Volumes and Risks Assessment in Petroleum Exploration

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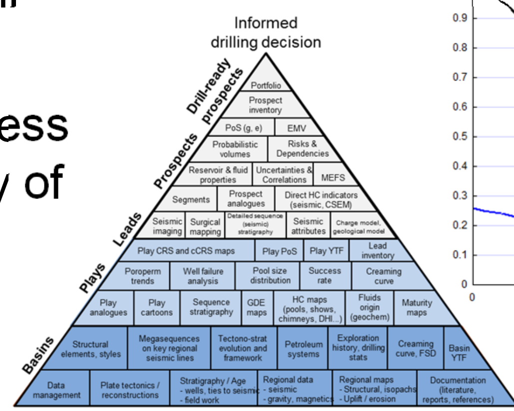
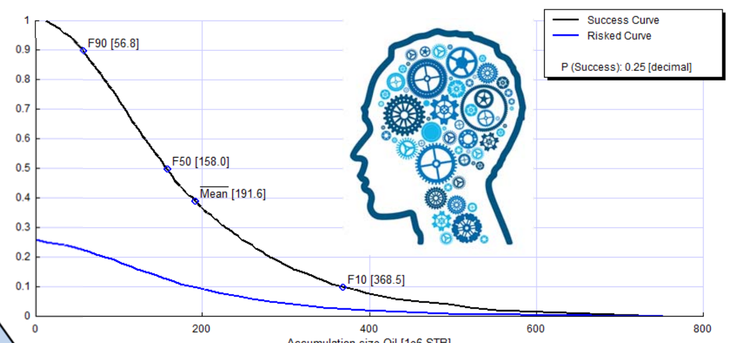
GPGN 558 (Seismic Interpretation) | April 9, 2019

Learning objectives

By the end of the lecture you should be able to describe:

- The trends of petroleum exploration since 1900 and its current state.
- Exploration process to find oil and gas.
- How explorers forecast success case volumes and probability of success.





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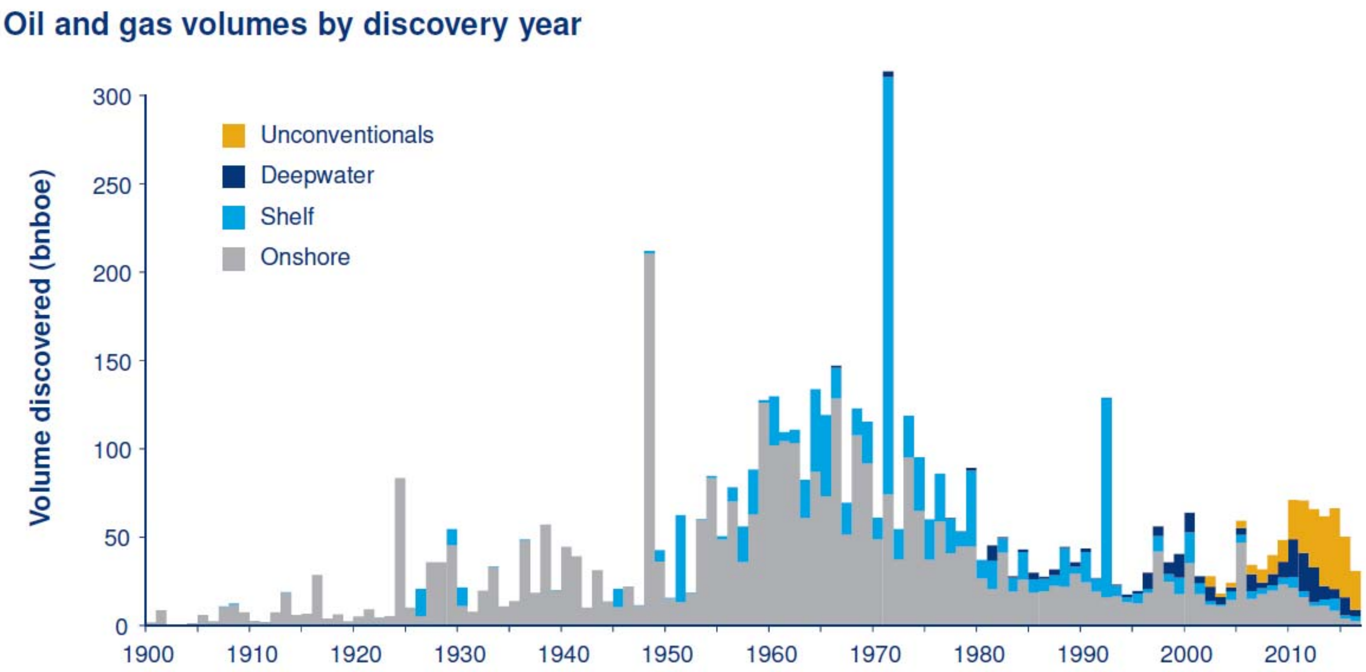
Why are we doing geology in E&P companies?

"Geology is a science, exploration is a business."
M. Downey

"My job is to make decisions. Your job is to make them good decisions."

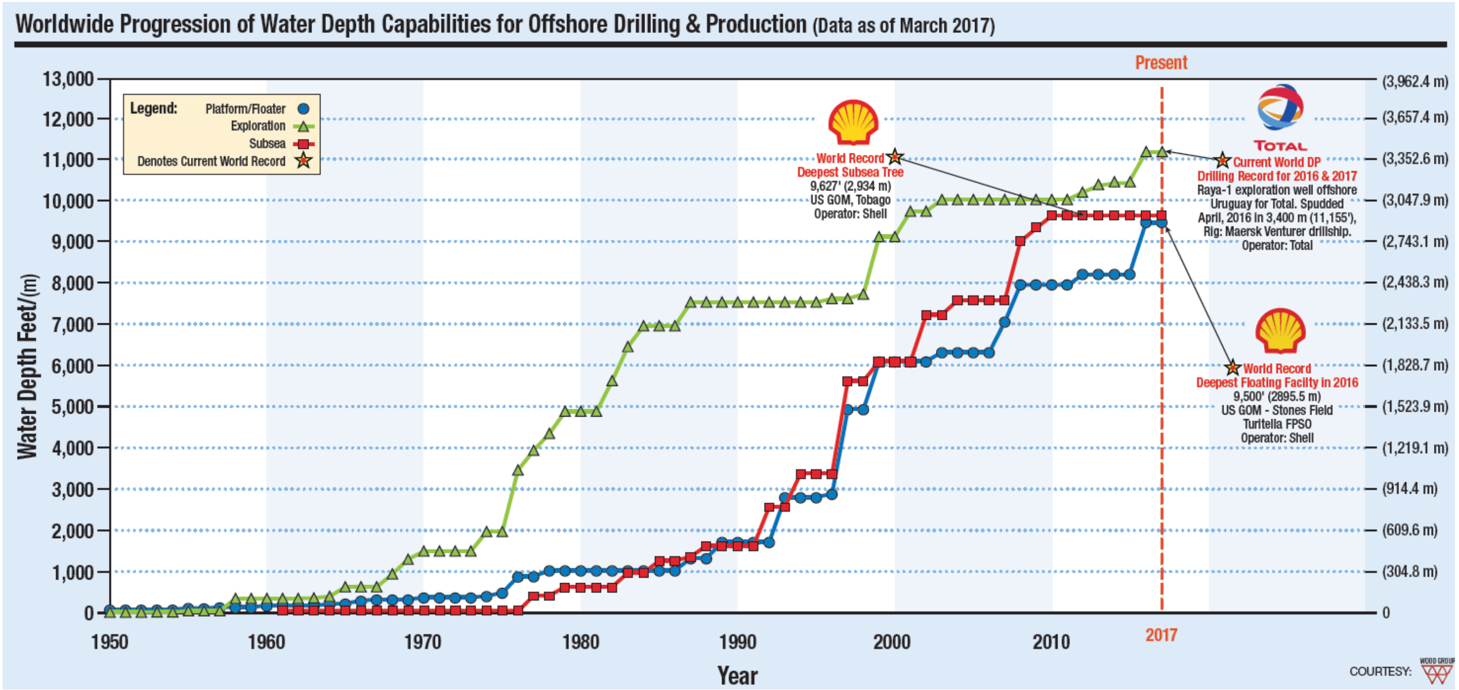
"The only reason to employ geologists is to make a profit from them."
John A. Masters, 1986

Brief history of petroleum discovery



Wood Mackenzie (2017, AAPG ICE)

Record water depth for drilling and production



http://www.offshore-mag.com/content/dam/offshore/print-articles/volume-77/05/2017-DeepwaterPoster-D6-Ads.pdf

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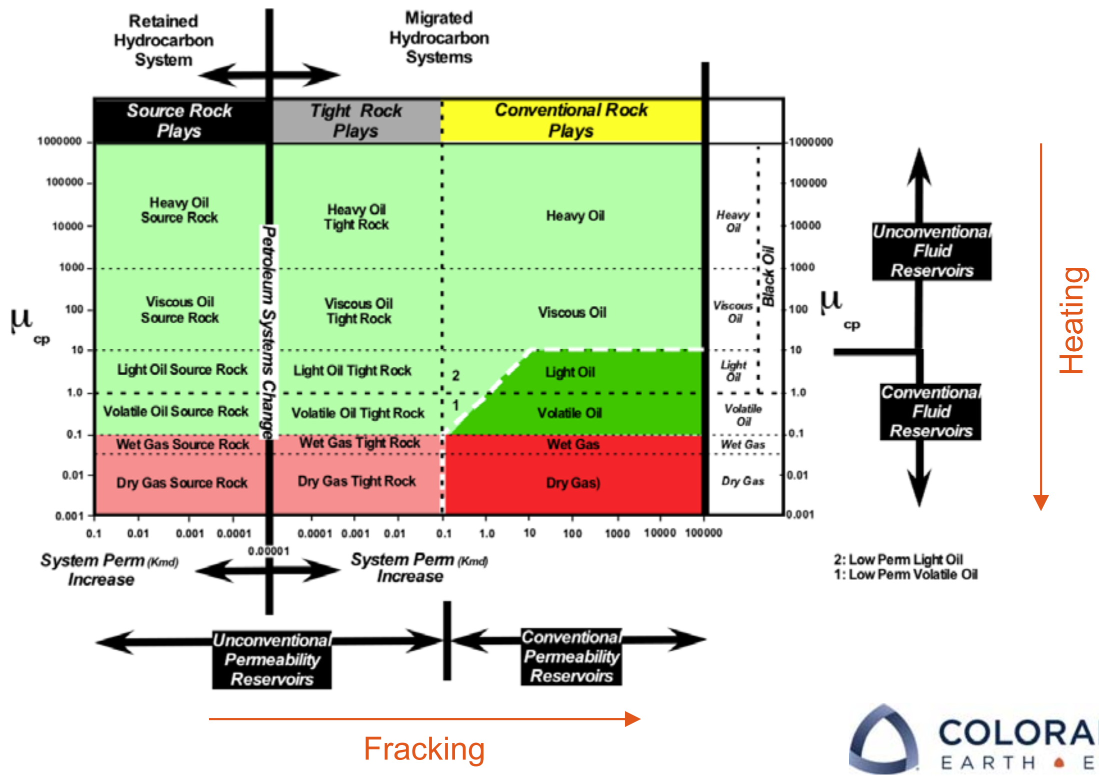
Conventional vs unconventional resources / reservoirs



Donovan et al. (2017)

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US shale plays changed the energy landscape

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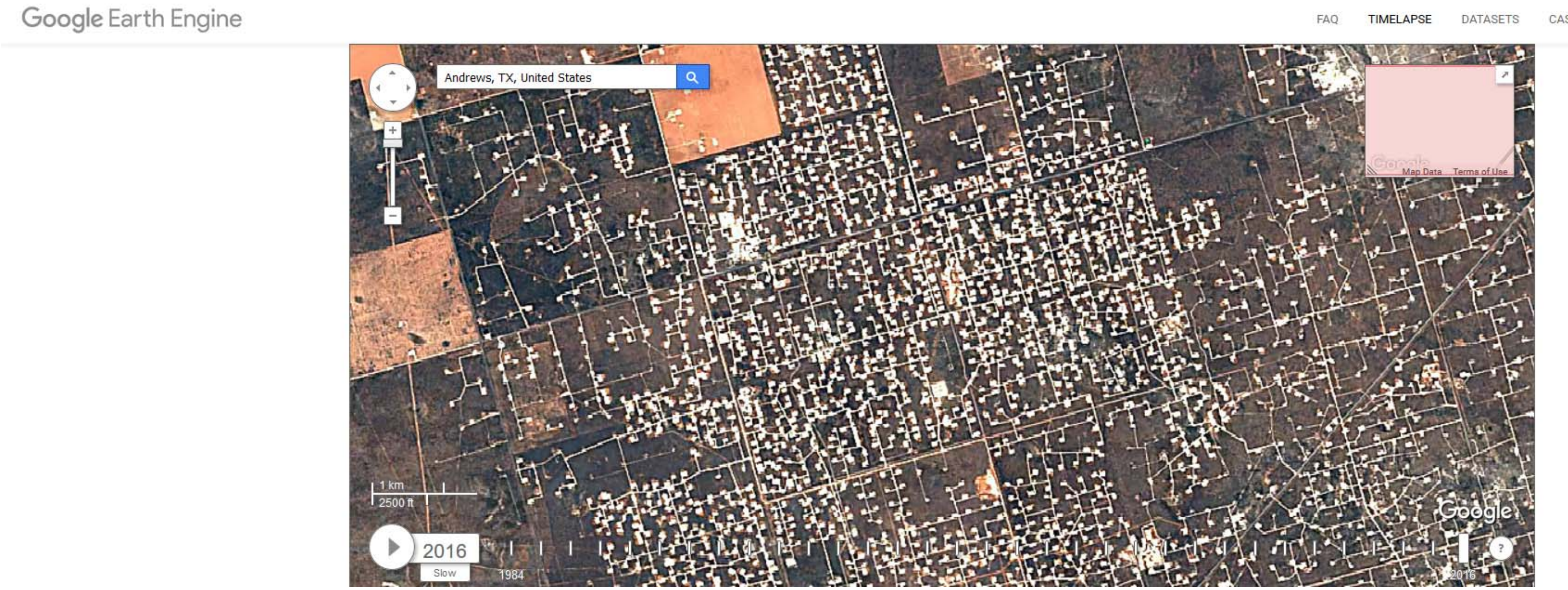

https://earthengine.google.com/timelapse/#v=32.26416,-102.70771,11.973,latLng&t=3.25

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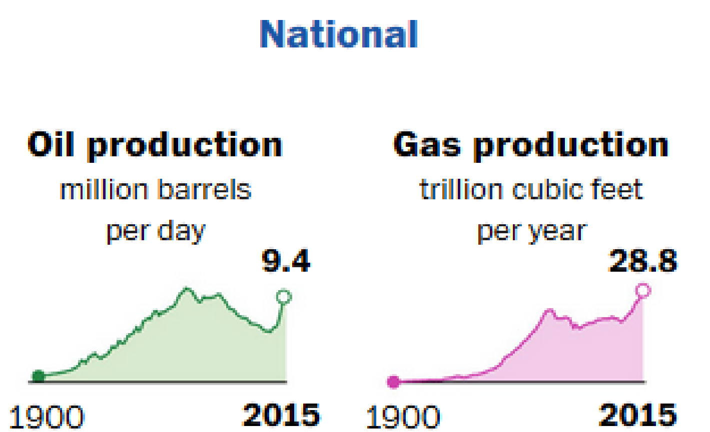
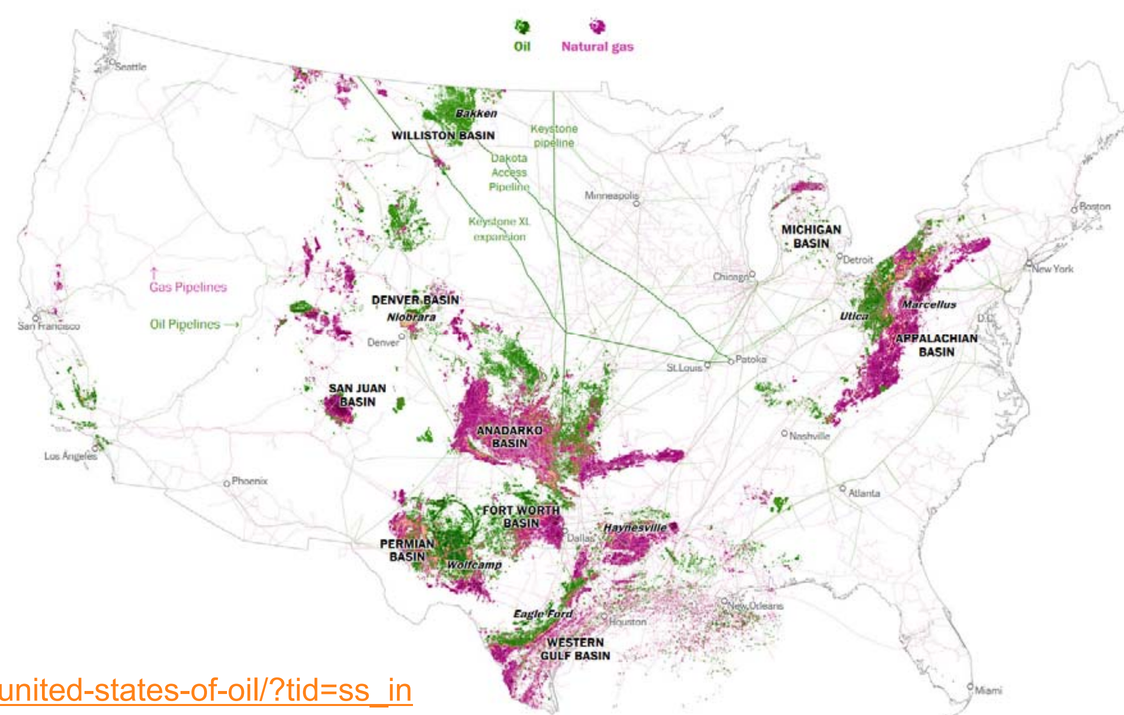
US oil and gas production



Every active oil and gas well in the United States



https://www.washingtonpost.com/graphics/national/united-states-of-oil/?tid=ss_in

US is now a net gas exporter

World Oil

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Offshore / Deepwater / Subsea / Shale / Geology & Geophysics / Drilling / Completions / Production /

Home > News > U.S. becomes a net gas exporter for the first time in 60 years

U.S. becomes a net gas exporter for the first time in 60 years

By NAUREEN S. MALIK on 1/11/2018

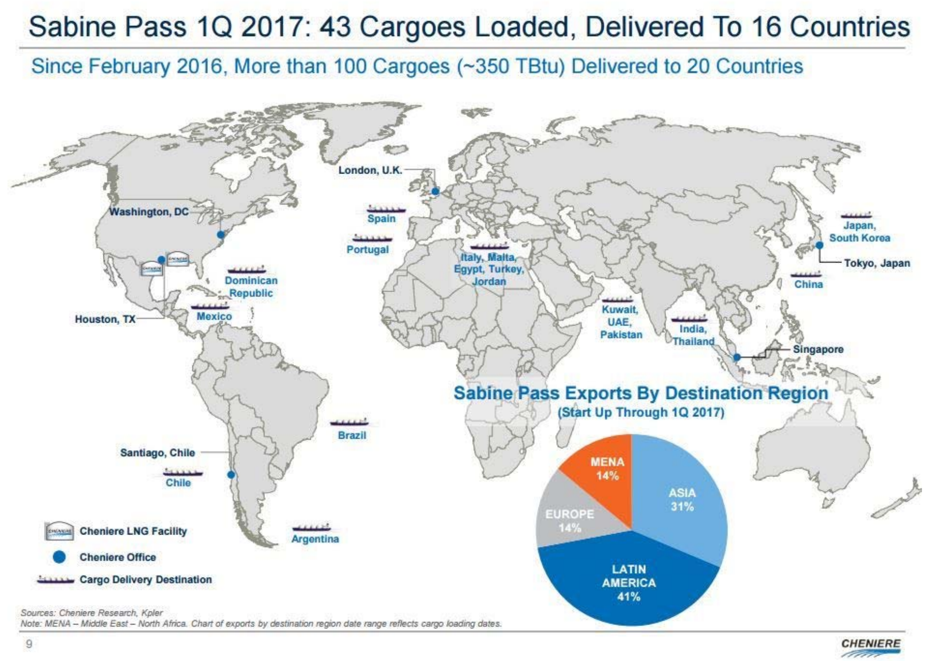
NEW YORK (Bloomberg) -- America's trade imbalance just got a bit smaller. The U.S. has now become a net exporter of natural gas on an annual basis for the first time since at least 1957.

Net exports averaged about 0.4 Bcfd last year, flipping from net inflows of 1.8 billion in 2016, according to Victoria Zaretskaya, a Washington-based analyst for the U.S. Energy Information Administration. The numbers will be officially released by the agency in a report Thursday, she said.

A "significant projected increase" in natural gas sent by pipeline to Mexico and a growing number of liquefied natural gas shipments to the rest of the world should guarantee the trend moving forward, Zaretskaya said by email on Wednesday.

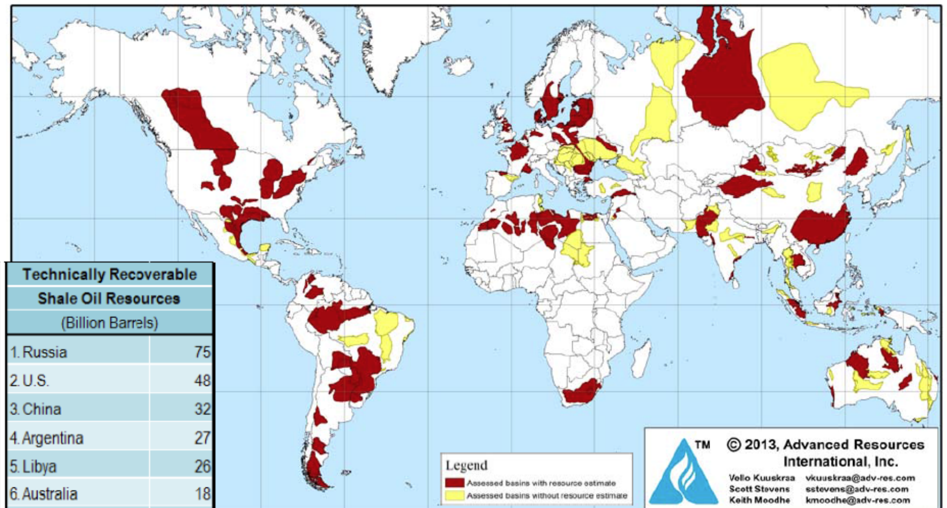
Now the U.S. has a single LNG export facility operating, Cheniere Energy Inc.'s Sabine Pass terminal in Louisiana. Two others are slated to start this year.

"Never before has the global LNG market had such significant flexible LNG volumes as the volumes coming online in the next three years, mostly from the U.S., which will lead to a fundamental shift in how LNG is marketed and traded globally," Zaretskaya said.



http://www.worldoil.com/news/2018/1/11/us-becomes-a-net-gas-exporter-for-the-first-time-in-60-years#.WlnA2H78zmQ.linkedin

Global shale oil and shale gas resources



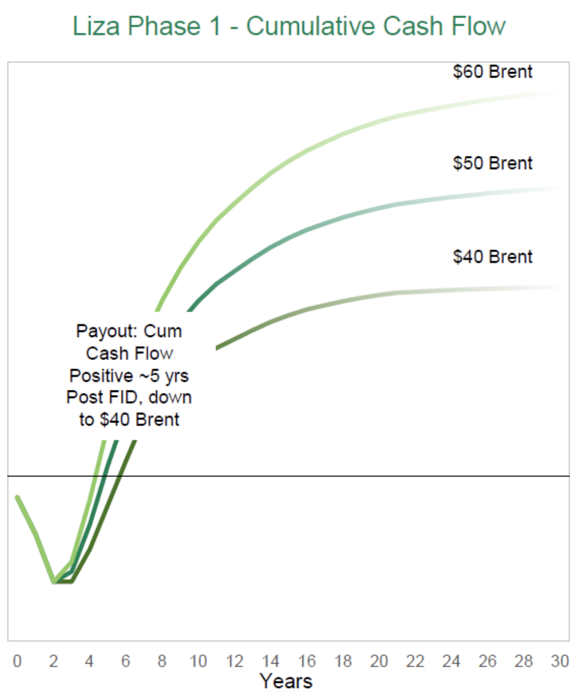
Technically Recoverable Shale Gas Resources (Tcf)		Technically Recoverable Shale Oil Resources (Billion Barrels)	
1. U.S.	1,161	1. Russia	75
2. China	1,115	2. U.S.	48
3. Argentina	802	3. China	32
4. Algeria	707	4. Argentina	27
5. Canada	573	5. Libya	26
6. Mexico	545	6. Australia	18
7. Australia	437	7. Venezuela	13
8. South Africa	390	8. Mexico	13
9. Russia	285	9. Pakistan	9
10. Brazil	245	10. Canada	9
11. Others	1,535	11. Others	65
TOTAL	**7,795**	**TOTAL**	**335**

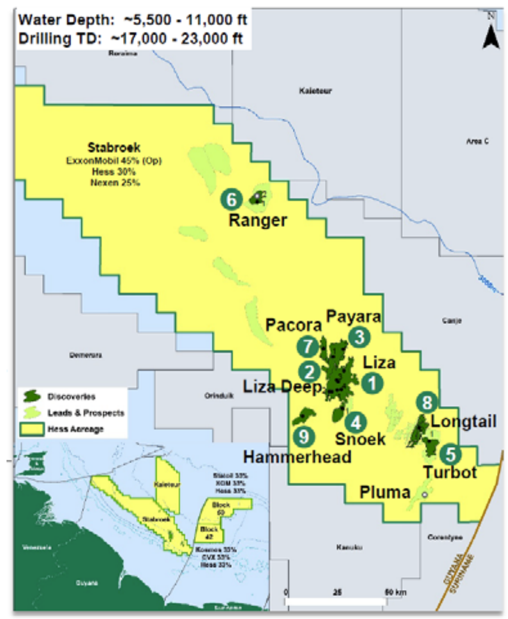
Source: EIA/ARI World Shale Gas and Shale Oil Resource Assessment, 2013

- EIA data as of end 2014 (world) and 2015 (US).
- Shale oil:
  - Unproved technically recoverable resources 114 billion bbl (liquids – oil and NGL) in the US.
  - Technically recoverable 340.6 billion bbl outside the US.
  - Risked shale oil in place 6,867 billion bbl outside the US.
- Shale gas:
  - Unproved technically recoverable resources 949.3 tcf in the US.
  - Technically recoverable 6,954 tcf outside the US.
  - Risked shale gas in place 32,946 tcf outside the US.

But deep-water exploration is alive!

	Guyana Liza Phase 1 Development[1]	Delaware Basin Illustrative 50,000 Net Acre Development[2]
Peak Production	120,000 BOED	120,000 BOED
Peak Production Oil	120,000 BOD	86,000 BOD
Initial Investment to Peak Production	3 years	10+ years
Reservoir Quality	Multi Darcy	Micro Darcy
Total Production Wells	8	1,400
Avg. EUR / Production Well	56 MMBO	0.9 MMBOE 0.6 MMBO
Development Capex	$3.2 Billion	$10.5 Billion
Unit Development Costs	~$7/BO	~$9/BOE ~$12.5/BO
Cost Environment	Deflating	Inflating
Required WTI price for 10% Cost of Supply	**~$35/bbl**	**~$45/bbl**

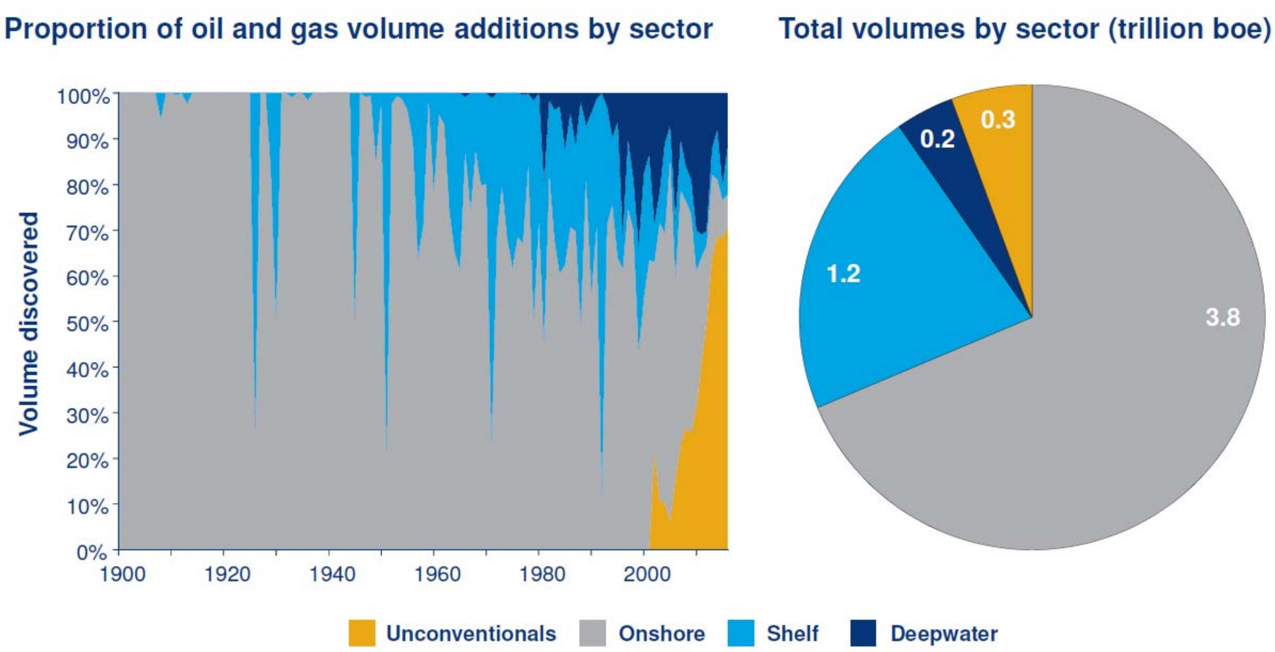




Hess, September 2018

Liza Phase I offers breakevens superior to the premier U.S. shale plays

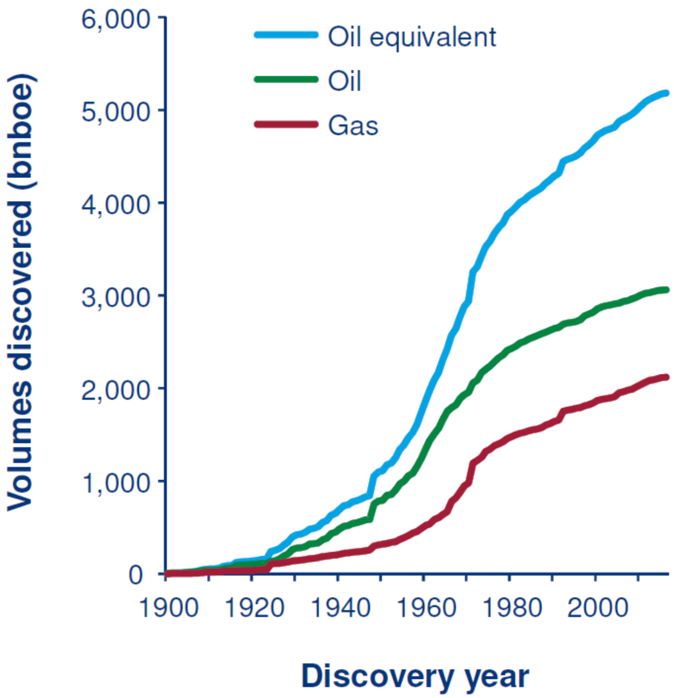
Resource additions by exploration sector



- A largely onshore history…
- Now deep-water and unconventionals.
- Exploration has added 5.5 trillion barrels of oil equivalent since 1900.

Wood Mackenzie (2017, AAPG ICE)

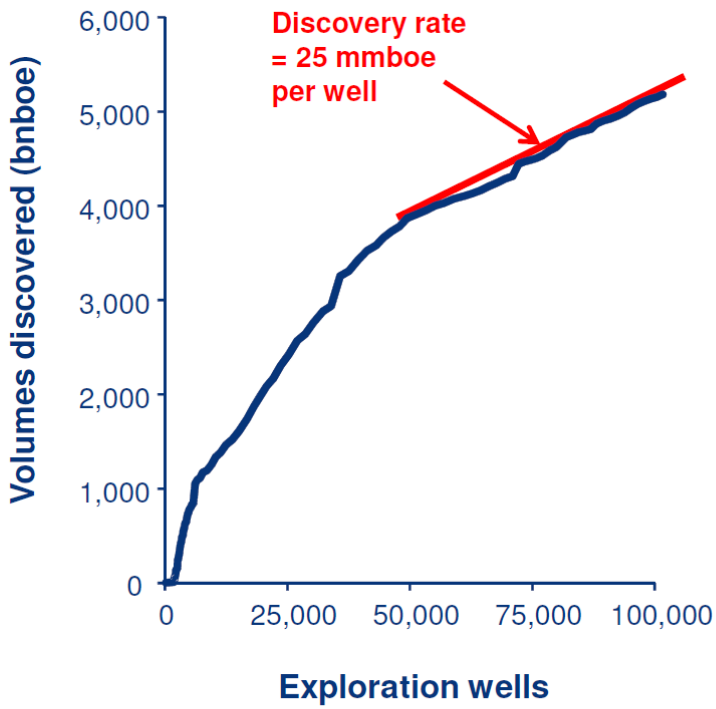
Volumes discovered vs Time



- Oil and gas creaming curves for 1900-2016.
- Approximately 50 million barrels found per wildcat drilled since 1900.
- Inflexion point around 1980.
- Average 100 billion boe found per year in 1950-1980.
- Average 40 billion boe found per year since 1980.

Wood Mackenzie (2017, AAPG ICE)

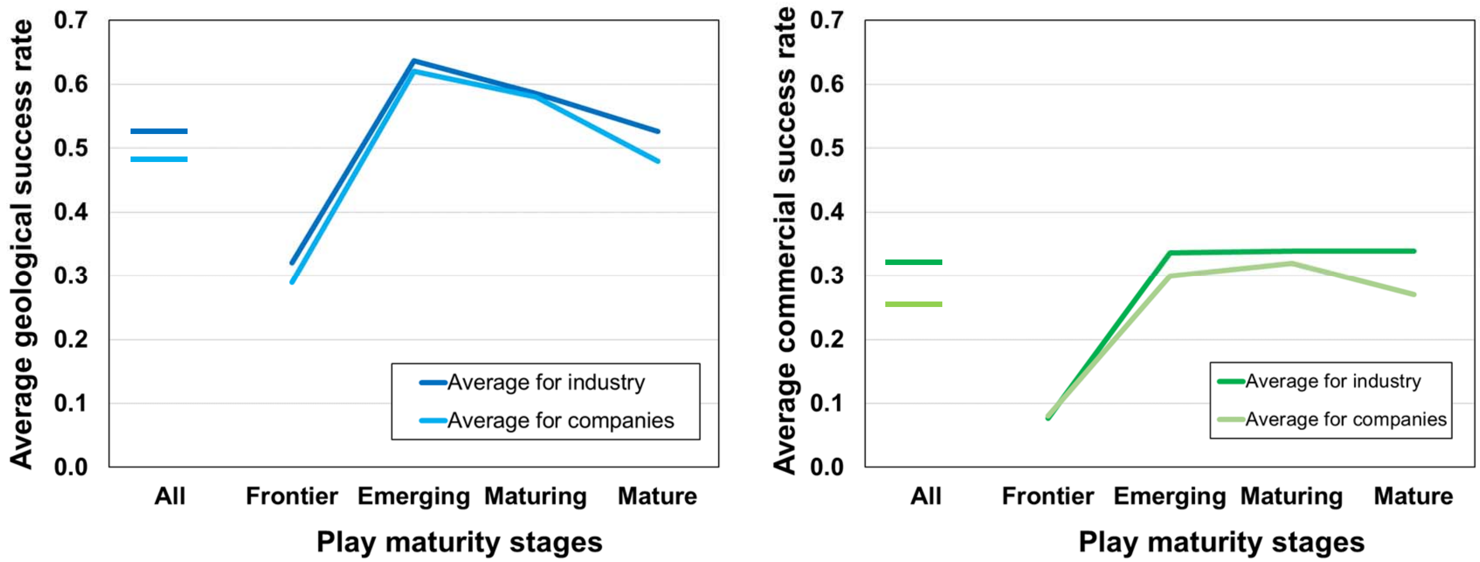
Volumes discovered vs wells (pure creaming curve)



Wood Mackenzie (2017, AAPG ICE)

- Average exploration well discovers ~25 mmboe.
- This is a global average, but similar creaming curves can be constructed for individual basins and plays.

Success rates for conventional wells



- Geological and commercial (economic) success rates for global exploration wells in 2008-2017.
- ~3,258 wells in which 733 companies had equities.

Milkov and Navidi (2019), data from Wildcat database (Westwood Energy)

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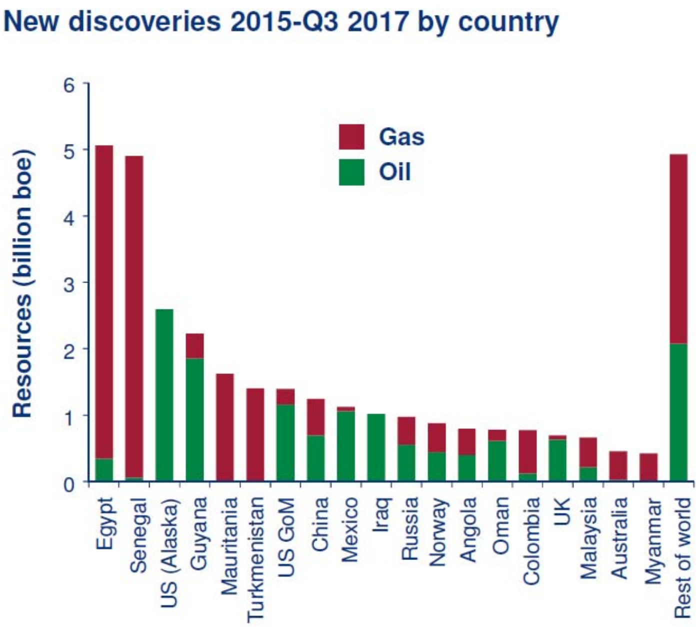
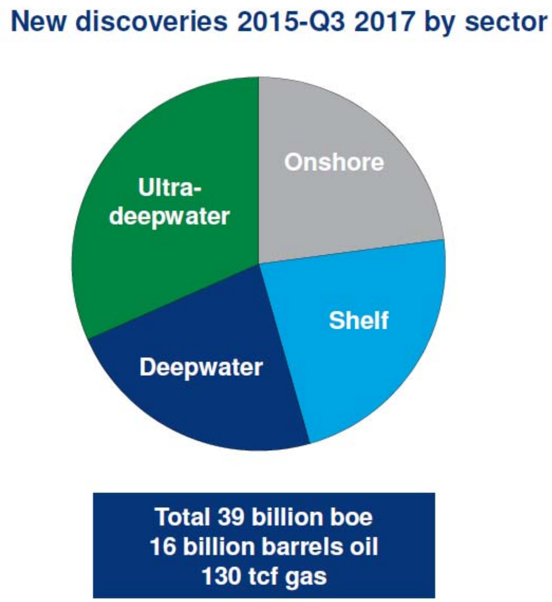
Recently discovered volumes

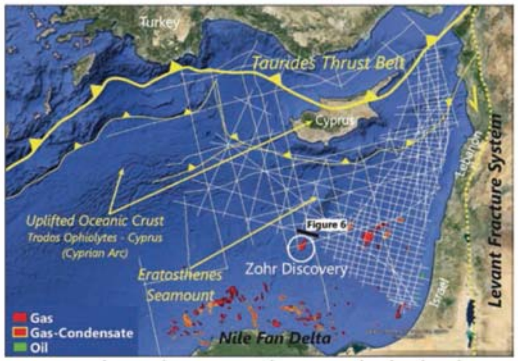


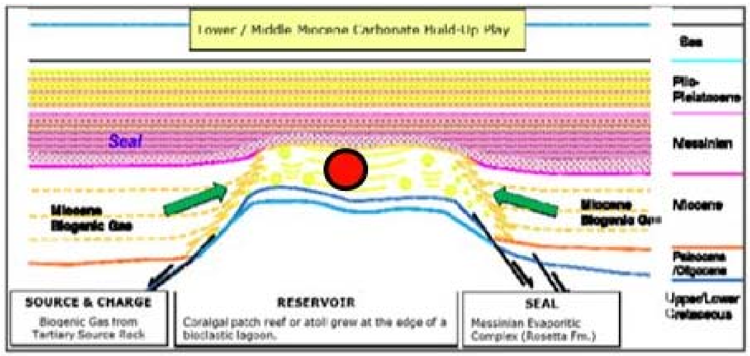


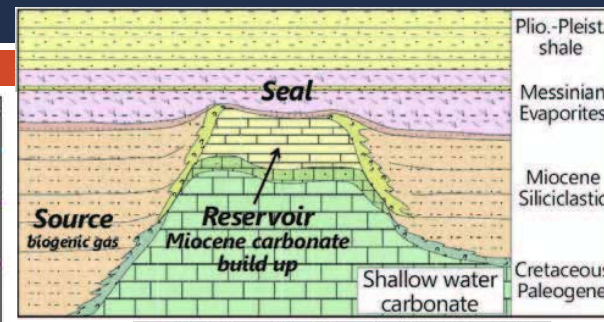
- Recent exploration volumes are mainly in new plays and basins.
- More than half of these volumes are in deep-water.

Wood Mackenzie (2017, AAPG ICE)

Zohr - giant microbial gas field discovered in 2015

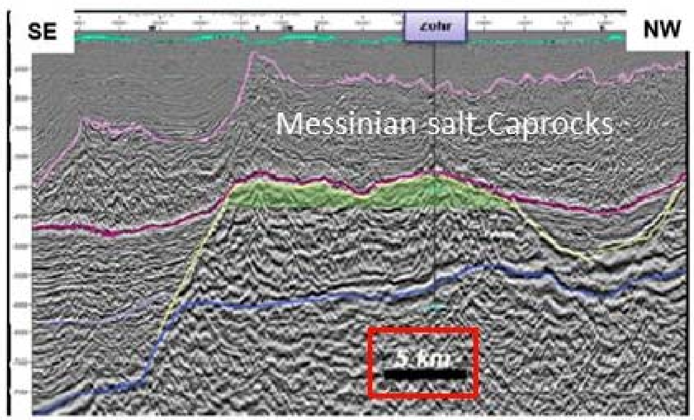


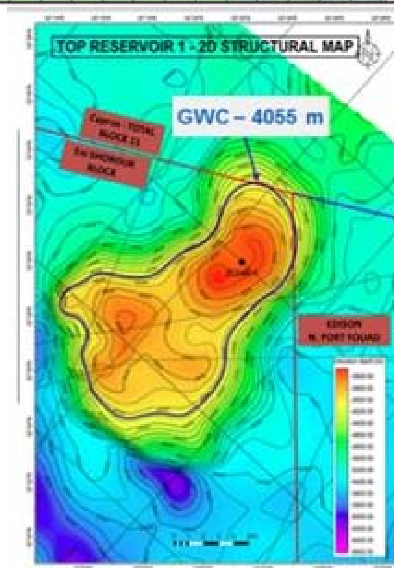




- Levant basin, Egypt.
- Primary microbial gas in Miocer reef complex (atoll carbonates) capped by Messinian salt.
- Lateral charge of microbial gas from Miocene/Oligocene shales sands from a large fetch area.
- EUR 22 to 27 TCF.

Esestime et al. (2016), ENI





Drivers of major conventional oil & gas provinces

- World-class source rock(s)
  - 6 geological intervals well known from global studies
- Petroleum generation and migration
  - Sufficient heat flow and major structural elements
- Reservoir
  - Thick, permeable sandstones and carbonates
  - The major deltas and carbonate platforms through geological time
- Trap
  - Giant structures sealed by mudstones or salt
- All factors are necessary for giant oil and gas provinces
  - They interact in complex yet predictable ways

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Major exploration questions

- **Where should we explore? Globally or some focus geography? Which continents / basins / plays?**
  - Depends on strategy, internal company constraints (funds, people, expertise…), market conditions...
- **Is petroleum there? What is the probability of success (PoS=1-Risk) for the well?**
  - Usually subjective expert judgement.
- **How much of oil&gas may be there if the well is successful?**
  - Usually distribution from Monte-Carlo simulations.
- **What is the Expected Monetary Value (EMV) of the project?**
  - $EMV = NPV \times PoS - (\text{Exploration Cost}) \times (1-PoS)$

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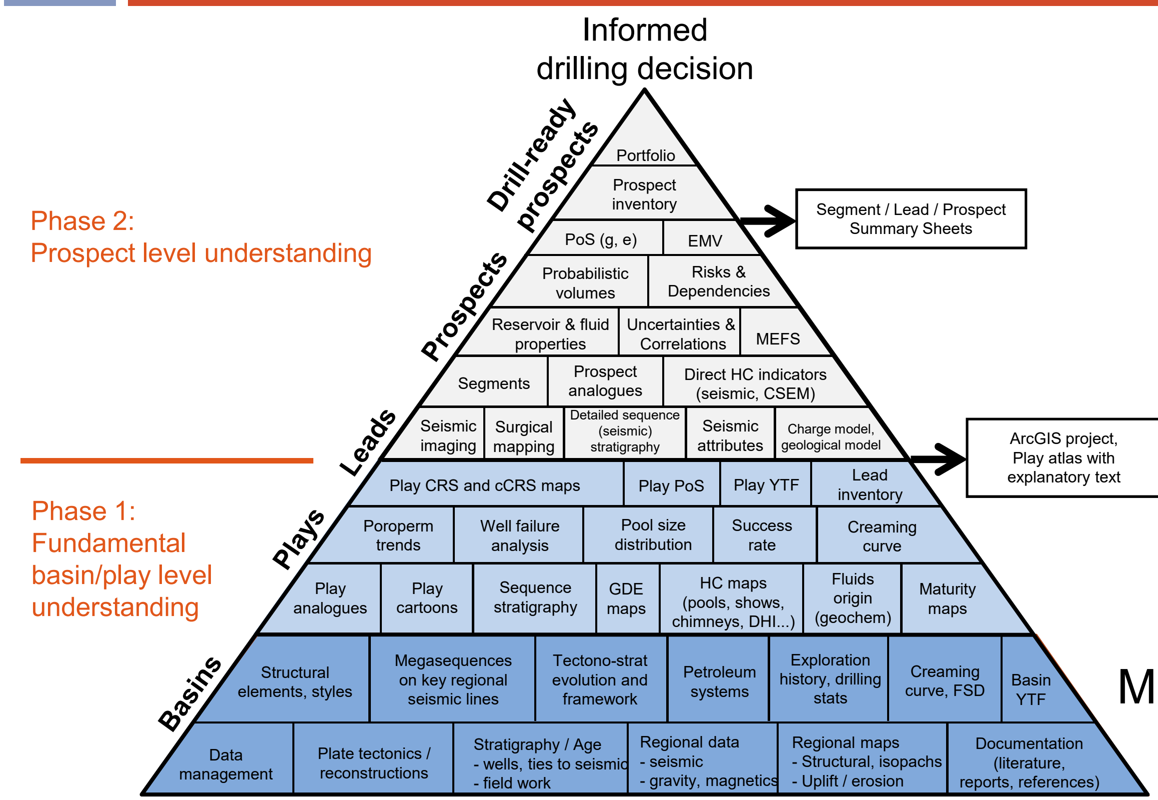
Integrated petroleum exploration



- Exploration triangle:
  - Describes the main deliverables of subsurface evaluation.
  - Ensures technical robustness and continuity of basin → play → lead → prospect evaluation.
- Key outcomes of exploration evaluation:
  - Probability of Success (PoS).
  - Success-case volumes.
- Risky business with many uncertainties. Billions of $ lost on dry holes.

Milkov (2015)

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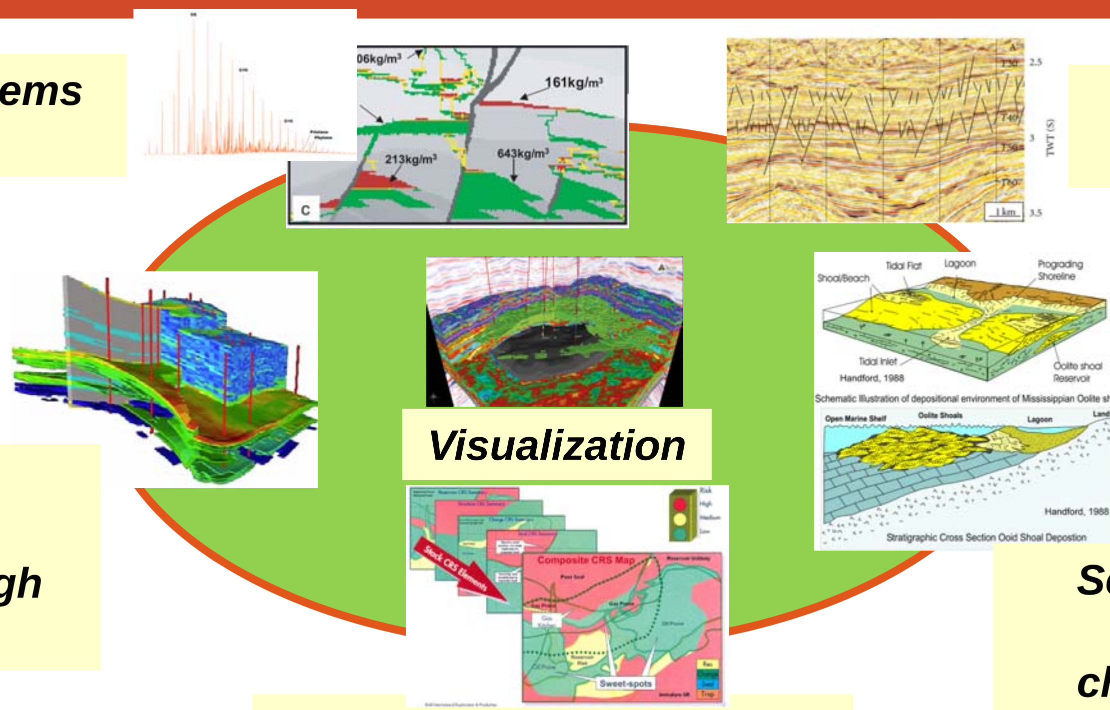
Key tools in the integrated petroleum exploration

Petroleum Systems Analysis

Structural Analysis



Visualization

Geological modelling, evolution through time

Sedimentology / Reservoir characterisation

Play Fairway Analysis and Risk segment mapping

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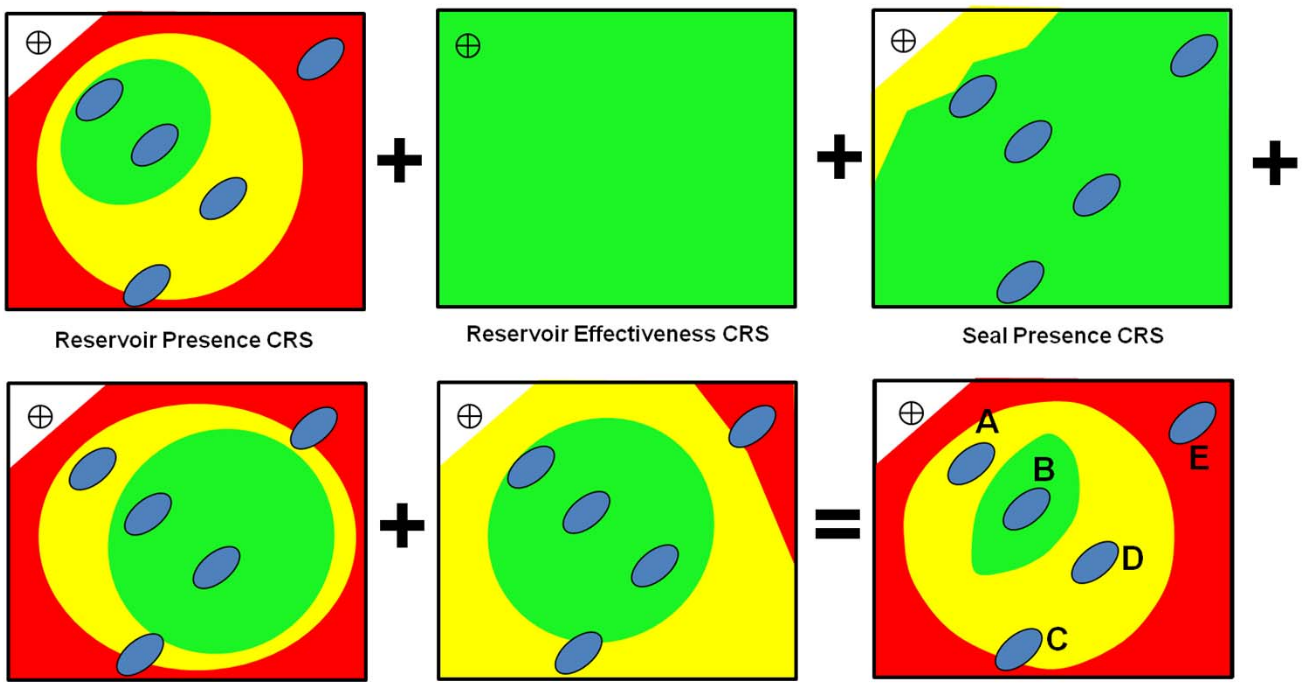
Common Risk Segment mapping for conventional exploration play



Reservoir Presence CRS

Reservoir Effectiveness CRS

Seal Presence CRS

SR Presence and Maturity CRS

Migration CRS

Composite CRS (cCRS) map with identified prospects

- Qualitative risk description:
  - Green is low risk.
  - Yellow is moderate (medium) risk.
  - Red is high risk.
  - White is outside of the play (play is absent).
- The composite CRS (cCRS) is assigned the risk of the most risky component CRS. The presence of one high-risk (red) component is sufficient to turn the composite CRS to high risk (red).

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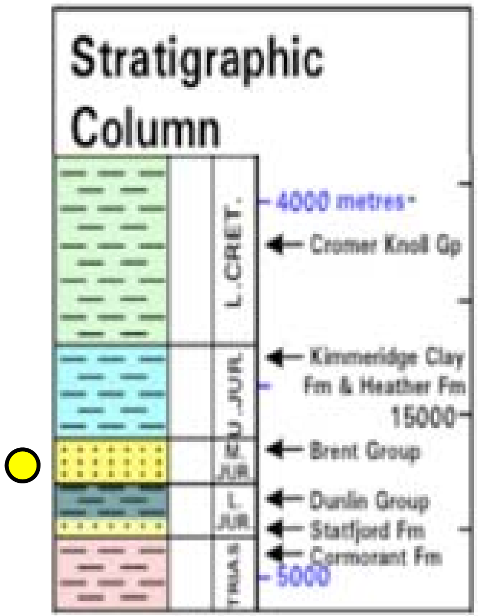
CRS map for reservoir presence: Brent play, UK Continental Shelf



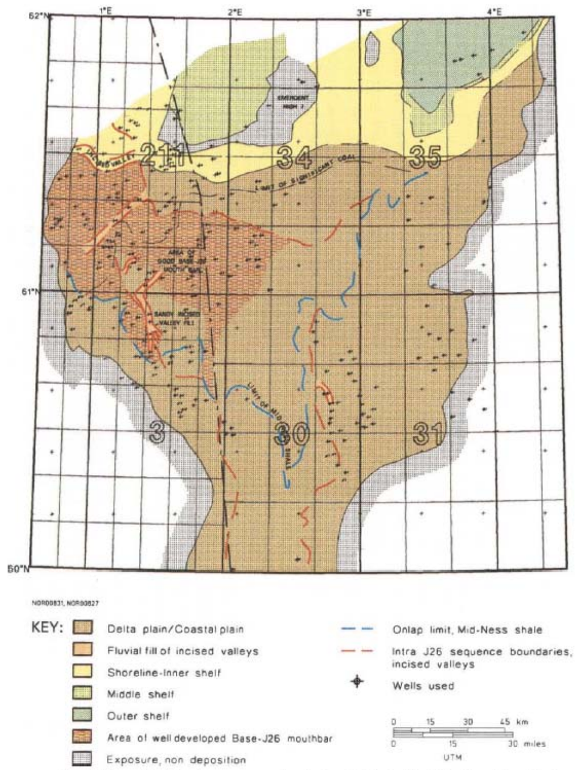


Fig. 4. Depositional environment map for the Late Bajocian (includes Upper Ness Fm.).

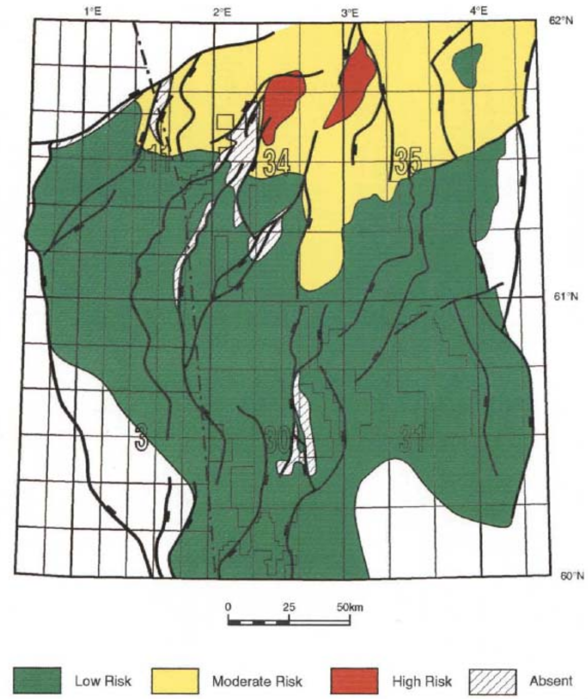
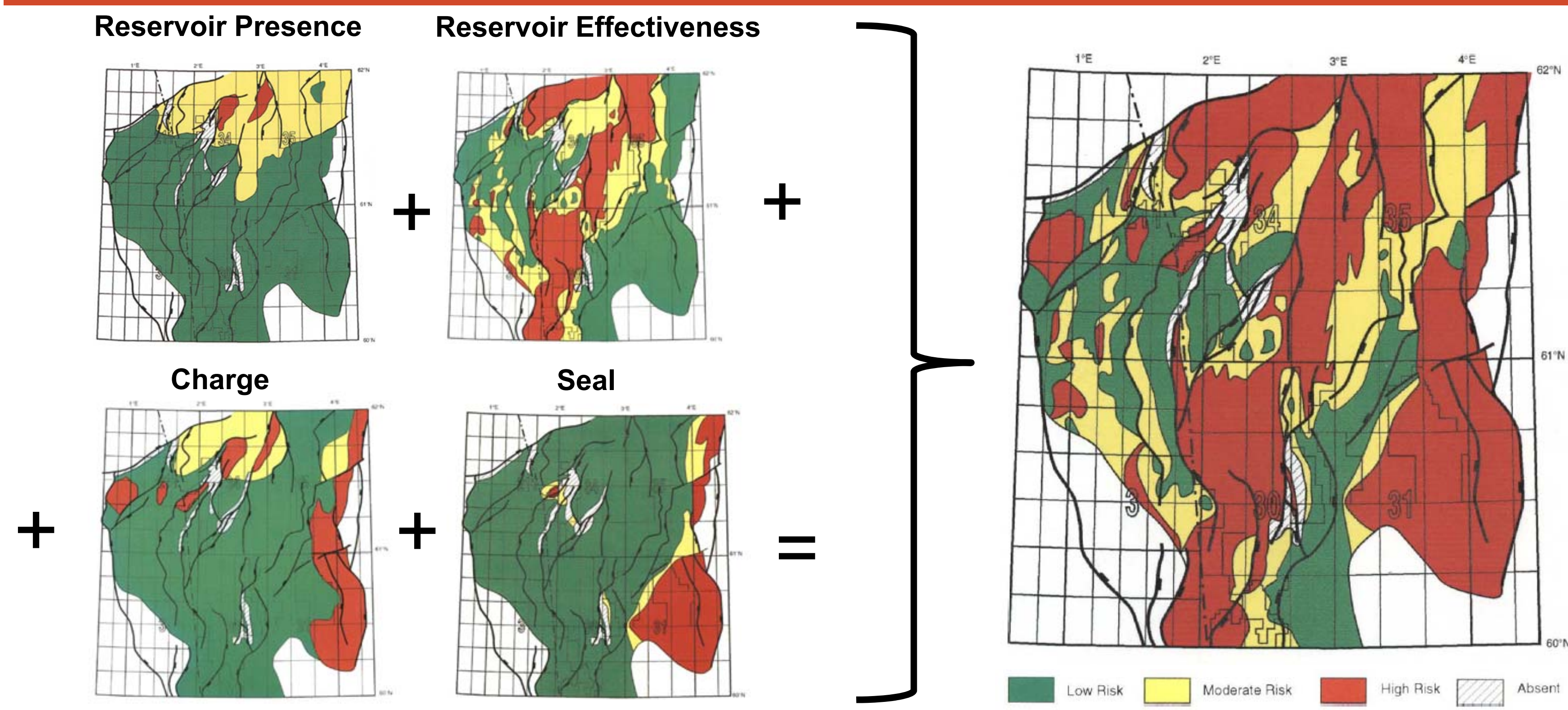


Fig. 5. Common risk segment map for Brent Gp. reservoir presence.

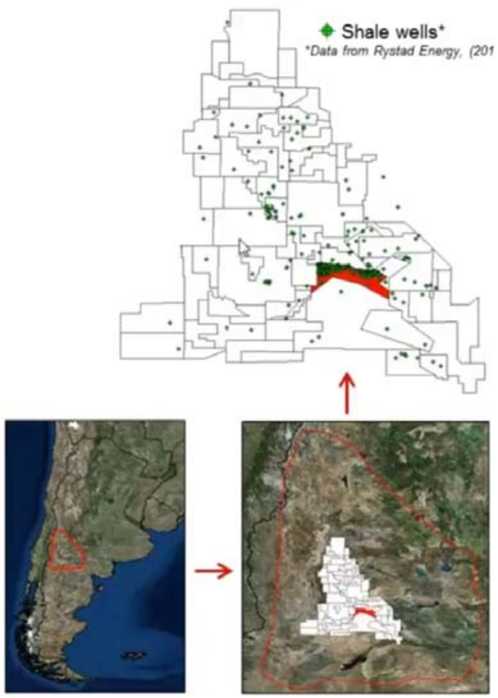
Grant et al. (1996)

Composite CRS map for Brent play

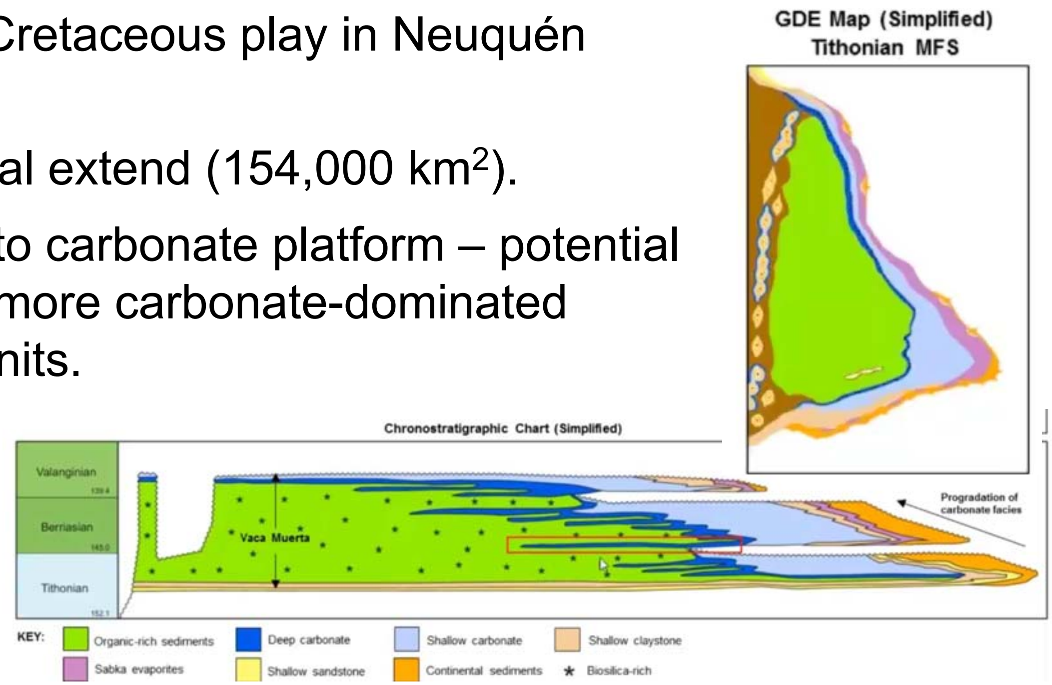
Grant et al. (1996)



Vaca Muerta shale play in Argentina

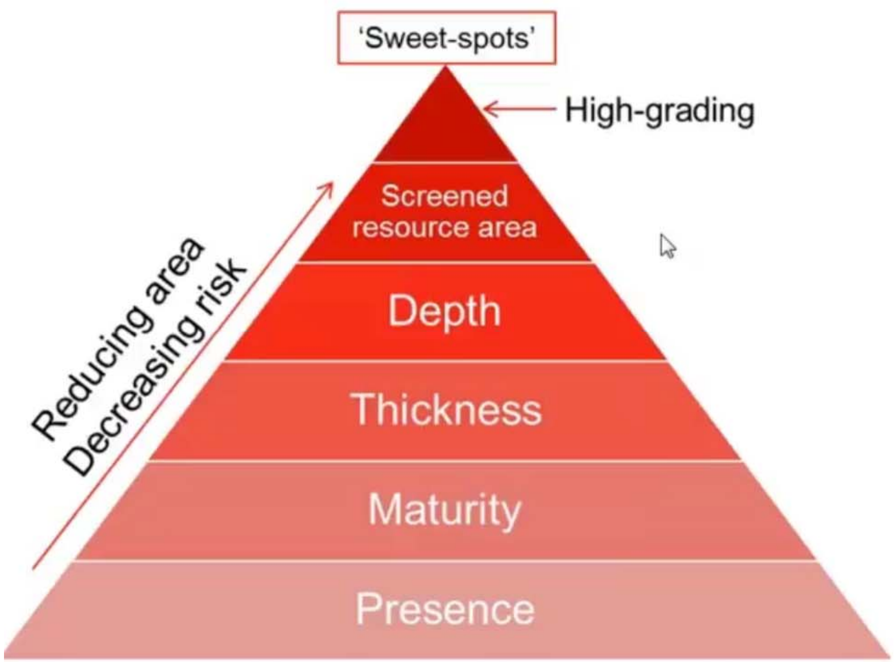


- Jurassic/Cretaceous play in Neuquén Basin.
- Large areal extend (154,000 km^2).
- Adjacent to carbonate platform – potential for brittle more carbonate-dominated fracture units.



Bromhead (2006)
Haliburton webinar: http://www.landmark.solutions/Webinar-Emerging-Unconventionals

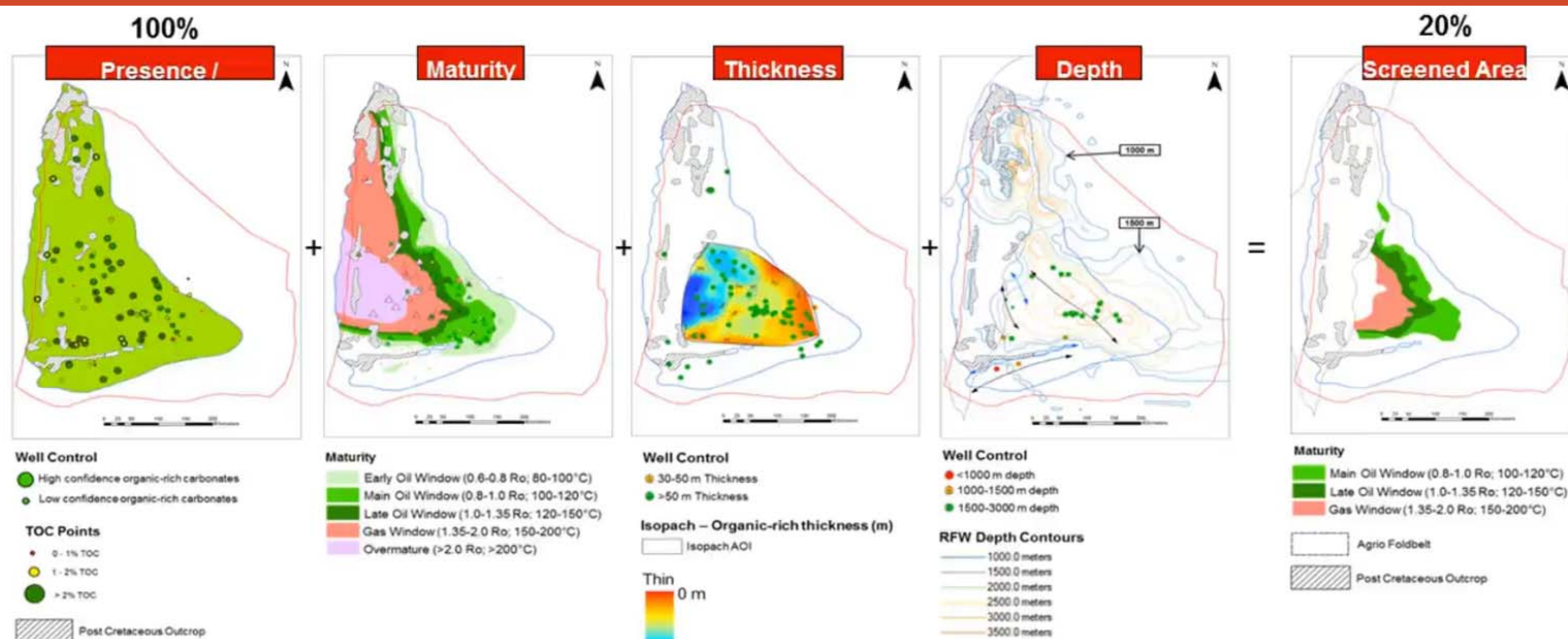
One CRS approach to shale plays

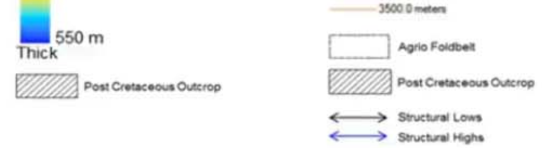


Parameter	Shale Oil / Shale Gas	
PRESENCE Average TOC (wt%)	>2	Good
	1 - 2	Fair
	<1	Poor
MATURITY Ro equivalence (%)	0.7-1.1 (Oil); 1.1-2 (Gas)	Good
	0.5-0.7 or 2-3.5	Fair
	<0.5 or >3.5	Poor
THICKNESS Composite organic-rich thickness (m)	>45	Good
	30 - 45	Fair
	<30	Poor
DEPTH Top of target interval (m)	1500 - 3000	Good
	3000 - 4500	Fair
	>4500	Poor

Bromhead (2006)
Haliburton webinar: http://www.landmark.solutions/Webinar-Emerging-Unconventionals

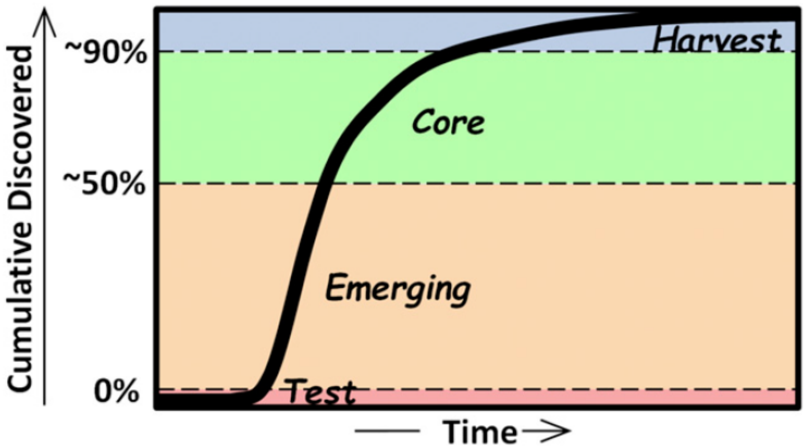
Sweet spot in Vaca Muerta shale play



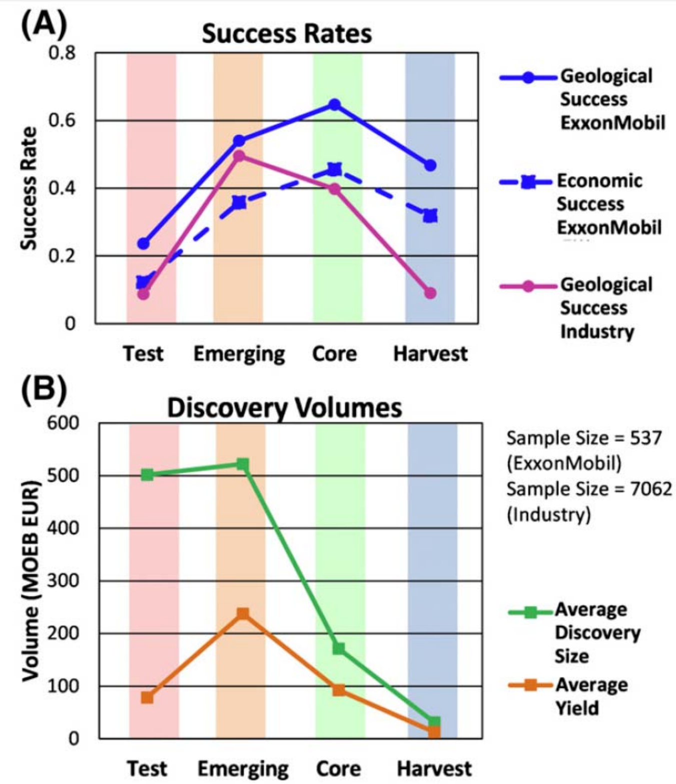


Simmons (2018) in Haliburton webinar:
http://www.landmark.solutions/Exploration-The-Ingredients-for-Future-Success

Success rate and size of discoveries change through exploration stages for basins/plays



Rudolph and Goulding (2017)



- ExxonMobil experience from drilling in 1995-2014:
  - Success rates increase from test to emerging to core, then decline in harvest stage.
  - Average discovery size declines from test through harvest, with yield (average commercial volume per wildcat) reaching a maximum during the emerging stage because of the combination of average field size and success rate.

Largest fields are usually discovered first within the parent population

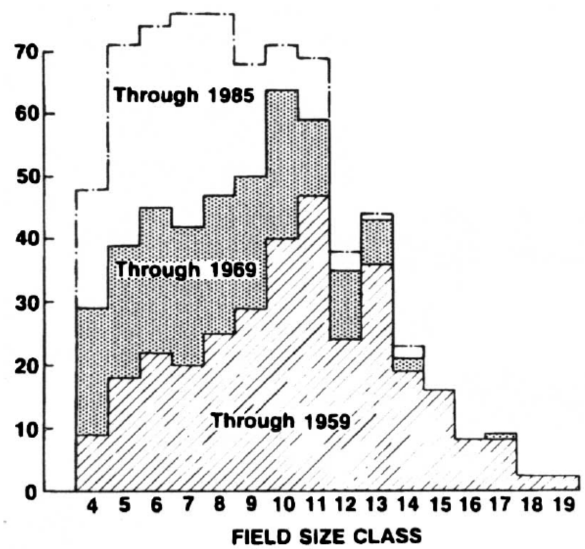


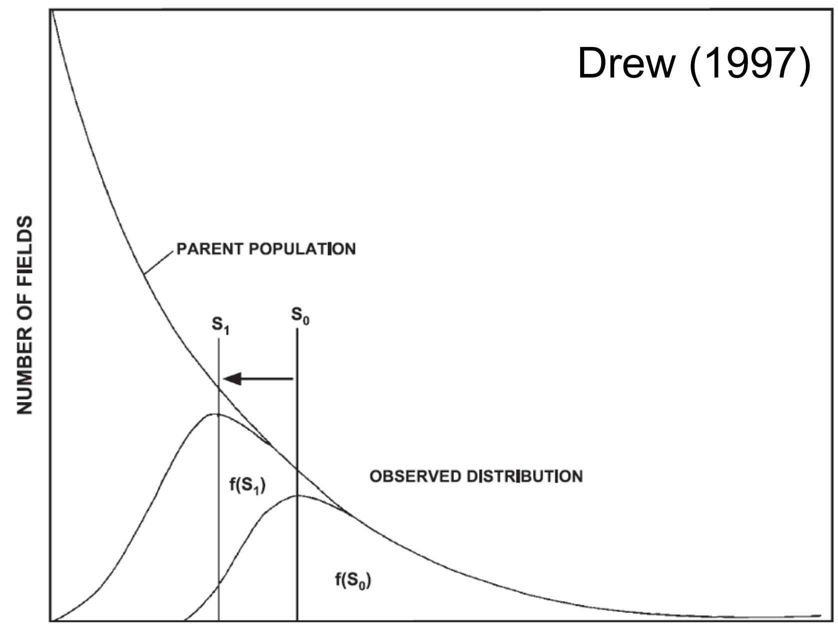
Figure 5. Empirical field size distribution for Frio Strandplain Play. Distribution has three segments that represent cumulative number of fields discovered through specified year. See Table 1 for definition of field size classes.

Schuenemeyer and Drew (1999)

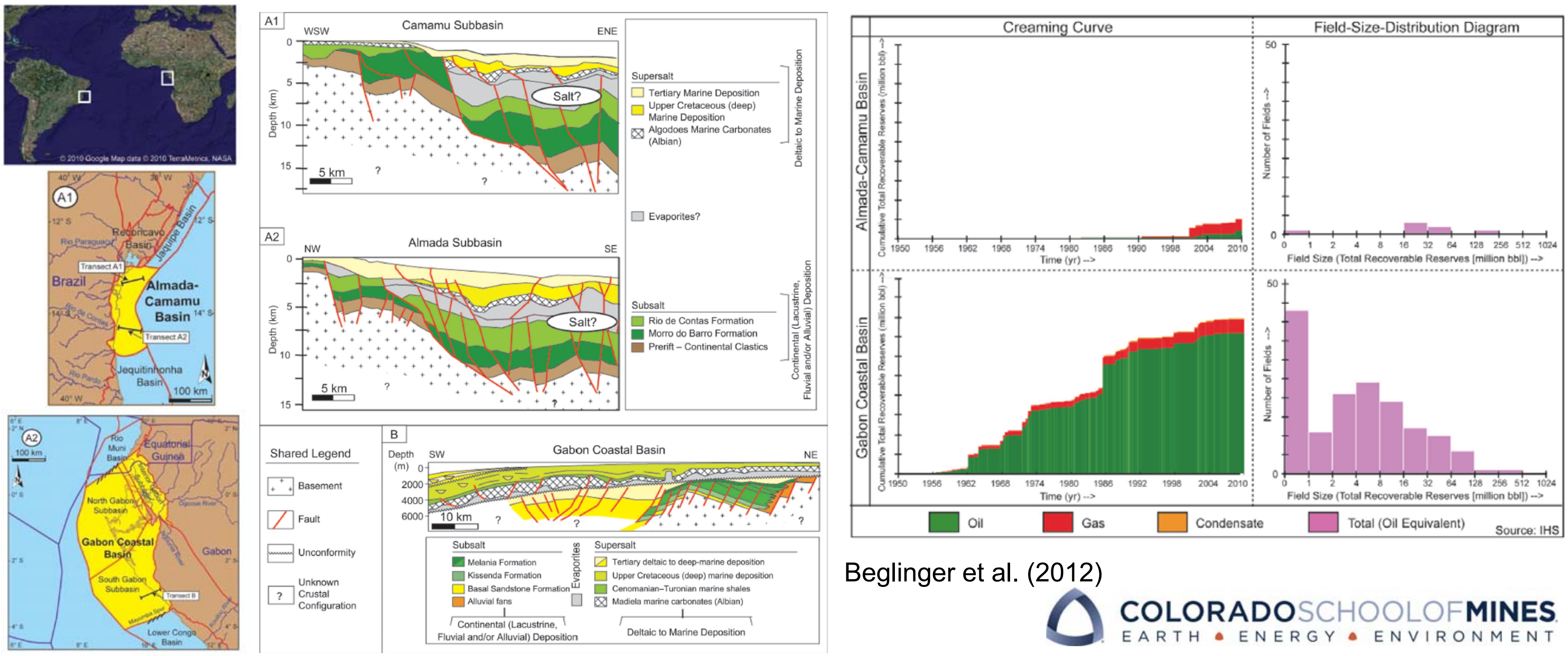
Table 1. Petroleum Field Size Classes[a]

Class	Size range
1–5	0–1
6	1–2
7	2–4
8	4–8
9	8–16
10	16–32
11	32–64
12	64–128
13	128–256
14	256–512
15	512–1024
16	1024–2048
17	2048–4096
18	4096–8129
19	8129–16384
20	16384–32768

[a] Millions of BOE equivalent.



Creaming curves and FSDs as indicators of exploration potential



Beglinger et al. (2012)

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Causes of failure of dry holes (conventional targets): XOM experience

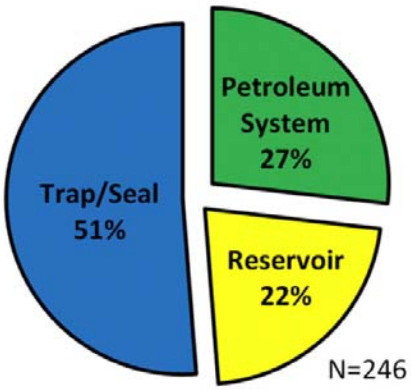


Figure 12. Causes of failure of geologic dry holes. About half of dry holes are caused by trap and seal failure. *N* = sample size.

ExxonMobil drilling in 1995-2014:

- Trap/Seal: top, fault and lateral seal (dominated) closure presence.
- Petroleum system: source presence, source maturity, migration, timing, petroleum preservation and biodegradation.
- Reservoir: presence (dominated) and quality.

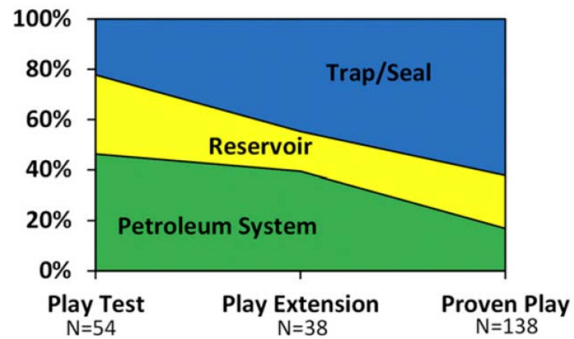


Figure 13. Reasons for wildcat failure by play maturity. Petroleum system is the most important cause of dry holes for conventional play tests and play extensions. For wildcats in proven plays, trap and seal is preeminent. *N* = sample size.

Rudolph and Goulding (2017)

Definitions of exploration success

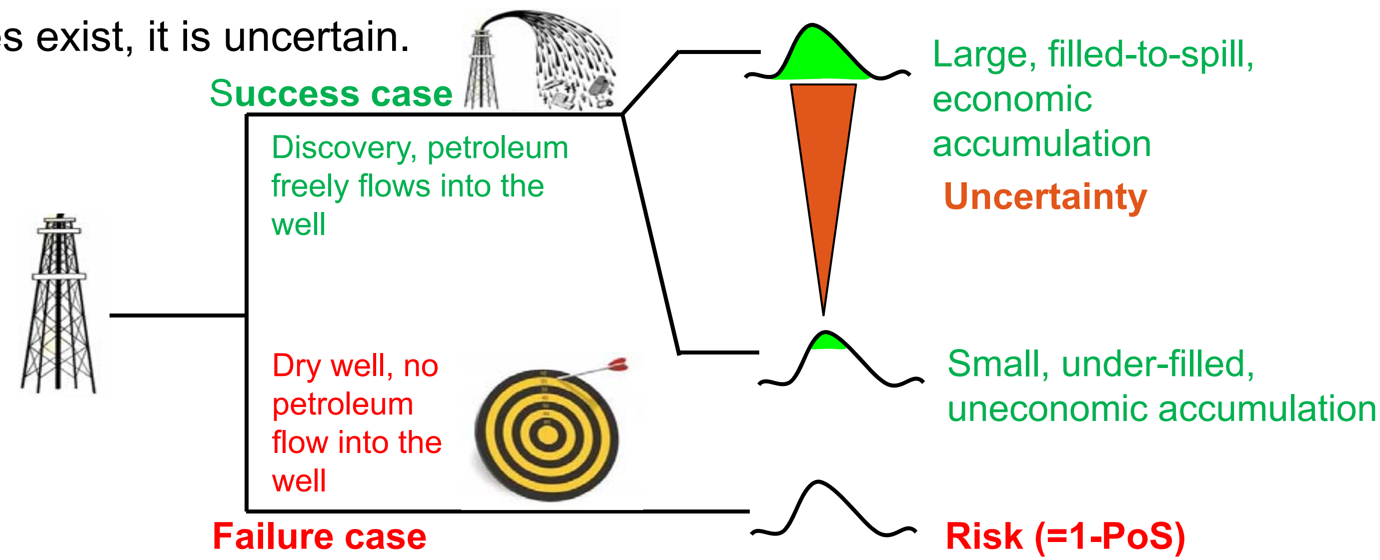
- Finding oil&gas accumulations.
  - Geological / technical success.

- Finding oil&gas accumulations that make money.
  - Commercial / economic success.

- Finding oil&gas accumulations that make money as predicted (on the portfolio basis).

Risk / PoS and uncertainty for exploration prospects

- Explorers evaluate an object – a pool of petroleum – which
  - may not exist at all...
  - if it does exist, it is uncertain.



Adapted from Sykes et al. (2011)

Assessment of success-case volumes in a prospective segment with oil

Recoverable Oil = GRV × N/G × Ø × S_o × 1/B_o × RF

GRV – Gross Rock Volume (m^3)
N/G – Average Net-to-Gross within the rock volume (fraction or %)
Ø – Average porosity (fraction or %)
S_o – Average oil saturation (fraction or %)
B_o – Formation Volume Factor (m^3/m^3 or bbl/stb). Oil shrinkage factor is 1/B_o.
RF – Recovery factor (fraction or %)

Results are in SI units (m^3) and can be converted to field units (stb, standard tank barrels: 1 m^3 = 6.29 stb)

Think-Pair-Share:
Calculate volume of recoverable oil in segment Z

- Segment Z with prospective oil resources has the following estimated characteristics:
- Calculate the volume of recoverable oil in this segment. Give your answer in m^3 and in stb.

GRV is 350×10^6 m^3
N/G is 60%
Ø is 17%
S_o is 60%
B_o is 1.2 bbl/stb
RF is 30%

- Discuss your answers with another person.
- Be ready to share with the group.

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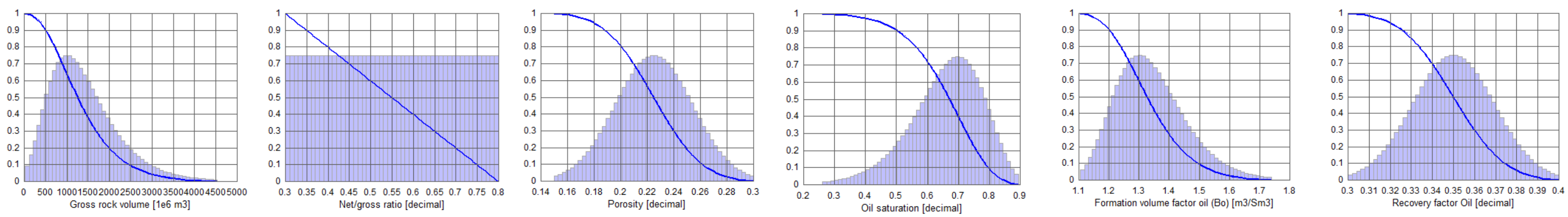
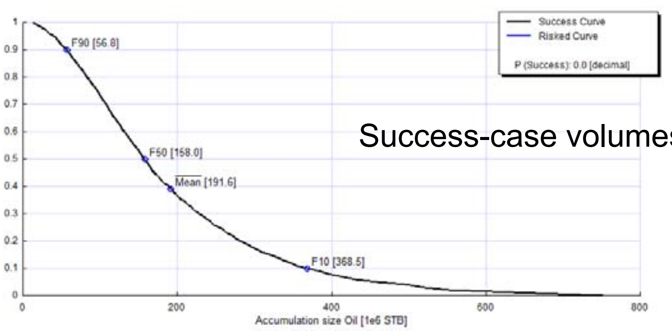
Assessment of success-case volumes in a prospective segment

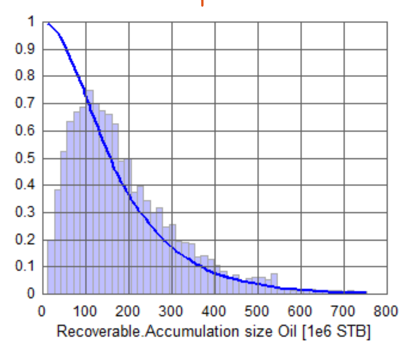
Deterministic: Recoverable Oil = GRV × N/G × Ø × S_o × 1/FVF × RF

Probabilistic / Stochastic:





Success-case volumes



- The volumetric equation is simple, but input reservoir and fluid parameters in the success case (discovery) are uncertain. Therefore they are described as probability density (distribution) functions.
- Success case (discovery) probabilistic volumes in the segment are calculated stochastically.

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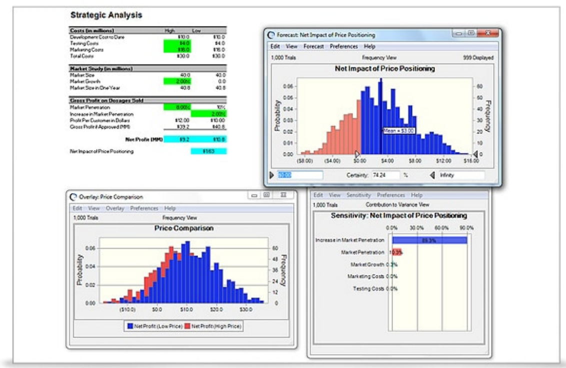
Tools for assessment: not specialized for resource evaluations



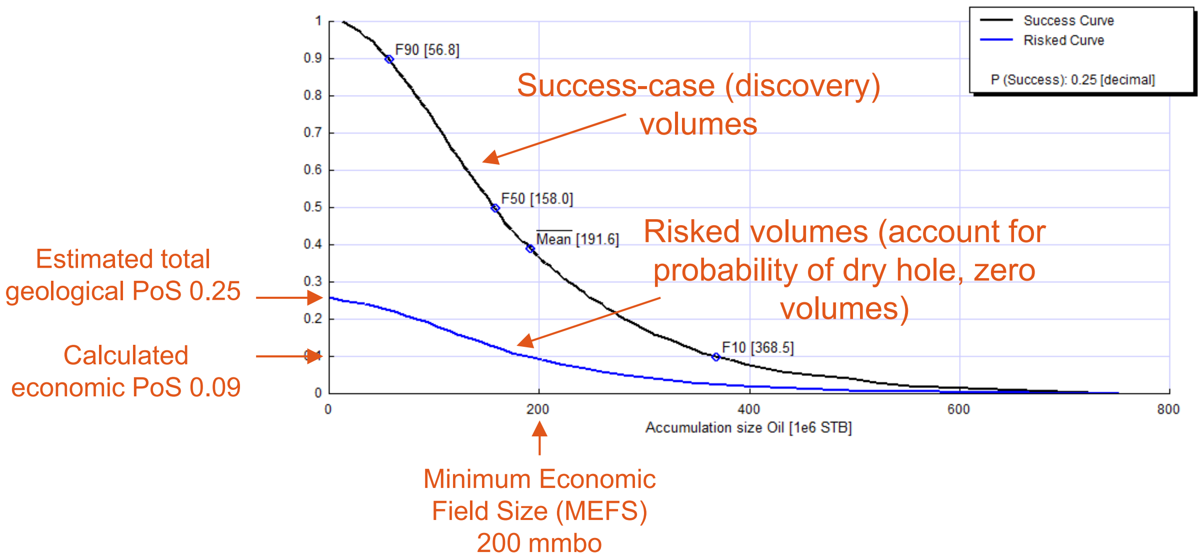
http://www.oracle.com/us/products/applications/crystalball/overview/index.html

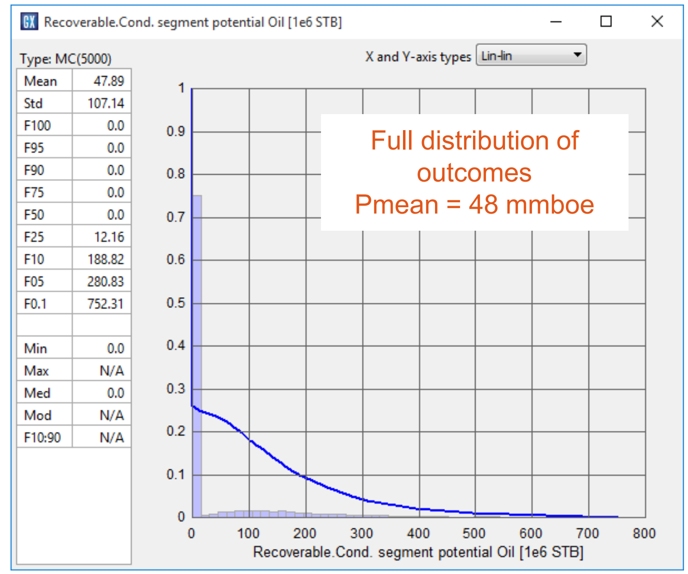
http://www.palisade.com/risk/

https://www.vosesoftware.com/products/modelrisk/

- Spreadsheet-based tools, add-ons to Excel, Monte Carlo simulations:
  - Oracle Crystal Ball
  - Palisade @Risk
  - Vose ModelRisk (free)
- Relatively cheap.
- Have to built segment and prospect analyses yourself, no relevant templates.
- Used by consultants and small companies.

Assessment of risked volumes





- The total geological PoS for the segment is estimated by the explorers.
- The economic PoS is then calculated based on the risked volumes curve and the estimated minimum economic field size (MEFS).
- Risked volumes for the segment is meaningless on its own, but needed for aggregations into prospects and portfolios.

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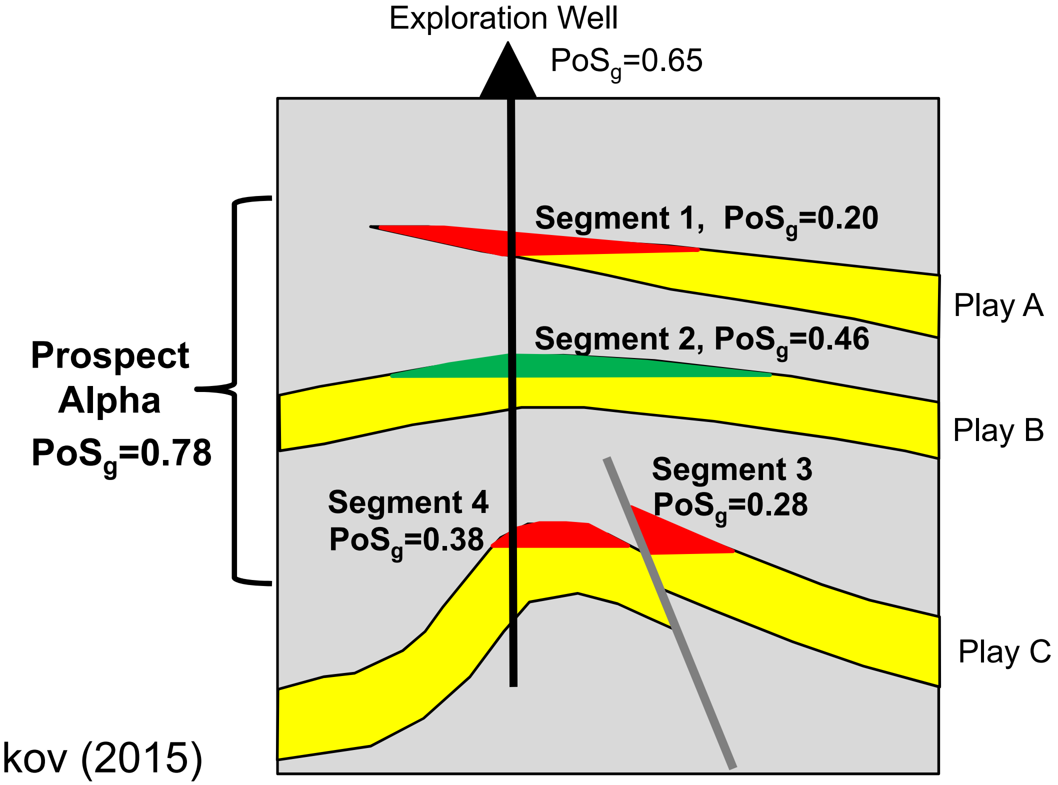
There are many geological PoSes…



Milkov (2015)

- PoS=1-Risk
- Segment is the smallest assessment unit for which explorers estimate volumes and risk/PoS.
- Volumes and PoS for the prospect, well, license etc. are not estimated directly, but are stochastically aggregated using inputs from the segments.

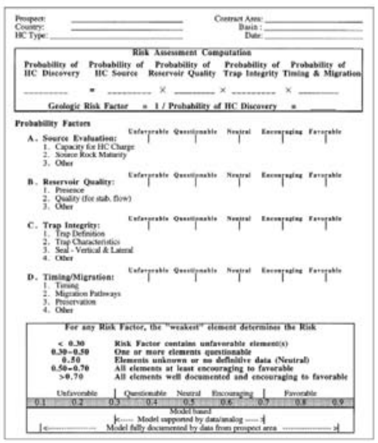
Estimation of geological PoS for segments

- Multiplying the probabilities of each independent risk factor (reservoir, seal etc.) which could cause the segment to fail.
- Different companies use from 4 to 19 independent risk factors – there is no consistency in the industry.

$$PoS = STR \times RP \times RD \times S \times MS \times M$$

- STR – probability of the mapped structure being present.
- RP – probability of the reservoir facies being present.
- RD – probability of sustainable free flow of specified hydrocarbons (oil, gas, oil + gas cap) from the reservoir.
- S – probability of the seal being present and holding a column of specified hydrocarbons.
- MS – probability of source rock(s) of required quality and maturity for specified hydrocarbons being present in the fetch area of the mapped structure.
- M – probability of effective migration of petroleum from source rock(s) to the mapped structure in the amount sufficient for the geological (technical) success.

Industry ways to estimate the geological risk factors


Prospect: ______ Contract Area: ______
Country: ______ Basin: ______
HC Type: ______ Date: ______

Risk Assessment Computation

Probability of HC Discovery = Probability of HC Source × Probability of Reservoir Quality × Probability of Trap Integrity × Probability of Timing & Migration

Geologic Risk Factor = 1 / Probability of HC Discovery = ______

Probability Factors (Unfavorable – Questionable – Neutral – Encouraging – Favorable)

A. Source Evaluation:
1. Capacity for HC Charge
2. Source Rock Maturity
3. Other

B. Reservoir Quality:
1. Presence
2. Quality (for stab. flow)
3. Other

C. Trap Integrity:
1. Trap Definition
2. Trap Characteristics
3. Seal - Vertical & Lateral
4. Other

D. Timing/Migration:
1. Timing
2. Migration Pathways
3. Preservation
4. Other

For any Risk Factor, the "weakest" element determines the Risk

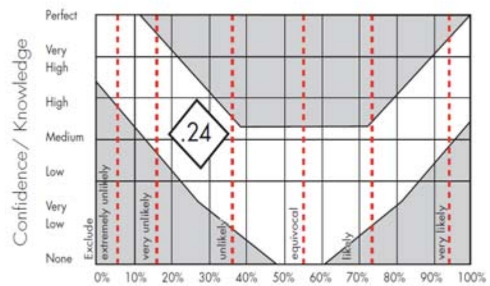
< 0.30	Risk Factor contains unfavorable element(s)
0.30–0.50	One or more elements questionable
0.50	Elements unknown or no definitive data (Neutral)
0.50–0.70	All elements at least encouraging to favorable
>0.70	All elements well documented and encouraging to favorable

Unfavorable | Questionable Neutral Encouraging | Favorable
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
Model based
Model supported by data/analog
Model fully documented by data from prospect area

Otis and Schneidermann (1997)

LEVEL OF GEOLOGIC UNDERSTANDING	Chance of Adequacy → ← Risk Severity: BAD NEWS	NEUTRAL	GOOD NEWS	EXAMPLE:
CONFIDENCE: HIGH	0-.2	X	.8-1	GOOD QUALITY, DEFINITIVE DATASETS
MEDIUM	.2-.4	.4-.6	.6-.8	
LOW	.4-.5	.5	.5-.6	POOR QUALITY, NON-DEFINITIVE DATASETS
EXAMPLE:	NEGATIVE INDICATIONS PREDOMINATE		POSITIVE INDICATIONS PREDOMINATE	

Sykes et al. (2011) ExxonMobil



Shell 2004 template (IBA PBA Guide)

Structure (closure, geometry, container)				Data (existence and reliability): 3D seismic	2D seismic – Number of lines per structure (with obligatory availability of in-line and cross lines): Dense (7 lines and more)	Sparse (3-6 lines)	Very sparse (2 lines) (Lead)
Models (existence and reliability)	Seismic mapping and correlation	High-relief structure (≥3 times higher than seismic accuracy) AND low structural complexity (4-way)	Easy to interpret, reliable correlation based on nearby (<50 km) wells	1.00	0.90	0.80	0.60
			Uncertain correlation (horizons are interrupted laterally) or based on remote (> 50 km) wells	0.95	0.85	0.75	0.55
			Difficult to interpret, unreliable correlation (horizons are interrupted by thrust faults, diapirs, etc.) or model developed using analogues without wells in the basin	0.85	0.75	0.70	0.45
		Medium-relief structure (1-3 times higher than seismic accuracy) OR high-relief structure with high structural complexity (3-way, stratigraphic)	Easy to interpret, reliable correlation based on nearby (<50 km) wells	0.80	0.70	0.60	0.35
			Uncertain correlation (horizons are interrupted laterally) or based on remote (> 50 km) wells	0.75	0.65	0.50	0.25
			Difficult to interpret, unreliable correlation (horizons are interrupted by thrust faults, diapirs, etc.) or model developed using analogues without wells in the basin	0.70	0.55	0.45	0.20
		Low-relief structure (lower than seismic accuracy) OR high uncertainty of depth conversion (subsalt, below lava flows) OR areas with rapidly changing lateral velocities in the overburden	Easy to interpret, reliable correlation based on nearby (<50 km) wells	0.55	0.45	0.35	0.15
			Uncertain correlation (horizons are interrupted laterally) or based on remote (> 50 km) wells	0.50	0.40	0.25	0.10
			Difficult to interpret, unreliable correlation (horizons are interrupted by thrust faults, diapirs, etc.) or model developed using analogues without wells in the basin	0.40	0.30	0.20	0.05
		Low-relief structure (lower than seismic accuracy) AND EITHER high uncertainty of depth conversion (subsalt, below lava flows) OR areas with rapidly changing lateral velocities in the overburden		0.35	0.25	0.15	0.05

Milkov (2015)

- Subjective expert judgement:
  - Individual geoscientists.
  - Modified during team discussions.
  - Modified by the assurance team and management.
- Tools to assist in the assessment, but very little specific guidelines.
- Lookup tables:
  - Evidence-based.
  - Reduce biases, improve consistency.

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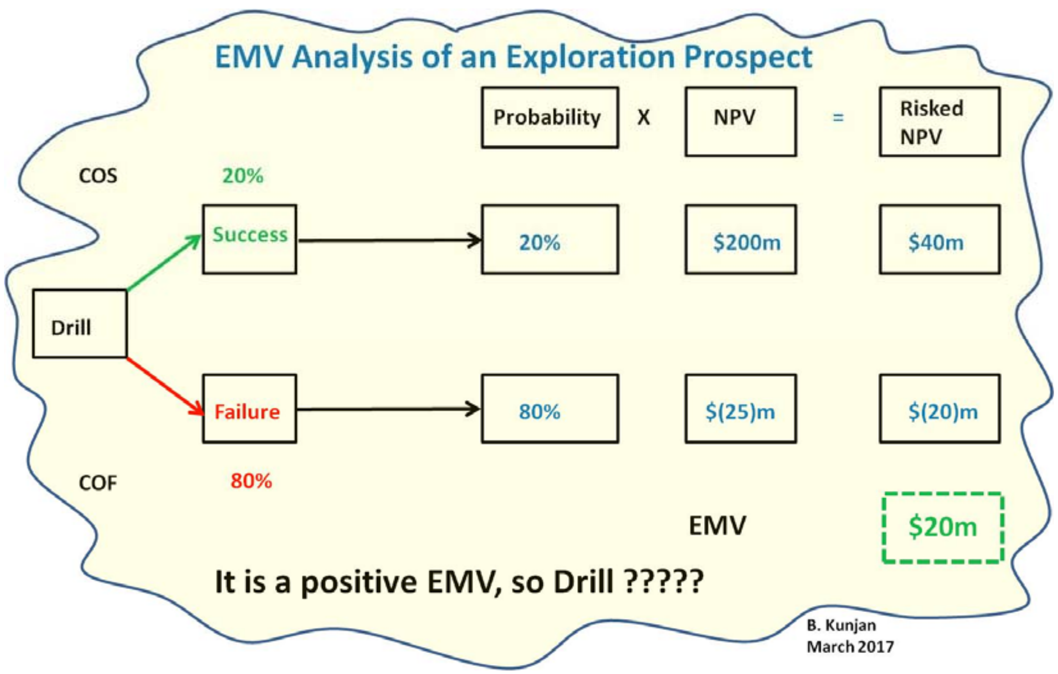
Expected Monetary Value (EMV) calculations

EMV = NPV × PoS – (Exploration Costs) × (1−PoS) = 200m × 0.2 – 25m × 0.8 = 40m – 20m = 20m



- Net present value (NPV) is determined by calculating the costs (negative cash flows) and benefits (positive cash flows) for each period of an investment.
- The cashflow is normally discounted (e.g., at 10% discount rate).

net cash inflow during the period t

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t}$$

number of time periods

discount rate

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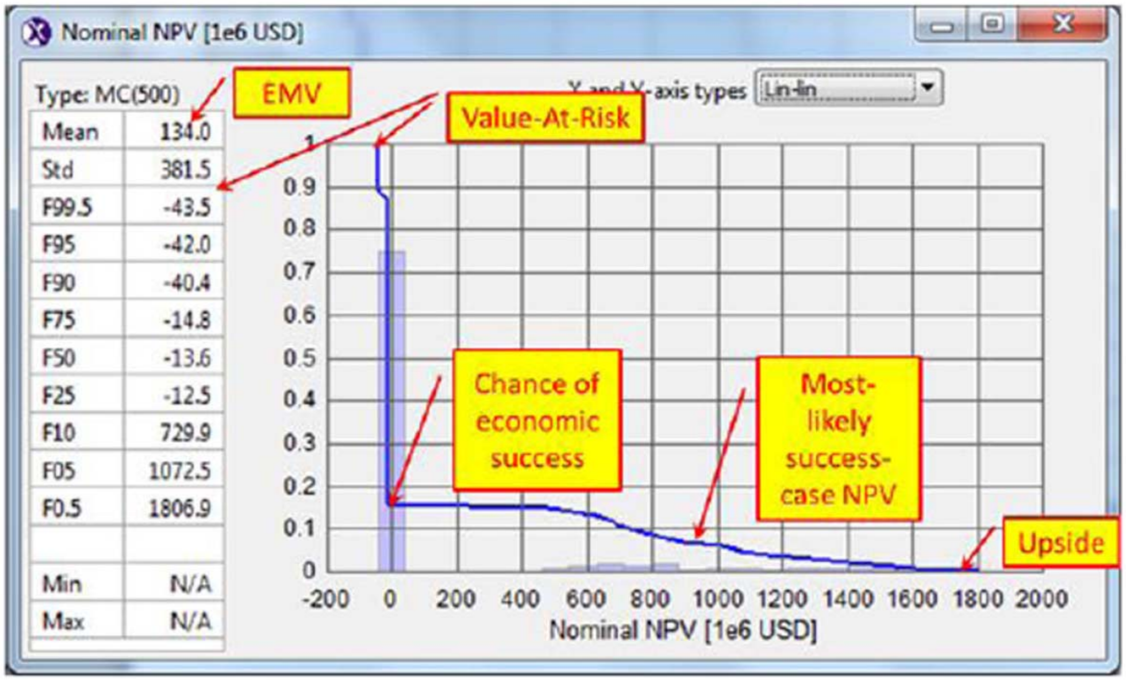
Probabilistic NPV distribution chart



Surovtsev et al. (2016)

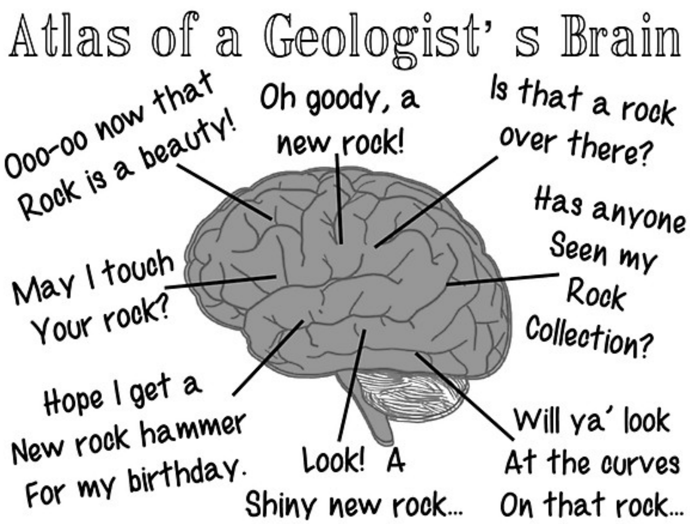
Why we do geology in E&P companies??

"My job is to make decisions. Your job is to make them good decisions."

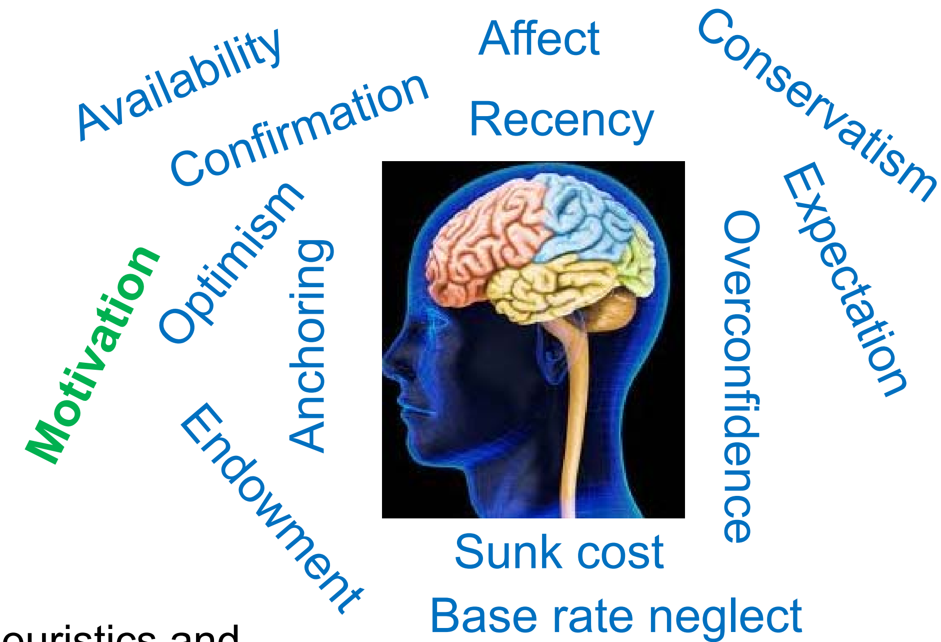
Why humans make bad decisions?

- Three reasons why [smart] humans are not good at decision making:
  - lack of information or bad quality of information/data,
  - cognitive biases,
  - greed/corruption.

Individual biases and fallacies in petroleum exploration



Gail Gabel, LLC



Milkov (2015)

- Individual subconscious judgement fallacies, heuristics and biases.
- Conscious motivational bias.

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Class activity: Let’s vote on words with letter K

- In 10 seconds, count how many English words you can think of that start with the letter K.

- In 10 seconds, count how many English words you can think of where K is the third letter.

- If a random word is taken from an English text, is it more likely that the word starts with a K, or that K is the third letter?

Based on Tversky and Kahneman (1973)

Availability bias / heuristic

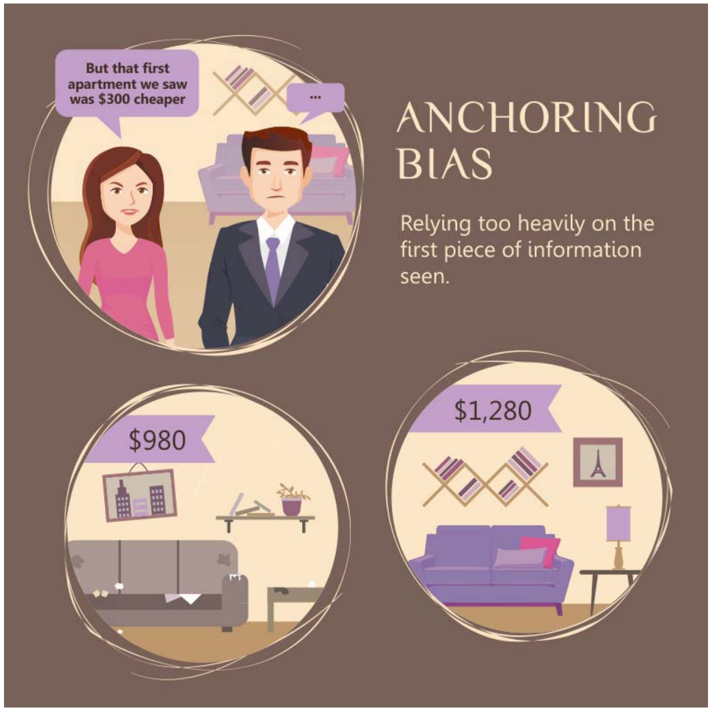
- Availability bias describes the tendency to overestimate the probability of the events with greater "availability" in memory, which can be influenced by the events that charged our emotions the most (salient or unusual events).
- Your judgements are influenced by what springs most easily to mind. Personal education, training, knowledge, specialization, previous experiences, preconceptions and preconceived notions dictate how easily (if at all) information comes to your mind.

https://imgur.com/gallery/AaX1b

- Exploration example:
  - Explorer is a seismic interpreter by background, so he spends more time thinking about the probability of structure (closure, geometry) to be present and to polarize risk for this factor (i.e., chose extreme probability values closer to 1.0 or 0.0). He thinks less about the risk of source rock presence and maturity because assigns "toss-up" probability (close to 0.5) to that risk factor even if the data required to polarize the probability does exist.

Class activity: Africa

Anchoring bias



- Remember Africa?
- Anchoring bias is the tendency of people to base estimates on any value they have at hand.
- Human minds are associative in nature, so the order in which we receive information helps determine the course of our judgements and perceptions.
- Exploration example:
  - Most explorers are aware that the current industry-average geological success rate of exploration drilling in the world is around 35%. Therefore, many of them think that the average prospect should have a total PoS of around 0.35 and push their estimation towards that value.

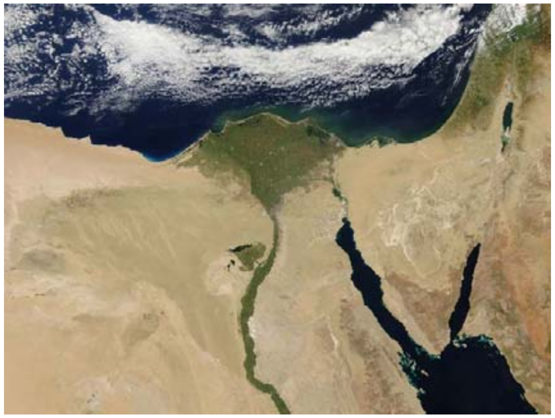
Fast and slow thinking

Fast (Type 1) thinking
Unconscious reasoning
Automatic
Instantaneous
Intuitive, Reflexive
Influenced by experiences, emotions and memories
Prominent in animals and humans

Illustration by David Plunkert, via The New York Times

Slow (Type 2) thinking
Conscious reasoning
Needs mental effort
Focused deliberation
Reflective
Influenced by facts, logic and evidence
Prominent in humans

Class activity: Length of rivers



- Is the length of the Nile River greater or less than 2000 km (~1250 miles)?
- What is your estimate of the length of the Nile River (in km?)

- Is the length of the Amazon River greater or less than 8000 km (~4970 miles)?
- What is your estimate of the length of the Amazon River (in km?)

1 km = 0.62 mile

Why petroleum explorers should care?

- Biases, logical fallacies and wrong heuristics lead to poor decisions, including those in petroleum exploration:
  - Prospect interpretations and models,
  - Assessment of risks (probability of success),
  - Assessment of success-case volumes,
  - Selection of prospects to be drilled.

Estimation of the PoS for the same segment by several exploration teams

Team	P of Reservoir	P of Seal	P of Charge	Total PoS
1	0.68	0.78	0.85	0.45
2	0.70	0.80	0.55	0.30
3	0.50	0.90	0.90	0.41
4	0.70	0.80	0.95	0.53
5	0.60	0.85	0.80	0.41
6	0.70	0.55	0.85	0.33
7	0.70	0.50	0.85	0.30

Milkov (2015)

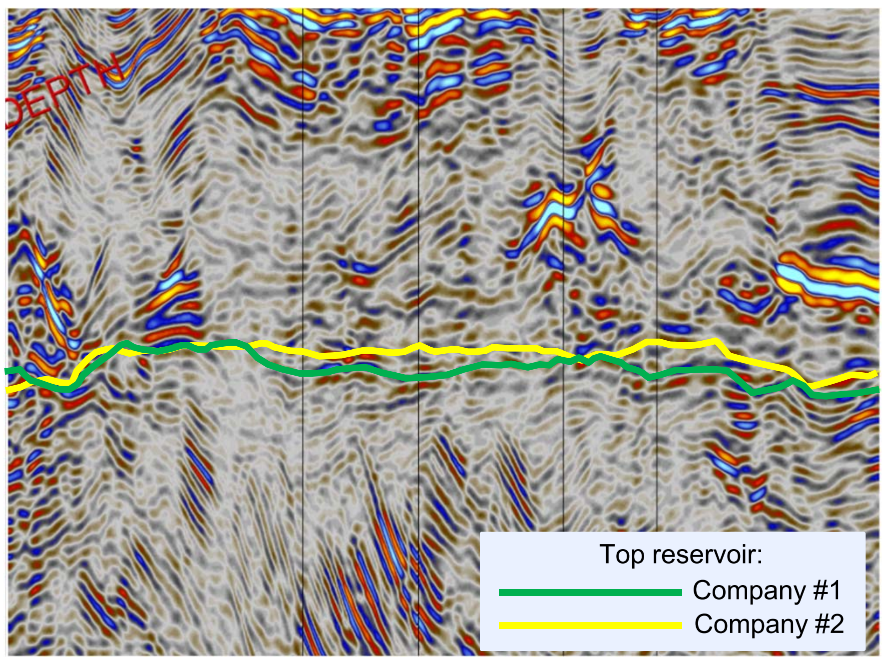
Inconsistent PoS assessments lead to biased exploration portfolio and poor long-term exploration performance

- Significant variations in probability of individual risk factors.
- The critical risk is the same only for 4 teams.
- Range of total PoS from 0.30 to 0.53.
- This inconsistency in geological PoS assessment is a well-known problem in industry (White, 1993 (Exxon), Watson, 1998 (BHP)).

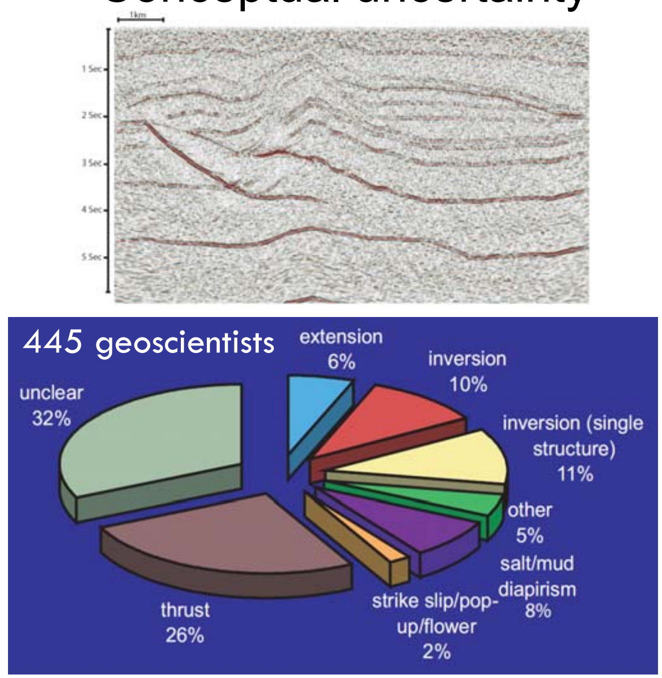
Why PoS values are so different?

- Geoscience is the science of subjectivity (Curtis, 2012).

Interpretational uncertainty

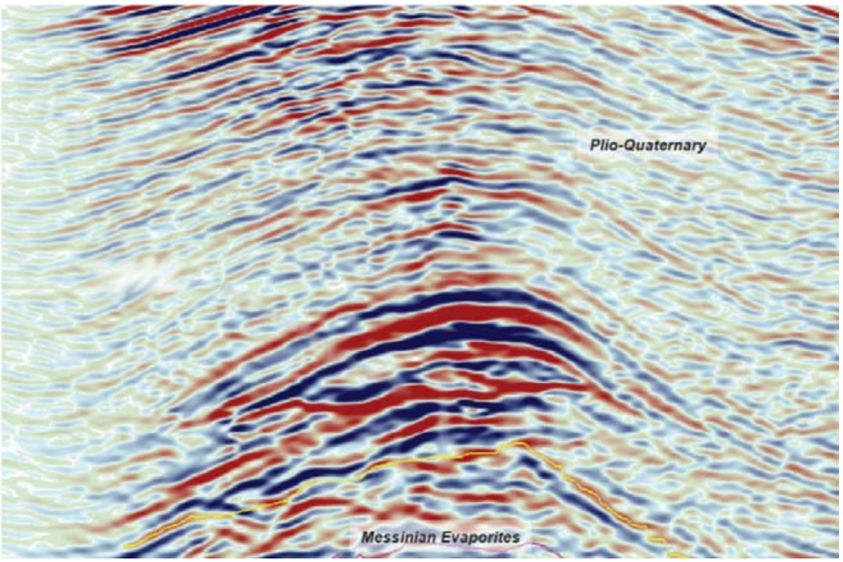


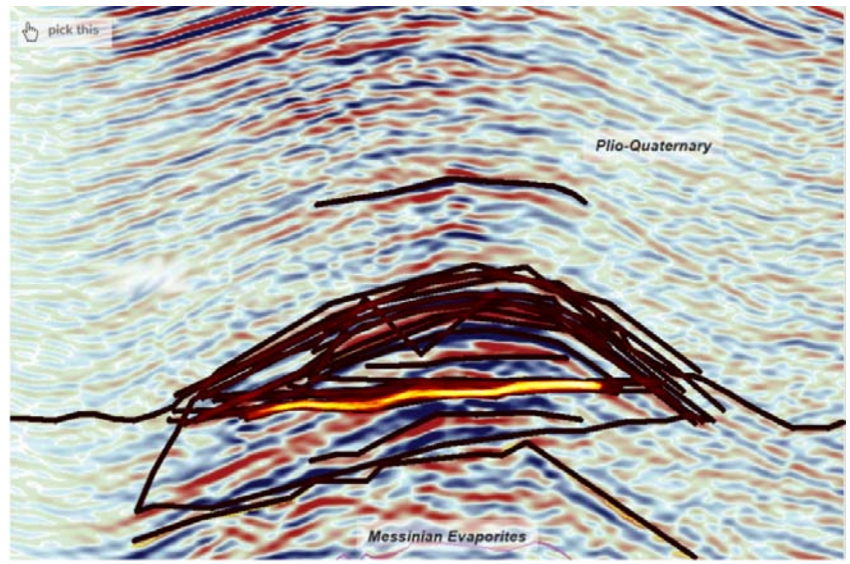
Conceptual uncertainty



Bond et al. (2007)

Interpretation uncertainty: can you pick hydrocarbon indications?





https://the-geophysicist.com/the-subjective-science-of-seismic-interpretation

https://pickthis.io/
Hall et al., 2015, SEG

- Seismic interpreters looking at the same image will interpret it in different ways. The image shows the interpretation of 39 different interpreters, generated into a heatmap.

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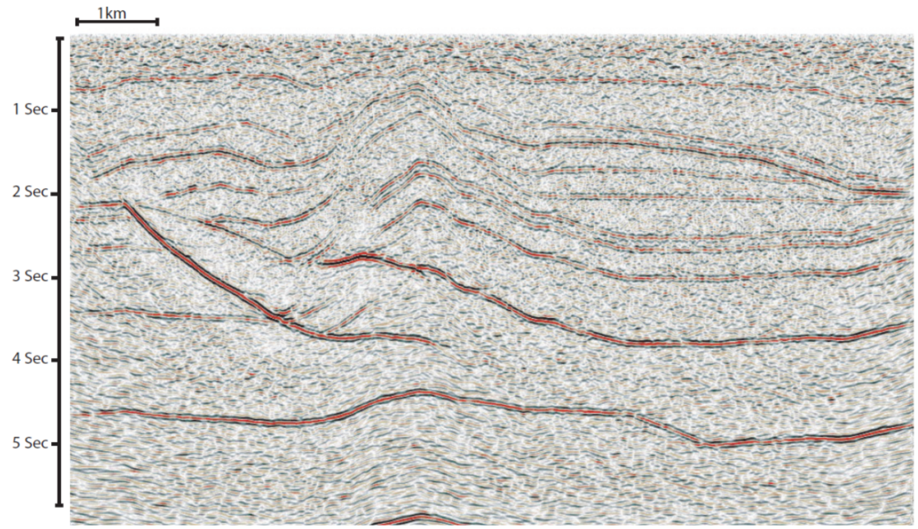
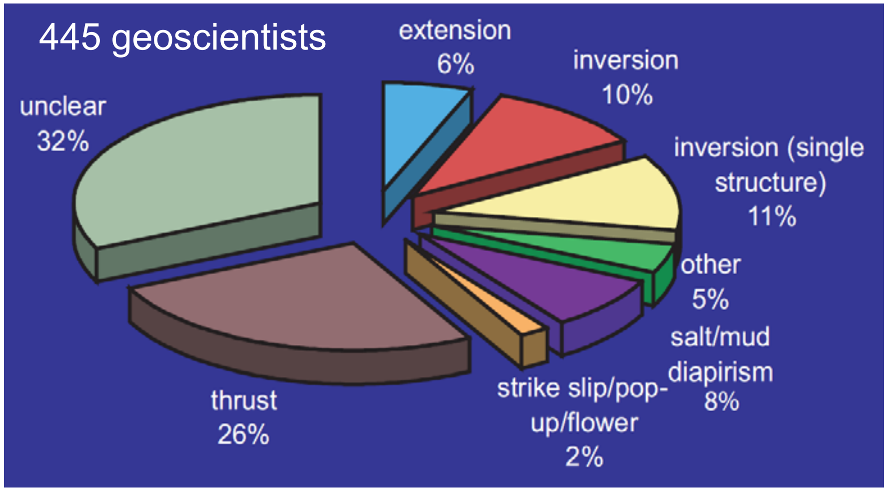
Conceptual uncertainty





- 445 geoscientists were asked to interpret a seismic line and determine the tectonic setting of the subsurface depicted on the line.
- The seismic line was a synthetic line created from the 2D geological forward model, so the “correct answer” (inversion) was known.
- Only 21% of all geoscientists correctly determined the tectonic setting (concept).

Bond et al., 2007

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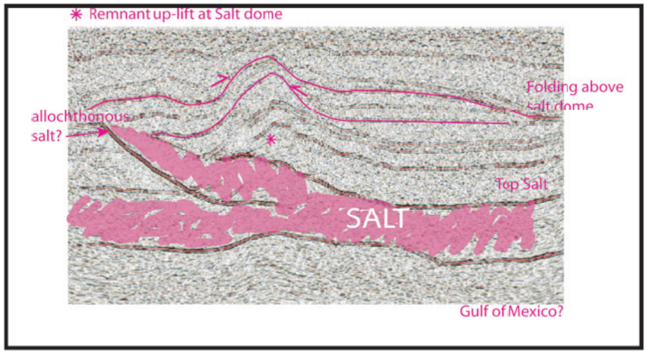
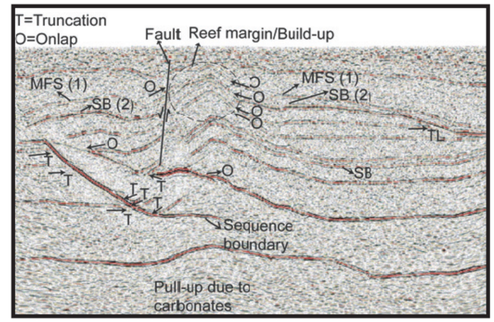
What bias is that?

- Examples of interpretation by people with different experience and expertise.

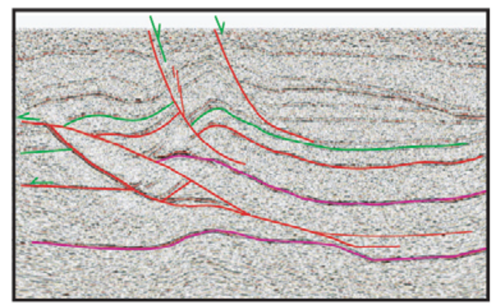


Student - PhD salt tectonics



Student - MSc sequence stratigraphy

+15 yrs - thrust expertise



+15 yrs - extensional expertise

Bond et al., 2007

How to reduce biases?

<u>Always</u>

- Be aware of biases in yourself and others. They are natural, normal and persistent.
- Use heuristics with caution.
- Engage in reflective (slow thinking) decision process.

<u>When interpreting, modeling and forecasting</u>

- Do not ignore data that contradict your assumptions. Proactively look for them and use them.
- Justify and document your assumptions.
- Focus on more uncertain elements.
- Consider alternatives.
- Estimate in ranges, not in single numbers.
- Solicit input and views from others. Listen.

<u>After your interpretations, models and forecasts were tested</u>

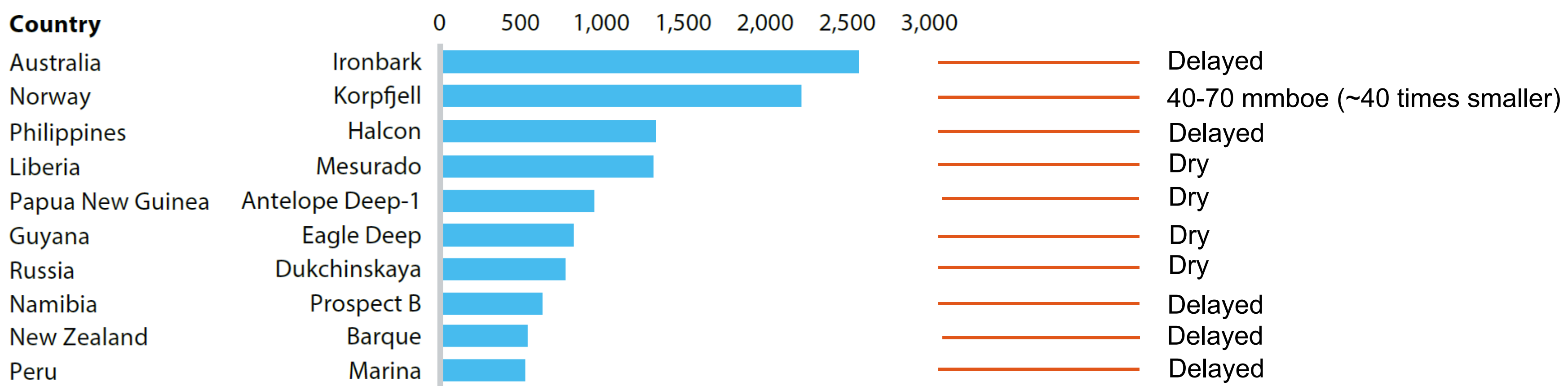
- Do not hide. Compare pre-drill predictions with the outcomes.
- Recognize biases that contributed to wrong interpretations.
- Use performance tracking to calibrate assessments and decisions.

Modified from Rose & Associates

Exploration plans *vs* reality

High-impact wells planned for 2017

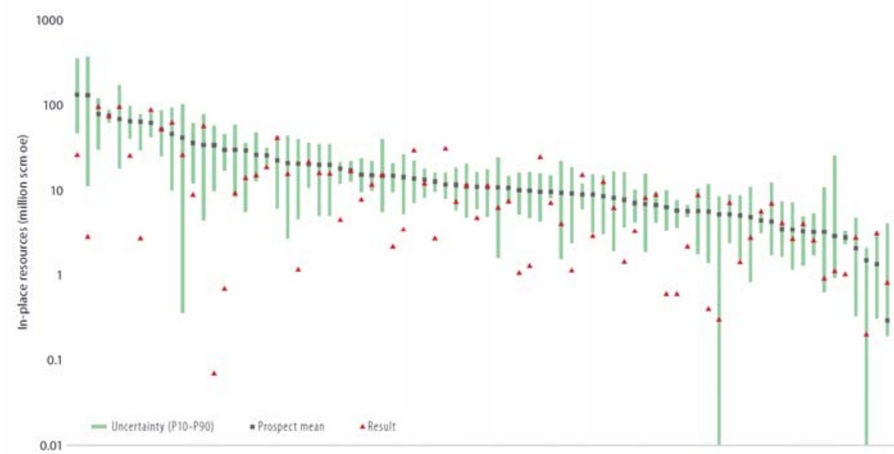
Outcome as of mid-2018

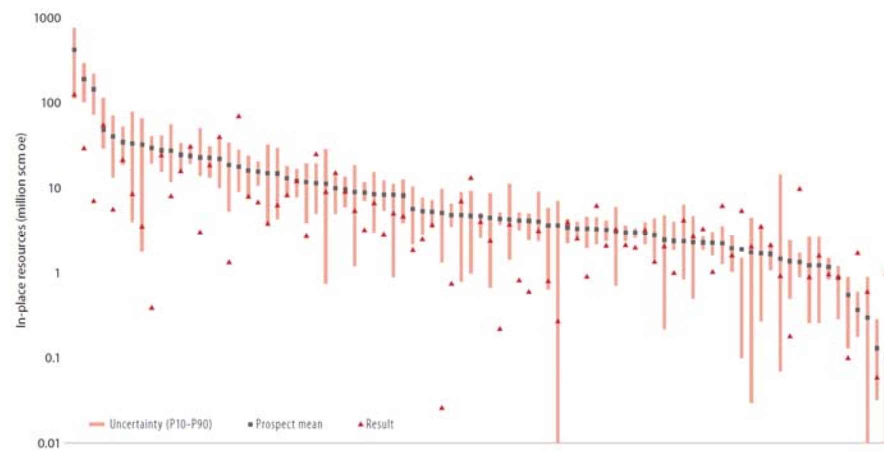


Upcoming high impact exploration wells with predrilled resource estimates, with figures in MMboe based on the latest reporting from operators.

GeoExPro (December 2016) based on Rystad Energy ECube

Do we predict volumes well?
Data from exploration on the NCS in 2007-2016



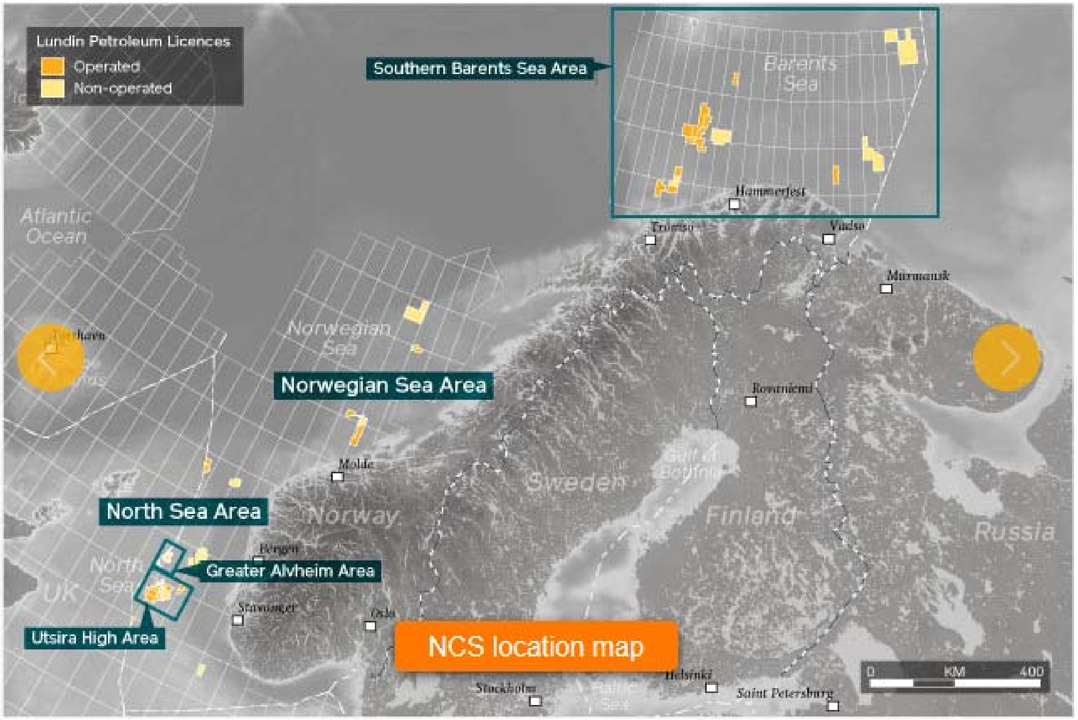


- About 58% of oil discoveries fell within the uncertainty range in the prognosed estimate.
- About 6% were above and 36% below this range.
- The companies overestimated resource expectations by an average factor of 1.4.

- About 47% of gas discoveries were within, 16% above and 37% below the uncertainty range in the prognosed estimate.
- The companies overestimated resource expectations by an average factor of 2.1

NPD (2018) Resource Report Exploration 2018

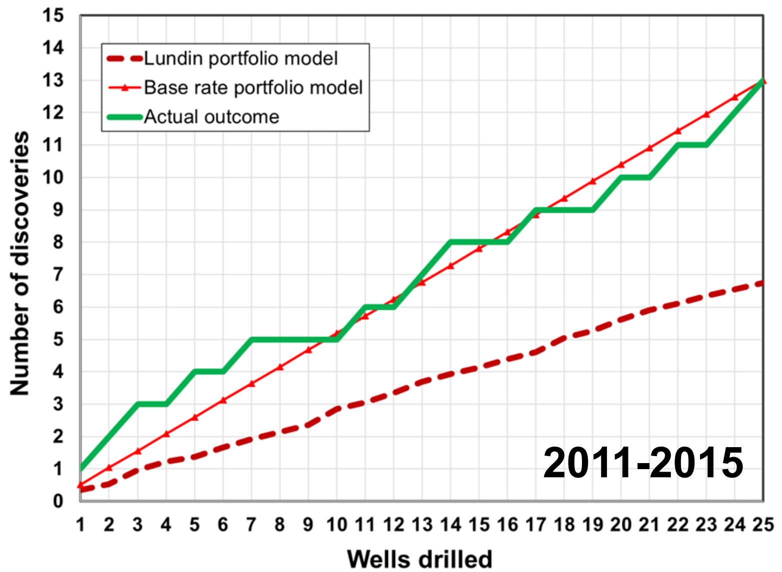
Case Study: Lundin on the Norwegian Continental Shelf (NCS) in 2011-2015



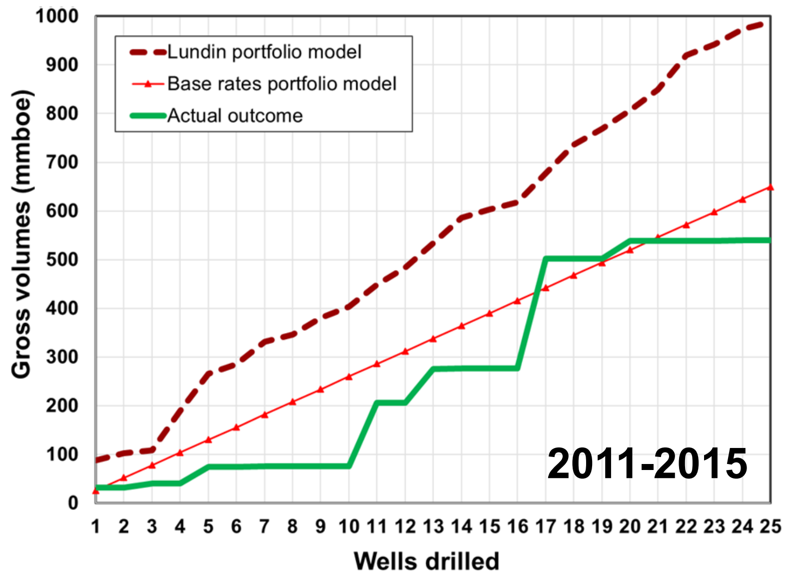
Source: www.lundin-petroleum.com

- Lundin Petroleum has 64 licenses on the NCS.
- Published pre-drill prospect information, including geological PoS and success-case volumes.
- Norwegian Petroleum Directorate (NPD) provides data on exploration wells and discoveries on the NCS.

Base rates and base rate neglect fallacy



Relevant base rate: 0.52 (5-year average industry success rate on the NCS in 2010).



Relevant base rate: 50 mmboe (average field size discovered in 2006-2010 was 54 mmboe. The area is “creamed”).

Milkov (2017)

This is a global industry-wide problem

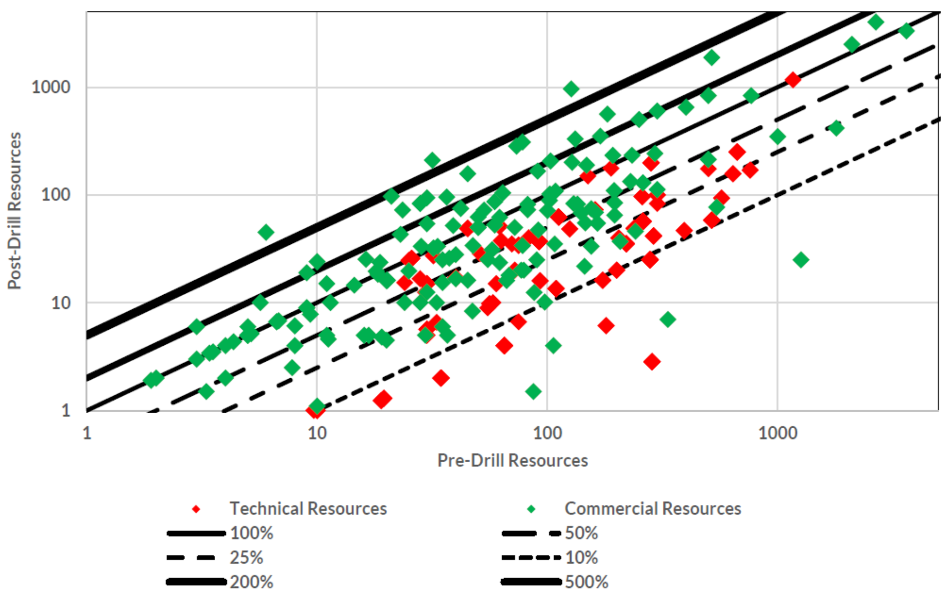


Figure 12: Cross plot of pre-drill expected vs post-drill estimated discovered volumes for discoveries smaller than 5000mmboe (Log-Log Scale)

- Westwood's Wildcat database includes 220 technical or commercial discoveries made since 2008 where both pre- and post drill resource estimates are available.
  - 78% of discoveries have found less than the pre-drill P50 estimate.
  - 28% have been lower than the pre-drill P90 (assuming that reported pre-drill volumes represent the P50 case).
  - 45% of frontier discoveries have found less than the pre-drill P90 estimate.

Bagley and Bond (2018)

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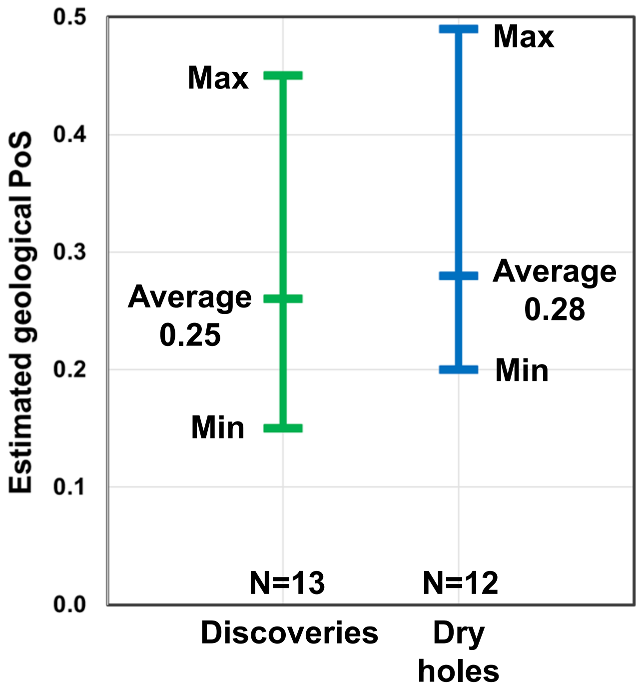
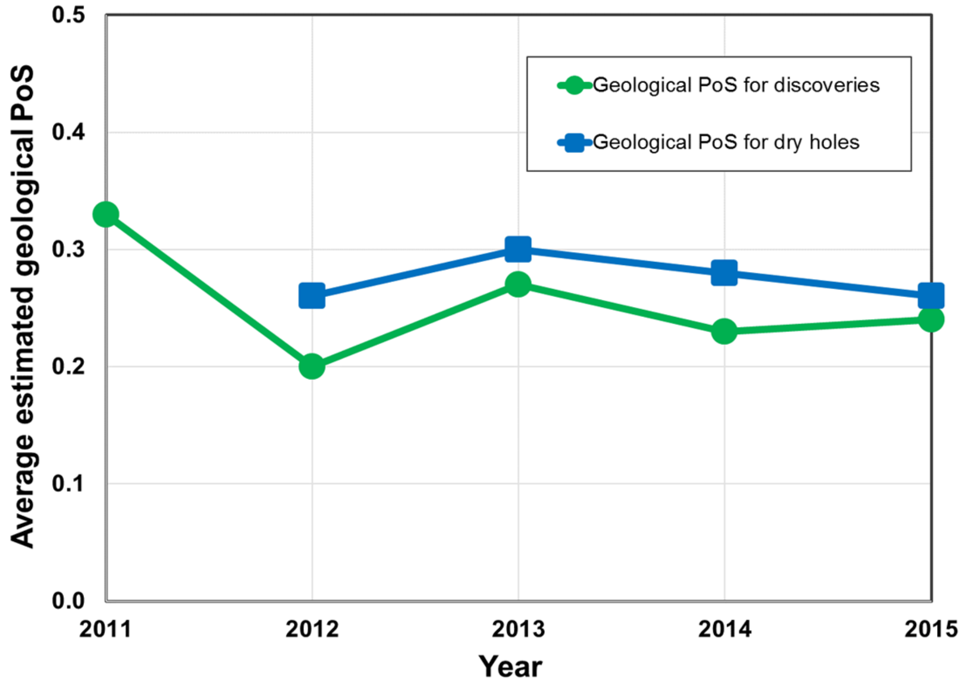
Future discoveries and dry holes have similar geological PoS values





Milkov (2017)

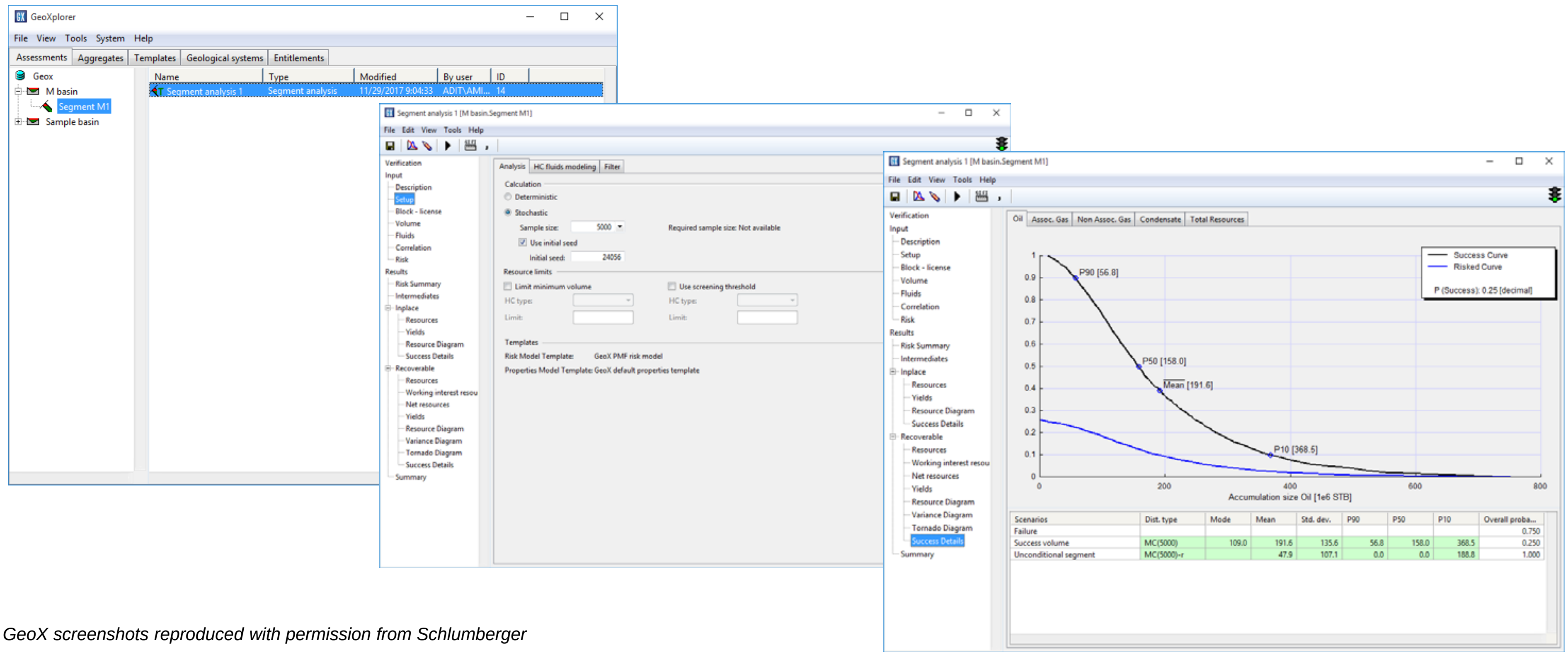
Source of data: Lundin Petroleum

Lookup table for probability of structure (STR)

Structure (closure, geometry, container)				Data (existence and reliability)			
				3D seismic	2D seismic Number of lines per structure (with obligatory availability of in-line and cross lines)		
					Dense (7 lines and more)	Sparse (3-6 lines)	Very sparse (2 lines) (Lead)
Models (existence and reliability)	Seismic mapping and correlation	High-relief structure (≥3 times higher than seismic accuracy) AND low structural complexity (4-way)	Easy to interpret, reliable correlation based on nearby (<50 km) wells	1.00	0.90	0.80	0.60
			Uncertain correlation (horizons are interrupted laterally) or based on remote (> 50 km) wells	0.95	0.85	0.75	0.55
			Difficult to interpret, unreliable correlation (horizons are interrupted by thrust faults, diapirs, etc.) or model developed using analogues without wells in the basin	0.85	0.75	0.70	0.45
		Medium-relief structure (1-3 times higher than seismic accuracy) OR high-relief structure with high structural complexity (3-way, stratigraphic)	Easy to interpret, reliable correlation based on nearby (<50 km) wells	0.80	0.70	0.60	0.35
			Uncertain correlation (horizons are interrupted laterally) or based on remote (> 50 km) wells	0.75	0.65	0.50	0.25
			Difficult to interpret, unreliable correlation (horizons are interrupted by thrust faults, diapirs, etc.) or model developed using analogues without wells in the basin	0.70	0.55	0.45	0.20
		Low-relief structure (lower than seismic accuracy) OR high uncertainty of depth conversion (subsalt, below lava flows) OR areas with rapidly changing lateral velocities in the overburden	Easy to interpret, reliable correlation based on nearby (<50 km) wells	0.55	0.45	0.35	0.15
			Uncertain correlation (horizons are interrupted laterally) or based on remote (> 50 km) wells	0.50	0.40	0.25	0.10
			Difficult to interpret, unreliable correlation (horizons are interrupted by thrust faults, diapirs, etc.) or model developed using analogues without wells in the basin	0.40	0.30	0.20	0.05
		Low-relief structure (lower than seismic accuracy) AND EITHER high uncertainty of depth conversion (subsalt, below lava flows) OR areas with rapidly changing lateral velocities in the overburden		0.35	0.25	0.15	0.05

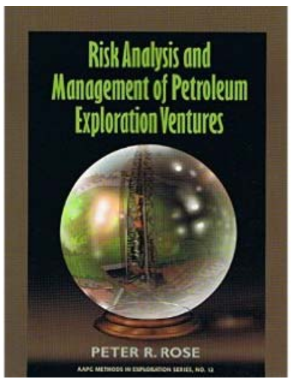
Milkov (2015)

GeoX demonstration: segment analysis

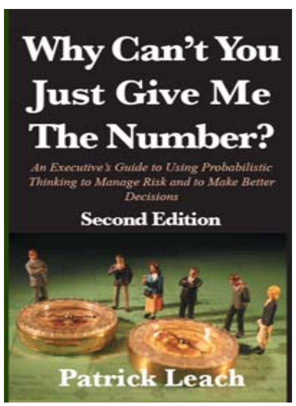


GeoX screenshots reproduced with permission from Schlumberger

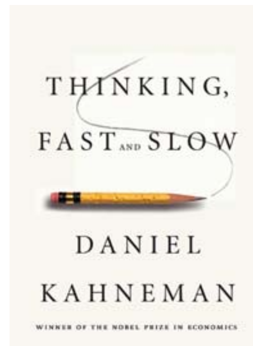
Highly recommended reading on petroleum exploration and decision-making



Risk Analysis and Management of Petroleum Exploration Ventures (2001)
Peter R. Rose
AAPG Methods in Exploration, No. 12



Why Can't You Just Give Me The Number? (2014)
Patrick Leach
240 pages
http://www.decisions-books.com/Number.html



Thinking, Fast and Slow (2011)
Daniel Kahneman
512 pages

Making Good Decisions (2010)
Reidar B. Bratvold and Steve Begg
207 pages
Society of Petroleum Engineers

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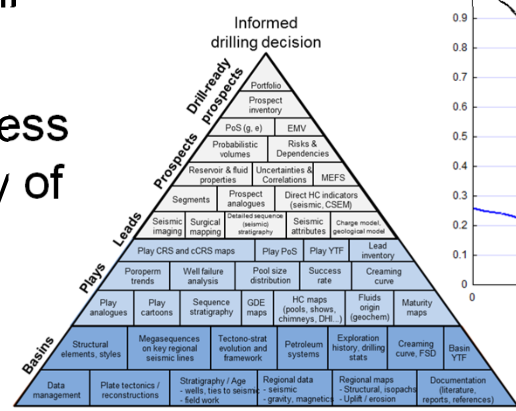
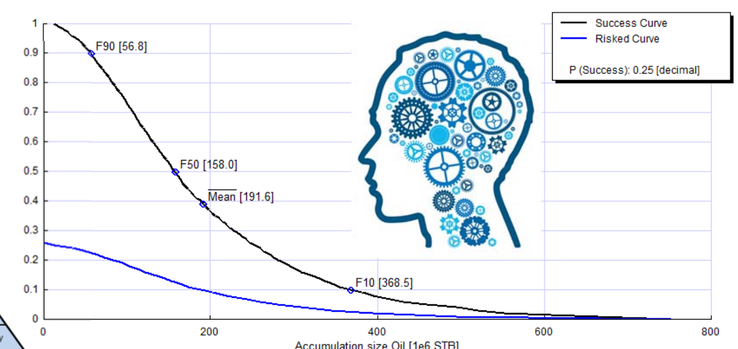
Did we achieve our learning objectives?

By the end of the lecture you should be able to describe:

- The trends of petroleum exploration since 1900 and its current state.
- Exploration process to find oil and gas.
- How explorers forecast success case volumes and probability of success.





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