Applied Geophysics: University of Houston

Robert R. Stewart
Director, AGL

Presented to the AGL Update Meeting

April 29th, 2011
Welcome to UH and AGL!

- **Overview of the day**
  - 9:00am – 10:30am Technical session 1  *break*
  - 10:45am – noon Session 2  *lunch (provided)*
  - 12:45pm – 2:15pm Session 3 (AGL students) *displays, lab, posters*
  - 3:00pm  Dobrin lecture (Thomas Bowman – resource plays)
  - 4:00pm  Student awards, discussion
  - 5:30pm  Mucky Duck Pub reception

Thank you so much to our AGL supporters:
Interlocking geoscience partnerships

University’s 4C mandate:
Create
Conserve
Communicate,
Commercialize
# UH/AGL geophysics faculty & their expertise

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
<th>Expertise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robert Stewart</td>
<td>PhD, Massachusetts Institute of Technology</td>
<td>Borehole geophysics (well logging, VSP, crosswell analysis), multicomponent seismic methods</td>
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<tr>
<td>Christopher Liner</td>
<td>PhD, Colorado School of Mines, U. Tulsa, Aramco, Conoco, Western Geo</td>
<td>Seismic data processing, seismic interpretation, time series analysis, CO₂ sequestration</td>
</tr>
<tr>
<td>Aibing Li</td>
<td>PhD, Brown University, Woods Hole Institute</td>
<td>Seismic tomography, inversion, crustal structure</td>
</tr>
<tr>
<td>John Castagna</td>
<td>PhD, University of Texas at Austin, ARCO, Fusion Geophysical</td>
<td>Rock properties, seismic attributes, AVO</td>
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<tr>
<td>Evgeni Chesnokov</td>
<td>PhD, Moscow State University, University College of London, University of Oklahoma</td>
<td>Theoretical seismology, anisotropy, fracture monitor</td>
</tr>
<tr>
<td>Gennady Goloshubin</td>
<td>PhD, Institute of Solid Earth, Moscow, Western Siberian Institute</td>
<td>Seismic exploration, reservoir analysis, permeability prediction</td>
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<tr>
<td>De-hua Han</td>
<td>PhD, Stanford University, Unocal, HARC</td>
<td>Laboratory rock properties, seismic monitoring</td>
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<tr>
<td>Fred Hilterman</td>
<td>PhD, Colorado School of Mines, Geophysical Development Corp., Mobil</td>
<td>AVO, seismic processing, petrophysics</td>
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<tr>
<td>Leon Thomsen</td>
<td>PhD, Columbia University, Amoco, BP, Delta Geophysics</td>
<td>Anisotropy, seismic processing, EM analysis</td>
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<tr>
<td>Robert Wiley</td>
<td>PhD, Colorado School of Mines, Marathon Oil</td>
<td>Physical modeling, instrumentation, shallow seismic analysis</td>
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## Further geophysics faculty and their interests

- **Edip Baysal** – seismic imaging
- **Stuart Hall** – potential fields
- **Bob Sheriff** – exploration geophysics
- **Jolante Van Wijk** – tectonics

### Three more geophysics faculty joining us:
- **Rock physics**
- **Tectonics & hydrocarbons**
- **Remote sensing & seismic**
<table>
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<tr>
<th>Course</th>
<th>Credits</th>
<th>Instructor</th>
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<tr>
<td>3-D Seismic Exploration I</td>
<td>40</td>
<td>Liner</td>
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<tr>
<td>Remote Sensing</td>
<td>80</td>
<td>Khan</td>
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<td>3-D Seismic Exploration II</td>
<td>32</td>
<td>Hilterman</td>
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<tr>
<td>Graduate Seminar (Applied Geophysics)</td>
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<td>Castagna</td>
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<tr>
<td>Graduate Seminar (Solid Earth)</td>
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<td>Khan</td>
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<tr>
<td>Computational Geophysics</td>
<td>30</td>
<td>Castagna</td>
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<tr>
<td>Multicomponent Seismic Exploration</td>
<td>60</td>
<td>Stewart</td>
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<tr>
<td>Rock Physics</td>
<td>60</td>
<td>Castagna/Chesnokov</td>
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<tr>
<td>Petrophysics &amp; Formation Evaluation</td>
<td>32</td>
<td>Myers</td>
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<tr>
<td>Seismic Wave &amp; Ray Theory</td>
<td>60</td>
<td>Chesnokov</td>
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<tr>
<td>Geophysical Data Processing</td>
<td>60</td>
<td>Liner</td>
</tr>
<tr>
<td>Geophysics of Plate Margins</td>
<td>30</td>
<td>Hall</td>
</tr>
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</table>
April, 2011 - over 125 geophysics grad students
~ over 60 geophysics undergrads
Allied Geophysical Lab

Applied Geophysics Research, Education, and Application for Hydrocarbon Exploration

Research
- Instrumentation, Robotic acquisition, Field surveys
- Near-Surface Methods
- Signal Processing & Imaging
- Multi-component Seismic Methods
- Well-logging, VSP, and Petrophysics

Education and Training
- Undergraduate (B.S.) and Graduate (M.S., Ph.D.) Programs
- International Training
- Continuous Professional Learning
- Professional Accreditation

Collaborations & Applications
- Joint Projects/Group Surveys
- Sponsored-research Transfer
- Other Institutions, Agencies, and Companies
Summary

• Pressing needs for better subsurface imaging, assessment, monitoring and personnel development

• Remarkable team of geophysical researchers and students assembled in the Allied Geophysical Lab

• Lots of exciting developments in land & marine acquisition and imaging – research needed

• AGL is looking to create further collaborations and projects with you (y’all)!

Bakken shale (Hess & AGL)
Time-lapse, 3C-3D imaging of SAGD reservoir changes

A. Kato$^1$ & R. Stewart$^2$

$^1$JACOS, Tokyo
$^2$University of Houston

Hangingstone heavy oilfield, Alberta

Organizing Committee

P. Williamson (Total), A. C. Ramírez (PGS), A. Cheng (Halliburton), S. Mallick (U. Wyoming), R. Lu (ExxonMobil), C. MacBeth (Heriot-Watt), K. Hokstad (Statoil), R. Stewart (U. Houston)
Primer on heavy oil

**Heavy Oil Reservoirs**
- 6 trillion barrels in place worldwide (= triple the total conventional oil/gas)
- Canada (1.7 trillion bbl)
- Venezuela (1.2 trillion bbl)

**Proved Reserves of Oil** (Oil & Gas J., 2009)

- Heavy Oil for 97.8% in Canada (175 billion barrels)

**Athabasca Oil Sands**
- Large deposit of heavy oil
- McMurray formation
- Estimated reserves: 133 billion bbl
SAGD Method

Steam Assisted Gravity Drainage (SAGD)

- 2 parallel horizontal wells
- Inject steam to heat reservoir and improve mobility of heavy oil
- Heated oil and condensed steam drain by gravity
- Steam movement is highly affected by geological heterogeneities within reservoirs (impermeable shale)

For reservoir management

Reservoir Delineation
Steam Monitoring

3D Surface Seismic Data

Curtis et al., (2005)
Study Area (Hangingstone Heavy Oilfield)

- **Geology**
  - Formation:
    - Lower Cretaceous McMurray formation
    - Low-stand, fluvial-estuarine incised valleys
  - Heavy Oil Reservoirs:
    - Vertically stacked channel sands
    - Horizontally and vertically very complex distribution
    - About 300 m deep

- **Hangingstone Oilfield**
  - JACOS has operated
  - (Extra) heavy oil of 8.5º API gravity
  - SAGD Production
  - 10,000 barrels/day

*Takahashi et al., (2006)*

* JACOS (Japan Canada Oil Sands Limited)
Elastic Property Changes

Well B (10 kHz)

Heavy oil is assumed to be replaced by injected steam at higher temperatures than 200°C.
**Study Area (Hangingstone Heavy Oilfield)**

### Field Map

- **Base 3D Seismic**
  - (5.4 km²) in February, 2002
- **Monitor 3D Seismic**
  - (4.3 km²) in March, 2006

### Time-lapse seismic data

- **Base Survey (2002)**: PP
  - Analog geophone array
- **Repeat Survey (2006)**: PP + PS
  - 3 C digital sensors

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Nakayama et al. (2008)
Three-term AVO Inversion

- Perform P-P and P-S joint three-term AVO inversion
- Use Bayesian theorem for constraints

Linear system
\[ \mathbf{d} = \mathbf{Gm} \]

Bayesian inversion
\[ \hat{\mathbf{m}} = \left( \mathbf{G}^\text{T} \mathbf{C}_n^{-1} \mathbf{G} + \mathbf{C}_m^{-1} \right)^{-1} \left( \mathbf{G}^\text{T} \mathbf{C}_n^{-1} \mathbf{d} + \mathbf{C}_m^{-1} \mathbf{m}_0 \right) \]

- \( \mathbf{G} = \mathbf{WAD} \)
  - \( \mathbf{G} \): Forward modeling operator
  - \( \mathbf{m} \): model parameter
  - \( \mathbf{d} \): Observation data
  - \( \mathbf{W} \): wavelet matrix
  - \( \mathbf{D} \): derivative operator

- \( \mathbf{A} \)

  - \( \mathbf{P-P wave} \)
  - \( \mathbf{P-S wave} \)

- AVO coefficients based on AR's approximation

- \( \mathbf{C}_n \): Data covariance matrix (Data Uncertainties)
- \( \mathbf{C}_m \): Model covariance matrix (Prior information)
- \( \mathbf{m}_0 \): A priori mean values (Background model)
Sand Thickness Map

Joint Inversion Result

Well logs

Density (kg/m³) vs. Vshale (fraction)

2,150 kg/m³

Sand Thickness Map

Integrated Two-way Time Thickness (ms)
Basic concept of the method

- **P-P time lapse data**

\[
\begin{bmatrix}
  d_{PP_{02}} \\
  d_{PP_{06}} \\
  d_{PS_{06}}
\end{bmatrix} = \begin{bmatrix}
  A_{\alpha 1} & A_{\beta 1} & A_{\rho 1} & 0 & 0 & 0 \\
  A_{\alpha 2} & A_{\beta 2} & A_{\rho 2} & A_{\alpha 2} & A_{\beta 2} & A_{\rho 2} \\
  0 & B_{\beta 2} & B_{\rho 2} & 0 & B_{\beta 2} & B_{\rho 2}
\end{bmatrix} \begin{bmatrix}
  L_{\alpha} \\
  L_{\beta} \\
  L_{\rho} \\
  \Delta L_{\alpha} \\
  \Delta L_{\beta} \\
  \Delta L_{\rho}
\end{bmatrix}
\]

- If P-S data is available in the repeat survey,

\[
R_{pp} = A_{\alpha}(\theta) L_{\alpha} + A_{\beta}(\theta) L_{\beta} + A_{\rho}(\theta) L_{\rho}
\]

\[
R_{ps} = B_{\beta}(\theta) L_{\beta} + B_{\rho}(\theta) L_{\rho}
\]

This process is repeated at each time step for angle-dependent amplitude data
Implementation with Field Data

**Study Area:** (1,100 m x 360 m)

8 SAGD well pairs penetrate the study area

<table>
<thead>
<tr>
<th>Well</th>
<th>Steam injection start</th>
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<tbody>
<tr>
<td>H, I</td>
<td>Feb. 2002</td>
</tr>
<tr>
<td>J, K</td>
<td>Aug. 2003</td>
</tr>
<tr>
<td>L</td>
<td>Jun. 2004</td>
</tr>
<tr>
<td>O, P, Q</td>
<td>Aug. 2005</td>
</tr>
</tbody>
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**Combination of PP and PS waves used in the inversion**

1) 02PP $\rightarrow (\alpha, \beta, \rho)$
2) 02PP + 06PP $\rightarrow (\alpha, \beta, \rho) + (\Delta\alpha, \Delta\beta, \Delta\rho)$
3) 02PP + 06PP + 06PS $\rightarrow (\alpha, \beta, \rho) + (\Delta\alpha, \Delta\beta, \Delta\rho)$

Initial elastic properties

Elastic property changes
Time-lapse inversion result

Vp change is consistent with interpretation based on start time of steam injection
Temperature Map

Based on Rock Physics Model

Using $\Delta V_p$ – temperature, Convert $\Delta V_p$ to temperature maps

Initial reservoir temperature: 11°C
Summary: 4D-3C thermal mapping

- **Reservoir Delineation**
  - Developed P-P and P-S joint AVO inversion
    - Bayesian inversion method
  - Implementation with field data
    - Reservoir distribution map

- **Steam Monitoring**
  - Develop time-lapse AVO inversion
    - Bayesian inversion method
  - Implementation with field data
    - Temperature map