The 4D Paradigm Shift
Impact on the Oil Industry

For Prudential Securities, Inc.

by

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4D Paradigm Shift
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4D Technology Overview
What is 4D?

- 4D processes 3D seismic differences observed over time to identify drainage and bypassed oil within each reservoir -- New oil from old fields.
- 4D is in the early stages of market penetration.
- 4D is expected to extract 30% added value (oil and gas) over 3D exploitation (Aylor, Amoco, 1996).
4D is Multiple 3D

In blue, are the amplitude envelopes surrounding producing reservoirs in the Eugene Island Block 330 field as they appeared in 1985 from a 3D seismic survey acquired by Pennzoil, Mobil and BP.

In red, are the same reservoirs imaged by a 3D survey acquired by Texaco and Chevron in 1988. Improved technology has lowered the noise and raised the high frequency components of the image.

In green, a third 3D survey was shot by Shell and Exxon in 1992. Notice the clear shrinkage in size of each reservoir and the noise-free definition of the bounds of each reservoir.
4D Technology Overview

What is 4D?

- 4D is more than just repeat 3D seismic surveys. It is that, updated with well logs and production histories.
- 4D is the monitoring of past drainage through the addition of time-lapse changes.
- 4D is the prediction AND verification of future drainage to lower risk and increase revenue.
4D Technology is Expected to Improve Recovery

Before 1980: 2D – 25-30% of oil recovered

1980-95: 3D – 40-50% recovered

1996 - future: 4D – 65-75% recovery*

*BP/Shell's Foenhaven field estimate, Petroleum Engineer International; January, 1996.
4D vs Current Best Practices

The structure map of the L sand top interpreted from wireline logging data. Note the gravity driven boundary interpretations between water (blue), oil (green), and gas (red).
Our 4D results overlain on old-fashioned gravity driven oil/gas/water boundary assumption in reservoir--the differences show bypassed oil (green) and gas (red) for future drilling!
4D seismic monitoring gives a volumetric, 3D view of the drainage and bypassed oil within each reservoir over time. Green is bypassed oil downdip.
4D can Simulate Drainage between Surveys
Why 4D Now?

4D is part of a paradigm shift in the oil industry -- why now?
4D experiments date to the 1970’s
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4D Reservoir Monitoring

Return-on Investment Rate & Volume Controlled
Especially in Ultra-Deepwater
Each Field a New Virtual Enterprise

Visit our Homepage, use Netscape or HotJava. http://www.ideo.columbia.edu/4d4/

5D Vision of the Future
Simulation & Verification in Real-Time over Secure Internet
HydroStratigraphy matched to 4D Seismic matched to Seismic Reservoir Simulator
Keys to the Promise of 4D

- Nature of the 4D Task = reservoir monitoring
  - Scale
  - Economics
  - Methodology
- 4D increases efficiency and reduces risk.
- Computers can now meet the computational challenge.
- Military influence finally hitting home.
- New drilling and completion technologies can realize value enhancement, and with 4D = increased production.
- Value of 3D now proven.
Military has done 4D for a Long Time
Reservoir is large, multi-scale, Earth problem.

Diversity of scale requires “heavy-iron” computation and massive data-warehousing and mining only JUST available to the oil industry.

Two separate oil field technologists ---- reservoir engineers and geophysicists are joining forces in 4D.
Scale and the 4D SeisRes Loop
Datasets are like TREASURE MAPS. 4D increases the dimension of these “maps” by adding time to length-width-depth.

4D can enhance value recovery through increased production.

Ever increasing capital investments in harder to exploit fields increase the potential RISK.

4D reduces risk, and thus makes “spend more to make more” a viable management decision.
Value Drivers

Value Drivers:
1. Finding Cost
2. Cycle Time
3. Hit Ratio

Diagram:
- Expenses
- Income
- Better analysis
- Different properties?
- Additional investment
- ROI
- Increase Hit Rate
  - More production, more revenue
  - More efficient use of assets
  - Fixed costs spread over more units
  - ?
- Investment

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Methodology of 4D

● 4D reservoir monitoring is an “inverse” problem.
● Inverse problems solve for Earth models that explain ALL the observations.
● Rapid Analysis for quick, qualitative answers.
● Inversion for more detailed, quantitative answers.
● This process is gated by the huge scale of the computational problem.
● The oil industry will use 4D to “close the loop” to achieve QUALITY control of oil and gas production.
4D Development Cycle

Mapping —
Gravity Gradiometry, 3D & 4D Seismic

Enables Exploration
In New Areas,
Production and
Exploitation

Generates
Strategies
for Exploration

Technology
& Geological
Understanding

4D Loop

Wildcats

Proving Grounds
Integrates Well Data
Into Map Control
New Drilling Technologies are Developed

The Development Wheel Unrolls
Along Successive Gulf Trends

2010
Deep
Ultradeep
4D Engages New Technologies

- 4D/3C Shear Wave Seismic
- 4D AVO
- Multi-Lateral Directional Drilling
- Deep Water Completions
- Pre-Stack Depth Migration
- Cased Hole Logging - Resistivity and Sonic
- 3D Gravity Gradiometry
- Prestack Depth Migration (subsalt)
4D Business Overview

- Service Companies will market 4D technologies to Oil companies, who will integrate them into reservoir monitoring operations to yield new value.
- Expect 4D technologies to speed future, real-time reservoir monitoring - a command-and-control environment we call 5D.
Financial Impact of 4D in Reservoir Management

Connected to production history graphs (middle) and income spreadsheet to the drainage of the IF reservoir (bottom) which, in turn, allows us to couple drainage to the business model to optimize value. Production decisions will be made after simulation of hundreds of scenarios, each with the bottom-line financial impact calculated in real-time.
Initial 4D Market Applications

- Large Fields First
- High Rates/Volumes
- Marine before land
- Expensive Developments
  - Deep Water Gulf of Mexico
  - Deep Water North Sea
  - Deep Water Nigeria
  - Caspian Sea
<table>
<thead>
<tr>
<th>No.</th>
<th>Project Description</th>
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<tr>
<td>1.</td>
<td>Amoco/Lamont - Eugene Island 193 - GOM</td>
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<tr>
<td>2.</td>
<td>Amoco Primrose steam flood - Athabasca Canada</td>
</tr>
<tr>
<td>3.</td>
<td>Amoco - West Hackberry - SW LA</td>
</tr>
<tr>
<td>4.</td>
<td>BP/Shell - Foinhaven - NS</td>
</tr>
<tr>
<td>5.</td>
<td>BP - Magnus - NS</td>
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<tr>
<td>6.</td>
<td>BP - Vietnam</td>
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<tr>
<td>7.</td>
<td>Chevron/Stanford - Duri steam flood Indonesia</td>
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<tr>
<td>8.</td>
<td>Chevron - Bay Marchand - GOM</td>
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<td>9.</td>
<td>Chevron/Lamont/Penn State - Eugene Island 360,361 - GOM</td>
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<tr>
<td>10.</td>
<td>Chevron/Lamont - NS</td>
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<td>11.</td>
<td>Conoco - Heidron - NS</td>
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<tr>
<td>12.</td>
<td>Elf - Heimdal</td>
</tr>
<tr>
<td>13.</td>
<td>Exxon Imperial - Cold Lake, Can</td>
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<td>14.</td>
<td>Exxon/Shell/Lamont - NS</td>
</tr>
<tr>
<td>15.</td>
<td>Holt Fireflood</td>
</tr>
<tr>
<td>16.</td>
<td>Intevep - Lake Maracaibo, Venezuela</td>
</tr>
<tr>
<td>17.</td>
<td>KOC - Kuwait</td>
</tr>
<tr>
<td>18.</td>
<td>Mc Elroy Tx - CO₂ flood</td>
</tr>
<tr>
<td>19.</td>
<td>Nordsk - Hydro/Western - Oseberg NS</td>
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<td>20.</td>
<td>PDO Shell - Yibal - Oman</td>
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<td>21.</td>
<td>Pennzoil/Lamont/Penn State - Eugene Island 330 - GOM</td>
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<td>22.</td>
<td>Phillips - Ekofisk</td>
</tr>
<tr>
<td>23.</td>
<td>Saga/Exxon - Snorre NS</td>
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<td>24.</td>
<td>Saudi Aramco - Marjan</td>
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<td>25.</td>
<td>Shell UK - Brent</td>
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<td>26.</td>
<td>Shell/Lamont/Penn State - South Timbalier</td>
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<td>27.</td>
<td>Shell US - Mars - GOM</td>
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<td>28.</td>
<td>Statoil - Gullfaks - NS</td>
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<td>29.</td>
<td>Texaco/Lamont/Penn State - Teal-GOM</td>
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<td>30.</td>
<td>Texaco/Lamont - Kileuea - GOM</td>
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<td>31.</td>
<td>Texaco/Colorado School of Mines - Vacuum Permian Basin</td>
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<td>32.</td>
<td>Unocal/Lamont - Vermillion - GOM</td>
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<tr>
<td>33.</td>
<td>Vastar - GOM shelf</td>
</tr>
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4D Increases Property Asset Value*

- Average of 20-30% recovery improvement when bright spots present.
- How?
  - Delays shutin and retirement costs.
  - Increases recovery & proven reserves.
  - Optimizes new well placements.
  - Plans work-over and infill targets.

*Source: Aylor, Amoco
4D Increases Property Value

» Identifies underproduced reserves.
» Optimizes capital expenditures & increases time-value of money.
» Better injector locations.
» Reduces dry holes.
» Preempts operational problems.
# 4D Field Estimate

<table>
<thead>
<tr>
<th>%</th>
<th>Areas</th>
<th>Blocks</th>
<th>Reserves</th>
<th>1 Sur</th>
<th>2 Sur</th>
<th>3 Sur</th>
<th>4 Sur</th>
</tr>
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<tbody>
<tr>
<td>15%</td>
<td>Gulf</td>
<td>15000 blocks</td>
<td>50 bil bbl</td>
<td>100%</td>
<td>50%</td>
<td>25%</td>
<td>10%</td>
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<tr>
<td>15%</td>
<td>Euro+ Africa</td>
<td>10000 blocks</td>
<td>50 bil bbl</td>
<td>100%</td>
<td>25%</td>
<td>10%</td>
<td>-</td>
</tr>
<tr>
<td>15%</td>
<td>Indonesia &amp; SE Asia</td>
<td>10000 blocks</td>
<td>50 bil bbl</td>
<td>?</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>15%</td>
<td>Russia</td>
<td>?</td>
<td>50 bil bbl</td>
<td>0%</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tbody>
</table>

**Total fields that are candidates for 4D:**
25,000 fields with >100 billion BOEs!
4D Value
Levers by Amoco

Production Value Levers

<table>
<thead>
<tr>
<th>Acquire Seismic</th>
<th>Timing, Cost, Quality of Seismic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build Facilities</td>
<td>Timing, Cost, Right Sizing</td>
</tr>
<tr>
<td>Development Drilling</td>
<td>Timing, Cost, # Locations, Success Rate, Completion Efficiency</td>
</tr>
<tr>
<td>Primary Production</td>
<td>Timing, Decline Rates, Production rates, Reserves per Well, Connectivity</td>
</tr>
<tr>
<td>In-fill &amp; Step-out Drilling</td>
<td>Timing, Cost, # locations, Production rates, Reserves per Well, Connectivity</td>
</tr>
<tr>
<td>Injectors</td>
<td>Timing, Cost, # locations, Connectivity</td>
</tr>
<tr>
<td>Secondary/Tertiary Production</td>
<td>Timing, Cost, # locations, Decline Rates, Production rates, Reserves per Well, Connectivity</td>
</tr>
</tbody>
</table>

Impacted by 3D Seismic
Impacted by 4D Seismic
Amoco’s 4D Value Analysis

Scenario Analysis

- With 3D restudy only:
  - 12 locations, 28% Success rate
- With 4D:
  - 11 4D locations with 59% success rate
  - Rate acceleration of 2 wells by converting 2 other wells to injectors
Amoco’s Bayesian Analysis of 4D Success Rates

Bayesian Determination of Locations and Success Rates

4D identifies 11 additional drill locations with a 59% success rate.

1.6 good to fair locations are undetected.

4D adds 3.2 good to fair producers and prevents one dry hole.
Benefits of 4D for Oil Service Cos.

- 4D seismic acquisition will cause 3D seismic market to grow by 5-7%/yr because of 4D reshoots and monitoring jobs.
Large numbers of multiple 3D surveys already exist for immediate 4D mining.
3D Marketplace

- 3D started 1979, widespread by 1985.
- Revenue per year now 2/3 of $3B/yr worldwide seismic business
- Proven value of 3D vs 2D

<table>
<thead>
<tr>
<th>Company</th>
<th>3D vs 2D improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amoco</td>
<td>30% well success</td>
</tr>
<tr>
<td>Exxon</td>
<td>25% well success</td>
</tr>
<tr>
<td>Shell</td>
<td>15%-30% (ROI)</td>
</tr>
<tr>
<td>Simmons</td>
<td>% constant/yr vs decline</td>
</tr>
</tbody>
</table>
3D Seismic Market Share


- WAI: 31%
- SLB: 22%
- CGG: 14%
- PGSAY: 13%
- DGC: 5%
- OTHER: 15%
4D Marketplace

- Market Size $3 Billion/yr in 5 years (Forbes Nov 6, 1995).

- 4D market large because much 3D is over existing fields. Instantly becomes 4D.

- 4D Market Segments:
  - Software/Maintenance
  - Interpretation Services
  - Planning for new 4D
  - Reservoir Monitoring
  - New 3D Acquisitions
  - New 4D Hardware
  - Downhole Sensors
  - Database Mining
Impact of 4D on Seismic Market Size

Seismic Market Size Data

Year

Est Income ($ Million)

- Total Seismic
- w/o 4D
- 4D- Total
- 4D- Marine
- Processing
- OBS- Marine
- Acq- Land
- Acq- Marine


0 500 1000 1500 2000 2500 3000 3500 4000

Seismic Market Size Data
4D Service Company
Value Estimates

Growth driven by 4D

Lamont 4D Software

4D Broadens market pie, broadens market slices.

Current 3D Market
4D Product Families from the Service Cos.

Deployment
- Sensors
- Cables
- Vertical Arrays
- Coiled Tubing
- Logging

Databases
- Data Mining
- Knowledge-Bases
- Data Banks
- Spec Resales

Processing
- Reprocessing
- Pre-Stack
- Post-Stack

Work Stations
- Lamont 4D Software
- POSC compatibility
- Reservoir Simulation

4D Interpretation
- Inversions
- Reservoir Characterization
- 3D Seismic Models

Fully Integrated 4D Field Monitoring
4D Software Opportunity

- 660 MM$ sales in 1995.
- 72,000 geophysicists -- but only 10,000 workstations.
- Workstations will double 3-5 years.
- Market penetration only 30-35%.
- Total growth 30-35%/yr for next 5 years.
- Gross margins -- 90%.

*(Source: Salomon Brothers, Jan 2, 1995)*
4D Software Requirements

- 4D must have extensive tools to correct old 3D seismic datasets.
- 4D interpretation environment must integrate seismic with well and production engineering information.
- 4D must include 3D tools for export to visuals such as maps that managers understand.
- 4D analyses must be Plug-and-Play with existing 3D Products: Landmark, GeoQuest, Tigress, Eclipse, VIP, etc.
Benefits of 4D to Oil Cos.

If 25,000 fields exist in the world with 4D POTENTIAL, each with 1 3D survey at a current estimated investment of:

\[25,000 \times \$1\text{MM/field} = \$25\text{B}\]

*These 25,000 fields have potential to be RESHOT every 2 years for the next 20-30 years!*

4D presents an asset potential with sales of $10s of B/yr!
Benefits of 4D to Oil Cos.

Integrated Multi-National Oil Companies with the Technological Skills to Internally Utilize the Lamont 4D Software

The Seismic Service Companies with the Field Expertise to Partner With the Lamont in Deploying The 4D Technologies

The National Oil Companies, Domestics, and Independents who Require Interpretation Services to Utilize the Lamont 4D Software
Benefits of 4D to Oil Companies

(Using Amoco methodology, based on 100 fields)

Identify 40 drill locations/yr
(8 wells/field x 5 fields/yr)

24 (60%) successful w/ 4D
12 (30%) successful w/ 3D

Incremental Added NPV for 4D:
12 additional wells successful x $15MM oil/well = $180MM
(Average well has 1.5 MMbbl oil @ $10/bbl net present value)

Incremental cost for 4D:
$6.5MM for new surveys over 5 fields/yr
+ $40MM (drilling) + $2MM/ 4D processing = $48.5MM/yr
(assumes $1.3 MM/3D survey and 1MM/well drilling costs)

Some Oil Companies are still cost-cutting and will miss 4D Paradigm Shift
4D Case Study
using Lamont 4D Software

- 10-25% production improvement anticipated
- New wells being drilled in 1997.
- Eugene Island, South Timbalier, Deep Water GOM, North Sea
- Underway: Vermillion, Nigeria, Western clients
Drilling of the first 4D well in 1994 produced 1500 b/d. Since then, a 4th 3D seismic survey has been acquired. Two new 4D wells are to be drilled in the 1st quarter, 1997.
Eugene Island Case Study

- Most of Field covered with two vintages of 3D
- Center covered by 3 surveys
- 4 corners (red triangle) by 4
Eugene Island Case Study

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<tr>
<th></th>
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<tbody>
<tr>
<td>Assumed Price of Oil</td>
<td>$15/barrel</td>
<td>$15</td>
<td>$15</td>
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<tr>
<td>Reserves Recovered</td>
<td>500MMBOE</td>
<td>22 MMBOE</td>
<td>55 MMBOE</td>
</tr>
<tr>
<td>Time to Extract</td>
<td>20 yrs</td>
<td>4 yrs</td>
<td>10 yrs</td>
</tr>
<tr>
<td>Cost to Extract</td>
<td>$5/B</td>
<td>$5/B</td>
<td>$6/B</td>
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<tr>
<td>Discount Rate</td>
<td>4%/ 6 mo</td>
<td>4%</td>
<td>4%</td>
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<tr>
<td>NPV of Asset</td>
<td>$5 Billion</td>
<td>$220 MM</td>
<td>$550 MM</td>
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<td>Revenue Increase</td>
<td>-</td>
<td>4%</td>
<td>11%</td>
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</table>
New Wells Drilled to Recover Bypassed Reserves – EI 330

New horizontal well finds sweet spot

A-8ST Production History

Pre-4D Production
1972-1994:
1.2 Million Barrels

Post-4D Production
1994-1996:
1.0 Million Barrels

Horizontal Drilling + 4D Monitoring = Even More Recovered Oil and Gas.
A 3D seismic survey was acquired in 1982, and production began almost immediately. In 1994, a modern vintage of 3D was shot over the northern quadrant of the field to identify new fault compartments. In 1996, a bid for the property was received. A 4D analysis identified no need for new processing of the 1982 survey (saving $1MM). Then, insufficient remaining bypassed pay was identified, so the property was sold.
A 4D study of a North Sea field, for which a company had a bid for sale, resulted in the identification of water encroachment (blue) and remaining bypassed pay (green). There was insufficient remaining pay for the company to keep the property. As new owner, where would you now drill?
A 3D Seismic survey was acquired in 1988, and production began in 1989 in this deepwater gas field. In 1996, water production far updip surprised operator, and a speculative 3D survey shot in 1994 was purchased for 4D analysis. Water breakthrough was identified in two wells, and a successful prediction made for the timing of water-hit into the third well (within months of the acquisition of the 1994 survey). Two new 4D wells are to be drilled DOWNDIP in 1997.
A 4D analysis of a deepwater Gulf of Mexico turbidite reservoir indicates that water (blue) has broken updip toward the 3 producing wells. Remaining gas (red) in the reservoir is found downdip and to the west. Where would you drill your next well, and how much will it likely produce?
In this North Sea field, an original 3D seismic survey was shot in 1977, but reprocessed in 1995 to match a new, modern 3D survey. After water breakthrough updip in 1995, the British government inquired about production practices. A 4D analysis showed that a new injector well had driven water rapidly updip. The injector was turned off, and a new downdip well planned to recover bypassed pay.
A 4D analysis of another North Sea field indicated that water (blue) quickly broke updip from an injector well that was newly drilled. Considerable bypassed pay remained downdip and to the right of this water breakthrough.
A 3D seismic survey was acquired in 1988, and production began in 1989. Water immediately broke updip, so another well was placed farther updip. It too began producing water 18 months later, so a 1995 speculative 3D survey was purchased and a 4D study initiated. Considerable water “channeling” was imaged, and oil “thieving” by the updip well observed. Squeezing-off perforations and a new downdip well are being considered.
4D Drainage in Deepwater Turbidite Field, GOM

4D analysis in this deepwater turbidite reservoir indicated that water (blue) had quickly broken updip to the producing wells (top right). A 4D drainage simulation indicated that water channeling and thieving by the most updip well (bottom right) had left considerable bypassed pay (green in top right image).
4D Technical Hurdles to Overcome on way to 5D

- Field tests need to be completed through Economics.
- Implementation by reservoir engineers of geophysical technologies.
- Techniques for 4D analysis in fields with subtle hydrocarbon indicators is next.
- Legacy 3D databank will have many old surveys that cannot be compared with modern 3D surveys.
- Coupling between a “reservoir” simulator and a “seismic simulator” will require significant computer cycles.
- Complexity of 4D software tasks.
- Methodologies of 4D monitoring still being debated – how to do, what, when.
- Future acquisition and processing differences must be overcome either by software or new sensor technologies (e.g., permanent bottom cables.)