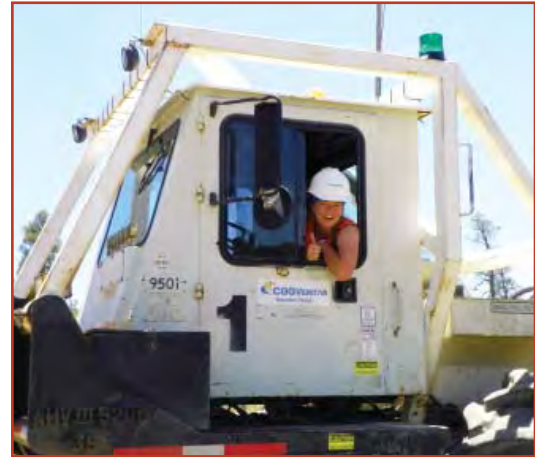
Half of our field camp was spent back at CSM where we processed all of the data that we had collected. This was a huge task for us and gave us the much needed experience of processing geophysical data. This is where it all came together, all of the methods combined to answer the question that we were all so curious about. We discovered a large fault in the area. This was a very surprising find for many of us and it helped us answer the big question, "Where is the water coming from?"

The entire experience of field camp is one that added to my academic experience in an incredibly valuable way. It took away the abstract element of geophysics that had been lingering in the back of my mind, and helped me to understand geophysics as a whole. Seeing all of the different methods come together to paint a geologic picture solidified my understanding of how incredible geophysics really is.

Magnetotellurics for Mount St. Helens   Emily Hart, Class of 2015

Imaging Magma Under St. Helens (iMUSH) is a National Science Foundation supported research project organized to image the structure of the Mount St. Helens magmatic system in southern Washington. The iMUSH project aims to determine the general architecture of the system by combining a variety of geophysical imaging techniques: magnetotelluric, high-resolution active source seismic imaging and passive seismic monitoring and imaging. A 70-element passive seismic array will be deployed for two years in a 50 km radius around the volcano for both structure and seismicity analyses. The active seismic experiment occurred in late July 2014 and involved the deployment of 3500 active seismic sensors in two days. The magnetotelluric portion of the fieldwork is ongoing over two field seasons and estimated to be completed in 2015.
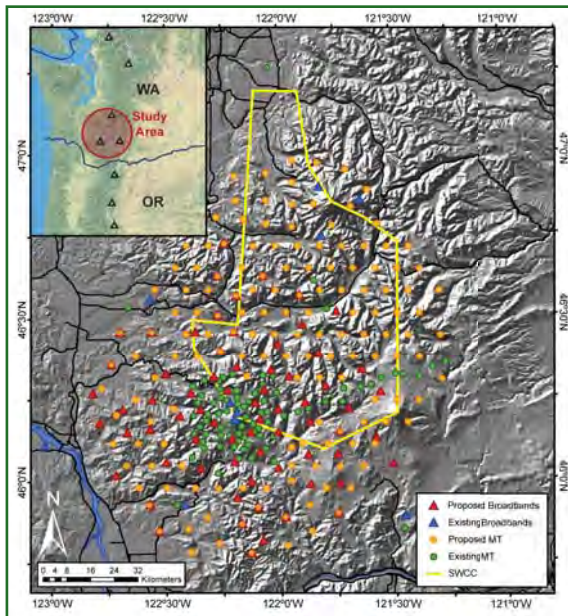
With combined direction from the U.S. Geologic Survey and Oregon State University, I had the opportunity to participate in one of the magnetotelluric field deployments this past summer. Our goal was to deploy two systems and take down two systems per day, allowing each to run for approximately two days. Each site consisted of two dipoles set perpendicular to each other with electrodes spaced 50 meters apart and three magnetometers buried in the x, y, z directions. All components are wired to a ZEN High-Res Receiver connected to a large car battery with a grounding rod and a GPS puck, hopefully located beneath a break in the canopy.

The majority of sites are located on either forest service or tree farm land, ranging from recently clear-cut debris four feet deep to an untouched and thorn-wielding dense thicket. Prime real estate consisted of a swath of tree farm land that had been clear cut and re-planted a few years back, where the debris had generally decomposed

and the saplings were tall enough to avoid stepping on. We quite often had to trudge the equipment through difficult terrain, but every time that I stopped to look around I couldn't help but think how lucky I was to work in such a beautiful setting. At one site, I legitimately felt like I was in Fern Gully and we found some awesome hidden waterfalls on the trek to another. Despite the many technical difficulties inherent with using a new system in what is practically a rainforest, the work was fulfilling and one of the neatest experiences I've had as a student in geophysics.

Making ShakeMaps at the USGS
Flannery Dolan, Class of 2016

Last summer, I worked in the USGS seismic hazards office in Golden. I worked in the earthquakes department making ShakeMaps. ShakeMaps are maps of ground shaking caused by an earthquake. A ShakeMap may include areas hundreds of kilometers away from the epicenter and shows the magnitude of the shaking at every point. The ground shaking is based on numerous factors such as the magnitude and depth of the earthquake, the soil conditions in the area, and topographical features like mountains and lakes. My job, in general, included everything having to do with ShakeMaps. I interpreted papers that detailed the causative fault of an earthquake and used that information to make a fault model in the ShakeMaps for those earthquakes. A fault model increases the accuracy of a ShakeMap, because the ground shaking on the map begins at the lines of the fault, much like an actual earthquake, rather than the point source of the epicenter. Additionally, I added strong motion data from stations in different countries to the ShakeMaps, created scenarios (earthquakes that have not occurred but may in the future), and dabbled in some Python code.Overall, working for the USGS is a fantastic way to learn how geophysics is used when researching natural hazards. It also provides an opportunity to work with incredibly brilliant geophysicists. The use of geophysics and the proximity of the seismic hazards center make the USGS an amazing opportunity for undergraduates and graduate students at the Colorado School of Mines.
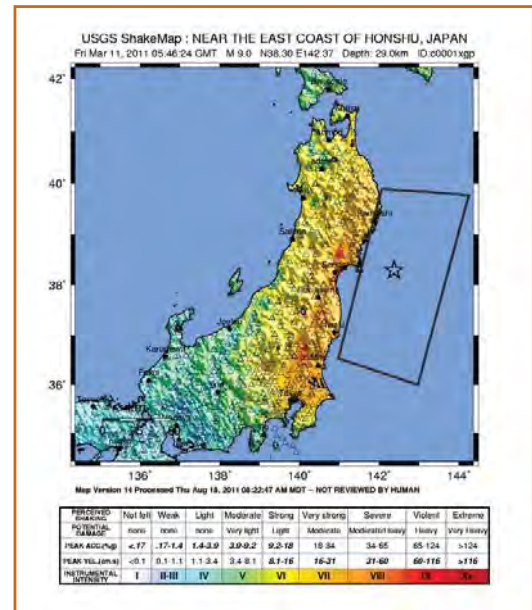
ShakeMap courtesy of the USGS

Congratulations to Eric Bunzli, recipient of the second annual *Ken Larner Prize for Exemplary Writing*. Eric is pictured with Department Head, Terry Young (left) and Dr. Gavin Hayes, USGS/CSM Adjunct Associate Professor (right).

A Summer in the Big Easy
Stephen Paskvich, MS candidate
Reservoir Characterization Project

Chevron gave me the opportunity to spend three months with them last summer. It was a great internship during which I learned a lot and made good friends – not to mention all the fun of New Orleans. Getting this opportunity was a direct result of the quality of the geophysics program here at Mines.

I was fortunate to work with a very experienced mentor in Chevron's Covington, Louisiana office. My mentor had decades of experience in a variety of roles in exploration as well as development. I worked with him and a number of other experienced geophysicists on an asset development team. As part of the team, I helped characterize existing reservoirs in the Gulf of Mexico to delineate reservoir properties and look for bypassed pay. Asset development is a faced paced unit where wells are drilled quickly, and your work can have an immediate impact. Though I drilled no wells, I was able to propose areas for further exploration and possible development.

My project consisted of performing attribute analysis as well as inversion, then interpreting the results and integrating them into the existing interpretation for the field. Through the analysis I was able to reinforce and extend the existing interpretation by expanding the fault interpretation as well as quantitatively estimating the porosity and lithology distribution in the reservoir. Local stratigraphic features and fluid content were investigated as well. Interpreting each of these features and combining with production data revealed useful trend and highlight locations within the reservoir favorable for further characterization and possible development.

I learned a great deal over the summer and feel fortunate to have worked on a project that may have real value to Chevron in the future. The training and mentoring was first class. The

opportunity to do an internship, with any company, is invaluable. The only reason the opportunity was available was because of the quality of the program at the Colorado School of Mines and the education I am receiving. It is top caliber and provides excellent preparation for a meaningful, scientific career.

The Summer Before Senior Year: An Informal Tour of the Geology of North America   Katerina Gonzales, Class of 2015

I was in the middle of the Arizona desert during spring break 2014 when I received confirmation that I was accepted to MIT Haystack Observatory's research internship program. I was beyond excited, but I had no idea of the great experience that the summer would be. I was to do research on the hemispherical differences between geomagnetic storms, and MIT let me arrive one week late to the program, since Geophysics field camp conflicted with the start of the program. The field camp was the awesome and crazy start to my summer, studying the geothermal system in Colorado's southwestern Rockies. I left the day after our final presentation to fly to Boston. The internship included 11 undergrads from all over the country and most of my colleagues were physics or astrophysics majors. It was different from being with geophysics peeps 24/7, but by the end of the summer we all grew to know each other pretty well. Their projects ranged from looking at quasars to Mars to building an antenna. My project, along with two others, was focusing on earth's upper atmosphere, or as my advisor called it, "Geophysics looking up".

Studying the ionosphere is important because some large geomagnetic storms can disrupt satellite communications. My research consisted of looking at case studies of geomagnetic storms in MATLAB and analyzing the total electron count (TEC, measured by GPS satellites) as a function of hour in each hemisphere during the day of the storm. I also looked at how TEC varies per hour in a non-stormy day in each month to provide a sort of baseline when looking at these case studies. I then compared the results between the hemispheres of my case-study storms. I was looking for storm-enhanced density (SED) of the TEC, which would appear as anomalies against the baseline that I created. My project found that SED events may be a function of the time of day. I had the honor of giving an oral presentation of my research at the American Geophysical Union's 2014 Fall Meeting.

The REU program had many extra perks including science seminars, tours of the Haystack telescope (a radio telescope) and a star party at the nearby Wallace Observatory (optical telescope). The highlight of the summer was going to Seattle with three other interns and a few of the research scientists to attend a conference/workshop on the field of Aeronomy. Our intern group also went on many informal excursions including visits to the MIT and Harvard campuses in Cambridge, eating lobster in Maine, hiking in New Hampshire's White Mountains, whale watching in Boston, and generally eating a lot of good seafood and ice cream.

Before leaving for my final flight of the summer (to vacation in Calgary for a week), I weighed my rocks I had collected from my adventures--seven pounds! I had collected some from the Appalachian gneiss in New Hampshire, a chunk of basalt from Maine's Marginal Way, and pumice from a day trip to Mt. Rainier National Park. I would pick up more sedimentary rocks from the Albertan Rockies--a good end to the informal sample of North American geology. I had an incredible three weeks interning at MIT Haystack, but by the end of summer, it was good to return to the foot of Colorado's Rocky Mountains in Golden.

REU

Research and Roos

Allie Grazulis, MS student, Reservoir Characterization Project

Beaches, kangaroos and red dirt….Just a few things that typically pop into someone's head when thinking about the Land Down Under. Yes, that's right, I'm talking about the great continent of Australia! This fall I was fortunate enough to take part in a study abroad semester at Curtin University in Perth, Australia. Perth is located on the far west edge of the country, thousands of miles from more well-known places, like Sydney and the Great Barrier Reef. The state of Western Australia (WA) takes up one third of the continent while being inhabited by only 2.5 million people over the entire state. From the great wilderness of the Kimberley to the white sand beaches of the South West, to the mining towns scattered throughout the Outback, Western Australia is a truly incredible place with adventures of all kinds.

Over the semester, along with enjoying the amazing sites, I conducted research in the shale gas consortium at Curtin. I teamed up with a PhD student working on seismic responses of synthetic shale blocks. We created several synthetic shale samples with varying amounts of total organic carbon (TOC). The majority of the semester was spent in the lab creating the samples as well as carrying out the experiments. Tests included core holder pressure tests, various shale compaction methods, and amplitude tests. An important aspect of the project was

learning about the different machines and equipment in the lab. There were two main pieces of equipment I used in the lab. The first was the Hooke's Cell (axial pressure machine), which was used to compact the samples. The second was the True Tri-Axial Stress Cell (machine that applied axial as well as confining stress on the samples), which was used during the seismic amplitude tests. The goal was to apply pressure of 0-2000psi on the samples while simultaneously collecting seismic amplitude data from the eight transducers that we had spread over the sample. Velocities and amplitudes were analyzed to understand how different TOC percentages affected these properties.

Studying the structure and rock properties of shale is very important in the understanding of shale on an exploration and production level. Knowing the composition and structural parameters of a formation is crucial when analyzing production, frac'ing and economic feasibility. Laboratory experiments are a good way to see the dynamics of a shale sample first-hand. Knowing the percentage of organic content in a prospective reservoir is one of the most important factors when developing a shale formation. Based on the lab experiments, TOC had a direct effect on amplitude response. The more TOC present, the lower the acoustic impedance and thus the reflection coefficient increased. In most cases, increasing amplitude was evident among shale with higher levels of TOC. A seismic amplitude baseline for determining TOC percentage over an area of interest would be extremely useful for shale exploration and production.

The past semester was not only beneficial on an academic level, but on a personal one as well. Over those few months I was able to work with people from all over the world, and learn about different work styles and cultures. I had the opportunity to interact with people who were studying a variety of different oil and gas related topics, and saw many interesting experiments take place. I greatly enjoyed my time abroad and met so many wonderful people. It was exciting to study in a new place as well as explore a city on the other side of the world!

"The world is a book and those who do not travel read only one page" – St. Augustine
Alex Mabrey, MS student, RCP

Before coming to the Colorado School of Mines, I had the amazing opportunity to travel the world for 9 months before starting my Master's degree. I began my journey in Western Europe and found myself walking through the ruins of Angkor Wat in Cambodia, sailing through Turkey and Croatia, busing through the Balkans, surfing in Australia and bartering my way through the Souks of Marrakech. Every day was a new adventure, and there was always something new to learn whether it was about the people, the food, or how to figure out the subway system in just about every other city.

Although traveling may seem to be the most interesting thing I've done since I was born, I also played water polo for 7 years of my life and even took part in the Junior Olympics two years in a row in sunny California. For my undergraduate research, I studied and interpreted the internal stratigraphy of the Greenland ice sheet with Dr. Ginny Catania and Dr. Joe McGregor (CSM Alumni) at The University of Texas at Austin. After I graduated from UT, I had another amazing opportunity of working at EOG in their Oklahoma City office. That summer is when I truly realized that I was in the right place. No, not in the city where I was constantly running from tornadoes, but working with and interpreting seismic data- a true geophysist.

So from Texas to Europe to Africa to Asia to Australia, I have finally arrived at my current destination: THE BEAUTIFUL STATE OF COLORADO. I still have to pinch myself every

time I look out the window and see that breathtaking mountains surround me. I have never felt more thankful than I do now being here at the Colorado School of Mines. I am so excited to be part of the Reservoir Characterization Project that is constantly in the forefront of new technology and discoveries in the industry. Even though I have just arrived, I hope to dive straight into research in the Watternberg field, specifically in the Niobara formation. My academic interests include, but are not limited, to: seismic processing, correlating seismic and well log data, seismic interpretation and characterization, and simply learning about new technologies in geophysics and the industry.

More Gravity, Please!

Patricia MacQueen, PhD student, Center for Gravity, Electrical and Magnetic Studies

I am a bit odd. I am one of those rare ones who entered undergrad not only knowing what geophysics was, but knowing that I was interested in it. I got even weirder when I heard about scientists using gravity measurements to study volcanoes. Not only had I managed to become ensnared by the off-the-beaten-path field of gravimetry, but I had gone even further off the beaten path by my fascination with using gravity to study volcanoes.

My undergrad adviser at the University of Oregon didn't help matters at all by assisting me in arranging a summer volunteer position at the Hawaiian Volcano Observatory. At HVO, I was given the task of completing that summer's 4-D gravity survey of Kilauea. I loved the fieldwork – hard to argue with no hole-digging (no seismometers to bury!), driving a government vehicle all around an active volcano, and getting to play with those sleek CG-5 gravimeters.

I also loved the lab work, the satisfaction of seeing the confirmation of a good day of surveying, and the challenge of extracting useful information from less than optimal data.

This experience in Hawaii drove me on to pursue a master's degree at Simon Fraser University in volcanology and geophysics. Thus it was I ended up destroying two pairs of boots while conducting a Bouguer gravity survey of Cerro Negro volcano in Nicaragua (when your adviser tells you to bring leather sided boots, believe him).

The master's thesis had only satisfied one side of my interests, however. I could never get my fill of Matlab coding. I realized I wasn't content using someone else's code to invert my gravity data, I wanted to write my own! I wanted to find new and more efficient ways of planning a survey. I wanted to know what other questions about the earth 4-D gravity could answer.

And so I've come to Mines looking for answers, or perhaps more questions, ones I haven't even thought of yet. I'm excited to finally be around people just as gravity-mad as me, if not more. Already I'm feeling energized by all the amazing people and fascinating research in this department after just two weeks – I can hardly wait for the next (hopefully) four to six years!

Grand Challenge: Carbon Sequestration
Austin Bistline, Class of 2015

Carbon sequestration is essentially the removal of carbon dioxide from the atmosphere [Katzer et al,. 2007] with the assertion that it has been placed there via the combustion of fossil fuels to meet energy needs over the last several centuries – emphasized over the last six decades. The scientific consensus is that "Human activities are modifying the concentration of atmospheric constituents that absorb or scatter radiant energy"and that "most of the observed warming over the last 50 years is likely to have been due to an increase in greenhouse gas concentrations" – mainly CO_2 [Oreskes, 2004] (Figure 1).

Increasing average global temperatures (Figure 2) are something to be concerned about, but even more concerning is the way increasing temperatures affect global and regional climate patterns. For instance, farmers in South Asia who have relied on rich farmland to survive for centuries, are increasingly seeing their fields flooded due to heavy rains and rising saline sea water. Rising sea levels are associated with melting ice in arctic/antarctic regions, as well as the nature of seawater to expand slightly as it is warmed.

Carbon-based fuels are currently our most economical fuel source – likely because coal, in particular, is found in abundance and is relatively cheap to produce. To curb the creation of excess CO_2, you might say that we need only to develop alternative energy sources to replace carbon-based fuels – and indeed, this is why making solar energy economical and providing energy from nuclear fusion made it onto the list of grand challenge problems for the next century. However, if we could somehow capture a good portion of the waste created through burning fossil fuels, then we could essentially mitigate the snowballing problem of global warming and climate change. This forms the basis for carbon sequestration. The question then is: If we are able to capture CO_2, what do we do with it? Where do we store the vast and expansive quantities of this low density medium?
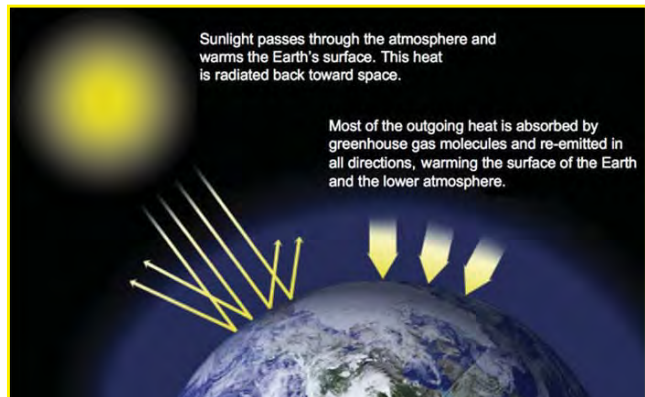

Figure 1: A simple demonstration showing how excess CO_2 can cause global warming. (www.nasa.gov)

MIT conducted a study on the longterm outlook of coal as an energy source and discussed in detail the possibilities of carbon sequestration. The study concluded that for the matter of carbon sequestration, subsurface sedimentary structures are the best storage solution for excess CO_2 – injecting it into sedimentary reservoirs [Katzer et al., 2007]. There are several large-scale carbon sequestration operations including one that is injecting CO_2 into reservoirs beneath the North Sea and another into reservoirs beneath Algeria in North Africa. The largest geological carbon sequestration operation [to date] harvests 2.8 million tons of CO_2 annually in Canada, where CO_2 injected into the subsurface also charges petroleum reservoirs, aiding its extraction [Kramer, 2012].

At first glance, it seems reasonable that such an operation will be a good longterm containment solution given the fact that natural gas (methane) has migrated, but remained trapped underground

for millions of years. However, if we imagine the natural gas reservoirs as the anomalies – analogous to the small puddles that remain after a flood – it seems less sustainable. The density contrast between subsurface material and CO_2 is such that the gas will constantly and forever try to move and migrate upward and/or laterally. Any fracturing or faulting of the subsurface in the near or extreme longterm future could essentially release the CO_2 back into the atmosphere, defeating the purpose of the sequestration effort. Therefore it is critical that we understand completely the subsurface sedimentary structure wherein CO_2 will ultimately be stored and for this objective, applied geophysical methods are the solution.

Figure 2: (above) Rising average global temperatures recorded since 1880 are likely due to human activity, specifically the burning of fossil-fuels for energy production.

The first thing that should be done to assess the viability of a sedimentary structure to sustainably contain CO_2, should be to identify whether it has held gas before. If it has produced natural gas in the past, then we can determine with some assurance that the reservoir has successfully contained gas for millions of years – otherwise it would have migrated away long ago. However, any reservoir that has been discovered and produced has likely undergone pressure fluctuations capable of creating fractures that extend through the sealing formation, decreasing the sedimentary structure's ability to contain CO_2.

Seismic imaging is perhaps the best method for determining the condition of subsurface sedimentary structures because – of all the geophysical methods – it returns the highest resolution image for the multi-kilometer depths required. Reservoirs that have been produced generally have consistent spatially sampled well-log data available which can effectively increase the accuracy of seismic imaging if parameters like sonic data for rock interval velocity (the velocity at which a wavefront moves through a specific rock layer) and facies boundary depths are accurately correlated with the seismic image during processing. Utilizing advanced seismic processing techniques including full-waveform inversion (Figure 3) could create subsurface images good enough to assess the condition of subsurface sedimentary structures.
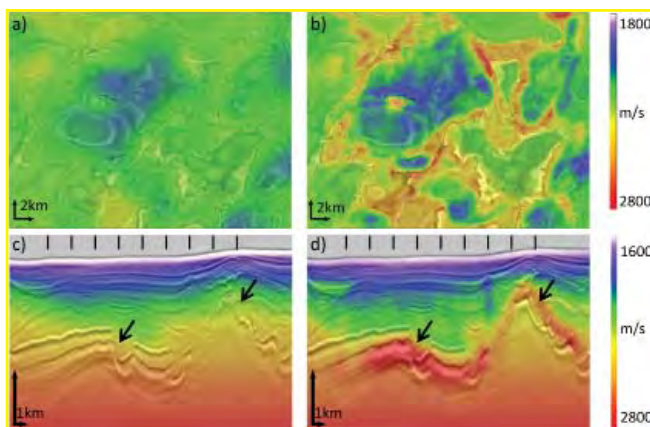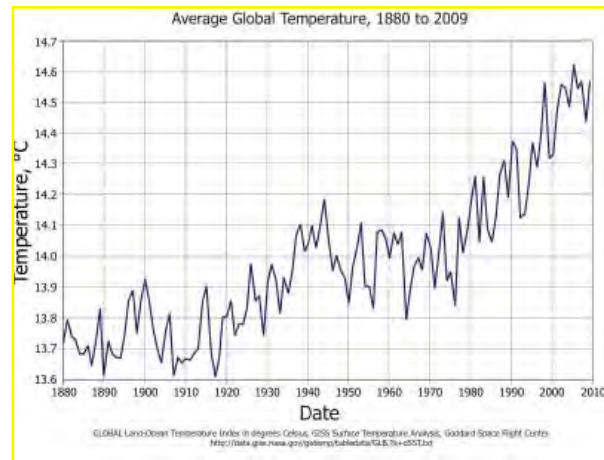

Figure 3: Image of Post stack depth migration without (left) and with (right) velocity model created via full-waveform inversion. Utilizing full-waveform inversion in seismic data processing can greatly enhance the final image of sedimentary, subsurface structures.
(http://www.cgg.com/default aspx?cid=15-59-8606)

Full-waveform inversion creates an accurate velocity model of the subsurface – a model that evaluates all velocities at which a wave front travels through all rock layers or formations in the subsurface. The key to accurate seismic imaging is identifying the unique velocity of the wavefront inherent to each rock formation. This velocity changes if the fluid within the rock pore-space changes. Once gas injection begins, continuous monitoring of the structure is

essential in order to identify any subsequent fracturing of the structure or subsequent migration of gas towards the surface and into the atmosphere.

There are several geophysical methods that may potentially detect the migration of gas. 4D Seismic, wherein seismic data is acquired and processed over one survey area at subsequent times, can effectively identify any change in the physical properties of the subsurface over time. Performing these time-lapse surveys consistently and creating accurate velocity models (Figure 4), can effectively demonstrate any changes within the subsurface sedimentary structure, indicating the presence of CO_2. To be effective, 4D seismic requires a high level of accuracy and consistency – specifically in the data processing phase. The red to blue color range in the images of Figure 3 demonstrate a velocity model, with blue representing slower velocities, and red representing faster. This is analogous to the speed of sound (a wavefront) traveling in air. The speed of sound generally decreases with elevation above the earth's surface, and velocities of waves traveling through rock generally increase with depth. This is a function of the density of the medium, as air is denser close to the earth's surface and rock becomes more dense as subsequent layers are deposited on top of it leading up to the surface.

Gravity gradiometry, a geophysical method that measures the spatial rate of change of the gravitational field, may also be an effective method for monitoring the movement of CO_2 by precisely measuring changes in the gravitational field above the storage reservoir. Gravity gradiometry is essentially a second-order tensor derived from the equation for gravitational acceleration, and therefore yields a higher resolution image of subsurface density anomalies than
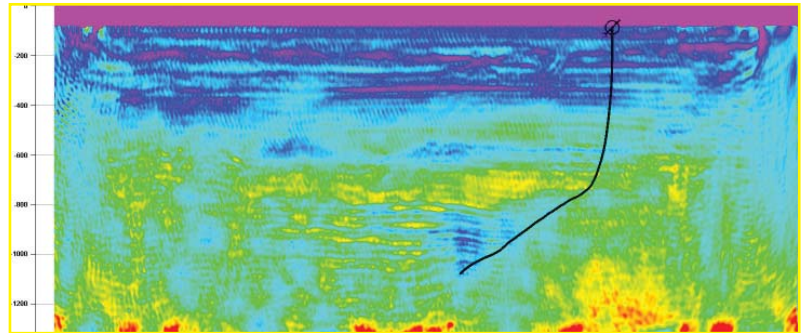

Figure 4: Velocity model created using full-waveform inversion. CO2 in the pore space of the rock changes the density and subsequently, the interval velocity of the rock structure which can potentially be used to track migration of the CO2. (www.bigccs.no)

traditional gravity methods. As the medium within the pore-space of a rock layer slightly changes the density (subsequently interval velocity) of the layer, gravity gradiometry is a geophysical method that can potentially measures these changes.

The idea of using gravity methods was originally met with skepticism, but a crew using gravity measurements for tracking subsurface sea-water movement in the North Sea experimented with tracking CO_2 movement, and ostensibly demonstrated the method's viability for doing so [Schrope, 2008]. Given the low signal-to-noise ratio of gravitational methods, gravity gradiometry will likely be most effective if CO_2 displaces a fluid that nets a relatively higher density contrast and is therefore potentially best suited for storage reservoirs that contain water or other liquids to begin with.

With global warming and climate change as a constant and imminent threat to our way of life, ridding the atmosphere of the excess carbon is categorically the best way to deal with the problem – outside of discontinuing the use of fossil fuels altogether, which simply isn't feasible for the foreseeable future. The grand challenge then is to engineer an effective way to do this on a large scale. By bringing together an array of engineering and scientific disciplines, it is a problem that can be solved, and I believe geophysics is the discipline that will ensure it is done sustainably.
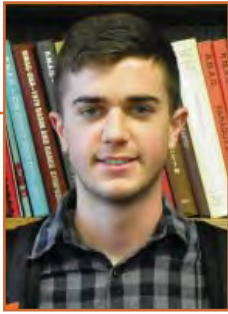
Grand Challenge: Clean Energy
John Hinton, Class of 2016

The many technologies and scientific advancements of the past two centuries have pushed the human race into an age of sustainable health, global communication of knowledge, and resource utilization. Along with the monumental achievements that make our quality of life possible comes a series of Grand Challenges. One major issue, of special interest to me, is that of energy production; specifically, the methods used in such industries, and their products' effects on the health of our planet and its inhabitants. A promising alternative to our current approach of energy production is to expand our renewable energy industry, in which the field of geophysics plays a key role.

"We just can't seem to break our addiction to the kinds of fuel that'll bring back a climate last seen by the dinosaurs; a climate that will drown our coastal cities and wreak havoc on the environment and our ability to feed ourselves." (Dr. Neil deGrasse Tyson, Cosmos: A Spacetime Odyssey). The issue of relying on fossil fuels plays a direct role in our atmosphere's composition, posing a threat to our health and future as a civilization. Identified as a Grand Challenge for Engineering, providing means for clean and renewable energy appears easier said than done.

Grand Challenges are, by definition, issues that prove to be a risk to mental and physical health as well as sustainability as a society, yet may be solved by engineers and scientists (available from the National Academy of Engineering at http://www.engineeringchallenges.org). Some of these issues are currently being confronted with the technology and understanding possessed by geophysicists. Of particular interest to me is the benefit of promoting renewable energy. As a geophysicist and engineer, I can apply my knowledge of hydrology, tidal forces, plate tectonics and the geothermal gradient, as well as technology used to map the subsurface for construction, and determine feasible sites for energy production, in hopes of ushering us into the age of renewable energy.

The United States' tradition of generating power by burning fossil fuels has resulted in an unhealthy dose of several greenhouse gases being released into our atmosphere, such as carbon dioxide, methane and chlorofluorocarbons. According to the National Aeronautics and Space Administration, the process of producing most of our energy has affected the atmosphere much more than other natural causes, such as volcanic eruptions and organic methane

Figure 1: Human-caused Forcings timeline (http://www.earthobservatory.nasa.gov/).
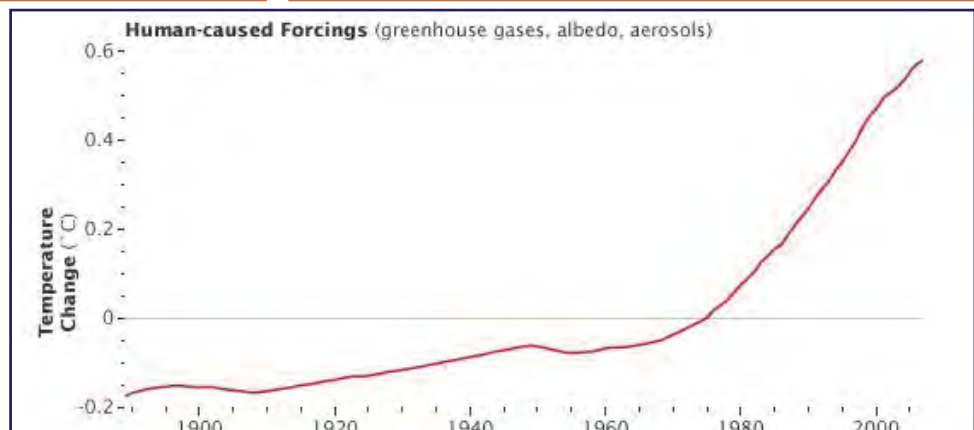
emission. Producing energy by combustion has increased the global temperature since the industrial revolution. This is illustrated in Figure 1, which shows the resulting change in global temperature as a function of time.

Although some greenhouse gases are natural, such as water and a fraction of the present carbon dioxide, humans are pushing their limits with an unnatural release due to the burning of natural gas, oil and coal. "We are not just experiencing increases in greenhouse gas emissions but also eutrophication, pollution of the air and water, massive land conversion, and many other insults, all of which will have interacting and accumulating effects." [McNutt, 2013]. In addition to increasing global temperatures, burning fossil fuels also poses a health risk with the production of sulfur dioxides, nitrogen dioxides and particulates. In the United States, this pollution marinades on the earth's surface, as well as water bodies, with no help from the wind. This effect is most obvious when temperatures are high and air conditioners call for more energy. Figure 2 represents the percentage of time in which pollution is stagnated in the U.S
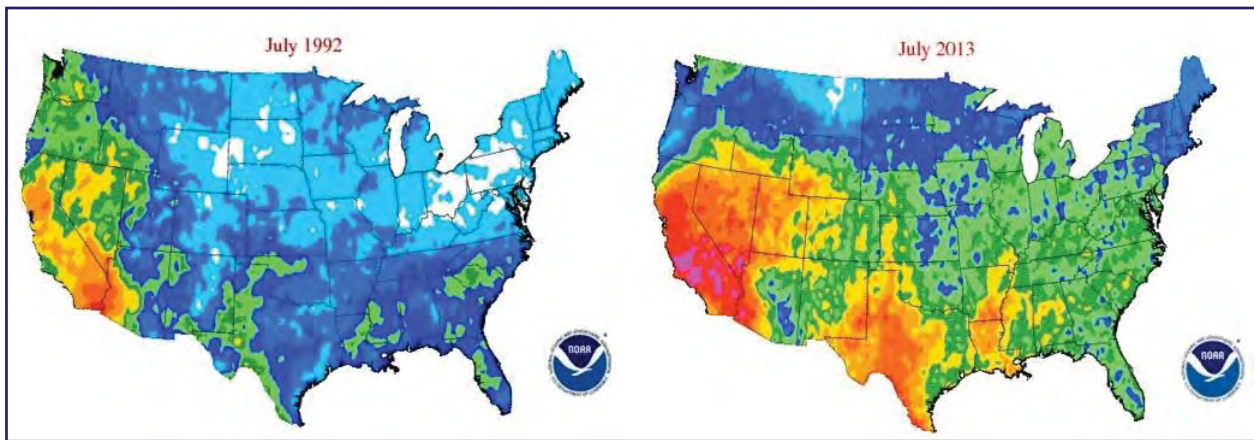

Figure 2: Stagnation Index (http://www.ncdc.noaa.gov/).

The recorded concentration of pollution in certain parts of the United States has increased dramatically over the past few decades. The above figures were chosen specifically to illustrate the difference in stagnant pollutants in my lifetime, of my home state. The right figure is a recent representation and, when compared to the left figure, it is easy to recognize that California has suffered in the past twenty-two years. Any resident of California has first-hand experience with the south's notorious air pollution.

Being a west coast native, the Grand Challenge problem of clean energy is of special interest to me. I have found that there are several alternatives to providing our nation's energy, most of which are already in place in the United States, in addition to many other countries. Much of Europe and Africa is largely powered by renewable energy, and although these alternatives may be expensive, the United States has entered the race. The U.S. Energy Information Administration has compiled years of recorded energy usage from renewable and nonrenewable sources (figure 3).

We are noticeably behind, producing only 9.135 quadrillion British Thermal Units (BTUs) of renewable energy while still producing 79.779 quadrillion BTUs of nonrenewable energy. In other words, 11.4% of the energy produced by America is from biomass, geothermal,
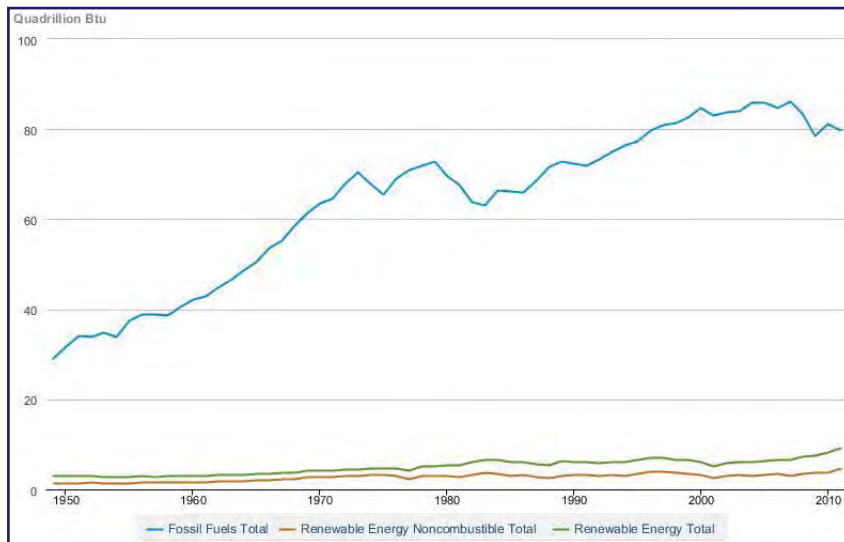
Quadrillion Btu

— Fossil Fuels Total — Renewable Energy Noncombustible Total — Renewable Energy Total

Figure 3: Annual Energy Report (http://www.eia.gov/).

hydroelectric, solar, wind or wood power plants.

All of the aforementioned energy alternatives require a geophysicist to map the subsurface to determine appropriate construction sites, which is one of the largest factors in deciding the fate of a renewable energy plant. Along with understanding the geothermal gradient as well as other geologic features for certain methods of green energy, additional roles of the geophysicist here are the study of geohazard and environmental impact mitigation. They might test for harmful chemicals in a hydroelectric plant's reservoir, geothermal plant's geyser, or the aquifers and water supplies near a biomass plant. In addition to testing for harmful substances below the earth's surface, geophysicists can also monitor the structure of the earth underneath and around any of these stations to determine if any mass wasting such as debris flow, mud flow and earth flow, as well as rockfall and creep of the landscape are possible.

Having relied on burning natural resources such as coal, oil and natural gas, the United States' energy industry has posed a major health risk to our atmosphere as well as our own bodies. Although the costs associated with moving past nonrenewables are high when considering the economic aspect, there has been proven research, in part by our very own government, which suggests a strong connection between the products of fossil fuel and hydrocarbon combustion and climate change. As a former Californian, and one who has seen the effects first hand, I am a proponent of renewable energy. From research and implementation, to keeping the public and the environment safe, there are several opportunities in this Grand Challenge for geophysicists to play a vital role. *See page 43 for references.*

Grand Challenge: Food/Precision Agriculture
Hanna Flamme, Class of 2017

Although our general knowledge and technology have greatly increased as humans advance, massive problems still exist in our world. Some of these issues are a direct result of our technological advances, and most, if not solved, threaten to diminish our quality of life or even destroy the human race. Often, these obstacles are called "grand challenges". Grand challenges can be defined as "ambitious yet achievable goals that capture the public's imagination and that require innovation and breakthroughs in science and technology to achieve" [Kalil, 2012]. Grand challenges have major impacts on the human race, especially health, energy, and sustainability. Some of the most common examples of grand challenges include clean drinking water, renewable energy, education system improvement, advanced medicines, climate change, and aging urban infrastructures reconstruction. Geophysics has the ability to be a large part of solving these grand challenges, especially those related to engineering. Geophysics applications can be used to explore undeveloped freshwater resources, map subsurface infrastructures to optimize future construction, or even discover more efficient means of hydrocarbon development. All of these grand challenges are important and will require inventive solutions. However, I find the food/precision agriculture grand challenge to be the most interesting.

According to the United Nations, nearly one out of every seven people in the world suffers from hunger, malnourishment, or both (FAO High-Level Expert Forum, How to Feed the World in 2050, available from Food and Agriculture Organization of the United Nations, 2009). By 2050, the world population is projected to increase by 34 percent, reaching 9.15 billion people [Edmeades et al., 2010]. (See Figure 1 for population projections [United Nations 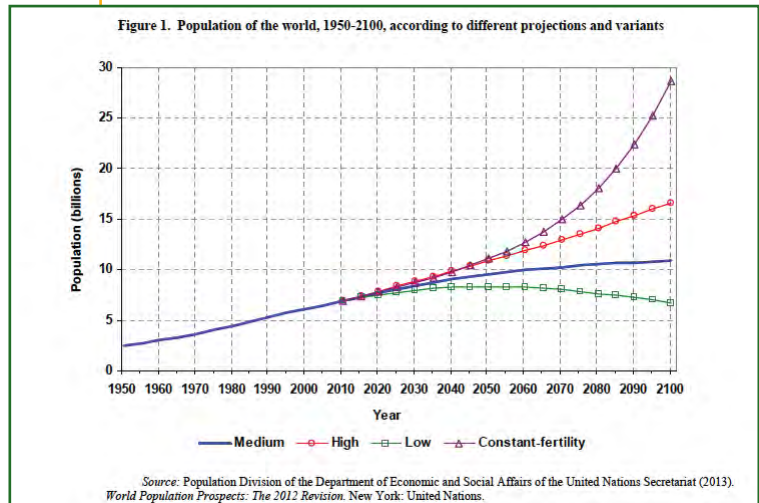Secretariat, 2013].) Urbanization will continue to increase rapidly to nearly 70 percent and income levels will soar (FAO High-Level Expert Forum, How to Feed the World in 2050, available from Food and Agriculture Organization of the United Nations, 2009). Based on this, food production will have to increase by 70 percent to meet the growing demand of this larger, richer, and more urban population. Annual cereal production will need to increase by 1 billion tons and annual meat production will need to rise by over 200 million tons [Edmeades et al., 2010].

In addition to the growing population, climate change creates even more competition for already limited resources. This suggests the question: How can we increase food production while practicing resource conservation and climate control? In order to solve this problem, innovative solutions must be designed and geophysical methods may be a main contributor.

At first, the relationship between geophysics and agriculture may be difficult to see. However, three geophysical methods are presently being used for agricultural advancement: resistivity, electromagnetic induction (EMI), and ground penetrating radar (GPR) [Allred, 2011]. Resistivity, EMI, and GPR systems can be integrated with GPS receivers to provide relatively quick, soil-electrical-conductivity mapping of large farm fields. These can provide useful soil surveys. Additionally, irrigation scheduling and controlled drainage operations within a field can be aided through soil moisture content monitoring via resistivity, EMI, and GPR methods [Allred, 2011]. The use of irrigation scheduling and controlled drainage operations can lead to more efficient water use and higher crop yields. High soil

salinity levels have the potential to cause serious crop damage. Generally, the salts are naturally occurring or originate from fertilizing or irrigating. If salinity levels are too high, the plant is unable to draw in the necessary water and nutrients causing the plant to wilt and die [Provin, 2001]. Soil electrical conductivity measurements made through resistivity and EMI methods can be used to detect soil salinity levels, helping avoid potential salt damage [Allred, 2011]. Airborne EMI techniques can also be used to assess salinity risks and suggest management options, especially for larger agricultural operations. The soil electrical conductivity mapping with resistivity and EMI methods can also be used to divide fields into different management zones, based on the varying soil properties [Allred, 2011]. These separate zones can then be used for precision farming techniques, such as restricting chemical applications in certain zones in order to increase crop yield, maximize economic benefits, and provide some environmental protection. Magnetometry, self-potential, and seismic geophysical methods are also being researched for possible agricultural uses [Allred, 2011]. The continued use and development of resistivity, electromagnetic induction, and ground penetrating radar techniques have the potential to increase crop yield, conserve resources, and improve farming operation efficiencies.

The food/precision agriculture grand challenge is of particular interest to me mainly due to my agricultural background. I grew up and attended school in rural Nebraska near a large farming community. Throughout high school, agriculture was one of my passions. I took multiple agricultural courses and was involved in FFA (Future Farmers of America). Classes based on natural resources were especially interesting and I often participated in statewide and national agricultural competitions. During the summer of 2014, I was a field agronomist intern, or rather field scout. As a field scout, I identified plant

Figure 1. Population of the world, 1950-2100, according to different projections and variants

Source: Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (2013). *World Population Prospects: The 2012 Revision*. New York: United Nations.

diseases, developmental growth stages, pest control, and soil characterizations. I even collected data via resistivity methods for irrigation scheduling. My experiences have allowed me to see first hand the struggles farmers encounter and also the opportunities presented to geophysicists to mitigate or even solve these problems. Additionally, I have considered specializing in agricultural geophysics, and I wanted to learn more about the geophysical techniques employed in agricultural practices.

If food production is to meet the demands of the growing population with limited resources, a wide range of disciplines will need to collaborate in order to solve this grand challenge. The application of geophysical methods will be an important part of this solution. Agricultural geophysical applications of resistivity, electromagnetic induction, and ground penetrating radar methods will continue to be developed so that yields and efficiencies may be optimized while limited resources are conserved. In the future, magnetometry, self-potential, and seismic assessment may also contribute to advanced agricultural geophysics methods. The common perception of geophysics, as vague or misconstrued as it can sometimes be, rarely connects geophysical principles to agricultural practices. In time this could change through necessity. *See page 43 for references.*

GRAND CHALLENGE

Grand Challenge: Climate Change
Mark Magdaleno, Class of 2015

As scientists it is our duty to investigate the problems facing the world and come up with solutions to those problems. Currently, many people would say that the top challenges facing the world today include fresh water, food and precision agriculture, geohazards, energy, minerals and mining, underground construction, aging urban infrastructure, hazardous waste, climate change, and planetary exploration [Young, 2007]. Now, as geophysicists, we get to have a great opportunity to tackle these challenges and make the world a better place. With geophysics we can use our knowledge of the earth along with different geophysical methods to help solve the problems of the grand challenges. We can monitor geohazards such as earthquakes using seismic methods. We can also use methods such as gravity and magnetic methods to look into the subsurface and see where underground construction can be done. Recently I did a project on using satellite remote sensing to monitor coral in the Great Barrier Reef and to see how the climate might be changing and what effects it might have. In this project I tackled the challenge of climate change that has caused the oceans to rise in temperature and change in composition. This peaked my interest in the challenge of how to monitor these global climate changes using applied geophysics.

In my project I found that since the late 19th century there has been a rise in temperature in Australia's tropical marine ecosystems. The temperatures have risen about 0.5°C. The change in temperatures has come from the greenhouse effect which is caused by more CO2 in the atmosphere. Since the late 18th century, about 30% of the extra carbon dioxide that humans have created has been absorbed into the oceans [Matsunaga, 2010]. Carbon dioxide is the main greenhouse gas and having more of it in our oceans changes the chemistry of the water. The carbon dioxide causes ocean acidification and has reduced global pH levels from 8.15 to about 8.05 [Matsunaga, 2010]. This now causes a problem because it will impact marine life. In my project I discovered that ocean acidification leads to a decrease in the availability of carbonate ions which are crucial in the formation of the shells and skeletons of marine organisms such as coral. Having an increase in acidity will impair the ability for corals to build their calcium carbonate skeletons. Corals are calcifying organisms that are able to take carbonate from seawater and use it for their skeletons by forming calcium carbonate ($CaCO_3$). As the pH of the ocean becomes more acidic the carbonate that the corals are using for their skeletons is converted to a bicarbonate that cannot be used by the corals anymore. Instead of being able to build strong skeletons corals will begin to dissolve. Organisms such as coral play a vital part in marine ecosystems because they provide a home for many other organisms. They also help break a wave as it approaches the shore and this can have an effect on the beach environment. Because the ocean plays a big part in marine and land environments it is important that we monitor the temperature and composition of the ocean which is altered by climate changes.

I am interested in this problem because it affects the entire planet. With warmer temperatures come changes in different environments all across the world. Many places are experiencing more droughts than before. I live in Colorado Springs and the recent wildfires could have been prevented, or at least better controlled, if the area wasn't as dry as it was. Using remote sensing and applied geophysics was a great way for me to see for myself if the climate is really changing. By monitoring the corals of the

Great Barrier Reef I was able to tell if the ocean temperatures have in fact been increasing due to more CO_2 in the atmosphere and if the CO_2 is causing ocean acidification. Because corals use the sun for photosynthesis they will grow in shallow waters, typically no more than about 60 meters. This made it possible for me to use remote sensing to monitor the health of the corals. Depending on the health of the corals I was able to get information about the temperatures and composition of the ocean environment. I used LANDSAT data to look at the surface of the area where the corals lived. Once I found a good area to investigate I used ASTER data to take spectra of the area and check the temperatures of the ocean and the spectra of the coral. By looking at data from a couple of years ago and from a present time I compared the spectra to see if it was changing. Because coral is made of calcium I checked the spectra of the coral and compared it to known calcium spectra to see if it was being affected by ocean temperatures or ocean acidification.
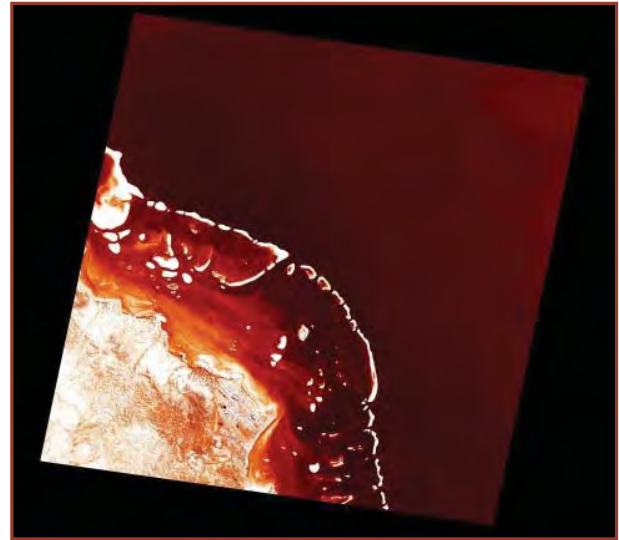
Red Temperature stretch was used to compare with the ASTER image [USGS, 2014].

Looking at the different spectra and thermal signatures of coral reefs through remote sensing gave valuable information about the changing temperatures and composition of the reefs. This gives a lot of information on global climate change because it is the only thing that can change global ocean temperatures. It was clear that the temperatures around the reefs are warmer. We could tell from the spectra that over the past couple of years the composition of the corals and the area around the corals has been changing. Climate change is one of the biggest challenges we are facing today and I was able to discover the effects and see that it really is happening right before us. However, it is comforting to know that I can use geophysics to monitor this problem. The next step that I hope to take is to get out in the world and actually work to make a difference by using my skills as a geophysicist.
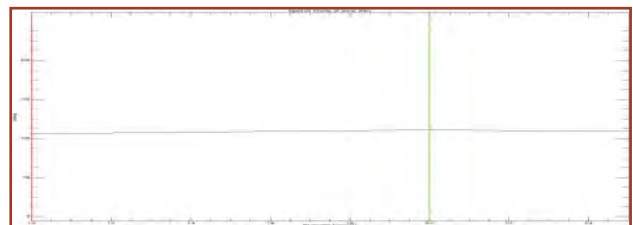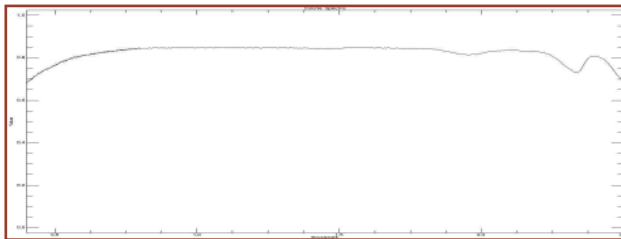
Top left image shows what the spectra for calcite should look like [Hanna, 2014]. The bottom left image shows the spectra from the ASTER image in 2002. The top right image shows the spectra from the 2011 image.

Grand Challenge: Decaying Urban Infrastructure
Eric Bunzli, Class of 2017

Engineering grand challenges are a class of major scientific problems that affect a large portion of our planet and society. These challenges also tend to be highly complex, and will require contributions from many people, and many fields of engineering. An example of this sort of engineering challenge would be to provide reliable and sustainable access to clean water for all. This would involve finding new sources, new ways of treating water, significant infrastructure improvements to deliver and protect water, and technological advancements to reduce the amount of water needed. I intend to identify ways that geophysics and geophysical engineering can be applied to help solve these problems, and particularly, how it can be used to restore and improve global infrastructure.

In more developed regions of the world, our infrastructure, like the power grid, road network, and water supply systems are decaying rapidly, and are at a point where they are unable to support the increasing demands placed on them. The infrastructure systems in many of these cities were designed using obsolete technology and with outdated population models, and, after decades of population growth, have been upgraded and repaired many times, and have exceeded their intended lifecycle.
In addition, the increasing demands of modern society have placed additional stress on already overloaded systems, increasing the rate of decay, and often leading to catastrophic failures like the 2007 Minneapolis I35 bridge collapse [Reid, 2008]. This issue is compounded by the low amount of funding that is reserved for infrastructure maintenance and upgrades: the United States spends between two and three percent of the annual GDP on infrastructure each year, as it has since 1950. This is substantially less than the five to nine percent spent by India and China, respectively [Reid, 2008]. In addition to the decayed state, many of the buried power, communications, water, gas, and sewage lines' exact locations are unknown, either because the records have been lost, or are outdated. This means that when something fails, it can be very difficult, time consuming and expensive to locate and access the source for repairs.

I have chosen this problem because, as a student living in a region with a mix of modern and obsolescent infrastructure, I have experienced many of the problems that are caused by outdated infrastructure. I have also seen some of the attempts to remedy them, some of which were more successful than others. In addition, I feel that if we can't find a long-term solution within the next few years, we will be faced with even more frequent failures. The increasing costs of maintaining our failing systems are already having a significant impact on our national economy, as is shown in Table 1. In addition, the spending and jobs that would be necessary to upgrade our infrastructure could provide a significant boost to our economy in a particularly slow time. In addition, if we can develop a solution early enough, we can incorporate it into the design of the younger cities in the less developed areas of the world, hopefully preventing this kind of crisis in the future.

In order to effectively improve our infrastructure systems, we need to know where all of the power lines, pipes, tunnels, and conduits are, as well as their conditions. Rather than digging up every

bit of every city to find something that may or may not be there, or guessing at the integrity of solid surface infrastructure like bridge abutments and supports, we can apply geophysical techniques like ground penetrating radar, microseismology, gravimetry, and magnetism to locate and analyze the condition of infrastructure elements. The use of ground penetrating radar to locate utilities, as well as archaeological structures, is already widespread, but it provides no information regarding the conditions of utilities located, or what function they serve [Eppelbaum, 2011; El-Diraby and Osman, 2007] .

TABLE 3 ★ Effects on Total U.S. Business Sales and GDP due to Declining Water Delivery and Wastewater Treatment Infrastructure Systems, 2011–40 (billions of 2010 dollars unless noted)		
YEAR	BUSINESS SALES	GDP
Losses in the Year 2020	–$140	–$81
Losses in the Year 2040	–$481	–$252
Average Annual Losses 2011–2020	–$73	–$42
Average Annual Losses 2011–2040	–$251	–$137
Cumulative Losses 2011–2020	–$734	–$416
Cumulative Losses 2011–2040	–$7.5 Trillion	–$4.1 Trillion

NOTE Losses in business sales and GDP reflect impacts in a given year against total national business sales and GDP in that year. These measures do not indicate declines from 2010 levels.

SOURCES EDR Group and LIFT model, University of Maryland, INFORUM Group, 2011

Table 1: This table shows the projected economic impacts if the continued rate of decay continues. This was presented in the American Society of Civil Engineers' 2011 report "Failure to Act: The Economic Impact of Current Investment Trends in Water and Wastewater Treatment Infrastructure". The full report can be found at http://www.asce.org/uploadedfiles/infrastructure/failure_to_act/asce%20water%20report%20final.pdf.

In addition to locating the existing subsurface structures and utilities with accuracy, we can use geophysical methods, like electrical resistivity tomography, to develop a model of the region and identify areas where the ground is likely to be more or less stable, or where the conditions might cause more rapid aging of piping. This method has already been used to map and model complex near-surface geologic structures, and would probably be easy to adapt to infrastructure planning [Cardarelli, 2006]. On a smaller scale, we might be able to monitor the conditions of buried or inaccessible structures, using the idea that the physical properties, like electrical resistivity and density, will change as the materials change.

Based on the abilities of current geophysical techniques, I feel that it would be relatively easy and inexpensive to adapt existing methods for use in locating and upgrading our infrastructure systems. The primary obstacle would likely be finding the funding to actually implement the upgrades, and provide continuing maintenance to prevent this sort of situation from reoccurring. Unfortunately, we, as geophysicists have limited influence on the public budgets where the vast majority of this funding would be coming from.   *See page for 43 references.*

Class of 2014

Doctor of Philosophy Geophysics

May 2014:

Marisa Barbara Rydzy, Patricia Evelyn Rodriguez
Not pictured: Bharath Chandra Shekar

Master of Science Geophysics

May 2014:

Stefan Compton, Claudia Duenas Velez, Andrew Munoz, Johannes Douma

Not pictured: Matthew Lee, Anya Reitz

December 2014:

Azar Hasanov, Brent Putman

Not pictured: Camriel Coleman, Esteban Diaz Pantin, Detchai Ittharat, Kritti Kreeprasertkul, Tyler McFarlane

Professional Master Petroleum Reservoir Systems:

Heather Johnson

Bachelor of Science Geophysical Engineering

May 2014: Back: Max Kosmicki, Linus Sebelin, Mohammed AlManaa, Ian Stone, Michael Dunham, Colton Kohnke, Paul Geimer, Steven Plescia. Middle: Max Kosmicki, Brennan Malcolm, Ibrahim Meer, David Huffington, Andrew Yanke, Spencer Haich, Karyn Stanley, Jarred Eppehimer, Stevie Newbill. Front: Ghadeer Alselemi, Joseph Jennings, Rami Al Ghamdi, Elijah Thomas, Elena Dutcher, Jennifer Brush, Staci Mueller, Alyson Lozier, Elizabeth Pettinger, Deema Albeesh.

December 2014:

Tiffany Lane, Thu Bui

Society of Women in Geophysics... Samara Omar, Class of 2016

The Society of Women in Geophysics (SWIG) was officially established as a school organization at the beginning of Fall 2014 semester. It began as a small group of young ladies seeking to build a stronger community for the sake of academic assistance, building friendships and finding support from other women in our field of study.

Our goal as an organization is to create an inclusive environment that fosters both individual and departmental development through guest speakers, social events and a unique mentorship program. A similar group was organized in the past called Women in Geophysics (WIG). We have based some of our goals on their past work and we hope that the careful planning we are putting into SWIG will continue to have universal benefits to future students in geophysics.

During the Fall 2014 semester we hosted several guest speakers with a variety of educational and career backgrounds, all grounded in geophysics. We have seen numerous students, both graduates and undergraduates, at our general meetings. Also, our meetings served as a casual networking opportunity for students as we often had many professors and other professionals in attendance.

Outside of our general meetings, we have also hosted several social events such as our Art on the Brix endeavour. At this social, the members of SWIG put together this collaborative artwork which we are excited to give back to the department as a small token of our appreciation. We are very grateful for all the time and effort the Geophysics faculty and staff have provided us and we would like to thank them for their continued support.

As of the end of Fall 2014, SWIG transitioned out of a temporary ad hoc leadership and into its first Executive board. Together, we are looking to jump into the next semester with full force. We launched our Mentorship program this spring and plan to further ground ourselves as a prominent society within the department and on campus.

SWIG

"Michael L. Batzle Endowed SEG Student Scholarship", page 6
Ludmila Adam1 and Ronny Hofmann2
1University of Auckland.
2Shell International Exploration and Production Inc.
Ludmila Adam and Ronny Hofmann (2015). "Michael L. Batzle Endowed SEG Student Scholarship." The Leading Edge, 34(4), 412–412. http://dx.doi.org/10.1190/tle34040412.1. 2015 Society of Exploration Geophysicists. Republished with permission.

"I think geophysics is like a candy store...", page 7
Excerpts from "An interview with Mike Batzle", CSEG Recorder, Mar 2006, vol. 31, no. 03. Article reprinted Apr 15 2015 with commentary by Kurtis Wikel, CSEG Director of Education. http://csegrecorder.com/assets/pdfs/full/RECORDER-2006-03.pdf. (c) 2015 Canadian Society of Exploration Geophysicists. Republished with permission.

"Grand Challenge: Carbon Sequestration", page 28
Katzer, James, et al. (2007), The future of coal: an interdisciplinary study, Massachusetts Institute of Technology, Cambridge, MA.
Kramer, David (2012), Scientists poke holes in carbon dioxide sequestration, Physics Today, 65(8), 22.
Oreskes, Naomi (2004), The scientific consensus on climate change, Science, 306(5702), 1686.
Schrope, Mark (2008), Going underground, Nature Reports, 2, 154-155.

"Grand Challenge: Clean Energy", page 31
McNutt, M. (2013), Climate Change Impacts, Science, 341 (6145), 435, doi:10.1126/science. 1243256.

"Grand Challenge: Food/Precison Agriculture", page 34
Allred, B. (2011), Agricultural Geophysics: Past/Present Accomplishments and Future Advancements, paper presented at The Second Global Workshop on Proximal Soil Sensing, McGill University, Montreal, Quebec, Canada.
Edmeades, G, R. A. Fischer, and D. Byerlee (2010), Can We Feed the World in 2050, paper presented at 15th ASA Conference, Australian Society of Agronomy, Lincoln, New Zealand.
Kalil, T. (2012), The Grand Challenges of the 21st Century, report, Information Technology and Innovation Foundation, Washington, D.C.
Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (2013), Population of the world 1950-2100, according to different projections, http://esa.un.org/wpp/documentation/pdf/WPP2012_%20KEY%20FINDIN GS.pdf, New York, NY.
Provin, T., and John L. Pitt, Managing Soil Salinity (2001), Texas AgriLife Extension Service, E-60, 1-5.

"Grand Challenge: Climate Change", page 36
Andrews-Hanna, J. C. ,2013, Lab 4: Prospecting from Space, GPGN/GEOL 470/570
Laboratory Descriptions.
USGS, EarthExplorer, Accessed April 23, 2014. http://earthexplorer.usgs.gov/
Young, Terry, (2007), Our expanding sphere —grand challenges for planet Earth and for
SEG, The Leading Edge, 26, 2, 202-208.

"Grand Challenge: Decaying Urban Infrastructure", page 38
The American Society of Civil Engineers (2011), Failure to act: The economic impact of current investment trends in water & wastewater treatment infrastructure, Prepared by Economic Development Research Group, Inc., Boston, Mass.
Cardarelli, E. and F. Fischanger (2006), 2D data modeling by electrical resistivity tomography for complex subsurface geology, Geophysical Prospecting, 54, 121-133, doi:10.1111/j.1365-2478.2006.00522.x.
Eppelbaum, L. V. (2011), Review of environmental and geological microgravity applications and feasibility of its employment at archaeological sites in Israel, International Journal of Geophysics, 2011, 1-9, doi:10.1155/2011/927080
El-Diraby, T. and H. Osman (2007), Implementation of Subsurface Utility Engineering in Ontario: Cases and a Cost Model, Canadian Journal of Civil Engineering, 34, 1529-1541.
Reid, R. L. (2008), The infrastructure crisis, Civil Engineering, 78, 40-65.

CITATIONS

15 Unexpected Lessons from Being an Undergrad in CSM Geophysics
Katerina Gonzales, Class of 2015

Geophysics at Mines is a unique experience. Sometimes we get less hours of sleep than there are hours of lab the next day. We almost certainly spend more hours in the Green Center than the hours of sleep we get per night. These were to be expected from studying in the rigorous yet rewarding undergraduate Geophysics program at Mines. But after declaring our majors, we never could have foreseen the fact that we would spend the majority of our time looking at wiggles and rainbow plots. Or that after field camp in Pagosa Springs, it would take infinite washes to get the sulphur hot springs smell out of our swimsuits. These are unique to the Geophysics life at Mines. Here are more unexpected lessons and experiences while living the GP life:

1. The art of defensive eating
2. How to stifle a yawn during a six-hour lab
3. How to dodge markers
4. Anything and everything about the geology of Kafadar
5. An increased love of donuts
6. A realization that every letter has at least four variations, especially R
7. How to deal with bear encounters
8. Being a select group to have explored the utility tunnels at CSM
9. An appreciation for etymology after having class with Dr. Bob
10. Learning what SWAG really is
11. Doing field work in 10 kinds of weather...all in the same day
12. Learning that any kind of weather can be programming weather
13. Participating in a rescue mission (RIP, Timmy…)
14. Being blinded by the sun when finally leaving the Green Center...if it's still out
15. That story time with Terry is the best time