

## Welcome From the Director

The Center for Wave Phenomena celebrates its 25th Anniversary this year. This milestone marks the continued innovation and education of a center originally founded by Norm Bleistein, Jack Cohen, Frank Hagin, and John DeSanto. It is a privilege in my new role as director of CWP to give leadership to our center. I am thankful for my predecessors, including recent past directors Ken Lerner and Ilya Tsvankin, for giving shape to such a vibrant center focused on discovery and learning. Over the summer we held a retreat with the faculty and staff of CWP to rethink and articulate our goals and values. Central in the outcome of the retreat was that we aim at not only producing world-class research, but also at creating a nurturing environment for students; a research and learning environment that helps students realize their potential and that fosters a balanced growth in intellectual and human skills needed for effective and compassionate leadership. The students, staff, and faculty at CWP constitute a wonderful composite of people. What a joy it is to work with this group!

With great pleasure, we welcome representatives of our sponsor companies to the 25th Annual Project Review Meeting, and look forward to the opportunity to exchange ideas and thoughts about this past year's projects and about plans for the future. Dialogue with sponsor representatives helps us to focus on the scientific problems that are important to your organizations. We look forward to using the Project Review Meeting as a platform for such discussions.

This edition of the report on the Consortium Project at the Center for Wave Phenomena summarizes much of the research conducted within CWP since the 2008 Project Review Meeting. Note that the papers in this report and those presented orally during the meeting, May 11–14, 2009, only partially overlap.

Roel Snieder, Director  
Center for Wave Phenomena  
May 2009

## Papers in this Report

The papers in this volume are grouped into the following categories: interferometry, electromagnetic fields, time-lapse, anisotropy, imaging, and image processing & interpretation. These categories show both similarities to and differences from those of the past few years, indicative of both the continuity and expanding breadth of our research program.

### Interferometry

The section on **interferometry** opens with an overview paper of *Snieder, Miyazawa, Slob, Vasconcelos, and Wapenaar* who compare approaches to interferometry based on correlation,

deconvolution, and the solution of an integral equation. They indicate the merits and drawbacks of these approaches and show that for electromagnetic applications the integral equation method is most applicable. *Snieder and Slob* derive a new formalism for interferometry that is applicable to static problems. This creates the possibility to extract the Green's function for potential fields and DC-resistivity from quasi-static field fluctuations. Previous formulations for interferometry were based on energy principles. The new approach presented in their paper is based on a Lagrangian formulation rather than on Hamiltonian (energy) principles. *Slob and Snieder* further refine the theory for Green's function extraction for static problems and deal in detail with the DC-resistivity problems. They relate the theory developed to the fluctuation-dissipation theorem, and show that for geophysical experiments, voltage fluctuations due to thermal fluctuations are strong enough to be measurable with current instrumentation.

## Electromagnetic Fields

The report features four papers on **electromagnetic fields**. The integral equation method for the interferometric extraction of the electromagnetic (EM) response completely removes the imprint of the overburden above the acquisition surface. In order to apply this method one needs an array to separate the EM-fields in upward and downward traveling components. *Hunziker, Slob, and Wapenaar* determine the required station spacing in two dimensions as a function of water depth and the depth of the source antenna. *Fan and Snieder* extend this analysis to fields propagating in three dimensions. In practice, Controlled Source ElectroMagnetic (CSEM) measurements are often used to complement seismic data. *Kwon and Snieder* study the uncertainty in the joint inversion of these two data sets. They quantify the relative contribution from errors in the seismic and CSEM data, and uncertainty in the rock physics that connects these data to porosity and water-saturation. *Tehrani and Slob* introduce an efficient iterative method for fast and accurate modeling of 3D controlled source electromagnetic data that is based on an approximation to the integral equation solution for EM fields. They show that the results are sufficiently accurate for modeling and inversion purposes.

## Time Lapse

In the section on **time-lapse** methods, *Miorali, Slob, and Arts* study the use of a downhole radar system in smart wells to monitor the encroachment of water towards a well equipped with inflow control valves. They determine the design parameters for such a radar system to be useful for this application. Their work is particularly relevant to optimize Steam Assisted Gravity Drainage processes and to prevent water encroachment in thin oil rims. *Snieder and Young* discuss the main stumbling blocks in carbon capture and sequestration for curbing global warming. They argue that this technique only has a chance for being implemented on a scale large enough to make a difference when (1) the cost is reduced significantly, (2) the technique is scaled up by a factor 1000 beyond current capabilities, and (3) predicting and monitoring leakage rates much less than 0.5%/year can be achieved. *Fuck, Tsvankin, and Bakulin* analyze

stress-related prestack traveltimes shifts for a compacting reservoir embedded in a medium with different elastic properties. They show that, although the excess stress field is sensitive to the contrast in the rigidity modulus across the reservoir boundaries, the influence of background heterogeneity is mostly confined to the reservoir and its immediate vicinity. As is the case for a homogeneous background medium, the offset dependence of traveltimes shifts for realistic layered models is mostly controlled by stress-induced anisotropic velocity perturbations. *Fuck and Tsvankin* employ the theory of nonlinear elasticity based on third-order elastic tensors to study stress-induced anisotropy observed, for example, near compacting hydrocarbon reservoirs and salt bodies. They present an intuitive and algebraically simple formalism designed to predict the anisotropic symmetry of a stressed medium from the symmetry of the third-order elastic tensor and properties of the applied stress/strain.

## Anisotropy

Four papers comprise the section on **anisotropy**. *Behura and Tsvankin* study the influence of the angle between the real and imaginary parts of the wave vector (“inhomogeneity angle”) on attenuation and velocity in arbitrarily anisotropic media using the first-order perturbation theory verified by exact numerical modeling. They show that the group attenuation coefficient measured from seismic data is insensitive to the inhomogeneity angle and can be used to estimate the intrinsic quality factor and the relevant attenuation-anisotropy parameters. *Söllner, Tsvankin, and da Silva* present a time-migration methodology for multi-azimuth P-wave data from azimuthally anisotropic, weakly heterogeneous media. They derive the azimuthally varying diffraction time function and define the “migration-velocity ellipse,” which solves the mismatch problem that occurs in conventional processing of multi-azimuth surveys. The algorithm is successfully tested on synthetic data generated for a horizontally layered azimuthally anisotropic medium and an isotropic model with a dipping interface in the overburden. *Wang and Tsvankin* combine 2D P-wave stacking-velocity tomography with borehole data to estimate the interval parameters of tilted transversely isotropic (TTI) media and build an initial anisotropic model for migration velocity analysis. They show that if the symmetry axis is nearly orthogonal to the medium interfaces, the algorithm can resolve the interval symmetry-direction velocity  $V_{P0}$  and the anisotropy parameter  $\delta$ , while the parameter  $\epsilon$  cannot be constrained without using nonhyperbolic moveout. *Yan and Sava* describe a procedure for elastic wave-mode separation in anisotropic TTI media based on polarization vectors evaluated at every location in space. This technique is implemented in the space-domain using finite-difference operators that represent the polarization vectors as functions of elastic parameters and tilt. The main application of this procedure is in multi-component elastic reverse-time migration.

## Imaging

Research on **imaging** is reported in four contributions. *Yang and Sava* explore the kinematic attributes of extended space-time imaging conditions developed for wave-equation migration.

Such imaging conditions provide access to robust velocity information and blend the attributes of more conventional techniques like depth focusing analysis and semblance analysis. These imaging conditions are applicable to imaging in complex media in connection to, for example, wave-equation migration velocity analysis. The second paper of *Yang and Sava* describes a procedure for constructing image perturbations consistent with linearized wave-equation migration velocity analysis operators. The technique takes advantage of focusing attributes derived from the analysis of time-lag extended imaging conditions. This procedure is cheap, robust and can be used for velocity model building in complex areas using shot-record wave-equation imaging of wide-azimuth data. *Xuan and Sava* propose a procedure for probabilistic micro-earthquake location using Bayesian inversion theory. Prior information about probable micro-earthquake locations and onset times is used to construct a wavefield database, which depends on the local velocity and the acquisition geometry. Reconstructed wavefields are compared at various locations with this database using pattern-matching procedures leading to maps of the probability of micro-earthquake occurrence. *Ma and Sava* investigate mid-scale model heterogeneity and possible techniques that can be used to derive statistical parameters characterizing realistic Earth models, or techniques that can be used to attenuate the effects of such model heterogeneity. The first part of the paper tests the possibility of discriminating between stochastic models with Gaussian or fractal distributions, and the second part investigates methods from the wavelet transform or time-frequency analysis families which could attenuate the effects of model heterogeneity.

## **Image Processing and Interpretation**

The section on **image processing and interpretation** describes algorithms that might typically be applied after seismic imaging to facilitate seismic interpretation and subsurface modeling. The paper by *Parks* describes methods for interactive freeform deformation and cutting of surfaces in seismic images. These surfaces represent geologic horizons and faults that may be cut by other faults. *Hale* presents a process for image-guided interpolation of scattered data. With seismic images, the scattered data might be measured in boreholes (or painted interactively), and image-guided interpolation represents a new way to use seismic images to interpolate measurements at locations between the boreholes. In his second paper *Hale* describes a simple and efficient algorithm for structure-oriented smoothing that leads to a new definition of semblance that is more generally useful than the one commonly used today. For seismic images, applications include highlighting faults and subtle amplitude variations within buried channels.

# Overview of Developments in CWP

## CWP Faculty and Staff

There has been no change in the CWP faculty group since the 2008 Project Review Meeting. The full-time CWP academic faculty includes Dave Hale, Paul Sava, Roel Snieder (director), and Ilya Tsvankin. In accordance with the rotation plan approved by the CWP faculty in 2004, Roel Snieder assumed the position of CWP director in June 2008. Ken Lerner and Norm Bleistein remain part of the team in their “retirement,” and are actively involved in many aspects of our research and education program. In December, 2008, Michelle Szobody changed positions and now is office manager of the Department of Geophysics at the Colorado School of Mines. She is succeeded in CWP by Pam Beckman who is the new program assistant. Pam manages the CWP office in a professional and cheerful way. Publication specialist Barbara McLennon provides essential assistance in preparing our publications. John Stockwell not only manages the computer systems of CWP, but his insight and expertise in the mathematical aspects of geophysics are also invaluable. John is the manager of Seismic Unix and is instrumental in maintaining and promoting this software for seismic data processing.

## Students, Post-Doctoral Fellows, and Long-Term Visitors

During the 2008-2009 academic year, 14 graduate students were doing research in CWP. Five new CWP students (Filippo Broggin, Luming Liang, Francesco Perrone, Bharath Shekar, and Mamoru Takanashi) started their graduate studies in the Fall of 2008. During 2008, three students completed their degree work: John Mathewson, MSc.; Gabriela Melo, MSc.; and Rodrigo Fuck, PhD. Eduardo Filpo Ferreira da Silva joined CWP as a post-doctoral fellow starting in March, 2007 for an 18-month period. Eduardo is a geophysicist with Petrobras, Brazil. Evert Slob has joined CWP as visiting professor for the period January-July, 2009, while on leave from Delft University of Technology. We have been pleased to welcome for several months, three of Evert’s students from Delft: Jurg Hunziker, Mattia Miorali, and Ali Tehrani. Also joining Evert has been postdoctoral fellow Seiichiro Kuroda. Chenghong Zhu, from Sinopec, is visiting CWP from March through September, 2009, with the goal of establishing a collaboration between Sinopec and CWP. Walter Söllner of PGS (Oslo, Norway) spent six months of 2008 with CWP as a visiting scholar working on joint research projects.

## Center Support

Currently the Consortium is supported by 25 companies including our newest sponsor, Marathon Oil Corporation. We thank the representatives of our sponsors for their continued support. A full list of sponsor companies over the term of the past year appears on the acknowledgment page at the beginning of this volume.

We have received approximately \$840K of additional support since June, 2008, from the U.S. Department of Energy, National Science Foundation, Petroleum Research Fund of the American

Chemical Society, the Research Partnership to Secure Energy for America, ExxonMobil, Shell, Statoil, and the Abu Dhabi National Oil Company through its educational partnership with the Colorado School of Mines. Also, in 2005, Landmark Graphics committed to support a research fellowship for a Ph.D. student (currently Derek Parks) in computer science and/or geophysics for four years, toward the goal of developing new methods for modeling the earth's subsurface. Our industrial and government support for research and education complement one another; each gains from, and strengthens, the other. As a net result, for the annual 2008-09 fee of \$52.8K, a company participates in a research project whose total funding level is close to \$2.11M, which means that the contribution of every sponsor is leveraged with factor 40.

### **Joint Projects with Industry and Non-profit Corporations**

Roel Snieder and his students continue their work with Shell within the framework of the company's Gamechanger program. Shell has provided funding for the three-year project "Stripping the overburden from the seismic and electromagnetic earth response" started by Roel in collaboration with Kees Wapenaar and Evert Slob of Delft University. Roel started a collaborative program with ConocoPhillips and Boise State University that is focused on various aspects of multiple scattering in imaging and monitoring. Roel received funding from the National Science Foundation and the US Department of Energy.

Paul Sava has initiated two new industry-funded projects. The first project, supported by a grant from ExxonMobil, addresses the problem of microearthquake location for 4D fluid monitoring. This two-year project, which began in 2007, is executed in collaboration with Roel Snieder and graduate student Ran Xuan. The second project is supported by a grant from ENI and dedicated to the development of migration velocity analysis using reverse-time migration techniques. This four-year project will provide full support for one graduate student (Francesco Perrone). In addition, Paul continues a three-year project supported by StatoilHydro on wave-equation velocity analysis and imaging for wide-azimuth data. This project provides 50% support for graduate student Tongning Yang.

Ilya Tsvankin and his students have begun working on the two-year project "Azimuthal AVO and attenuation analysis for fracture characterization" funded by the Research Partnership to Secure Energy for America (RPSEA). This is a non-profit corporation formed by a consortium of premier U.S. energy research universities, industry, and independent research organizations.

Dave Hale and CWP graduate student Luming Liang worked last year with Marco Maučec and Bob Howard of Landmark on new methods to interpret seismic images, as part of a four-year project on subsurface modeling that has provided funding for a graduate research fellowship.

Joint research by CWP students and faculty with researchers in sponsoring companies has proven to be extremely valuable for connecting CWP research with the research problems of sponsors. The complementary nature of academic and industrial research has led to significant additional value in a number of projects. For this reason, CWP encourages directly sponsored research with companies and non-profit corporations that could lead to sharing of results with

the Consortium.

## **Educating our Students**

The Department of Geophysics and other departments at the Colorado School of Mines offer numerous graduate courses from which CWP benefits. In addition to these courses, we have taken the following initiatives to educate CWP students.

### ***English writing & speaking***

For many students, especially international students, writing scientific papers is an onerous activity. Over the past several semesters, Diane Witters, a writing consultant whose expertise is English as a second language, has worked with CWP students to improve their writing skills, through one-on-one tutoring sessions and writing workshops. Diane closely coordinates her efforts with CWP faculty. In addition to helping students advance their writing skills, she has assisted foreign students to transition from the work-culture in their home country to the professional style common in the United States.

### ***Mathematics***

In order to ensure that CWP students master the mathematics needed for wave propagation and imaging, John Stockwell teaches a math clinic, which is a graduate course covering the mathematics needed for much of the research within CWP. The course is attended by a record number of students from CWP as well as from other research groups in the geophysics department. The feedback from students has been extremely positive.

### ***The Art of Science***

Roel Snieder offers the course “The Art of Science,” which is aimed at helping graduate students develop effective research habits.

## **Short Courses and Workshops**

The CWP faculty has been active in sharing their professional expertise by offering short courses to groups in academia and industry. Please contact CWP if you are interested in hosting one of these short courses.

- Ilya Tsvankin, with his long-time collaborator Vladimir Grechka of Shell, continued to offer the short course *Seismic anisotropy: Basic theory and applications in exploration and reservoir characterization* as part of the SEG Continuing Education Program. The course provides the necessary background information about anisotropic wave propagation and discusses modeling, inversion, and processing of seismic reflection and VSP data in the presence of anisotropy. The main emphasis of the course is on practical parameter-estimation methods for transversely isotropic and orthorhombic subsurface models.

- Paul Sava traveled extensively giving his course *Wavefield Seismic Imaging*. This course provides a survey of current seismic imaging methods designed for acoustic wavefield data. Wavefield seismic imaging, also known as wave-equation migration, is presented in a unified theoretical framework in connection with related topics, including migration velocity analysis (MVA) and amplitude-versus-angle analysis (AVA). The main target audiences for this course are graduate students engaged in seismic imaging research and practicing geophysicists with a basic understanding of seismic data processing and imaging who wish to get familiar with modern imaging techniques available to the industry. Geologists and reservoir engineers can also benefit from a short version of this course, by familiarizing themselves with the concepts that underly practical imaging techniques, their applicability, and limitations.
- Norm Bleistein continued to enjoy his “retirement” by giving his short course *Mathematics of Modeling, Migration and Inversion with Gaussian Beams*. This course is designed for data processing developers with some knowledge of ray theory, migration, and inversion methods, and a desire to learn the fundamentals of modeling, migration and inversion using Gaussian beams. As such, it is a course based on the mathematics that underlies the theory and implementation of Gaussian beams in seismic modeling.
- CWP played a major role in organizing the *13th International Workshop on Seismic Anisotropy* (13IWSA) in Winter Park on August 10-15, 2008. Ilya Tsvankin and Ken Larner teamed up with Edward Jenner and James Gaiser of ION/GXT Imaging Solutions on the organizing committee, while Michelle Szobody and Barbara McLenon provided outstanding administrative support. The workshop was enthusiastically supported by oil and service companies, with ION/GXT, Chevron, Devon Energy, ExxonMobil, PGS, Shell, and WesternGeco forming an impressive sponsorship group. The workshop continued the great tradition of biennial gatherings of experts in anisotropy, which dates back to the 1980’s. The previous workshops, attended by scientists from all over the world, are widely credited with helping to move anisotropy to the forefront of applied seismology. In Winter Park, more than 70 geophysicists from industry and academia discussed both theoretical aspects of anisotropy and application of anisotropic processing/inversion methods to seismic exploration and reservoir monitoring. CWP faculty and students actively contributed to the technical program by giving eight oral and poster presentations. The workshop proceedings will be published in a special issue or section of *Geophysics* edited by Ilya, Ken, and James Gaiser.

## **Interaction with Other Research Projects at CSM and Elsewhere**

During this past year, as in previous years, faculty and students of CWP have interacted closely with those in other industry-funded research projects in the CSM Department of Geophysics. These include the Reservoir Characterization Project (RCP), led by Tom Davis; the Center for

Rock Abuse, led by Mike Batzle; and the Gravity/Magnetics Project, led by Yaoguo Li.

In addition, the CWP faculty have engaged in collaborative efforts with researchers elsewhere. Ilya Tsvankin is spending the Spring 2009 semester on sabbatical leave. He is working on a new book and plans an extended trip to Europe where he will do joint research with Sergei Shapiro at the Free University of Berlin and other colleagues from academia. He will also teach the anisotropy course in several European locations, give a seminar at the PGS office in Oslo, and present a paper at the EAGE Conference in Amsterdam. Other collaborations of the CWP faculty include:

- Norm Bleistein
  - Sam Gray and Yu Zhang (CGGVeritas)
  - Guanquan Zhang (Chinese Academy of Sciences)
- Dave Hale
  - Sverre Brandsberg-Dahl (PGS)
  - Richard Clarke (BP)
  - Marco Maučec and Bob Howard (Landmark)
  - Dave Nichols and John Mathewson (WesternGeco)
  - Joe Stefani (Chevron)
- Paul Sava
  - Clara Andreoletti and Nicola Bienati (ENI)
  - Sergey Fomel (UT Austin)
  - Paul Fowler (WesternGeco)
  - Ivan Vasconcelos (ION Geophysical)
  - Scott Morton (Hess)
  - Michael Payne, Jie Zhang, Anupama Venkataraman, Rongrong Lu, Alex Martinez (ExxonMobil)
  - Ioan Vlad (StatoilHydro)
  - Stewart Wright (Dawson Geophysical)
  - Yu Zhang and Sam Gray (CGGVeritas)
  - Malcolm McNeil (Woodside Energy)
  - Peter Traynin and Lorie Bear (ExxonMobil)
  - Eduardo Filpo Ferreira da Silva (Petrobras)
- Roel Snieder
  - Andrew Curtis and David Halliday (Edinburgh University)
  - Malcolm Sambridge (Australian National University)
  - Johannes Singer and Jon Sheiman (Shell International E&P)
  - Ivan Vasconcelos and Huub Douma (ION Geophysical)
  - Kees Wapenaar and Evert Slob (Delft Institute of Technology)
  - Kasper van Wijk (Boise State University)

- Phil Anno, Partha Routh, and Mark Willis (ConocoPhillips)
- Frank Wüttke (Bauhaus-University Weimar)
- Ilya Tsvankin
  - Milana Ayzenberg (StatoilHydro)
  - Andrey Bakulin and Jörg Herwanger (WesternGeco)
  - James Gaiser (ION/GXT)
  - Vladimir Grechka (Shell Exploration & Production)
  - Ivan Pšenčík (Czech Academy of Sciences)
  - Sergey Shapiro (Free University of Berlin)
  - Walter Söllner (PGS)
  - Eduardo Filpo da Silva (Petrobras)

## Travels and Activities of CWP People

Interactions and collaborations that have taken place away from Golden include the following:

- Norm Bleistein
  - Presented the paper "Asymptotically true-amplitude one-way wave equations in time: Modeling, migration, and inversion" at the 2008 SEG Annual Meeting in Las Vegas. This contribution was recognized as one of the top 30 papers at the meeting.
  - Presented a one-week course on Gaussian beams and other topics in modeling, migration, and inversion at the University of Campinas (May 2008).
  - Presented a one-week short course on Gaussian beams and other topics in modeling, migration and inversion at Petrobras, December, 2008.
- Dave Hale
  - Presented early results of image-guided interpolation to Landmark in Highlands Ranch (July 2008).
  - Presented work on analysis of apparent horizontal displacements in time-lapse seismic images with Barbara Cox and Paul Hatchell (Shell) at the SEG Annual Meeting in Las Vegas (November 2008), which was recognized as one of the top 30 presentations.
  - Traveled to Houston to present work on image-guided interpolation and to work with Dave Nichols and John Mathewson on implementing methods for structure-oriented smoothing (December 2008).
  - Developed the open-source Mines Java Toolkit with various collaborators (ongoing).
- Ken Larner
  - In cooperation with Roel Snieder wrote the book *The Art of Being a Scientist* to be published by Cambridge University Press in August, 2009.

- Served as Chair of the Board of Directors of the SEG Advanced Modeling Project (SEAM).
  - Served on the Organizing Committee of the 13th International Workshop on Seismic Anisotropy (13IWSA), Winter Park, Colorado, August, 2008.
  - Invited speaker for the Geophysical Society of Houston/SEG 2009 Spring Symposium honoring Frank Levin.
- Paul Sava
    - Presented a paper at the EAGE Annual Meeting in Rome (June 2008).
    - Served on the Technical Program Committee for the Annual SEG Meeting, Las Vegas.
    - Presented a paper at the SEG Annual Meeting, Las Vegas (November 2008), and co-authored two other presented papers.
    - Co-author of paper presented at the 13IWSA, Winter Park, CO (August 2008).
    - Traveled to Houston to collaborate with colleagues from ExxonMobil.
    - Traveled to Milan, Italy, to collaborate with colleagues from ENI.
    - Presented the two-day course Wavefield Seismic Imaging (WSI) in Houston, Paris, London, Singapore, Kuala Lumpur, Perth, Calgary, and Perth (again).
    - Served on the EAGE research committee.
    - Co-organized the Madagascar School held in Golden, Colorado (May, 2008).
  - Roel Snieder
    - Served on the selection panel of the Spinoza Award of the Netherlands Organisation for Scientific Research. He made two trips to the Netherlands for meetings of the panel.
    - Served on the Earth Science Council of the US Department of Energy (DOE). He presented the lecture “Education for the Global Energy Challenge” at DOE
    - Organized, with co-conveners Kasper van Wijk, Alex Calvert, Matt Haney, and Alben Mateeva, the session “Innovations in Geophysics: A Tribute to Rodney Calvert” at the 2008 SEG Annual Meeting in Las Vegas.
    - Served on the SEG committee Geoscientists Without Borders and organized the session “Increasing the societal impact of geophysics” at the 2008 Fall meeting of the American Geophysical Union.
    - Presented five papers at the 2008 Fall meeting of the American Geophysical Union.
    - Presented his outreach lecture “The Global Energy Challenge” more than 50 times at universities, community colleges, high school and elementary schools, service clubs, and churches. More information can be found at [http://www.mines.edu/~rsnieder/Global\\_Energy.html](http://www.mines.edu/~rsnieder/Global_Energy.html).
    - Visited the University of Edinburgh to give a seminar on coda wave interferometry and present his course “The Art of Science” in a condensed form.

- Visited the University of California, Irvine, to give seminars and prepare a joint proposal on medical imaging with diffuse fields.
- Was invited speaker at the NATO Advanced Research Workshop on Coupled Site and Soil-structure Interaction in Borovets, Bulgaria.
- Co-authored a presentation “Energy technology choices in CO<sub>2</sub> emissions reductions” at the 2008 Rocky Mountain Natural Gas Strategy Conference and Investment Forum.
- Visited Saudi-Aramco on Dharhan for a mini-workshop on seismic interferometry.

- Ilya Tsvankin

- Taught the two-day SEG Continuing Education Course “Seismic anisotropy: Basic theory and applications in exploration and reservoir characterization” at the SEG Annual Meeting in Las Vegas (November 2008) and in Houston (February 2009).
- Developed an online version of the SEG course on anisotropy to be produced in May 2009.
- Chaired the Organizing Committee of the 13th International Workshop on Seismic Anisotropy (13IWSA) held in Winter Park, Colorado (August 2008), and served as editor of the proceedings to be published as a special issue of *Geophysics*.
- Began writing a new book for SEG (in cooperation with Vladimir Grechka) on azimuthal anisotropy and fracture characterization.

Our students traveled considerably as well. Most of them gave presentations at the SEG Annual Meeting in Las Vegas (November 2008). The internships many students had over the summer months have enriched these students and helped foster valuable contacts with potential employers. Jyoti Behura, Rodrigo Fuck, Xiaoxiang Wang and Jia Yan gave oral presentations at the 13th International Workshop on Seismic Anisotropy in Winter Park, Colorado (August 2008). Behura gave a presentation at the 2008 AGU Fall Meeting in San Francisco (December 2008). Steve Smith traveled to Houston to discuss joint research with Andrey Bakulin and Jörg Herwanger of WesternGeco (July 2008). Yongxia Liu spent two weeks in Prague working on a joint project with Ivan Pšenčík of the Czech Academy of Sciences (March 2009).

## Visitors to CWP

CWP has benefited again this year from visits by a number of scientists and friends from other universities and industry. We strongly encourage visits from our sponsor representatives, whether it be for a single day, or for an extended period.

- Paul Fowler (WesternGeco), James Gaiser and Edward Jenner (both of ION/GXT) have regularly participated in the A(nisotropy)-Team seminar and collaborated with CWP faculty and students. Paul has also attended seminars of the I(maging)-Team.
- Walter Söllner of PGS in Oslo, Norway, spent his six-month leave with CWP (March-October 2008).

- Alexandre Araman, from Total S.A. in Pau (France) came to CSM in January 2008 to collaborate with CWP and RCP (the Reservoir Characterization Project) on research projects. Alexandre also took courses in the Professional M.S. Program and recently transferred to the thesis-based M.S. Program in geophysics.
- Clement Fleury, an MSc student from The City of Paris Industrial Physics and Chemistry Higher Educational Institution (ESPCI) is doing research with Roel Snieder (March–September 2009).

We also had a number of short-term visitors:

- Brad Artman, Spectraseis
- Craig Beasley, WesternGeco
- Jack Bouska, BP
- Sverre Brandsberg-Dahl (PGS)
- Richard Clarke (BP)
- Peter Duncan, Micro Seismic Inc.
- Richard Lindsay, Nobel Energy
- Marco Maučec and Bob Howard (Landmark)
- Rustom Mody, Baker Hughes
- Peter Molnar, University of Colorado
- Louise Pellerin, Green Engineering
- Kaoru Sawazaki, Tohoku University
- Niven Shumaker, Nobel Energy
- Don Vasco, Lawrence Berkeley National Lab
- Paul Williamson, Total
- Dan Wisecup, Wisecup Geophysical Consulting
- Frank Wuttke, Bauhaus University

## Papers at SEG

CWP students and faculty presented a total of fifteen oral presentations, poster papers, and workshop contributions at the SEG Annual Meeting in Las Vegas. A number of these presentations resulted from collaborations with sponsor companies and academic groups. In addition, CWP faculty and students contributed seven presentations at the 2008 EAGE meeting in Rome.

## Publications

### *Student Theses*

During recent months, the theses of CWP students John Mathewson (MSc), Gabriela Melo (MSc) and Rodrigo F. Fuck (PhD) were distributed to sponsors and others:

- Mathewson, J., 2008, Detection of channels in seismic images using the steerable pyramid: CWP-614, M.Sc. thesis, Colorado School of Mines.
- Fuck, R. F., 2008, Modeling of seismic signature for reservoir characterization: Application involving fracture- and stress-induced seismic velocity anisotropy: CWP-617, Ph.D. thesis, Colorado School of Mines.
- Melo, G., 2008, Range and resolution analysis of wide-azimuth angle decomposition: CWP-618, M.Sc. thesis, Colorado School of Mines.

If you would like to receive a copy of these, or any other CWP publications, contact Barbara McLenon at “barbara@dix.mines.edu”. The PhD thesis defense of Jyoti Behura is upcoming. Jyoti’s thesis will also be distributed to sponsors.

### *Book to be Published*

Roel Snieder and Ken Larner completed the book *The Art of Being a Scientist*. This book, which grew out of a graduate course that Roel has been teaching for the past six years, will be published in August, 2009, by Cambridge University Press (ISBN: 9780521743525). The book is a hands-on guide aimed at helping graduate students and other young researchers acquire the skills needed for a career in research. Though some aspects of the philosophy of science are covered in the book, most of the material is of a practical nature—applicable to all fields of science, engineering, and humanities.

### *Research Reports*

As in past years, a significant number of papers authored or co-authored by CWP faculty and students have been published in leading journals. The complete list of CWP papers from 1984 onward is on our web site at <http://www.cwp.mines.edu/bookshelf.html>. Most papers are available there for downloading as PDF files.

### *Publications in 2008 from CWP Faculty and Students*

- [1] Gipprich, T.L., Snieder, R.K., Jibson, R.W., & Kimman, W. 2008. The role of shear and tensile failure in dynamically triggered landslides. *Geophys. J. Int.*, **172**, 770778.
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## Computing Environment

In the past year, CWP purchased 8 desktop PC systems, each consisting of dual-core quad-processor 64 bit, each with 8GB of RAM, and 1 Terabyte of disk space for each system. We now have in excess of 84 new nodes that are available to our students for inhouse parallel applications. Our operating system of choice is Linux (Fedora 9 on most platform, though we may change to Ubuntu in the next year). The CWP research computing environment also includes an aging 32 processor Linux cluster system that was purchased in 2003. The total amount of disk space available on the CWP Net exceeds 20 Terabytes, roughly double of that available last year. For data transport, our preferred medium consists of USB hard drives, formatted with the ext3 filesystem. CWP faculty and students make regular use of the following commercial packages: Mathematica, Matlab, the Intel C and Fortran compilers, as well as the NAG95 (Fortran 90/95 compiler). In addition to the CWP internal computing facilities, the CSM campus facilities now include a 2144 node high-performance cluster system purchased by CSM from Dell in the past year.

## Software Releases

CWP releases open-source software as well as software that is confidential to the Consortium. Most confidential codes depend heavily on the free software environment, so both are relevant to the Consortium. The period of confidentiality is three years. Some of the codes developed at CWP are part of government-funded research projects, and have to be released as open source. Software developed using in-house resources of sponsor companies generally is not available to us for release.

A widely used vehicle of open software distribution is the CWP/SU:Seismic Unix (SU) package. This package has been installed at more than 3800 sites at locations defined by 68 internet country codes, as determined by voluntary direct emails. Another measure of the user

base is the active membership in the “seisunix” listserver group (750 to 800 members), and general interest via downloads of more than 10 per day, though these may be more reflecting of internet bots, rather than real users. Release 42 of SU was issued on April 20, 2008, and contained many updates and new software. For details, please download the release notes from <http://www.cwp.mines.edu/cwpcodes>.

The open-source Mines Java Toolkit is available online from Dave Hale’s home page at <http://www.mines.edu/~dhale/jtk/>. This software is the foundation for most of Dave’s teaching and research, and is also being used by commercial software companies. Anyone with a web browser can view and download the always up-to-date source code repository.

Paul Sava and his students continue to work with and develop software for Madagascar, an open-source software package for geophysical data processing and reproducible numerical experiments. Its mission is to provide a convenient and powerful environment and a technology transfer tool for researchers working with digital image and data processing. The technology developed using the Madagascar project management system is transferred in the form of recorded processing histories, which become “computational recipes” to be verified, exchanged, and modified by users of the system. This open-source package is available from <http://rsf.sourceforge.net/>.

## **Annual Project Review Meeting**

This year’s Annual Project Review Meeting will be held on May 11-15, 2009, in Vail, Colorado. A tradition of recent years is that, prior to the meeting, we hold a short course for sponsors on a topic of particular interest within CWP. This year, in the afternoon of May 11, Bill Symes of Rice University will give a short course entitled “Velocity Analysis and Waveform Inversion.” During the following three days, CWP students and faculty will present more than 20 research papers. In addition, the program will include two guest speakers: John Etgen from BP and Bill Dragoset from Western Geophysical. Thank you for joining us!

