Analysis of ARM64's Competence for Oil&Gas Seismic Data Processing Applications

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Date: Sept 2020
Motivation: To look for new Computing Hungry Applications

Deep Learning
Convolution Algorithms
FMA, FP32, BF16
Tensor Core AVX/SVE

What we learned: DL training is a computing hungry process & 90% of the ops are FMA, requiring hundreds of thousands of iterations.

FWI: Final & Ultimate


1000X in Compute for 15Hz to 125Hz

2.5EFlops for 125Hz FWI

https://www.nextplatform.com/2019/05/16/dug-sets-foundation-for-exascale-hpc-utility-with-xeon-phi/

No.1 barrier: Gigantic Computation Cost

Gigantic computation cost FWI is achieved using local or global search methods to find the optimal solution so that the inversion solves wave equations numerically in hundreds of times.
Some Big Data about Oil & Gas Industry

$3.3$ Trillion, $4M$ Jobs, $3.8\%$ GDP
Global Oil & Gas Exploration & Production industry in 2019
(Source: www.ibisworld.com)

Market Opportunities

$9.28B$ Seismic Survey Market by 2022, $11.8B$ by 2025
(ResearchandMarkets, 2017)

$22B$ Oil & Gas Analytics Market by 2025
(brandessence Research, 2020)

$49B$ Global Oil & Gas Analytics Market by 2030
(Transparency Market Research 2020.08)

Big Data about Oil & Gas Exploration

$200+$TB Data in a $24000$ km$^2$ survey
(DUG, 2018)

5000-35000ft Well Depth

$5M$-$8M$ / onshore
$100M$-$200M$ / Offshore Oil Well (USEIA, 2016)
3 Key Oil & Gas E&P Activities – Exploration, Production & Prediction

**Exploration - Seismic Data Processing**
- Where and How Much is the Oil & Gas?
  - ✓ Build accurate HD earth Subsurface Models
  - ✓ Interpret the Models Automatically

**Production - Drill Operations**
- How are the wells going in Real-Time?
  - ✓ Well Operation & equipment status Monitoring
  - ✓ Predictive Maintenance to avoid operation disruptions

**Prediction - Reservoir Simulation**
- How Much Oil & Gas Left & How would the reservoir be changing?

Acquisition ➔ Processing ➔ Interpretation

Raw Data ➔ Geology

[Image of oil rigs and reservoir simulation]

https://www.omnisci.com/blog/the-next-wave-of-oil-and-gas-analytics-reservoir-behavior
3-Step of Oil & Gas Exploration

✓ 2D/3D/4D Seismic Wave Data collection with vibrators or air-guns & sensors for up to 200Hz
✓ 100s TB data per Survey recorded in SEG-Y Format

✓ To Collect Seismic Wave Data

✓ Remove Noises and Transform the Raw SEG-Y Seismic Data
✓ Use Inversion Algorithms to build a Layered HD Subsurface model
✓ High-Frequency FWI (Full Waveform Inversion) is the Game Changer

✓ To Prepare the raw Seismic data for Inversion
✓ To Build a Layered HD Velocity Model from the collected & Preprocessed seismic Data

✓ Use of Human, Legacy Computer Vision or Deep-Learning to Interpret the generated Velocity Model
✓ Advanced Deep-Learning could play a key role for Automated Seismic Data Interpretation

✓ To Determine where, how deep and How Much the Oil & Gas for Where to Drill

Source: https://slideplayer.com/slide/1385324/
https://fluidpowerjournal.com/repairing-hydraulic-valves/
https://www.geolink2.com/expertise/3d-seismic-interpretation-training/
A seismic trace represents the response of the elastic wavefield to velocity and density contrasts across interfaces of layers of rock or sediments as energy travels from a source through the subsurface to a receiver or receiver array.

The Seismic wave data collected by the survey instrument is arranged & saved in the SEG-Y format defined by SEG.

The Seismic Wave data value uses 32-bit Single-Precision Floating-Point format (FP32).

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### SEG-Y seismic data exchange format

<table>
<thead>
<tr>
<th>Revision</th>
<th>File Headers</th>
<th>Data Trace(s)</th>
<th>Data Trailer(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rev 0 1975</td>
<td>Textual file header</td>
<td>24-bit integer</td>
<td>Textual file header</td>
</tr>
<tr>
<td></td>
<td>Textual file header</td>
<td>48-bit integer</td>
<td>Textual file header</td>
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<td></td>
<td>Ab header</td>
<td>1st data trace</td>
<td>Ab data trail</td>
</tr>
<tr>
<td></td>
<td>Ab header</td>
<td>2nd data trace</td>
<td>Ab data trail</td>
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<td>Ab header</td>
<td>3rd data trace</td>
<td>Ab data trail</td>
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<td>Ab header</td>
<td>4th data trace</td>
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<td>Ab header</td>
<td>5th data trace</td>
<td>Ab data trail</td>
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<td>6th data trace</td>
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<td>Ab header</td>
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<td>Ab header</td>
<td>9th data trace</td>
<td>Ab data trail</td>
</tr>
<tr>
<td></td>
<td>Ab header</td>
<td>10th data trace</td>
<td>Ab data trail</td>
</tr>
</tbody>
</table>

### Changes from Rev 0 to Rev 1
- Added support for extended binary data, 72-bit integer precision.
- Added support for extended textual data, 128-bit integer precision.
- Added support for extended binary file headers, 128-bit integer precision.
- Added support for extended textual file headers, 256-bit integer precision.

### Changes from Rev 1 to Rev 2
- Added support for extended binary data, 192-bit integer precision.
- Added support for extended textual data, 512-bit integer precision.
- Added support for extended binary file headers, 512-bit integer precision.
- Added support for extended textual file headers, 1024-bit integer precision.

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The seismic data recorded for one channel


IEEE 754-1985 32-bit Single-Precision Floating-Point value
Many Waves Received by the Sensors

- Direct Waves, Diving Waves, Reflected Waves, Refracted Waves
- Reflected and Refracted Waves from different subsurface layers of materials – rock, oil, gas, water, etc
Many Formulas/Equations to Calculate

- Seismic Sound Waves travel at different speeds through different materials
- A lot of Laws & Equations for governing wave travel paths

### Diving Wave Speed

\[ V = V_0 + kZ, \text{ where } Z \text{ is depth} \]

### Pythagorean Theorem:

\[ (z + \lambda/4)^2 = z^2 + R^2 \]

### Snell’s Law:

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

### Acoustic wave equation

\[ \frac{1}{k(r)} \frac{\partial}{\partial r} \left( r \frac{\partial}{\partial r} v(r, t) \right) = s(r, t) \]

### P-Wave Velocities for Different Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>( V_p \text{ (m/s)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>330</td>
</tr>
<tr>
<td>Water</td>
<td>1450-1530</td>
</tr>
<tr>
<td>Petroleum</td>
<td>1300-1400</td>
</tr>
<tr>
<td>Loess</td>
<td>300-600</td>
</tr>
<tr>
<td>Soil</td>
<td>100-500</td>
</tr>
<tr>
<td>Snow</td>
<td>370-5000</td>
</tr>
<tr>
<td>Solid glacier ice</td>
<td>3000-4000</td>
</tr>
<tr>
<td>Sand (loose)</td>
<td>200-2000</td>
</tr>
<tr>
<td>Sand (dry, loose)</td>
<td>200-1000</td>
</tr>
<tr>
<td>Sand (water saturated, loose)</td>
<td>1500-2000</td>
</tr>
<tr>
<td>Glacial moraine</td>
<td>1500-2700</td>
</tr>
<tr>
<td>Sand and gravel (near surface)</td>
<td>400-2300</td>
</tr>
<tr>
<td>Sand and gravel (at 2 km depth)</td>
<td>3000-3500</td>
</tr>
<tr>
<td>Clay</td>
<td>1000-2500</td>
</tr>
<tr>
<td>Estuarine muds/clay</td>
<td>300-1800</td>
</tr>
<tr>
<td><em>Loess/plain alluvium</em></td>
<td>1800-2200</td>
</tr>
<tr>
<td><em>permafrost</em> (Quaternary sediments)</td>
<td>1200-4900</td>
</tr>
<tr>
<td>Sandstone</td>
<td>1400-4500</td>
</tr>
<tr>
<td>Limestone (soft)</td>
<td>1700-4200</td>
</tr>
<tr>
<td>Limestone (hard)</td>
<td>2600-5000</td>
</tr>
<tr>
<td>Dolomite</td>
<td>2500-6200</td>
</tr>
<tr>
<td>Anhydrite</td>
<td>3500-5500</td>
</tr>
<tr>
<td>Rock salt</td>
<td>4000-5500</td>
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<td>Gypsum</td>
<td>2000-3500</td>
</tr>
<tr>
<td>Shales</td>
<td>2000-4100</td>
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<td>Granites</td>
<td>4600-6200</td>
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<td>Basalts</td>
<td>5500-6500</td>
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<tr>
<td>Gabro</td>
<td>6900-7000</td>
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<tr>
<td>Peridotite</td>
<td>7800-8400</td>
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<tr>
<td>Serpentinite</td>
<td>5500-6900</td>
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<tr>
<td>Gneiss</td>
<td>3500-5600</td>
</tr>
<tr>
<td>Marbles</td>
<td>3780-7000</td>
</tr>
<tr>
<td>Sulphide ores</td>
<td>3950-6700</td>
</tr>
<tr>
<td>Pulverised fuel ash</td>
<td>600-1000</td>
</tr>
<tr>
<td>Made ground (rubble etc.)</td>
<td>160-400</td>
</tr>
<tr>
<td>Landfill refuse</td>
<td>400-750</td>
</tr>
<tr>
<td>Concrete</td>
<td>3000-3500</td>
</tr>
<tr>
<td>Disturbed soil</td>
<td>180-355</td>
</tr>
<tr>
<td>Clay landfill cap (compacted)</td>
<td>355-380</td>
</tr>
</tbody>
</table>

\* Strongly temperature dependent (Kolman 1974)

Source & Credit: https://slideplayer.com/slide/10729456/ , Lee M. Liberty, Boise State Univ

http://www.ukm.my/rahim/Seismic%20Refraction.htm
Inversion & Full Waveform Inversion (FWI)

- **Inversion**: To Generate subsurface structures from the known source waves and the waves received/observed by the sensors
  - Constrained Sparse-Spike Inversion (CSSI), Reverse Time Migration (RTM), Reflection Waveform Inversion (RWI), Full Waveform Inversion (FWI), etc.,

- **Full Waveform Inversion**: To Generate High Resolution Subsurface Velocity model using all waveforms observed by the sensors
  - Diving Waves, Refraction Waves and Reflections, Primaries and Multiples, etc.,

- **High Frequency FWI**: FWI for seismic sound source waves of frequency up to 125-200Hz for High Resolution Imaging
  - Vertical Resolution: $\lambda/4 = V/4F$. For example, for 3000m/s and 100Hz wave, the vertical resolution is $3000m/s / 400 = 7.5m$
Some FWI use cases

- FWI is being used to build High-Resolution & High-Fidelity Subsurface Model recently for up to 15Hz-20Hz
- Up to 125Hz High Frequency FWI is preferred but not in use mainly due to the required computing power constraint

Source & Credit: https://www.pgs.com/publications/case-studies/


BP found billion-barrel oil deposit with FWI in the Gulf of Mexico, to expand to Brazil & Angola

BUSINESS NEWS JANUARY 18, 2019 / 1:08 AM / UPDATED 2 YEARS AGO

After billion-barrel bonanza, BP goes global with seismic tech

By Ron Bousso

The new deposit was found with software known as Full Waveform Inversion (FWI), which is run on a super-computer and analyses reverberations of seismic soundwaves to produce high-resolution 3D images of ancient layers of rock thousands of meters under the sea bed, helping geologists locate oil and gas.

It is more accurate than previous surveying methods, BP said, and processes data in a matter of days, compared with months or years previously.

Source & Credit: https://www.pgs.com/publications/case-studies/

https://www.reuters.com/article/us-bp-seismic-focus/after-billion-barrel-bonanza-bp-goes-global-with-seismic-tech-idUSKCN1PC0HF
Potential: FWI workshop in SEG in 2013 declared: “Full-waveform inversion has emerged as the final and ultimate solution to the Earth resolution and imaging objective.” It emphasized that FWI is the final and ultimate solution of seismic data inversion and imaging.

Why not yet:
No.1 Gigantic Computation Cost
No.2 Insufficient information in seismic data
No.3 Incomplete theory
No.4 Unsophisticated acquisition technology

Source: A review on reflection-waveform inversion, Yao etc, Springer 2020

FWI Computing requirement is proportional to the fourth Power of Frequency (DUG)
FWI Workflow: A Nonlinear Optimization Problem

Starting Model Optimization Iteration Process from Low frequency to High Frequency

- **Step-1:** Pick an initial velocity model having the same source and receiver locations as the recorded data and Create synthetic shot records;
- **Step-2:** Forward the model with the synthetic shot records to generate outputs – (Similar to DL forward propagation);
- **Step-3:** Calculate the differences and gradients between the model outputs and the field data. If the difference is small enough then the velocity model is achieved and go to Step-2 with a next frequency until it is all done, otherwise go to Step-4
- **Step-4:** Update the model with calculated gradients – (Similar to DL backward propagation) and Go to Step-2 for next iteration >> Many Iterations May Required

For each iteration, the model difference & gradient calculation in Step-3 triggers Single-Precision Floating-Point operations on Huge matrixes of trillions of entries, thus requires Gigantic computing power. For more details, please refer to following:

https://www.crewes.org/ForOurSponsors/ResearchReports/2012/CRR201270.pdf
DownUnder GeoSolutions (DUG) HPC for Seismic Processing

- A dedicated HPC System for High-Frequency FWI Seismic Data Processing Applications & Services with 250 Petaflops @ SP32 and plan to double

- Why Xeon Phi 7250:
  - High SP32 Performance – 6.1TeraFlops
  - Many Cores – 68 cores/socket
  - High Memory Bandwidth – 16GB & 400GB/s McDRAM

- DUG Bubba HPC System in Houston

- Max 250 Petaflops @FP32 w/ 40,000 Nodes of Intel Xeon Phi 7250
- 50GE to Each Node & 10MB/s-30MB/s/Node Network BW required
- No Need for Global MPI Communications, only within a few dozens of Nodes

Source & Credit: https://www.nextplatform.com/2019/05/16/dug-sets-foundation-for-exascale-hpc-utility-with-xeon-phi/
IEEE Floating-Point Data Format, Ranges and Precision

If BF16 or TF32 could be used for Seismic Data Processing, Much Higher Performance than FP32 would be achieved

<table>
<thead>
<tr>
<th>Format</th>
<th>64b Double Precision</th>
<th>32b Single Precision</th>
<th>16b Half Precision</th>
<th>Tensor FP32</th>
<th>Bfloat16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Bits</td>
<td>64</td>
<td>32</td>
<td>16</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>Significand Bits</td>
<td>52+1</td>
<td>23+1</td>
<td>10+1</td>
<td>8+1</td>
<td>8+1</td>
</tr>
<tr>
<td>Sign Bits</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Exponent Bits</td>
<td>11</td>
<td>8</td>
<td>5</td>
<td>8</td>
<td>8</td>
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<tr>
<td>Exponent Bias</td>
<td>1023 (2^{10}-1)</td>
<td>127 (2^7-1)</td>
<td>15 (2^4-1)</td>
<td>127</td>
<td>127</td>
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<tr>
<td>Exponent Max</td>
<td>+1023</td>
<td>+127</td>
<td>+15</td>
<td>+127</td>
<td>+127</td>
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<tr>
<td>Exponent Min</td>
<td>-1022</td>
<td>-126</td>
<td>-14</td>
<td>-126</td>
<td>-126</td>
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<tr>
<td>Decimal Exponent Max</td>
<td>307.95 (2^{1023})</td>
<td>38.23 (2^{127})</td>
<td>4.51 (2^{15})</td>
<td>38.23(2^{127})</td>
<td>38.23 (2^{127})</td>
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<tr>
<td>Mantissa Bits</td>
<td>52</td>
<td>23</td>
<td>10</td>
<td>10</td>
<td>7</td>
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<tr>
<td>Relative Accuracy</td>
<td>2^{-52}/2</td>
<td>2^{-23}/2</td>
<td>2^{-10}/2</td>
<td>2^{-10}/2</td>
<td>2^{-7}/2</td>
</tr>
<tr>
<td>Min Normalized Positive number</td>
<td>2^{-1022}</td>
<td>2^{-126}</td>
<td>2^{-14}</td>
<td>2^{-126}</td>
<td>2^{-126}</td>
</tr>
<tr>
<td>Max number</td>
<td>2x1023 (1.8x10^{307})</td>
<td>2x1023 (3.4x10^{118})</td>
<td>2x2^{15}</td>
<td>2x2^{127}</td>
<td>2x2^{127}</td>
</tr>
<tr>
<td>Latest Supported</td>
<td>GPU, NPU</td>
<td>Nvidia A100</td>
<td>Intel, Nvidia</td>
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<tr>
<td>Typical Applications</td>
<td>Technical Computing HPC</td>
<td>HPC, Gaming, DSP</td>
<td>DL, AI, HPC</td>
<td>DL, AI</td>
<td></td>
</tr>
</tbody>
</table>
### Initial Assessment of ARM64 for O&G Seismic Data Processing

- ARM64 SoC will need to further improve its FP32/BF16/TF32/INT8 FMA & Matrix-Multiply performance to support conventional and DL-based Seismic Data Processing

<table>
<thead>
<tr>
<th>Domain</th>
<th>Data Pre-Processing</th>
<th>Data Processing/Model Inversion</th>
<th>Data Interpretation</th>
</tr>
</thead>
</table>
| Computing Characteristics, Requirements     | 1. Data Demultiplexing  
2. Noise Reduction/Attenuation  
3. Swell Attenuation  
4. Amplitude Adjustment (AGC)  
5. Geometric Correction  
6. Trace Gathering  
7. Static Correction  
8. Dynamic Correction  
9. Data Filtering (frequency, deconvolution, velocity, etc)  
10. Data stacking & Migration  
11. Data Enhancement using GAN | 1. FWI is the final and ultimate solution  
2. FWI requires Gigantic Computing power, grows 10x in compute with every frequency doubling, ~10Eflops needed for 125Hz  
3. FP32 Intensive Huge Matrix Operations  
4. Parallelable (many sources and many sensors seismic survey) with light or No global MPI required  
5. Not sure if BF16 or TF32 could be used  
6. Huge amount of data to be processed | 1. Conventional Computer vision for Image recognition  
2. Deep-Learning based image recognition  
3. Use of DL/GAN to enhance images after Inversion |
| ARM64 SoC Competences, enhancements         | 1. FP32 FMA Support on SIMD/MMA  
2. BF16/INT8 Tensor Instructions on SIMD/MMA as Data Enhancement using GAN is gaining attraction | 1. Many cores (~100) design: ++++  
2. N x FP32 support on 512b SIMD: +++  
3. Multiple 512b SIMD Units: ++  
4. Matrix Multiply Acceleration (MMA): ?  
5. High Memory Bandwidth HBM/DDR5: ?  
6. FMA on SIMD & Matrix-Multiply Units: +++ | 1. Tensor Instructions Support on SIMD/MM units for Image recognition and GAN (Generative Adversarial Network) |
Call for Action

✓ Seismic Data Processing is a key & complex process in Oil & Gas Exploration and Production for building a Layered High Definition Velocity Model from the collected FP32 seismic Data, and it is also Highly Parallelizable in nature due to the Many Seismic Wave Sources and Many Seismic Sensors seismic survey.

✓ High Frequency Full Waveform Inversion (FWI) has the best potential to produce the Highest Resolution/High Fidelity Velocity model but requires 10x growth in compute with every frequency doubling and is ONLY becoming available with the latest High-Performance Microprocessors.

✓ Form an Industry-Academic collaboration project at Linaro HPC-AI to implement and benchmark High Frequency FWI on ARM64 Architecture to identify the weakness and improvement opportunities of ARM64 for Oil & Gas applications, as well as the feasibility of using Bfloat16 or similar high-efficiency floating-Point formats.
Thank you