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 → TensorCore AVX/SVE

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

Springer Link

Review | Open Access | Published: 18 March 2020

A review on reflection-waveform inversion

have been achieved in the industry. However, FWI has not reached the expectation of the industry. The reasons may include:

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.

FWI: Final & Ultimate

The open mark of the FWI workshop in SEG of that year (2013) is "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. This point of view was questioned by some peers working on other seismic imaging

HOME › HPC › DUG Sets Foundation For Exascale HPC Utility With Xeon Phi

DUG SETS FOUNDATION FOR EXASCALE HPC UTILITY WITH XEON PHI

May 16, 2019 Timo… Morgan

"… batch processing," Schwan explains. "But what has really lit the industry on … Waveform Inversion, particularly now that computing is finally catching up … theory said was possible. We are building this exascale compute center, first and …most, for FWI because it is a process that grows in compute with frequency to the factor of four. Historically, people have run 10 Hz or 12 Hz FWI, meaning that the output of that process is a model that has 10 Hz or 12 Hz frequency content in it. But with today's compute, we are able to run 50 Hz, 80 Hz, even 100 Hz models where you are getting out of the model basically everything that you recorded in that wavefield. And this takes 5,000X to 10,000X as much compute as running that 10 Hz or 12 Hz model. You need at exascale computer to do that. The

10000X from 10Hz to 100Hz

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

OIL IMMERSION COOLING CRANKS UP OIL SIMULATION HPC

November 9, 2018 Dan Olds

High frequency FWI — dug

- Double frequency = 10x compute
  - Currently doing ~15Hz
  - Want to do 125Hz
  - Currently have 25PFlops
  - 2.5EFlops needed!

10X in Compute vs 2X in Frequency

1000X in Compute for 15Hz to 125Hz

2.5EFlops for 125Hz FWI

https://www.nextplatform.com/2018/11/09/oil-immersion-cooling-cranks-up-oil-simulation-hpc/

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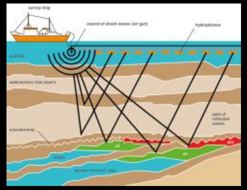
Some Big Data about Oil & Gas Industry

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

Market Opportunities

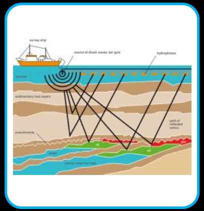


$9.28B Seismic Survey Market by 2022, $11.8B by 2025
(ResearchandMarkets, 2017)

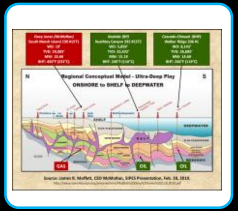
$22B Oil&Gas Analytics Market by 2025
(Brandessence Research, 2020)

$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)

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3 Key Oil & Gas E&P Activities – Exploration, Production & Prediction

Exploration - Seismic Data Processing

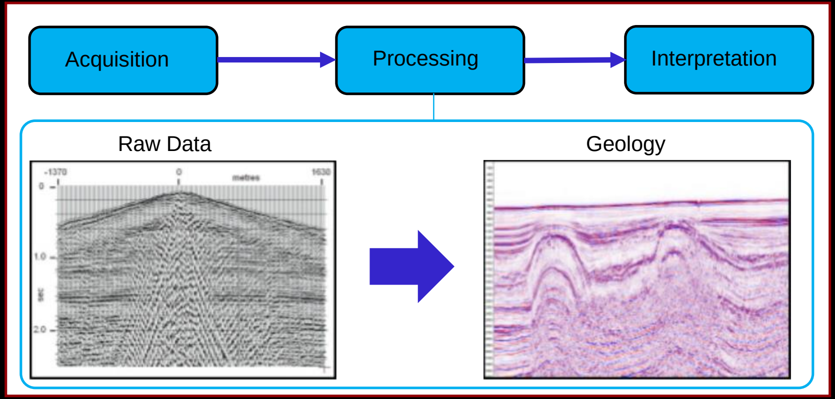
- Where and How Much is the Oil & Gas?
  - ✓ Build accurate HD earth Subsurface Models
  - ✓ Interpret the Models Automatically

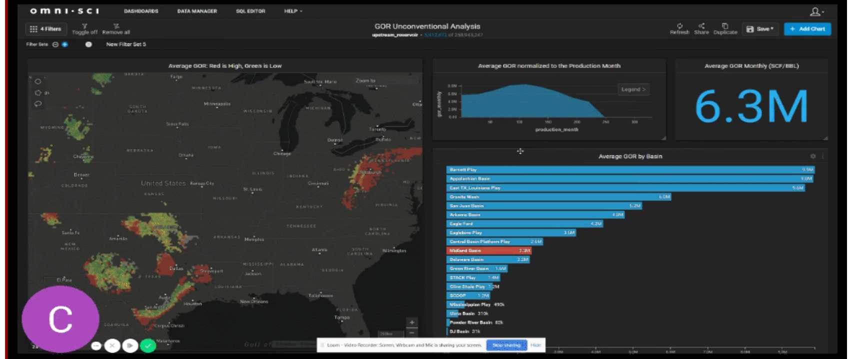
Production - Drill Operations

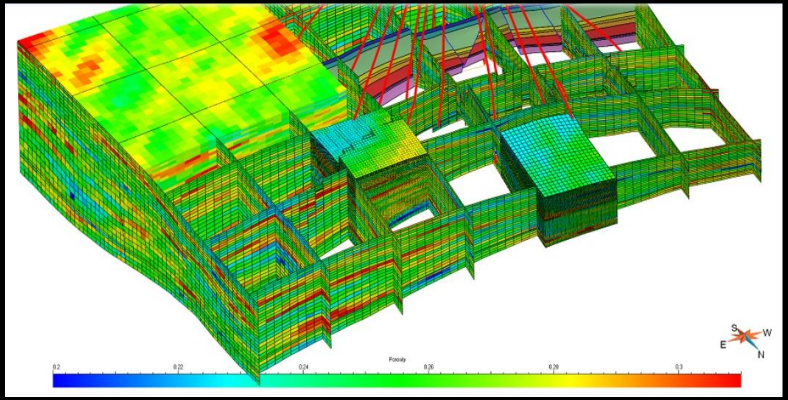
- How are the wells going in Real-Time?
  - ✓ Well Operation & equipment status Monitoring
  - ✓ Predictive Maintenance to avoid operation disruptions

Prediction - Reservoir Simulation

- How Much Oil & Gas Left & How would the reservoir be changing?







https://www.omnisci.com/blog/the-next-wave-of-oil-and-gas-analytics-reservoir-behavior

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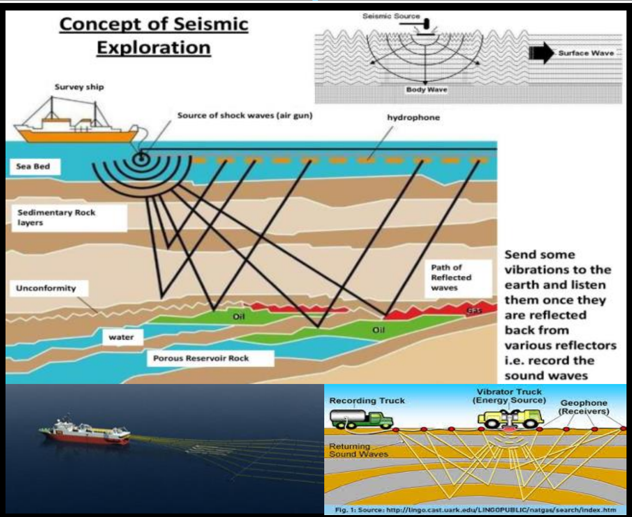
3-Step of Oil & Gas Exploration

- ✓ 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

- ✓ 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

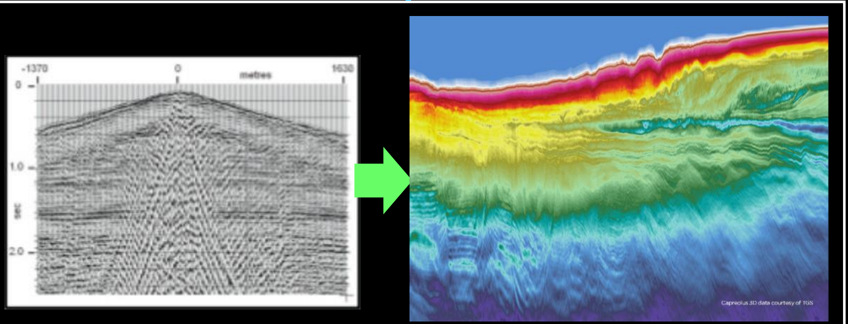
- ✓ Use of Human, Legacy Computer Vision or Deep-Learning to Interpret the generated Velocity Model
- ✓ Advanced Deep-Learning could play a key role for Automated Seismic Data Interpretation

Acquisition → SEG-Y format → Processing → Interpretation → Reservoir Simulation



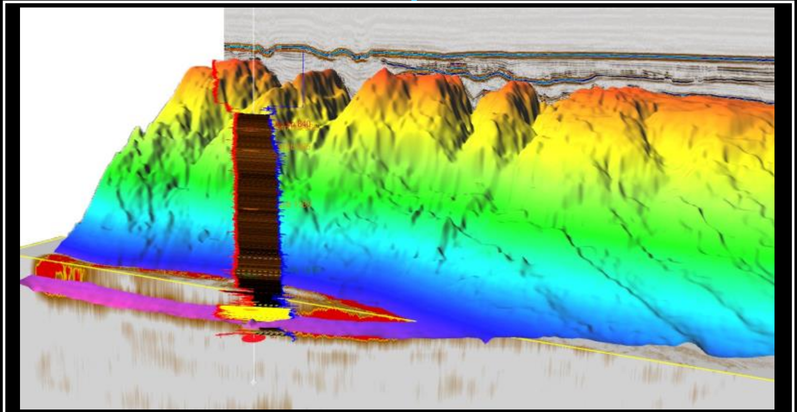
- ✓ To Collect Seismic Wave Data

Source: https://slideplayer.com/slide/13787934/
https://fluidpowerjournal.com/repairing-hydraulic-valves/



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

https://dug.com/dug-geo/full-waveform-inversion-fwi/



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

https://www.geolink-s2.com/expertise/3d-seismic-interpretation-training

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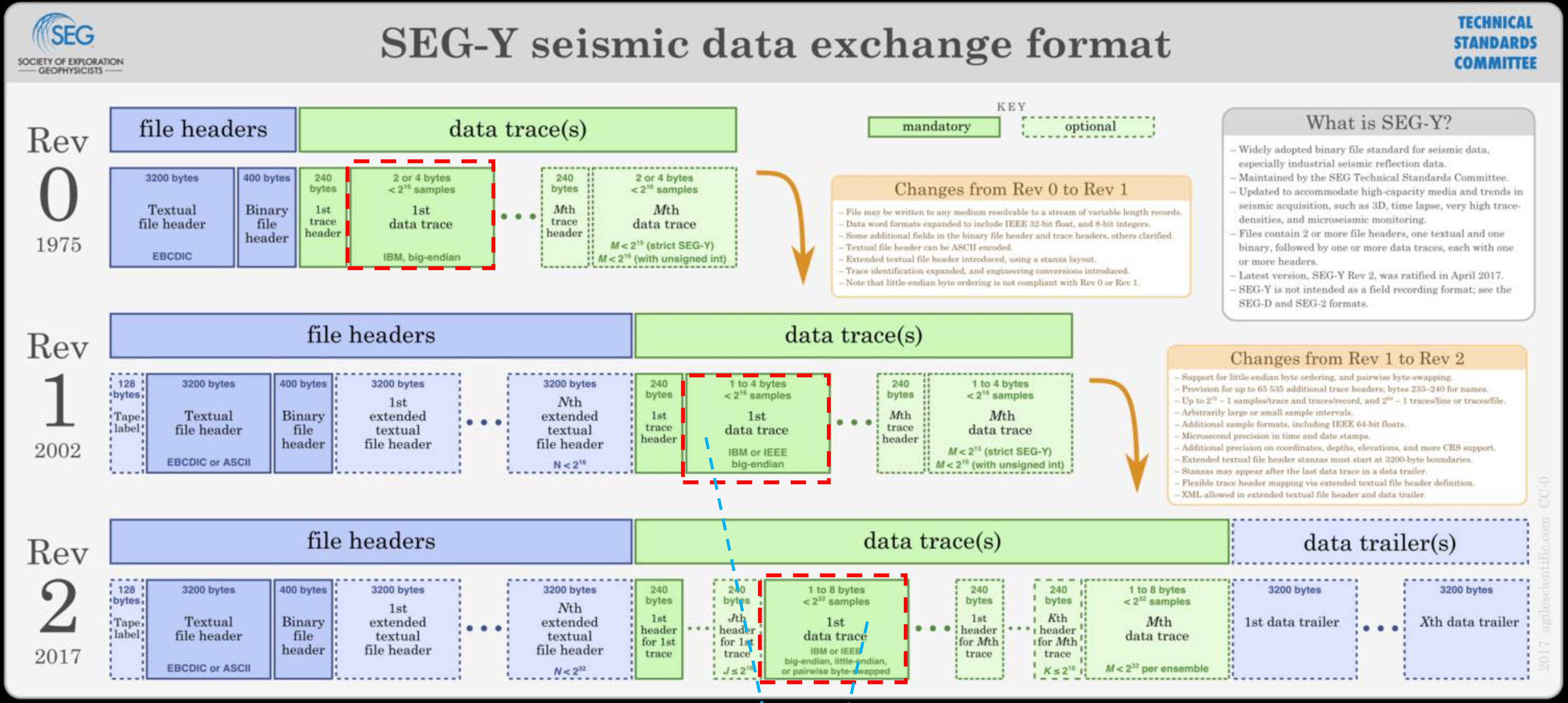
SEG-Y: Seismic Survey Data Format

- ✓ 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)



The seismic data recorded for one channel

https://www.troika-int.com/about-us/resources/segy-seismic-data-exchange-format

IEEE 754-1985 32-bit Single-Precision Floating-Point value

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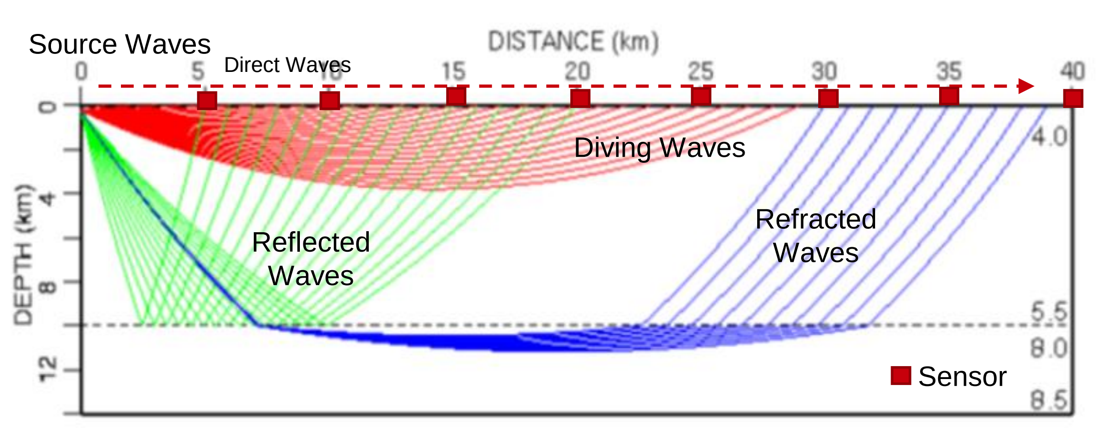
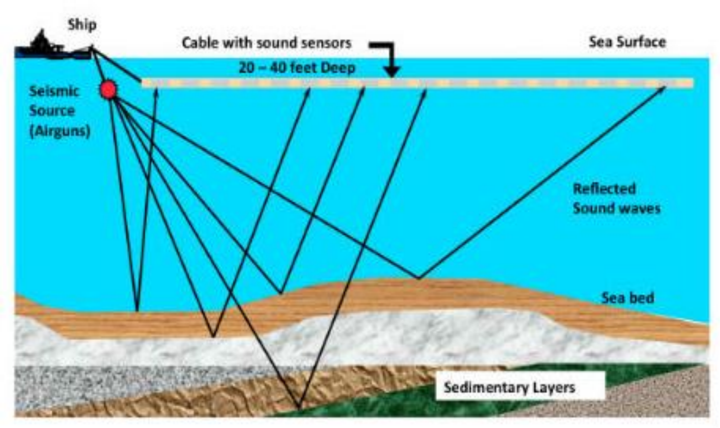
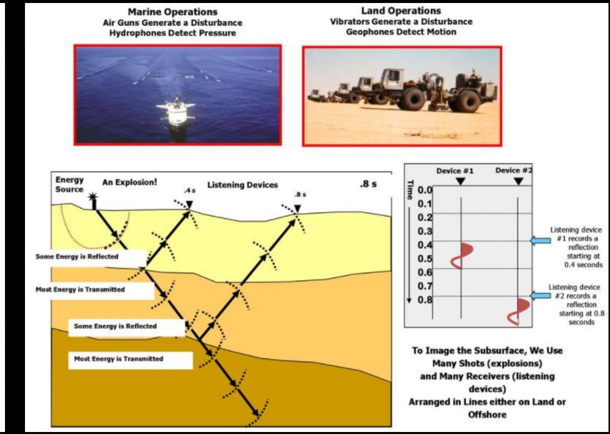
Many Waves Received by the Sensors

- Direct Waves, Diving Waves, Reflected Waves, Refracted Waves
- Reflected and Refracted Waves from different subsurface layers of materials – rock, oil, gas, water, etc





Source & Credit: American Petroleum Institute



Source & Credit: Elfreda Robertson on slideplayer.com

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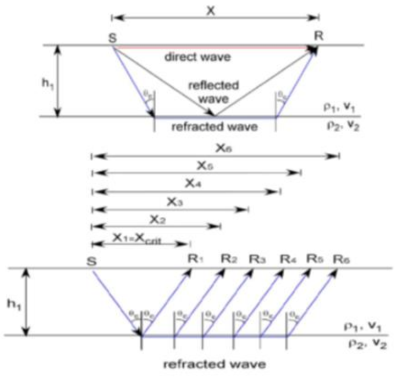
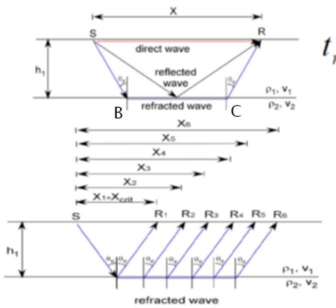
Many Formulas/Equations to Calculate

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



$$t_{direct} = \frac{x}{v_1}$$

- The ray path and the travel time for the refracted wave for a 2-layer model can be derived as



$$t_{refract} = \frac{SB}{v_1} + \frac{BC}{v_2} + \frac{CR}{v_1}$$

$t_{refract} = x/v_2 + ti$

Diving Wave Speed

$v = v_0 + k^*z$, where Z is depth

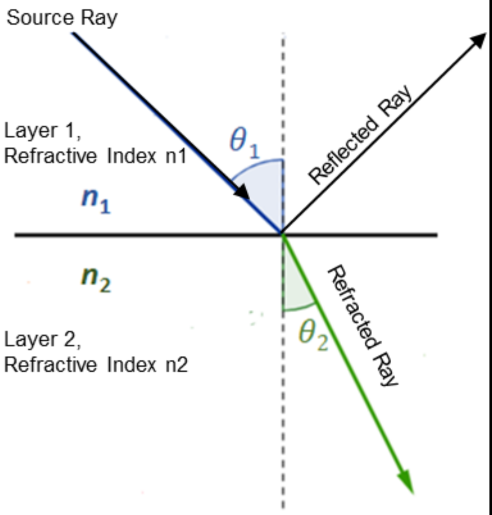
Pythagorean Theorem:
$(z+\lambda/4)^2 = z^2 + R^2$

Snell's Law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Snell's Law

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$



Following from the fact that $\cos\theta_1 = \frac{z_1}{SA}$ and:

$$\cos\theta_2 = \frac{z_2}{AB}$$

We can deduce that:

$$T_{SA} = T_{DG} = \frac{z_1}{v_1 \cos\theta_1}$$

And:

$$T_{AB} = T_{CD} = \frac{z_2}{v_2 \cos\theta_2}$$

Since $BC = X - 2Z_1 \tan\theta_1 - 2Z_2 \tan\theta_2$:

$$T_{BC} = \frac{X - 2z_1 \tan\theta_1 - 2z_2 \tan\theta_2}{v_3}$$

Hence Equation 10 becomes Equation 11 and 12:

$$T_{SG} = \frac{2z_1}{v_1\cos\theta_1} + \frac{2z_2}{v_2\cos\theta_2} + \frac{X}{v_3} - \frac{2z_1\sin\theta_1}{v_3\cos\theta_1} - \frac{2z_2\sin\theta_2}{v_3\cos\theta_2} \quad (11)$$

$$= \frac{X}{v_3} + \frac{2z_1}{\cos\theta_1}\left[\frac{1}{v_1} - \frac{\sin\theta_1}{v_3}\right] + \frac{2z_2}{\cos\theta_2}\left[\frac{1}{v_2} - \frac{\sin\theta_2}{v_3}\right] \quad (12)$$

$$= \frac{x}{v_3} + \frac{2Z_1}{v_1\cos\theta_1}\left[1 - \frac{v_1}{v_3}\sin\theta_1\right] + \frac{2Z_2}{v_2\cos\theta_2}\left[1 - \frac{v_2}{v_3}\theta_2\right] \quad (13)$$

Since $\sin\theta_1 = \frac{v_1}{v_2}, \sin\theta_2 = \frac{v_2}{v_3}$ and $\sin^2\theta + \cos^2\theta = 1$

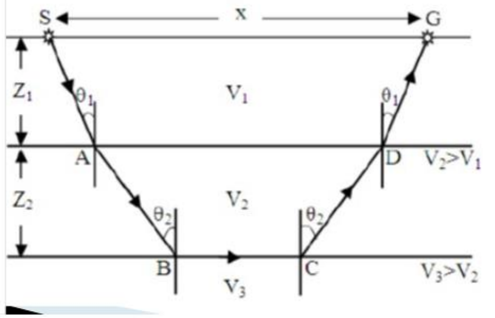
Equation 13 becomes:

$$T_{SG} = \frac{x}{v_3} + \frac{2z_1\cos\theta_1}{v_1} + \frac{2z_2\cos\theta_2}{v_2} \quad (14)$$

3 layer refraction problem

$$T_{SG} = T_{SA} + T_{AB} + T_{BC} + T_{CD} + T_{DG}$$

$$T_{SG} = \frac{SA}{V_1} + \frac{AB}{V_2} + \frac{BC}{V_3} + \frac{CD}{V_2} + \frac{DG}{V_1}$$



Acoustic wave equation

$$\left[\frac{1}{K(\mathbf{r})}\frac{\partial^2}{\partial t^2} - \nabla \cdot \left(\frac{1}{\rho(\mathbf{r})}\nabla\right)\right] p(\mathbf{r}, t) = s(\mathbf{r}, t)$$

$$v = \left[\frac{\left(V_p/V_s\right)^2 - 2}{\left\{2\left[\left(V_p/V_s\right)^2 - 1\right]\right\}}\right],$$

$$E = \frac{p_b V_p^2 (1-2v)(1+v)}{(1-v)}$$

$$G = \frac{E}{[2(1+v)]}, \qquad p_b = \frac{G}{V_s^2}$$

P-Wave Velocities for Different Materials

Material	V_P (m/s)
Air	330
Water	1450–1530
Petroleum	1300–1400
Loess	300–600
Soil	100–500
Snow	350–3000
Solid glacier ice*	3000–4000
Sand (loose)	200–2000
Sand (dry, loose)	200–1000
Sand (water saturated, loose)	1500–2000
Glacial moraine	1500–2700
Sand and gravel (near surface)	400–2300
Sand and gravel (at 2 km depth)	3000–3500
Clay	1000–2500
Estuarine muds/clay	300–1800
Floodplain alluvium	1800–2200
Permafrost (Quaternary sediments)	1500–4900
Sandstone	1400–4500
Limestone (soft)	1700–4200
Limestone (hard)	2800–7000
Dolomites	2500–6500
Anhydrite	3500–5500
Rock salt	4000–5500
Gypsum	2000–3500
Shales	2000–4100
Granites	4600–6200
Basalts	5500–6500
Gabbro	6400–7000
Peridotite	7800–8400
Serpentinite	5500–6500
Gneiss	3500–7600
Marbles	3780–7000
Sulphide ores	3950–6700
Pulverised fuel ash	600–1000
Made ground (rubble etc.)	160–600
Landfill refuse	400–750
Concrete	3000–3500
Disturbed soil	180–335
Clay landfill cap (compacted)	355–380

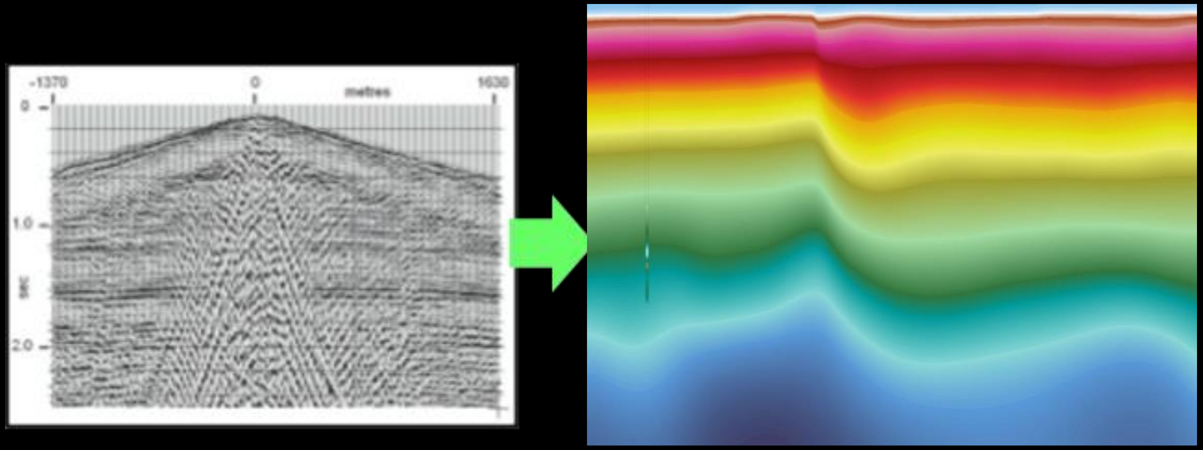
* Strongly temperature dependent (Kohnen 1974)

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

http://www.ukm.my/rahim/Seismic%20Refraction%20Surveying.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



Inversion: from SEG-Y records to subsurface image

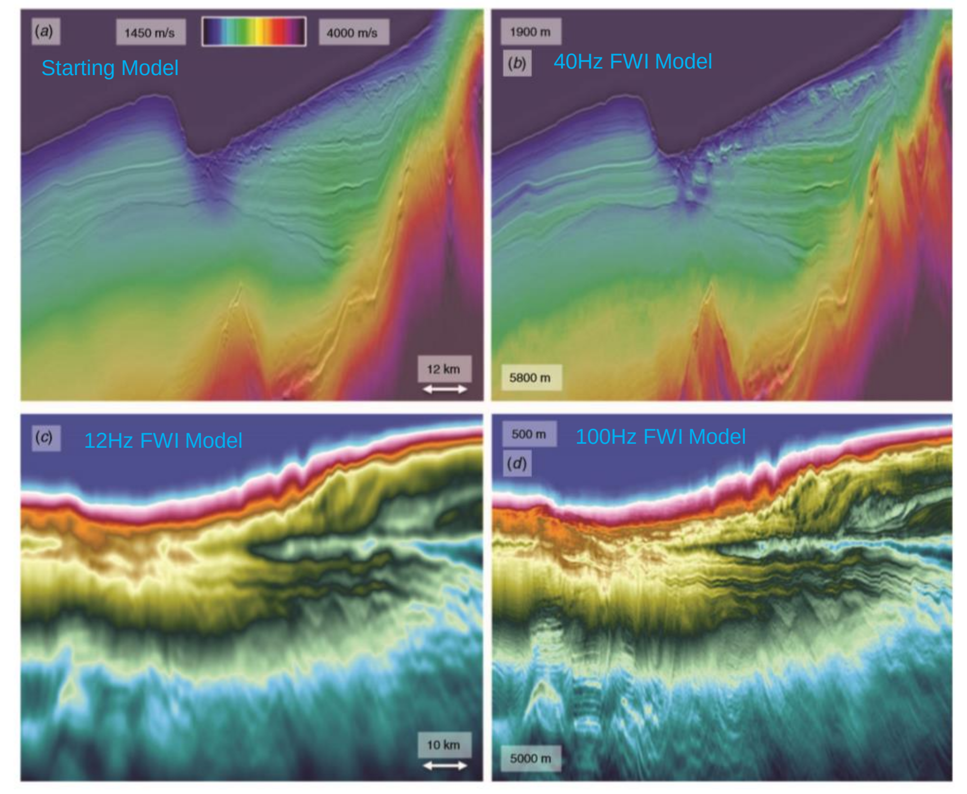


Fig. 3. (a) Full waveform inversion (FWI) starting model and (b) 40-Hz FWI model (data courtesy of Spectrum); (c) 12- and (d) 100-Hz FWI models (Capreolus 3D data courtesy of TGS). Note the increasingly sharp stratigraphic and structural details in the 100-Hz model (d).

FWI & High Frequency FWI, Source & Credit: www.dug.com

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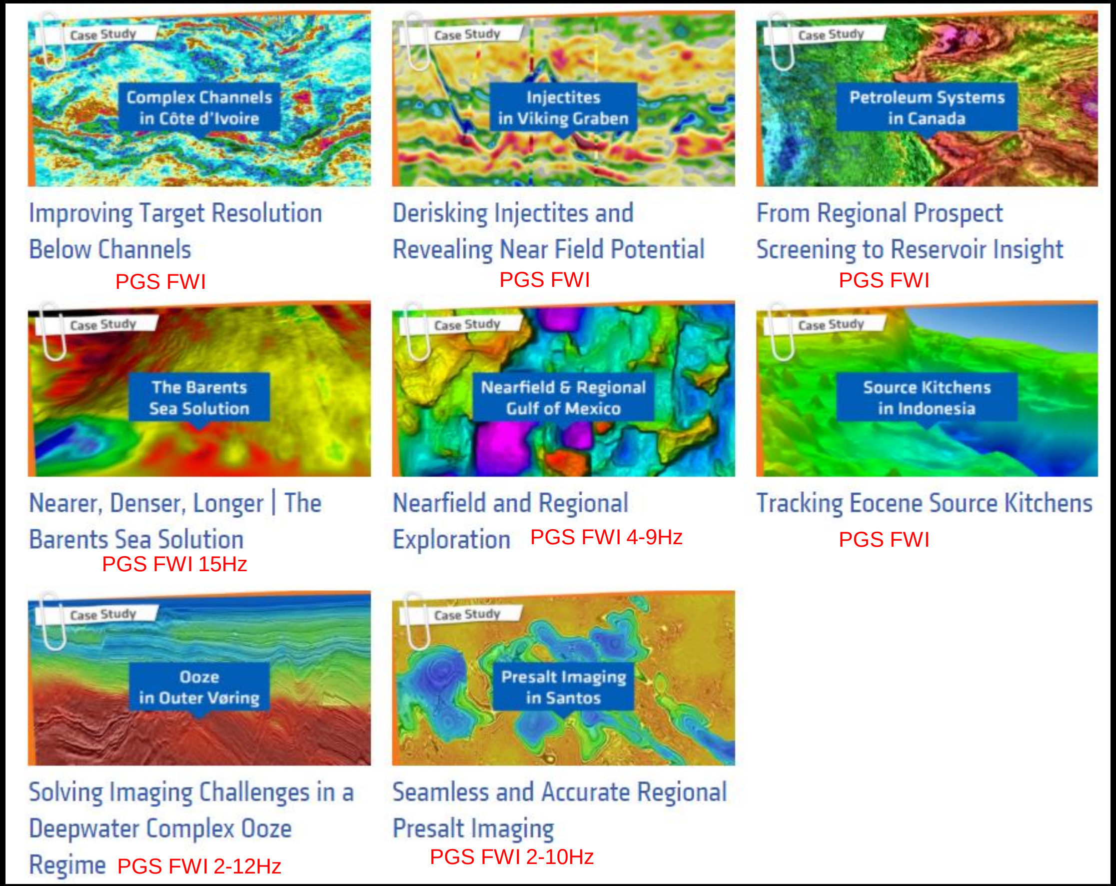
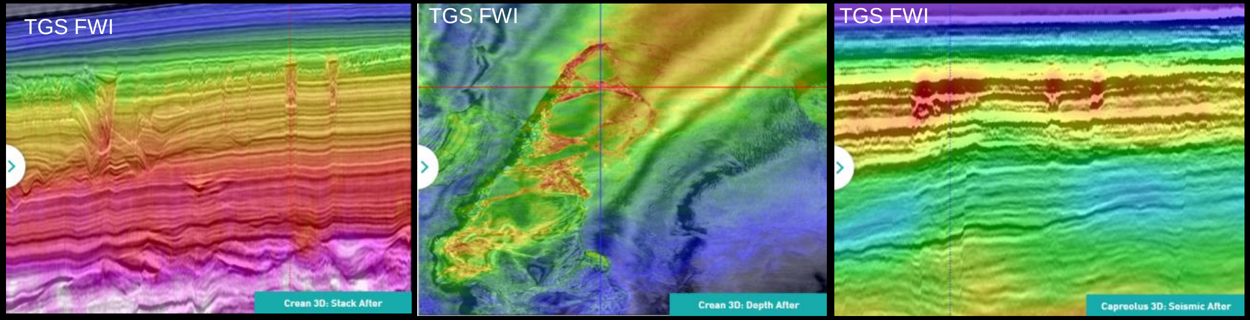
Some FWI use cases

- 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

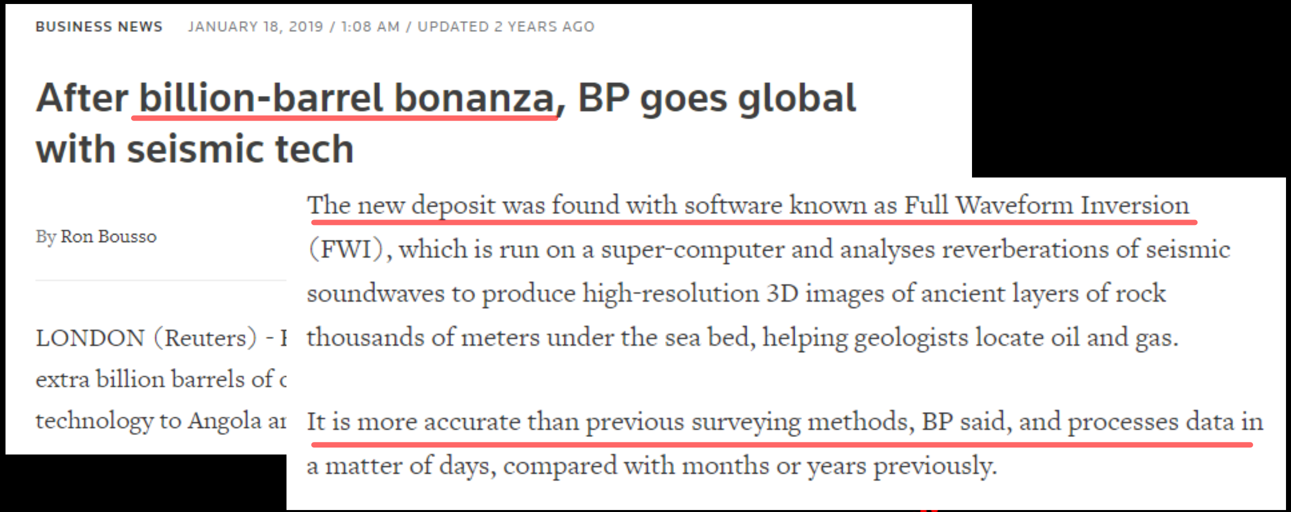


Source & Credit: https://www.pgs.com/publications/case-studies/



Source & Credit: https://www.tgs.com/products-services/processing/earth-modeling/velocity-anisotropy/full-waveform-inversion

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

LONDON (Reuters) - I
extra billion barrels of c
technology to Angola ar

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.

https://www.reuters.com/article/us-bp-seismic-focus/after-billion-barrel-bonanza-bp-goes-global-with-seismic-tech-idUSKCN1PC0HF

FWI is not New, but Why has not been widely used?

Potential:

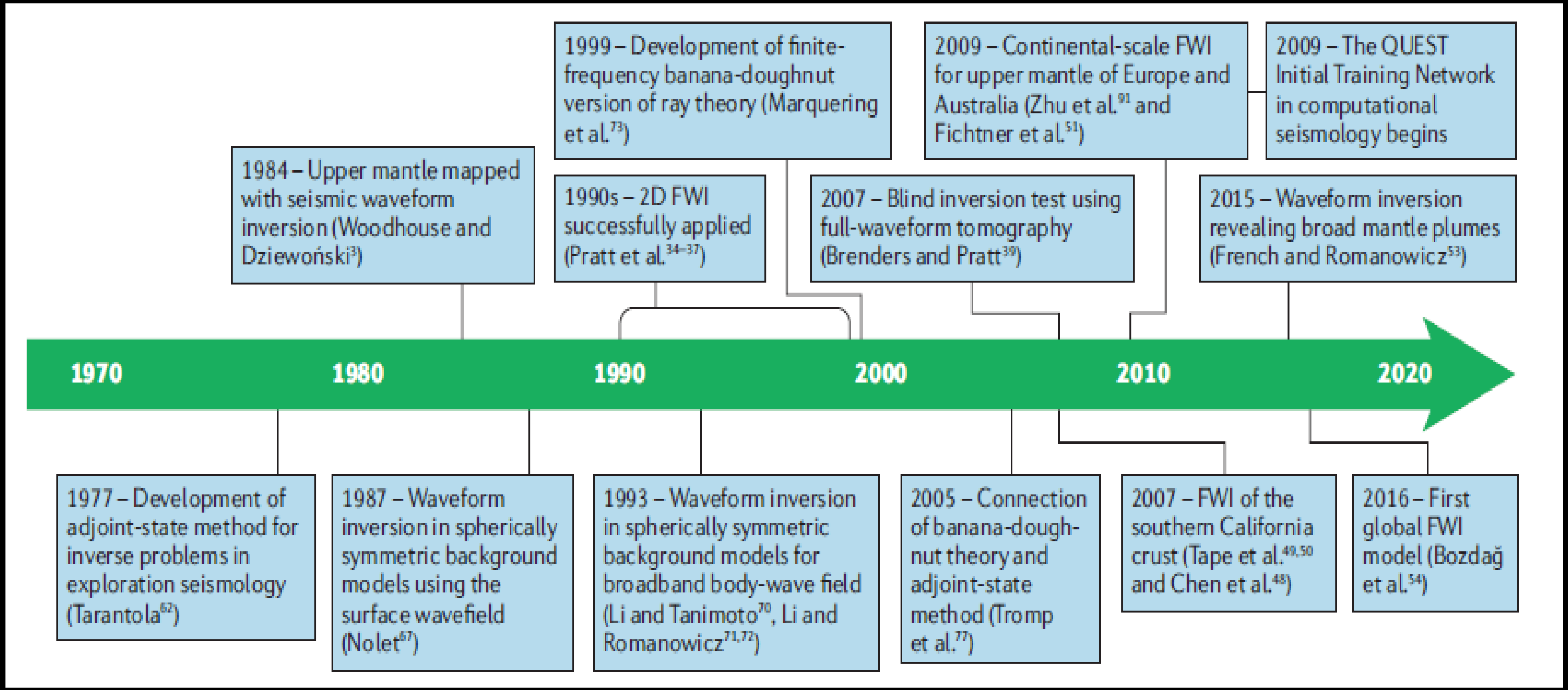
FWI workshop in SEG in 2013 declared: “Full-waveform inversion has emerged as the final and ultimate solution to the Earth resolution and imaging objective.” It emphasized that FWI is the final and ultimate solution of seismic data inversion and imaging.

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)



Source: “Seismic wavefield imaging of Earth’s interior across scales”, by Jeroen Tromp, Nature Reviews Earth & Environment volume, 2020

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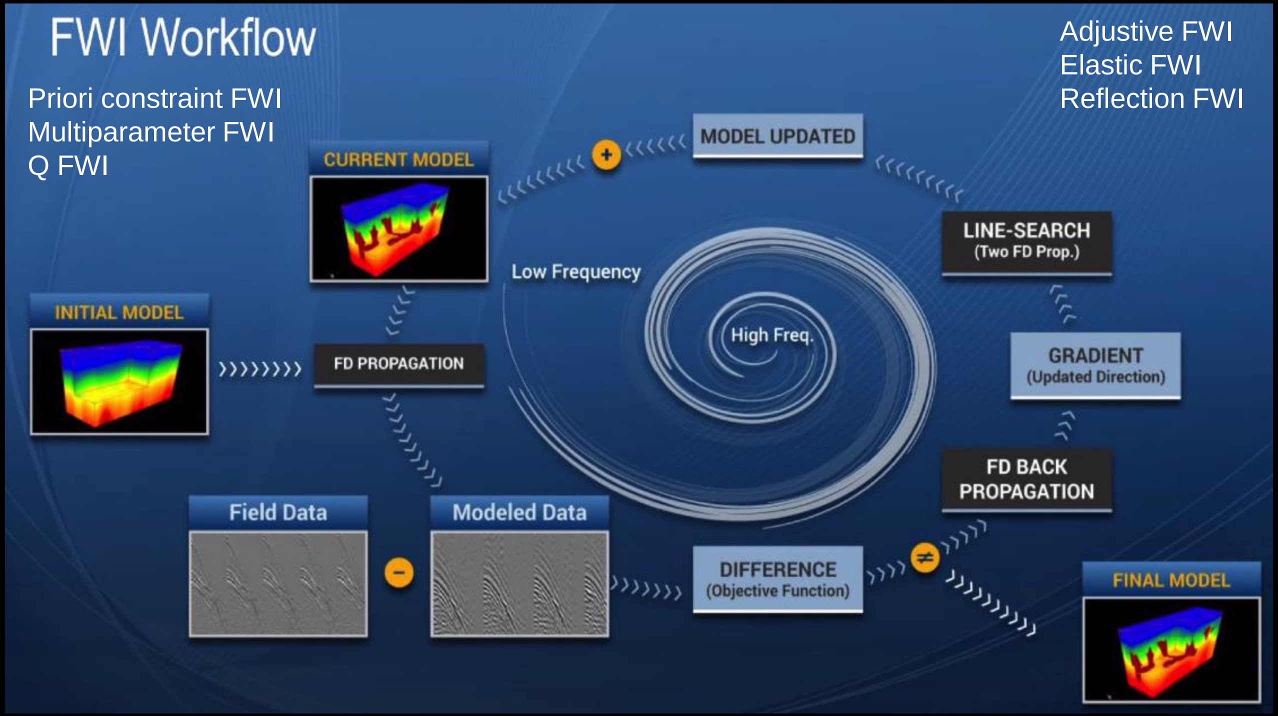
FWI Workflow: A Nonlinear Optimization Problem

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



Source & Credit: SLB & WesternGeco at https://www.slb.com/reservoir-characterization/seismic/seismic-imaging/earth-model-building/full-waveform-inversion

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

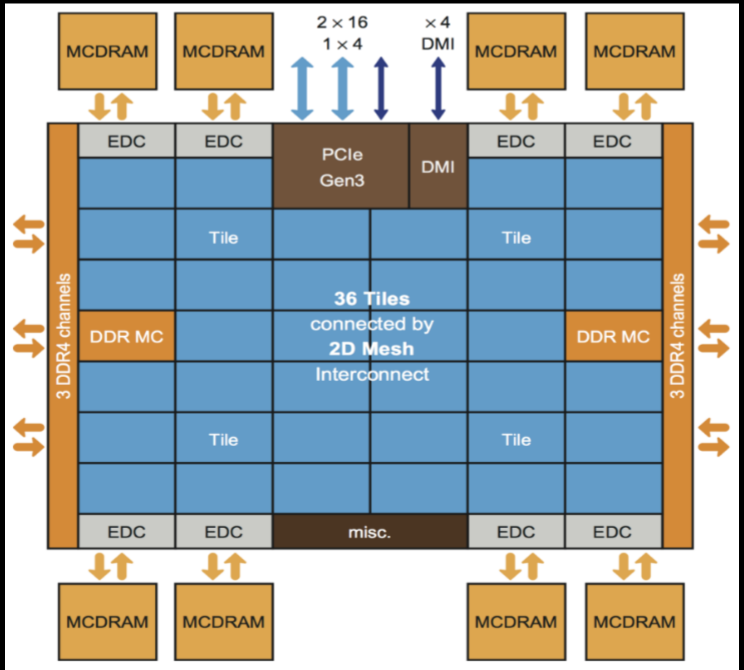
DUG Bubba HPC System in Houston

- 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/

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

Intel Xeon Phi 7200 Family



Source & Credit: Intel

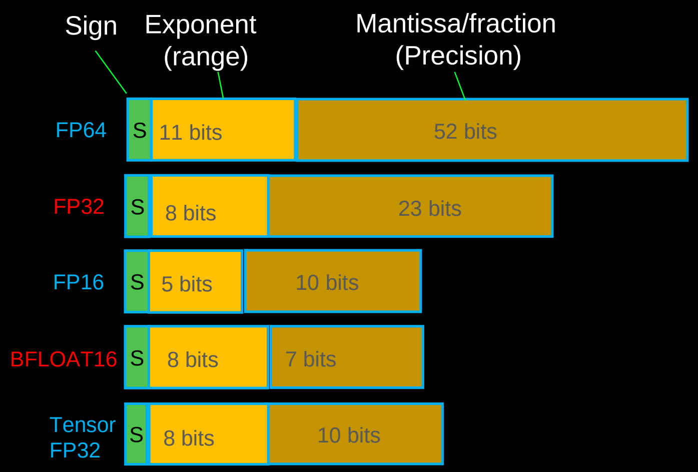
IEEE Floating-Point Data Format, Ranges and Precision

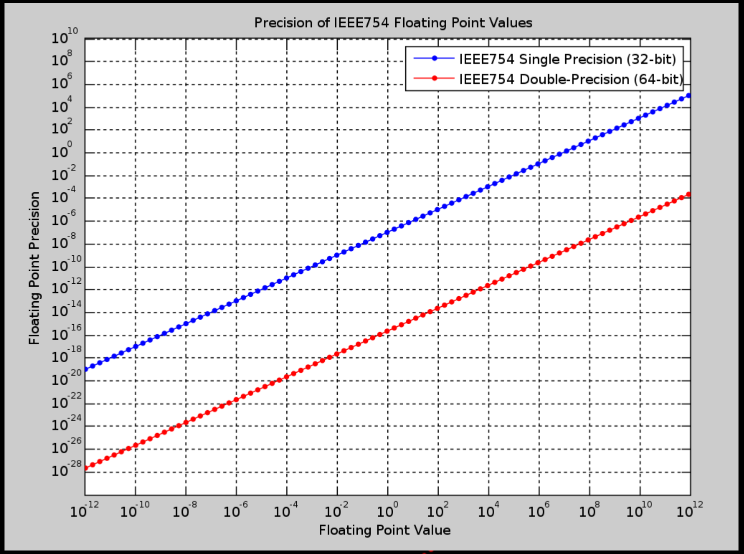
✓ If BF16 or TF32 could be used for Seismic Data Processing, Much Higher Performance than FP32 would be achieved

BF16

Up to 2X Performance to FP32
8X Smaller Multiplier than FP32
2X Smaller Multiplier than FP16

Format	64b Double Precision	32b Single Precision	16b Half Precision	Tensor FP32	Bfloat16
Total Bits	64	32	16	19	16
Significand Bits	52+1	23+1	10+1	8+1	8+1
Sign Bits	1	1	1	1	1
Exponent Bits	11	8	5	8	8
Exponent Bias	1023 (2^{10}-1)	127 (2^{7}-1)	15 (2^{4}-1)	127	127
Exponent Max	+1023	+127	+15	+127	+127
Exponent Min	-1022	-126	-14	-126	-126
Decimal Exponent Max	307.95 (2^{1023})	38.23 (2^{127})	4.51 (2^{15})	38.23(2^{127})	38.23 (2^{127})
Mantissa Bits	52	23	10	10	7
Relative Accuracy	$2^{-52}/2$	$2^{-23}/2$	$2^{-10}/2$	$2^{-10}/2$	$2^{-7}/2$
Min Normalized Positive number	2^{-1022}	2^{-126}	2^{-14}	2^{-126}	2^{-126}
Max number	$2x2^{1023}$ ($1.8x10^{307}$)	$2x2^{127}$ ($3.4x10^{38}$)	$2x2^{15}$	$2x2^{127}$	$2x2^{127}$
Latest Supported			GPU, NPU	Nvidia A100	Intel, Nvidia
Typical Applications	Technical Computing HPC	HPC, Gaming, DSP		DL, AI, HPC	DL, AI





https://en.wikipedia.org/wiki/IEEE_754

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

Domain	Data Pre-Processing	Data Processing/Model Inversion	Data Interpretation
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)

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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 Parallelable 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

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