Exploration and Development Geophysics Education and Research (EDGER)

The University of Texas at Austin
Jackson School of Geosciences
Department of Geological Sciences

www.jsg.utexas.edu/edger/

Prospectus 2019

The UT-Austin EDGER Forum is a consortium of petroleum producing and service companies focused on educating graduate students and conducting research on development and application of geophysical methods to support exploration and development of petroleum reserves. The Forum also coordinates education and technology transfer among producing and service companies and academia.

RESEARCH: *Pushing the limits of seismic resolution*

In the past decade, efforts have increased to search for hydrocarbons in difficult areas and in unconventional and fractured reservoirs. This search prompted acquisition of multi-azimuth and wide-azimuth datasets, acquisition in boreholes using DAS, and development of processing algorithms using more complete physics of wave propagation. Currently the primary focus of EDGER is on advancement in understanding of seismic wave phenomena in complex geological environment (including fractures) and quantitative seismic interpretation (QSI). The scope of research encompasses four major themes:

- Development of 3D seismic modeling algorithms in media containing fractures, pores and fluids, and development of new techniques for seismic imaging;
- Application of *Machine Learning* in seismic inversion and reservoir characterization;
- Development of new rock physics models and laboratory measurements of attenuation in the seismic frequency band;
- Integration of seismic inversion and rock physics models using novel statistical approaches and validation with field datasets.

Our imaging and inversion efforts include development of new theory and numerical algorithms for forward seismic modeling that are computationally efficient and accurate. These are used in full waveform imaging and inversion. Inversion for reservoir parameter estimation will be carried out using hybrid Markov Chain Monte Carlo methods. Effective medium models are being tested by computing the seismic responses of realistic rock models based on distributions of rock properties. We are developing new data integration techniques using geostatistical methods and Bayesian analysis and new laboratory tools to characterize and study wave propagation in saturated and fractured rocks.

Current and Planned Research:

1. <u>Seismic modeling and imaging</u>

1.1. Modeling of seismic wave propagation in fractured media: We are developing a 3D seismic wave propagation modeling algorithm based on extended Galerkin and hybrid finite element methods and on integral formulations. These algorithms overcome the limitations of standard finite difference and finite element methods and are able to embed discrete fractures in the model. Thus we can test the validity of the effective media theories. Realistic spatially variable fracture swarms can be easily incorporated into the model. Realistic simulations of wave propagation at different stages of hydraulic fracturing can also be made.

1.2. Pre-stack reverse-time migration (RTM) in frequency-ray parameter domain: We are developing a new RTM algorithm that reduces the data volume significantly and thus will perhaps reduce the computational burden of RTM. Feasibility of least squares migration in the coupled ray-parameter domain is also being examined.

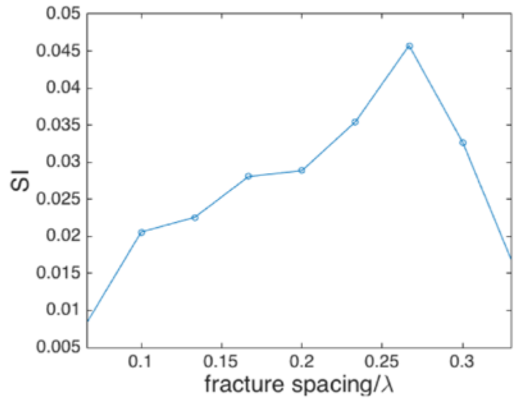


Figure. Fracture index values for a set of models with varying fracture spacing were computed from the synthetic seismograms (at different frequencies) computed by the integral formulation. Note that when fracture spacing is small, we obtain very low SI value indicating that the medium behaves like an effective anisotropic medium. With the increase in fracture spacing, the SI increases until a threshold value where they essentially act as individual diffractors.

2. Seismic inversion for reservoir characterization

2.1 Transdimensional inversion: In the past year, we developed a basis pursuit inversion (BPI) scheme and a fractal based stochastic inversion algorithm for reservoir parameter estimation. Currently we are focusing on one fundamental question: “How many layers are constrained by seismic data?” In other words, in our transdimensional inversion, the number of layer parameters is also a variable that we solve for. The optimization will be carried out using Hamiltonian Monte-Carlo approach.

2.2 Quantitative fracture characterization: Most recently we extended the AVOA method to directly estimate fracture weaknesses that can be directly related to fracture density. Our current effort is to extend this algorithm to orthorhombic media.

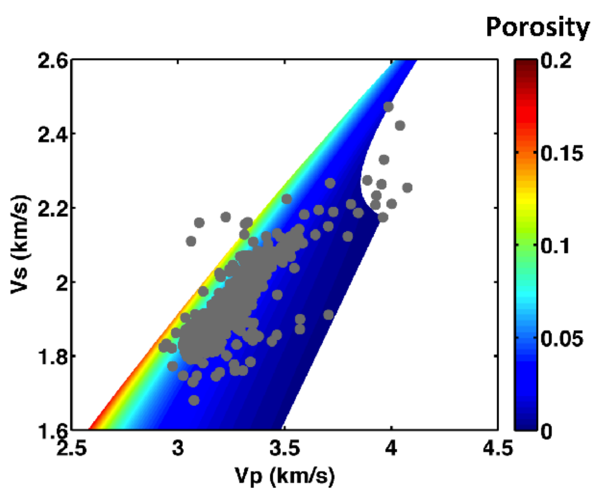
2.3 *Machine learning applications*: In the past (early 2000s), we reported on the application of feedforward artificial neural network (ANN) to some problems of parameter estimation in Geophysics. They include: NMO interval velocity estimation and resistivity and thickness estimation. A variant called Hopefield neural network (HNN) was also applied to deconvolution and multiple attenuation. We also developed algorithms for facies classification using seismic and well log data.

The resurgence of ANN as machine learning has witnessed significant development in algorithms and implementation of these in several different fields. We plan to build on our experience on ANN and develop machine learning tools for at least two applications in the next couple of years. These include:

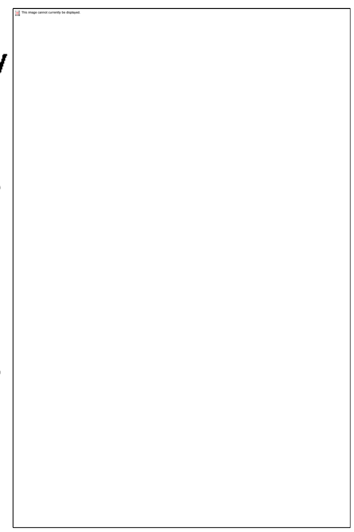
(1) post and pre-stack seismic inversion using Convolutional neural network (CNN). We believe that CNN will results in higher resolutions impedance models than can be achieved by conventional angle stack inversion. (2) development of probabilistic models of reservoir characteristics using seismic, well, core and other ancillary data. We are also developing new AVA and least squares migration methods using Hopfield Neural networks (HNN).

3. Advanced rock physics modeling

3.1 Rock-physics models link rock properties and seismic responses, thus enabling a quantitative approach to seismic interpretation. For anisotropic rocks, resulting from alignment of platy clay minerals and non-spherical pores differentiate shale from conventional reservoir rocks. This high degree of anisotropy affects both the seismic response and log measurements, and should be accounted in rock-physics modeling. We investigate anisotropic rock physics modeling by using rock types and anisotropic effective medium models. The effective medium models consist of distributions of minerals, mineral moduli, pore types, and orientation functions. For conventional reservoir rocks, the modeling approaches account for compaction, diagenesis, lithology, and fluid distributions. Statistical and numerical approaches aid in describing scenarios observed in well and core data and in assessing scenarios not observed in well locations but are geologically likely.



(a)



(b)

Figure. Modeled anisotropic stiffness components compared to well log measurements from an anisotropic interval. Color is porosity on the left and volume of clay (a). (b) is the comparison of modeled and measured porosity logs where the model comes from statistical sampling from (a).

3.2. *Experimental rock-physics and rock-mechanics:* The Rock Deformation Laboratory is the new experimental facility of the Department of Geological Sciences at The University of Texas at Austin. The Rock Deformation Laboratory comprises a preparation room of 650 sq ft hosting equipment to prepare rock plugs that are suitable for mechanical testing, and an experimental room of 640 sq ft that hosts the experimental machines: a large 200 MPa (30000 psi) triaxial pressure vessel (NER autolab 1500), a X-ray transparent triaxial pressure vessel for in-situ rock-mechanics and rock-physics tests (e.g., failure or permeability tests), a benchtop press to determine the dynamic bulk modulus of fluids, a high-speed rotary machine to study friction in rocks, ultrasonic transducers to measure Vp and Vs in core plugs, two high-end GPU-based DELL workstations for numerical simulations.

The EDGER Forum takes advantage of the Rock Deformation Laboratory to characterize geomaterials and to test rock-physics models. In particular, we have developed new tools to measure low-frequency (<100 Hz) complex elastic moduli, attenuation of seismic waves and wave-induced-fluid-pressure in rock samples. Currently, we are studying the propagation of seismic waves in fractured rock samples and wave-induced fluid flows in partially saturated rocks, and we are developing new algorithms for Digital Rock Physics. Our philosophy is to combine laboratory measurements and numerical modeling to gain insights about the physics controlling the propagation of seismic waves. Once the physics is captured, the task of upscaling the laboratory measurements to reservoir-scale problems is simplified. Numerical modeling tools that are available in the Rock Deformation Laboratory include: Sofi 2D and Sofi3D (Viscoelastic Finite-Difference Seismic Wave Simulators), COMSOL Multiphysics Modeling software and Irazu geomechanics simulation software by Geomechanica Inc.

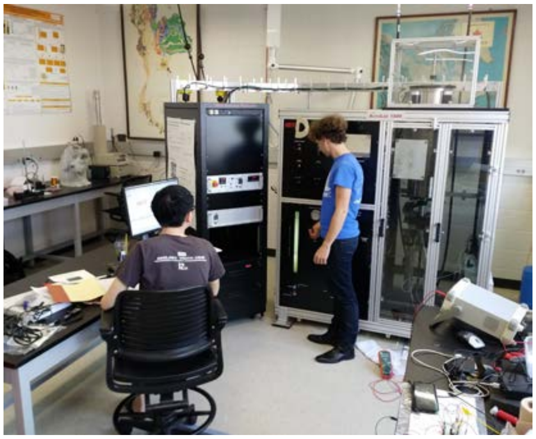


Figure. Students are using the NER autolab 1500 pressure vessel in the Rock Deformation Laboratory.

4. Quantitative Seismic Interpretation: Integration of rock physics modeling and seismic inversion

Our recent applications of rock physics and seismic inversion for reservoir characterization have been in the areas of conventional and unconventional reservoirs and for CO2 injection for EOR and storage. In each case, the heterogeneity of the reservoirs must be accounted as well as pertinent geologic factors such as cementation or geophysical factors such as anisotropy. Our seismic-scale estimates are derived through rigorous rock-physics modeling done at the well log and core scale scales and validated at test wells. This integrated approach also provides uncertainty estimates at every step of the forward and inverse problems.

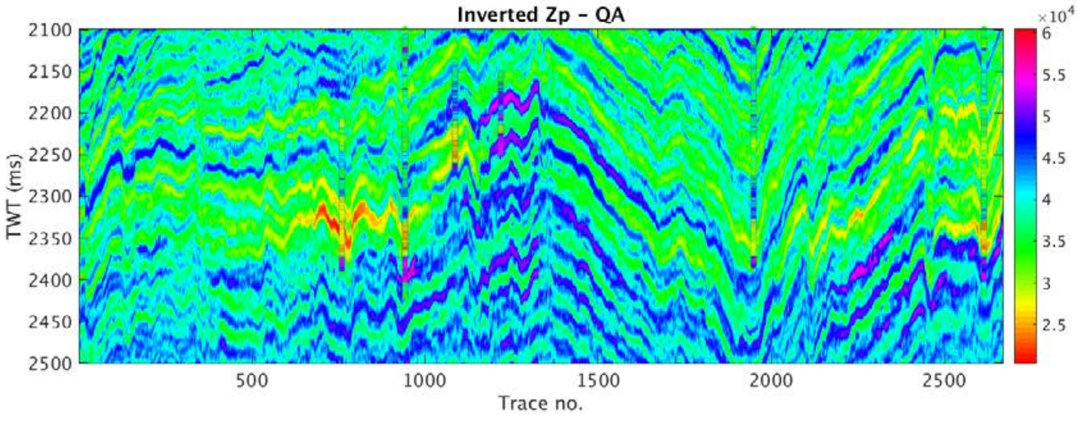


Figure. Global-optimization impedance realization. A thin-bed inversion routine resulted in high-resolution estimates of elastic properties.

Research Team

Dr. Mrinal K. Sen, Co-principal Investigator

Mrinal K. Sen is a professor and holder of Jackson chair in Applied Seismology with joint appointment at the institute for Geophysics and the Department of Geological Sciences. His research interests include seismic wave propagation and inverse theory. He has co-authored two books on geophysical inversion. His group has been engaged in developing new techniques for seismic modeling and inversion including data integration for subsurface model building.

Dr. Kyle T. Spikes, Co-principal Investigator

Kyle T. Spikes is an associate professor in the Department of Geological Sciences with a focus in rock physics. His interests primarily involve the integration of geologic information with quantitative tools for seismic reservoir and basin characterization. This area of research includes both forward and inverse problems that combine rock physics, stochastic geologic modeling, and seismic-attribute analysis.

Dr. Nicola Tisato, EDGER Investigator

Nicola Tisato is an assistant professor in the Department of Geological Sciences who focuses on low-frequency measurements of seismic attenuation and investigating an attenuation mechanism due to bubble exsolution and dissolution. His additional interests include computation of effective elastic properties of digital images without the use of segmentation approaches.

Thomas E. Hess

Mr. Hess provides crucial technical support for the EDGER Forum's research efforts as Seismic Applications Software Manager. He oversees seismic data sets from our sponsors and supports graduate students, faculty and researchers for the Exploration Geophysics program in the Dept. of Geological Sciences as well as for the UT Institute for Geophysics.

Current EDGER Graduate Students:

Anthony Barone, Advisor: Sen, Ent. Fall 2014, PhD
Reetam Biswas, Advisor: Sen. Ent. Fall 2014, PhD
Ricardo De Braganca, Advisor: Sen, Ent. Fall 2018, PhD
Eric Goldfarb, Advisor: Tisato, Ent. Fall 2016, PhD
Ken Ikeda, Advisor: Tisato, Ent. Fall 2016, PhD
Xin Liu, Advisor: Sen, Ent. Fall 2018, PhD
Michael McCann, Advisor: Spikes/Tisato, Ent. Fall 2017, MS
Son Phan, Advisor: Sen, Ent. Spring 2018, PhD
David Tang, Advisor: Spikes, Ent. Fall 2014, PhD
Jackson Tomski, Advisor: Sen, Ent. Fall 2018, MS
Janaki Vamaraju, Advisor: Sen, Ent. Fall 2016, PhD
Wei Xie, Advisor: Spikes, Ent. Fall 2017, PhD

EDUCATION

A principal objective of the EDGER Forum is the education of students who have expressed interest in employment in the petroleum industry. Our students commonly serve summer internships in the industry. The current enrollment of graduate students associated with the Forum is 9. Four (2 MS and 2 PhD) graduated in the last calendar year. Since 2000, nearly 40 graduate students have completed.

FORUM

One of the major benefits of participation is, perhaps, "community activities" sponsored by the Forum. Symposia and workshops have provided a platform for exchange of ideas between industry members (contractors, equipment manufacturers and producers), academics and the graduate students. Discussions of research directions by industry and academic participants have led to student and faculty research projects. The EDGER Forum is in an excellent position to facilitate communication between the various elements to encourage participation within the exploration and development geophysics community.

2018 Publications

1. Aluliaw, B., and M. K. Sen, 2018, A fast algorithm for computing the response from multiple fluid-filled fractures, SEG Expanded Abstracts, 3808-3812.
2. Amalokwu, K., K. Spikes, and K. Wolf, 2018, On the effect of kerogen on the bulk electrical and elastic properties of organic-rich shales: Geophysical Journal International, in review.
3. Agrawal, M., J. Pulliam, M. K. Sen, and S. P. Grand, 2018, Lithospheric removal beneath the eastern flank of the Rio Grande Rift from receiver function velocity analysis, G-cubed, In press.
4. Bader, S., K. Spikes, and S. Fomel, 2018, Missing well-log data prediction using Bayesian approach in the relative-geologic time domain. SEG Expanded Abstracts, 804–808. doi: 10.1190/segam2018-2997278.1.
5. Biswas, R., A Vassiliou, R Stromberg, MK Sen, 2018, Stacking velocity estimation using recurrent neural network, SEG Technical Program Expanded Abstracts, 2241-2245.
6. Chapman, S., Quintal, B., Holliger, K., Baumgartner, L., & Tisato, N. (2018). Laboratory measurements of seismic attenuation and Young's modulus dispersion in a partially and fully water-saturated porous sample made of sintered borosilicate glass: Geophysical Prospecting. https://doi.org/10.1111/1365-2478.12643.
7. Chouhan, M. S*., M. Fedi, and M. K. Sen, 2018, Gravity inversion by the MHODE method for investigating salt domes and complex sources, Geophysical Prospecting, doi: 10.1111/1365-2478.12603.
8. Dahl, E. J. H., K. Amalokwu, and K. T. Spikes, 2018, Velocity dispersion model for global and local flow: Geophysical Journal International, in review.
9. Dahl, E. J. H., and K. T. Spikes, 2018, Local and global fluid effects on flexural waves: Geophysics, in review.
10. Datta, D., D Appelhans, K Jordan, M. K. Sen, 2018, A two-level checkpointing framework for RTM/FWI for GPUs in heterogeneous memory systems, SEG Technical Program Expanded Abstracts, 4025-4029.
11. De Waele, J., D'Angeli, I. M., Bontognali, T., Tuccimei, P., Scholz, D., Jochum, K. P., A. Columbu, S. M. Bernasconi, J. J. Fornos, E. R. G. Gonzales & N. Tisato (2018). Speleothems in a north Cuban cave register sea-level changes and Pleistocene uplift rates: North Cuban cave registers sea level changes and Pleistocene uplift. Earth Surface Processes and Landforms. https://doi.org/10.1002/esp.4393.
12. Goldfarb, E. J., Ikeda, K., & Tisato, N. (2018). Constraining the effect of image resolution in digital rock physics without segmentation. In SEG Technical Program Expanded Abstracts 2018 (pp. 3688–3692). Anaheim, California: Society of Exploration Geophysicists. https://doi.org/10.1190/segam2018-2997871.1.
13. Jaisaval, P., D. Datta, M. K. Sen, and A. Arnulf, 2018, Fast frequency-domain 2D elastic-wave modeling using a Schur complement-based finite-difference method, SEG Technical Program Expanded Abstracts, 3903-3907.
14. Jaisaval, P., D. Datta, M. K. Sen, and A. Arnulf, 2018, Fast finite-difference simulations of DC borehole measurements using a Schur complement approach, SEG Technical Program Expanded Abstracts, 764-768.
15. Liu, H., M. K. Sen, and K. T. Spikes, 2018, 3D simulation of seismic wave propagation in fractured media using an integral method accommodating irregular geometries: Geophysics, 83, 1, WA121–WA136, doi: 10.1190/geo2017-0060.1.

16. Liu, Y., and M. K. Sen, 2018, An improved hybrid absorbing boundary condition for wave equation modeling, Journal of Geophysics and Engineering, 15, 2602-2613.
17. Mandal, B., V. Vijaya Rao, M. K. Sen, P. Karuppannan, and D. Sarkar, 2018, Common reflection surface stack imaging of the Proterozoic Chambal Valley Vindhyan basin and its boundary fault in the northwest India: Constraints on crustal evolution and basin formation, Tectonics, 37.
18. Merzilikin, D*., S. Fomel, and M. K. Sen, 2018, Least-squares path-summation diffraction imaging using sparsity constraints, Geophysics, In press.
19. Mishra, P. K.*, G. E. Fasshauer , M. K. Sen, and L. Ling, 2018, A stabilized radial basis finite difference method with hybrid kernels. Computers and mathematics with applications, In press.
20. Mishra, P. K.*, S. K. Nath, M. K. Sen, and G. E. Fasshauer, 2018. Hybrid Gaussian-cubic radial basis functions for scattered data interpolation, Computational Geosciences, 22(5), 1203-1218.
21. Phan, S., and M. K. Sen, 2018, Hopfield networks for high-resolution prestack seismic inversion, SEG Technical Program Expanded Abstracts, 526-530.
22. RU Silva, JD De Basabe, MK Sen, and M González-Escoba, 2018, Joint acoustic full waveform and gravimetric inversion, SEG Technical Program Expanded Abstracts, 1053-1057.
23. Spikes, K. T., N. Tisato, T. E. Hess, and J. W. Holt, 2018, Comparison of geophone and surface-deployed DAS seismic data: Geophysics, 84, 2, 1–5, doi: 10.1190/GEO2019-0528.1.
24. Tang, D. G. and K. T. Spikes, 2018, Measuring local phase slowness in the Bend Arch-Fort Worth Basin. SEG Expanded Abstracts, 804–808. doi: 10.1190/segam2018-2998373.1.
25. Tisato, N., Duranti, L., & Madonna, C. (2018). Measurements of seismic-wave attenuation and dynamic pore pressure in Berea sandstone. In SEG Technical Program Expanded Abstracts 2018 (pp. 3567–3571). Anaheim, California: Society of Exploration Geophysicists. https://doi.org/10.1190/segam2018-2998063.1.
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27. Vamaraju, J.*, M. K. Sen, J. DeBasabe, and M. F. Wheeler, 2018, Enriched Galerkin finite element approximation for elastic wave propagation in fractured media, Journal of Computational Physics, 372, 726-747.
28. Zhang, P*., M. K. Sen, M. M. Sharma, J. Gableman, and D. Dlowka, 2018, Modeling of Low-Frequency Downhole Electrical Measurements for Mapping Proppant Distribution in Hydraulic Fractures in Cased hole Wells, SPE Journal. https://doi.org/10.2118/189884-PA.
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30. Zhao, Q., Tisato, N., Kovaleva, O., & Grasselli, G. (2018). Direct observation of faulting by means of rotary shear tests under X-ray micro-computed tomography. Journal of Geophysical Research: Solid Earth. https://doi.org/10.1029/2017JB015394.

31. Zhao, Z., D. Kumar, D. J. Foster, D. Dralus, and M. K. Sen, 2018, A new frequency-dependent reflectivity model and estimating seismic AVO attributes, SEG Technical Program Expanded Abstracts, 416-420.
32. Zhao, Z*., and M. K. Sen, 2018, Fast image domain target oriented least squares reverse time migration, Geophysics, Geophysics, 83(6), A81-86.

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