Empirical Analysis of the Stratigraphic Control on Production in Clastic Reservoirs of the Norwegian Continental Shelf*

Kachalla Aliyuda[1], John Howell[1], and Adrian Hartley[1]

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[1]Department of Geology and Petroleum Geology, University of Aberdeen, Aberdeen, UK (k.aliyuda@abdn.ac.uk)

Abstract

Inherent reservoirs properties are dependent on reservoir genesis or depositional processes, these properties are modified overtime, hence limited understanding of the geology of a hydrocarbon reservoir is a great deficit in recovery efficiency, adequate knowledge of reservoir architecture is key in placement of injector wells, pressure maintenance and secondary recovery and in turn contribute to reserve growths. The main objection of this study is to determine the impact of depositional environment and the primary facies architecture on reservoir performance. All the major reservoir intervals in the key fields on the Norwegian continental shelf have been classified within the SAFARI data standard. SAFARI uses a systematic hierarchical schema to describe depositional environments, basin types, paleoclimate architectural elements. Parameters such as recovery factor, maximum oil well rate, depletion rate and other 40 variables were recorded, and a unique database was built of all the reservoirs classified into nine depositional sub-environments. All these parameters were analysed using multivariate statistics to find out the relative importance of these parameters Stratigraphically dependent variables porosity, permeability, depth was found to control performance of the reservoir, parameters such as reservoir volume, well density, net to gross, temperature and trap type/geometry contribute less to reservoir recovery. Reservoir performance varies for the three gross depositional environments, deep marine has better performance followed by paralic/shallow marine then continental. Similarly, performance varies across the nine depositional sub-environments, detailed evaluation of architectural elements of the reservoirs showed intra reservoir sedimentological heterogeneities exists in reservoirs with low recovery. Maximum well rate however is better continental reservoirs compared to deep marine and paralic/shallow marine which is inconsistent with recovery making it very difficult for huge discovered oil to be extracted.

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Larue, D.K., and Y. Yue, 2003, How stratigraphy influences oil recovery: a comparative reservoir database concentrating on deep-water reservoirs: The Leading Edge, April, p. 332–339.

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Tyler, N., and R.J. Finlay, 1991, Architectural controls on the recovery of hydrocarbons from sandstone reservoirs: in A.D. Miall and N. Tyler (eds), The Three-Dimensional Facies Architectures of Terrigenous Clastic Sediments and its Implications for Hydrocarbon Discovery and Recovery, SEPM Concepts in Sedimentology and Palaeontology, No. 3, p. 1–5.

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PETROLEUM TECHNOLOGY DEVELOPMENT FUND PTDF

Presentation Outline

- Introduction
- Study Location
- Data and Methods
- Results/discussion
- Conclusion

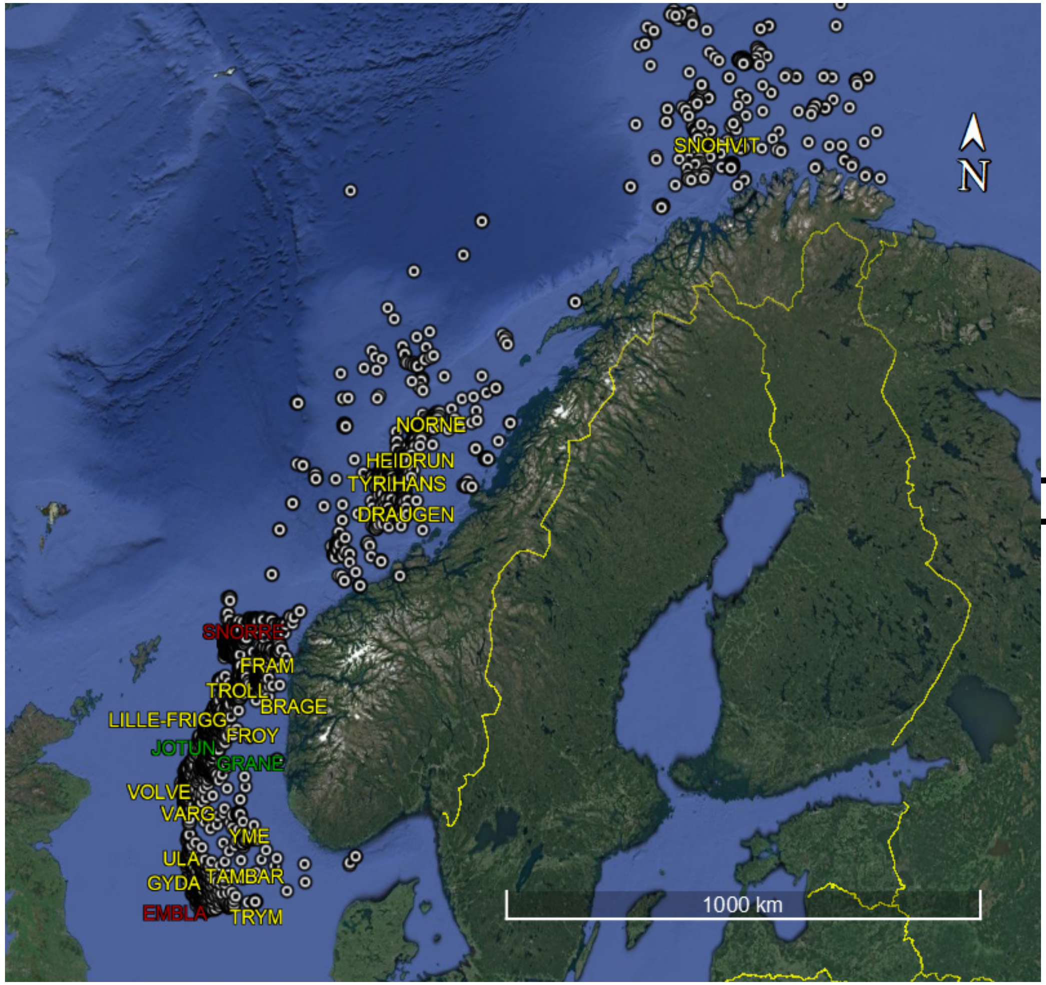
What controls production ?

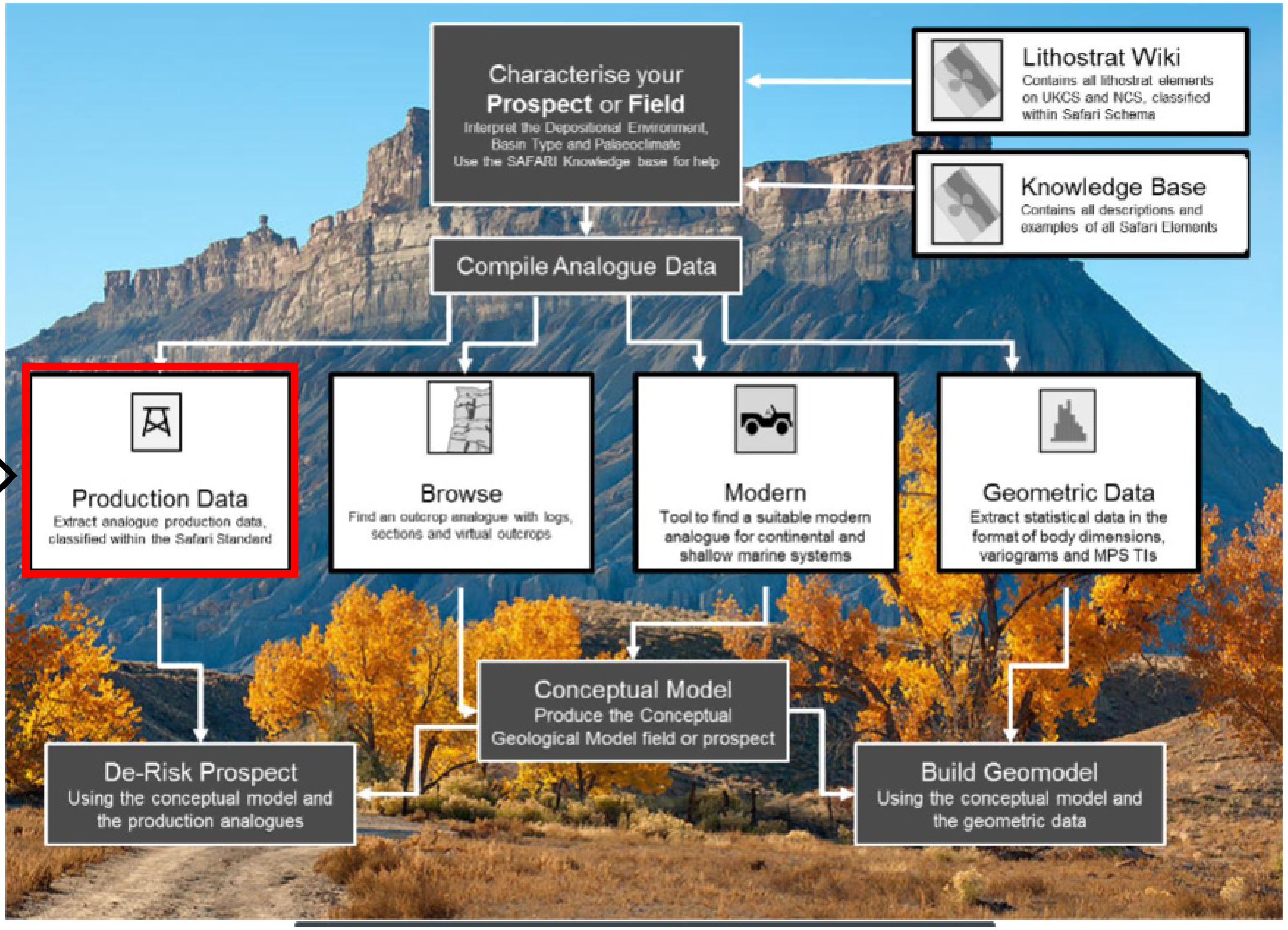
Diagenesis
Well spacing
Fluids density
Viscosity
Porosity
Permeability
Reservoir depth
Depositional environment
Temperature
Pressure
Structural complexity
Faults density
well spacing
Pay area
Reservoir thickness
net to gross
Production mechanism
water saturation

Previous Studies

- Tyler and Finley (1991) on the study of oil fields in Texas concludes that drive mechanism and depositional environment are related to recovery efficiency.
- Larue and Yue (2003) analysed different dataset of deep water environments reservoirs and conclude that average permeability and API gravity obviously influences recovery.
- Skorstad et al (2008) studied the production behavior of a synthetically generated models of depositional environments, and analyze the effects of structural, stratigraphic and well controls on production, they conclude that sedimentological and fault-related parameters are important for describing uncertainty in recovery factor.
- None considered the reservoir depth, depth affects a lot of reservoir properties.

Introduction





Aim and Objectives

- The goal of this project is to examine the stratigraphic controls on reservoir performance. It is also expected to achieve the following;

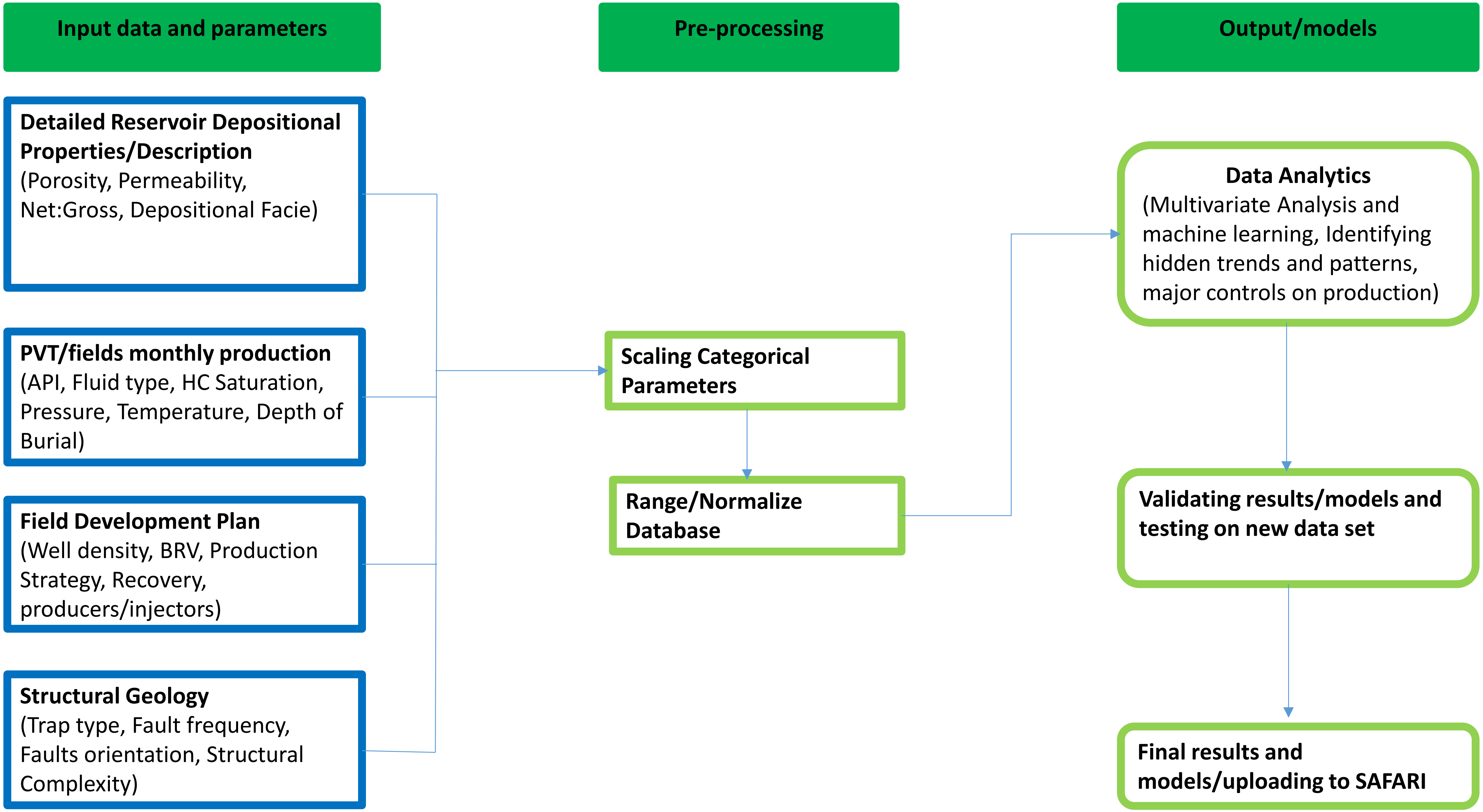
- Classify all fields in the Norwegian continental shelf using the SAFARI Schema

- Investigate and compare production respond of the various GDE in the NCS

- Relative importance of primary depositional facies on production

- Other major controls on fields’ performance apart from sedimentary environment.

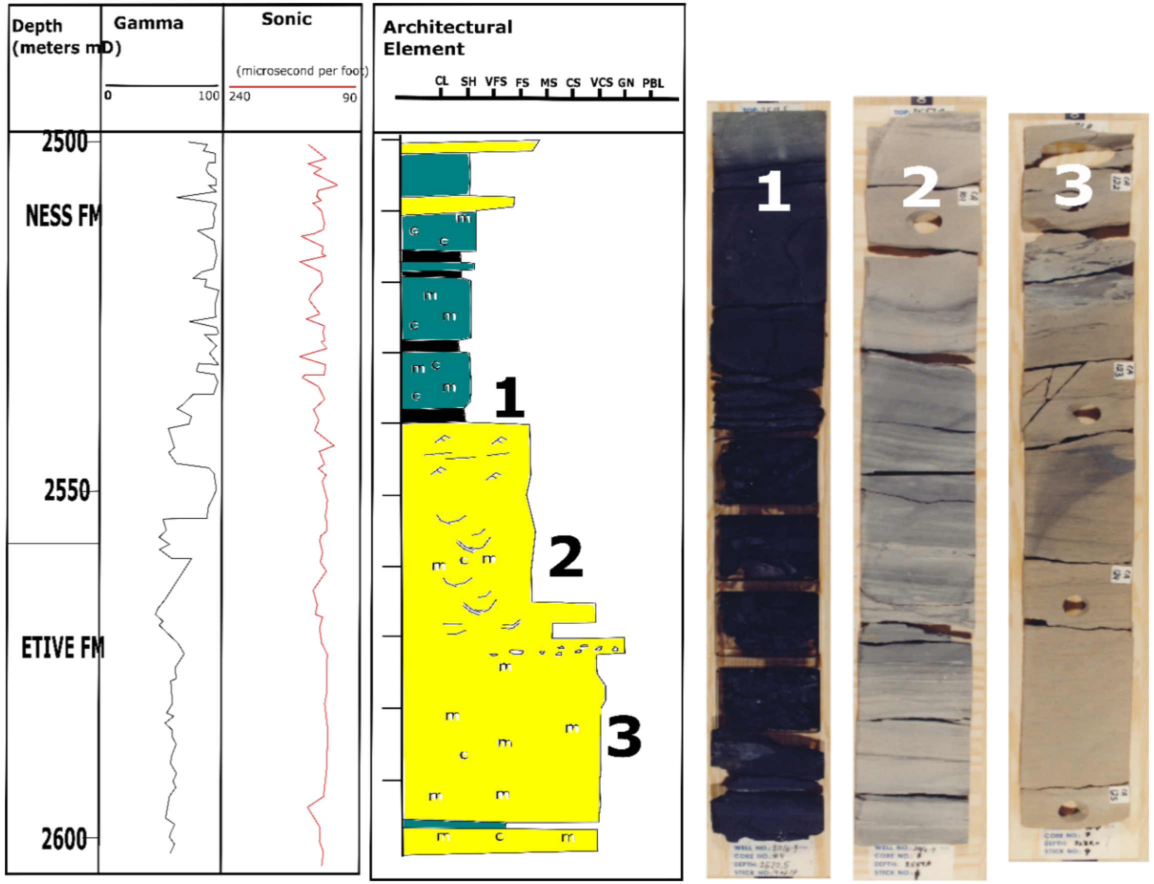
Workflow


Input data and parameters
Pre-processing
Output/models
Detailed Reservoir Depositional Properties/Description (Porosity, Permeability, Net:Gross, Depositional Facie)
PVT/fields monthly production (API, Fluid type, HC Saturation, Pressure, Temperature, Depth of Burial)
Field Development Plan (Well density, BRV, Production Strategy, Recovery, producers/injectors)
Structural Geology (Trap type, Fault frequency, Faults orientation, Structural Complexity)
Scaling Categorical Parameters
Range/Normalize Database
Data Analytics (Multivariate Analysis and machine learning, Identifying hidden trends and patterns, major controls on production)
Validating results/models and testing on new data set
Final results and models/uploading to SAFARI

Reservoir classification

- Analysis of wireline data from 225 wells
- core described at 1:100 scale
- Quantify stratigraphic heterogeneity using sedimentological logs on a scale of 0-8
- All from publicly available data (Norwegian Petroleum Directorate)

Delta front mouth bar deposit: Oseberg field



SAFARI Classification Schema

Gross Depositional Environment	Climate Filter	Depositional Environment
Continental	equatorial	Lake
		Alluvial
	arid	Erg
		Lake
		Alluvial
	warm temperate	Lake
		Alluvial
	snow/polar	Erg
		Lake
		Alluvial
Paralic and Shallow marine		F: Fluvio-deltaic
		Ft: Tide-influenced delta
		Fw: Wave-influenced delta
		W: Shoreface
		Wt: Tide-influenced shoreface
		Wf: Wave-dominated delta
		T: Tidal shoreline - non-deltaic
		Tw: Wave-influenced tidal shoreline
		Tf: Tide-dominated delta
		W: Barrier island
		Wf: Wave-dominated estuary
		Wt: Tide-influenced barrier island
		Tf: Tide-dominated estuary
		Shelf
Deep marine		Slope
		Basin Floor

Subenvironments
Lacustrine delta
Dune complex
Alluvial plain
Sandsheet
Delta top
Delta front
Backshore
Foreshore
Lagoon
Barrier
Epicontinental shelf
Slope-non turbidite

The schema includes about 105 sub-environments and 130 architectural elements in addition to the three gross depositional environments.

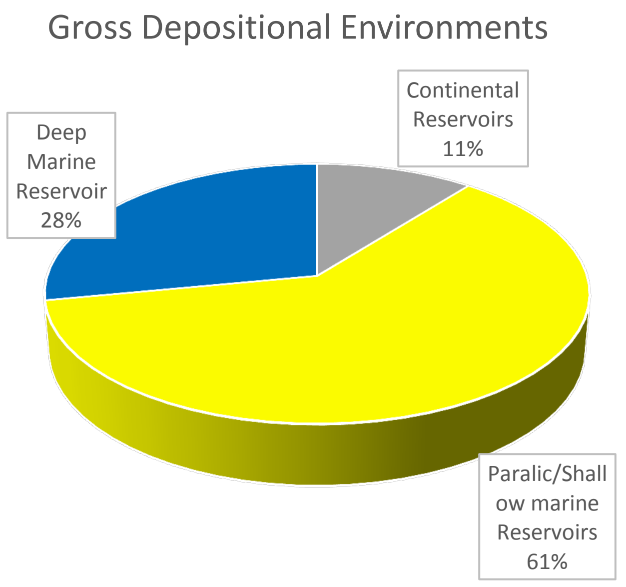
Database/Methods

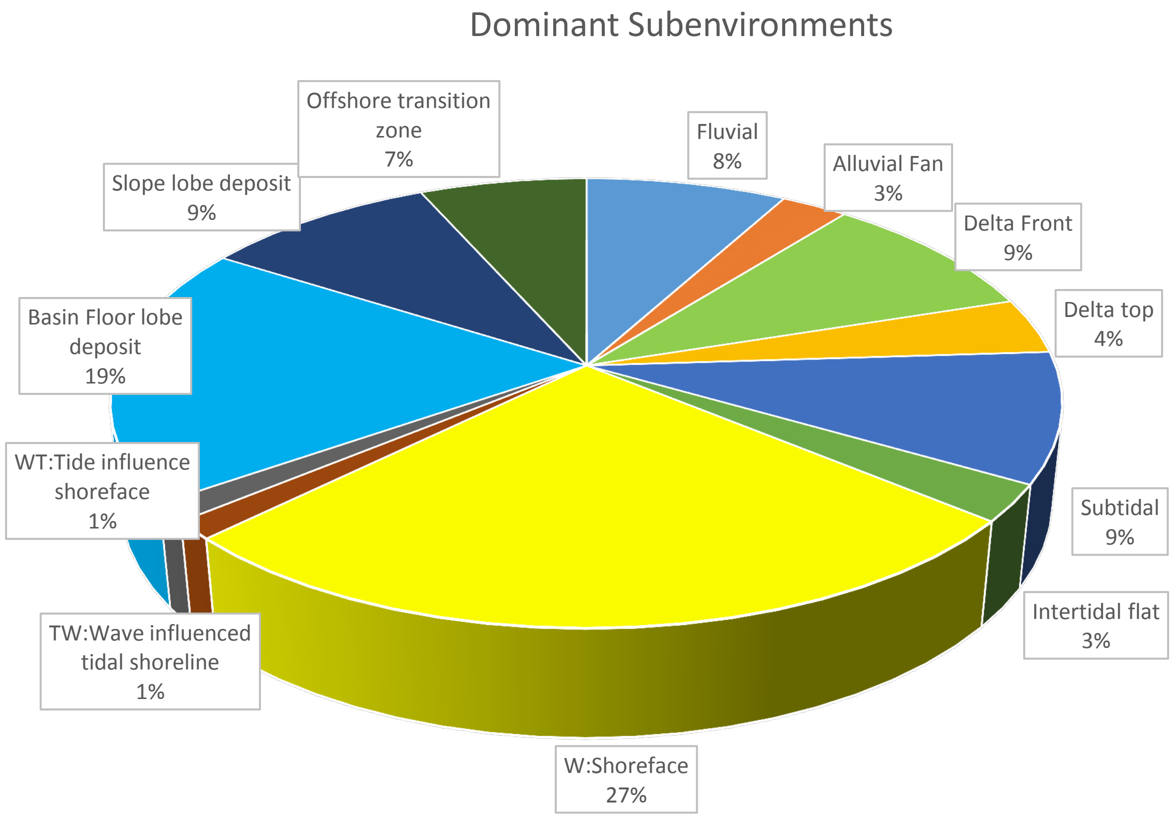
ALVE	
Reservoir 1	
Lithostratigraphy	
Main Reservoir	Jurassic Fanst Group
Group	Fanst
Formation(s)	Garn, Not and Ile
Gross Depositional Environment	Paralic/Shallow Marine
Depositional Environment	T:Tidal shoreline non-deltaic
Subenvironment	Subtidal
Depth (m)	3, 608
Paleoclimate	Warm Humid
Reservoir Properties	
Net:gross	0.9
Porosity (%)	14.2
Permeability (mD)	16
Water saturation (%)	16.6
Reservoir 2	
Lithostratigraphy	
Secondary Reservoir	Jurassic Bat Group
Group	Bat
Formation(s)	Ror, Tofte and Tilje Formation
Gross Depositional Environment	Paralic/Shallow Marine
Depositional Environment	T:Tidal shoreline non-deltaic
Subenvironment	Intertidal flat
Depth (m)	3, 723
Paleoclimate	Warm Humid

Database

Reservoir Properties	
Net:gross	0.46
Porosity (%)	21.2
Permeability (mD)	5.3
Fluid saturation (%)	53
Structural Geology	
Trap type	Structural
Structural Complexity	Low
Faults Frequency	
Faults Orientation	
Number of Faults Population	
Fluids, PVT and Volumes	
Main Fluid	Gas
Other Fluids	Oil, Condensates
API (0)	48
Temperature (0C)	135.9
Pressure (bar)	472
Aquifer size (km2)	12.7
Reservoir Thickness (m)	44
Field area (km2)	12.7
Bulk Rock Volume (m^3)	5.588×10^8
OIP (Mill Sm3)	3
GIP (Bill Sm3)	13.5
Produced Oil (Mill Sm3)	1.698
Produced Gas (Bill Sm3)	5.754
Field Development	
Number of Wells	7
Development Strategy	via subsea template
Production Strategy	Pressure Depletion
Producers	3
Injectors	0

Reservoirs in the database





Gross Depositional Environments	Depositional Environments	Subenvironments	Field name (Reservoirs)	Formation	Paleoclimate	NPD Play	Location
			EMBLA	Devonian Sand	Arid	npl-2	Norwegian North Sea
			GULLFAKS SOR 2	Statfjord FM	Humid	nru,jm-1	Norwegian North Sea
			GAUPE	Skagerrak FM	Arid/Semi Arid	njl,jm-1	Norwegian North Sea
			GUNGNE	Skagerrak FM	Arid/Semi Arid	njl,jm-1	Norwegian North Sea
			SIGYN	Skagerrak FM	Arid/Semi Arid	njl,jm-1	Norwegian North Sea
	Alluvial	Fluvial	GULLFAKS 2	Statfjord FM	Humid	nru,jm-1	Norwegian North Sea
			SNORE 1	Lunde FM	Arid/Semi Arid	nru,jm-1	Norwegian North Sea
Continental	Alluvial	Alluvial Fan	SNORE 2	Statfjord FM	Arid/Semi Arid	nru,jm-1	Norwegian North Sea
Paralic/Shallow Marine		Delta Front	HULDRA 1	Etive FM	Humid	nru,jm-1	Norwegian North Sea
		Delta Front	HULDRA 2	Ness FM	Humid	nru,jm-1	Norwegian North Sea
		Delta top	TUNE 2	Tarbert FM	Warm Humid	nju-1	Norwegian North Sea
		Delta top	TUNE 1	Ness FM	Warm Humid	nju-1	Norwegian North Sea
		Delta Front	VOLVE	Hugin FM	Warm Humid	njl,jm-1	Norwegian North Sea
		Delta Front	MIKKEL	Fanst GP	Warm Humid	nhjl,jm-2	Norwegian Sea
		Delta Front	OSEBERG 1	Oseberg FM	Warm Humid	nju-1	Norwegian North Sea
	F:Fluvio-deltaic	Delta top	OSEBERG 2	Tarbert/Ness FM	Warm Humid	nju-1	Norwegian North Sea
		Delta Front	TRYM 2	Sandnes FM	Warm Humid	njl,jm-4	Norwegian North Sea
	Fluvial delta	Delta Front	TRYM 1	Bryne FM	Warm Humid	njl,jm-4	Norwegian North Sea
			KRISTIN 2	Ile FM	Warm Humid	nhjl,jm-2	Norwegian Sea
			KRISTIN 1	Garn FM	Warm Humid	nhjl,jm-2	Norwegian Sea
		Subtidal	ALVE 2	Fanst GP	Warm Humid	nhjl,jm-2	Norwegian Sea
		Intertidal flat	ALVE 1	Bat GP	Warm Humid	nhjl,jm-2	Norwegian Sea
		Intertidal flat	NORNE 2	Tofte/Tilje FM	Warm Humid	nhjl,jm-2	Norwegian Sea
			NORNE 1	FanstGP (Garn/Ile FM)	Warm Humid	nhjl,jm-2	Norwegian Sea
			HEIDRUN 2	Bat GP (Tilje/Are FM)	Warm Humid	nhjl,jm-2	Norwegian Sea
			SNOHVIT	Sto/Normela	Warm Humid	bjl,mj-5	Barents Sea
	T:Tidal shoreline Non deltaic	Subtidal	HEIDRUN 1	Fanst GP	Warm Humid	nhjl,jm-2	Norwegian Sea
	TW: Wave influenced tidal shoreline	Shoreface	FROY	Sleipner FM	Warm Humid	njl,jm-1	Norwegian North Sea
			TAMBAR	Ula FM	Warm Humid	nju-3	Norwegian North Sea
			GYDA	Ula FM	Warm Humid	nju-3	Norwegian North Sea
			VALE	Tarbert FM	Warm Humid	njl,jm-1	Norwegian North Sea
			TYRIHANS	Garn FM	Warm Humid	nhjl,jm-2	Norwegian Sea
			LILLE FRIGG	Hugin FM	Warm Humid	njl,jm-1	Norwegian North Sea
			ULA	Ula FM	Warm Humid	nju-3	Norwegian North Sea
			GULLFAKS SOR 1	Brent GP	Warm Humid	nru,jm-1	Norwegian North Sea
			VARG	Hugin FM	Warm Humid	njl,jm-1	Norwegian North Sea
			FRAM 3	Rannoch FM	Warm Humid	nju-1	Norwegian North Sea
			OSEBERG SOR 2	Ness FM	Warm Humid	nju-1	Norwegian North Sea
			OSEBERG SOR 1	Tarbert FM	Warm Humid	nju-1	Norwegian North Sea
			STATFJORD OST	Etive/Rannoch FM	Warm Humid	nru,jm-1	Norwegian North Sea
			SKIRNE	Tarbert FM	Warm Humid	nru,jm-1	Norwegian North Sea
			FRAM 2	Fensfjord FM	Warm Humid	nju-1	Norwegian North Sea
			BRAGE 2	Fensfjord FM	Warm Humid	nju-1	Norwegian North Sea
			BRAGE 1	Sognefjord FM	Warm Humid	nju-1	Norwegian North Sea
			FRAM 1	Sognefjord FM	Warm Humid	nju-1	Norwegian North Sea
			GULLFAKS 1	Brent GP	Warm Humid	nru,jm-1	Norwegian North Sea
			DRAUGEN	Brent GP	Warm Humid	nhju-2	Norwegian Sea
		Shoreface	TROLL	Sognefjord/Fensfjord	Warm Humid	nju-1	Norwegian North Sea
			MIME	Ula FM	Warm Humid	nju-3	Norwegian North Sea
			BRYNHILD	Ula FM	Warm Humid	nju-3	Norwegian North Sea
			YME	Sandnes FM	Warm Humid	njm-1	Norwegian North Sea
			GJOA 2	Fensfjord FM	Warm Humid	nju-1	Norwegian North Sea
	W:shoreface	Offshore transition zon	GJOA 1	Sognefjord FM	Warm Humid	nju-1	Norwegian North Sea
	WT:Tide influence shoreface	Shoreface	SLEIPNER VEST	Hugin FM	Warm Humid	njl,jm-1	Norwegian North Sea
			MARULK 2	Lysing FM	Deep marine	nhkl-2	Norwegian Sea
			MARULK 1	Lange FM	Deep marine	nhkl-2	Norwegian Sea
			STATFJORD NORD	Draupne FM	Deep marine	nju-2	Norwegian North Sea
			SLEIPNER OST	Heimdal FM	Deep marine	npc-1	Norwegian North Sea
			GLITNE	Heimdal FM	Deep marine	npc-1	Norwegian North Sea
			ALVHEIM	Heimdal FM	Deep marine	npc-1	Norwegian North Sea
			HEIMDAL	Heimdal FM	Deep marine	npc-1	Norwegian North Sea
			NORDOST FRIGG	Frigg FM	Deep marine	neo/frigg-1	Norwegian North Sea
			OST FRIGG	Frigg FM	Deep marine	neo/frigg-1	Norwegian North Sea
			SVALIN	Heimdal FM	Deep marine	npc-1	Norwegian North Sea
			GRANE	Heimdal FM	Deep marine	npc-1	Norwegian North Sea
			BLANE	Forties FM	Deep marine	npc-2	Norwegian North Sea
			COD	Forties FM	Deep marine	npc-2	Norwegian North Sea
	Basin Floor	Lobe	FRIGG	Frigg FM	Deep marine	neo/frigg-1	Norwegian North Sea
		Lobe Deposit	OSELVAR	Forties FM	Deep marine	npc-2	Norwegian North Sea
			JOTUN	Heimdal FM	Deep marine	npc-1	Norwegian North Sea
			VOLUND 1	Heimdal FM	Deep marine	npc-1	Norwegian North Sea
			BALDER 1	Heimdal Sand	Deep marine	npc-1	Norwegian North Sea
			VOLUND 2	Grid/Frigg Sand	Deep marine	npc-1	Norwegian North Sea
			BALDER 3	Hermod Sand	Deep marine	npc-1	Norwegian North Sea
Deep Marine	Slope	Lobe Deposit	BALDER 2	Balder FM	Deep marine	npc-1	Norwegian North Sea

Results
Principal Component Analysis

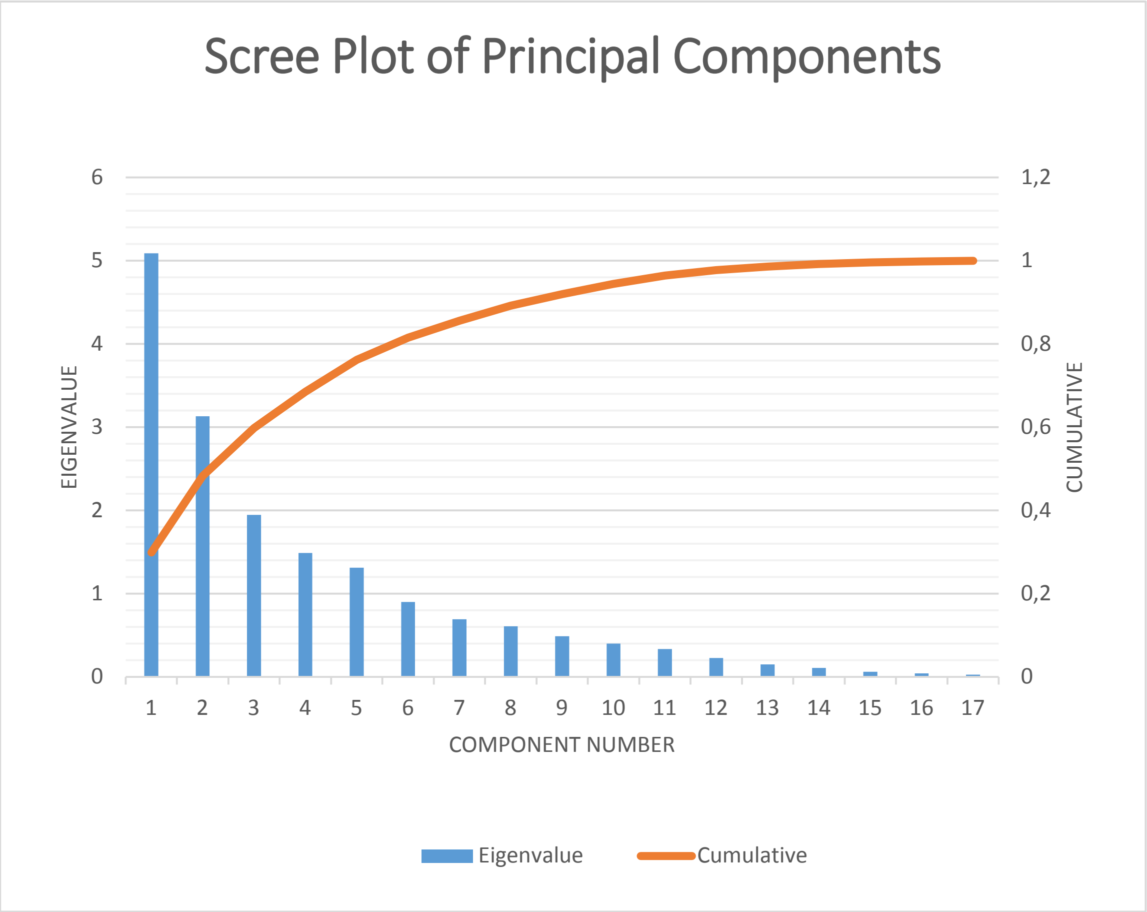
- Dimensionality reduction method

- Reveals hidden data structures

- Exploratory data analysis method (extract information)

- Dataset is reduced into number of principal components (PC)

Scree Plot



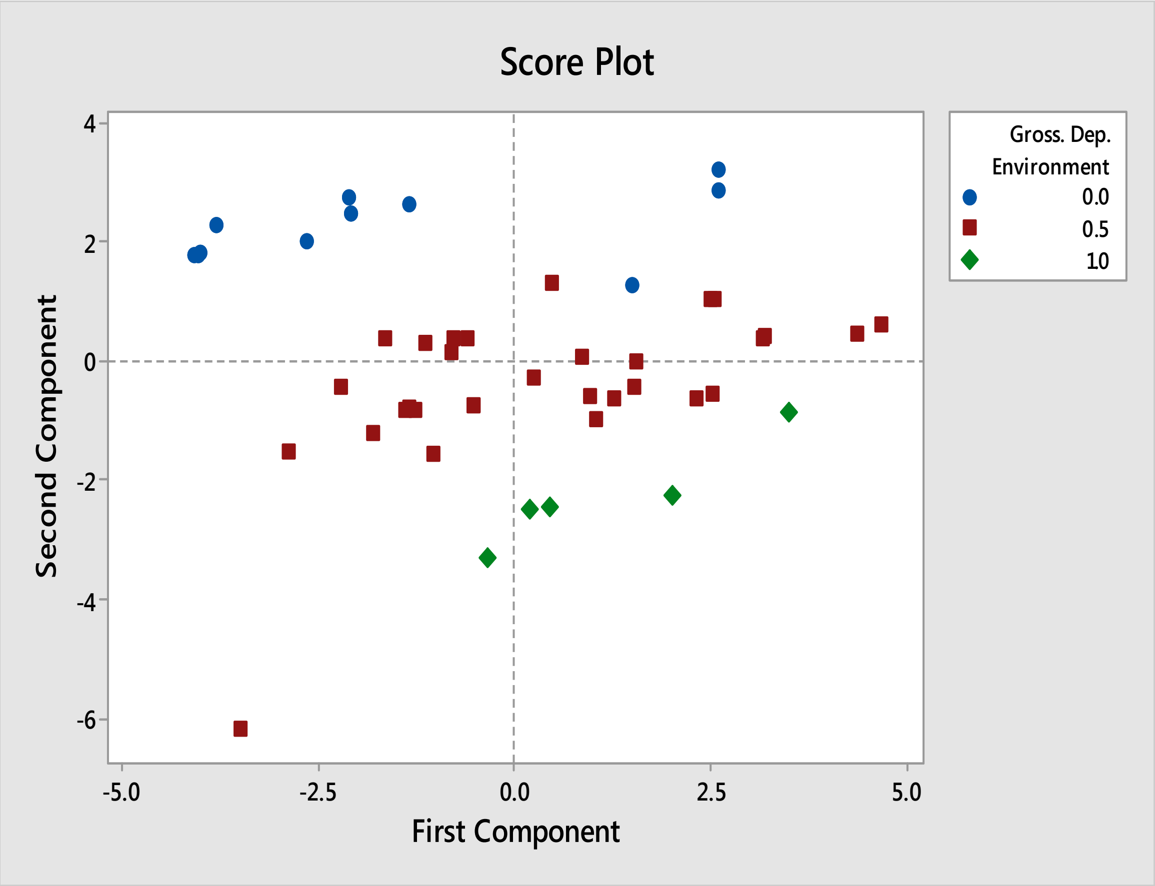
	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
Eigenvalue	5.087	3.1327	1.9452	1.489	1.3121	0.9013	0.6937	0.6082	0.4893	0.4020
Proportion	0.299	0.184	0.114	0.087	0.077	0.053	0.041	0.036	0.029	0.024
Cumulative	0.299	0.483	0.598	0.685	0.762	0.815	0.856	0.892	0.920	0.944

	PC11	PC12	PC13	PC14	PC15	PC16	PC17
Eigenvalue	0.3368	0.2262	0.1517	0.1095	0.0610	0.0417	0.0262
Proportion	0.020	0.013	0.009	0.006	0.004	0.002	0.002
Cumulative	0.964	0.977	0.986	0.992	0.996	0.998	1.000

First seven Principal Component

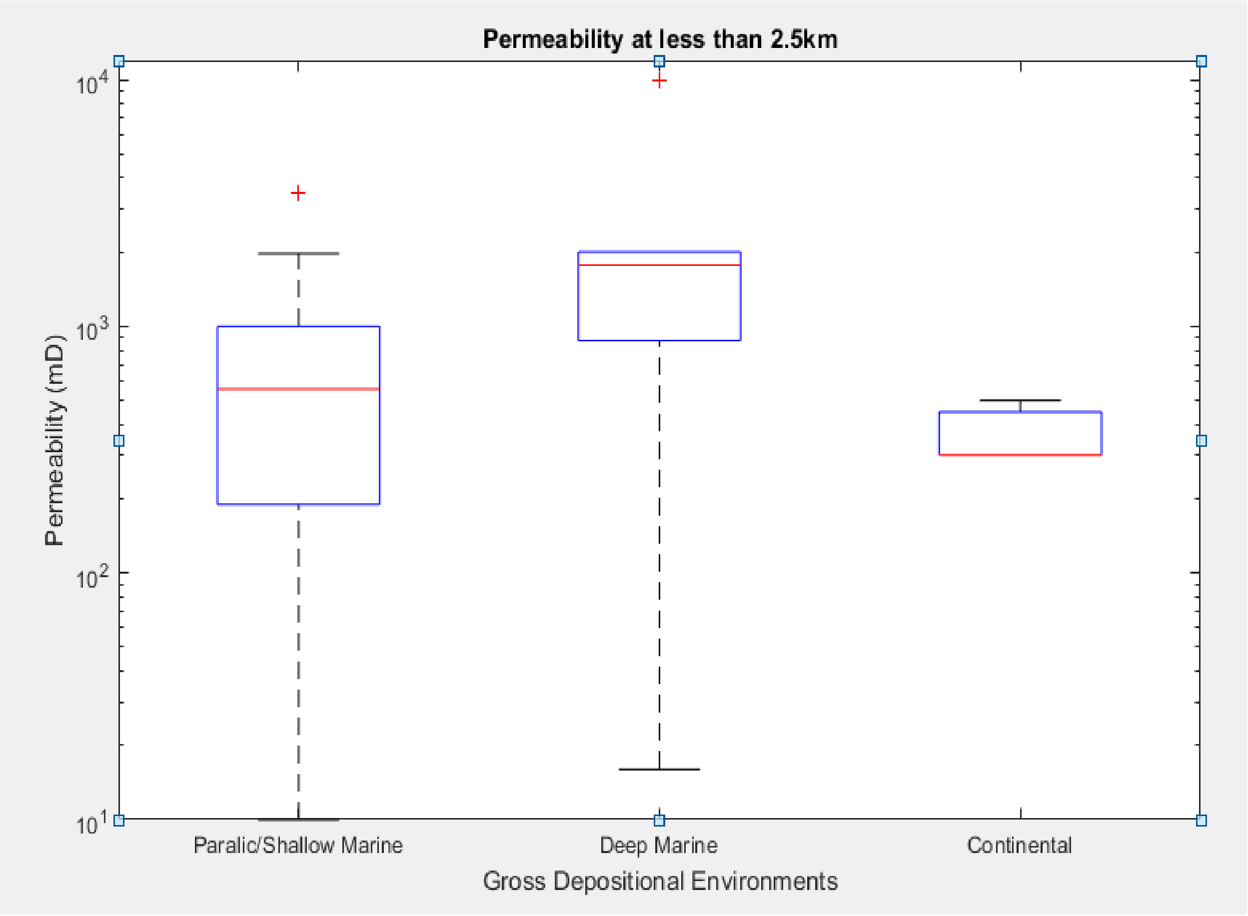
Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Gross Dep.Environment	0.162	-0.435	-0.163	-0.193	-0.033	-0.016	0.141
Reservoir Depth (m)	0.388	0.037	-0.031	0.046	-0.02	-0.337	-0.055
Avg. Porosity (%)	0.360	0.157	-0.049	0.052	0.05	-0.153	-0.033
Avg. Permeability (mD)	0.287	0.11	-0.103	-0.06	0.004	-0.08	0.266
Initial Pressure (bar)	0.347	-0.054	-0.048	0.069	0.039	-0.499	0.024
Initial Temperature (0C)	0.324	-0.103	0.172	0.288	0.054	-0.299	-0.239
Fault Compartments	-0.216	-0.12	0.366	-0.15	-0.057	-0.363	0.347
API (0)	0.267	0.008	-0.283	0.294	-0.048	0.31	0.032
Pay Area (km2)	0.157	-0.369	0.319	0.295	0.131	0.103	-0.114
Bulk Rock Volume (108 m3)	-0.141	-0.384	0.319	0.291	0.085	0.102	-0.23
Water Saturation (%)	0.146	-0.095	-0.222	-0.056	0.62	-0.002	0.364
Production Strategy	0.159	0.212	0.384	0	-0.22	0.061	0.314
Trap Type	0.002	-0.399	-0.267	-0.113	-0.334	0.142	-0.058
Diagenetic impact	0.183	-0.149	0.153	0.239	-0.365	0.155	0.569
Stratigraphic Heterogeneity	0.201	-0.213	0.071	-0.503	-0.074	0.196	-0.099
well Spacing (km2/well)	0.209	0.18	0.225	0.098	0.416	0.404	0.128
OIP (Mill. Sm3)	-0.198	-0.381	-0.153	0.052	0.269	-0.132	0.247
Recovery Factor (%)	-0.142	0.053	-0.373	0.497	-0.185	-0.051	0.122

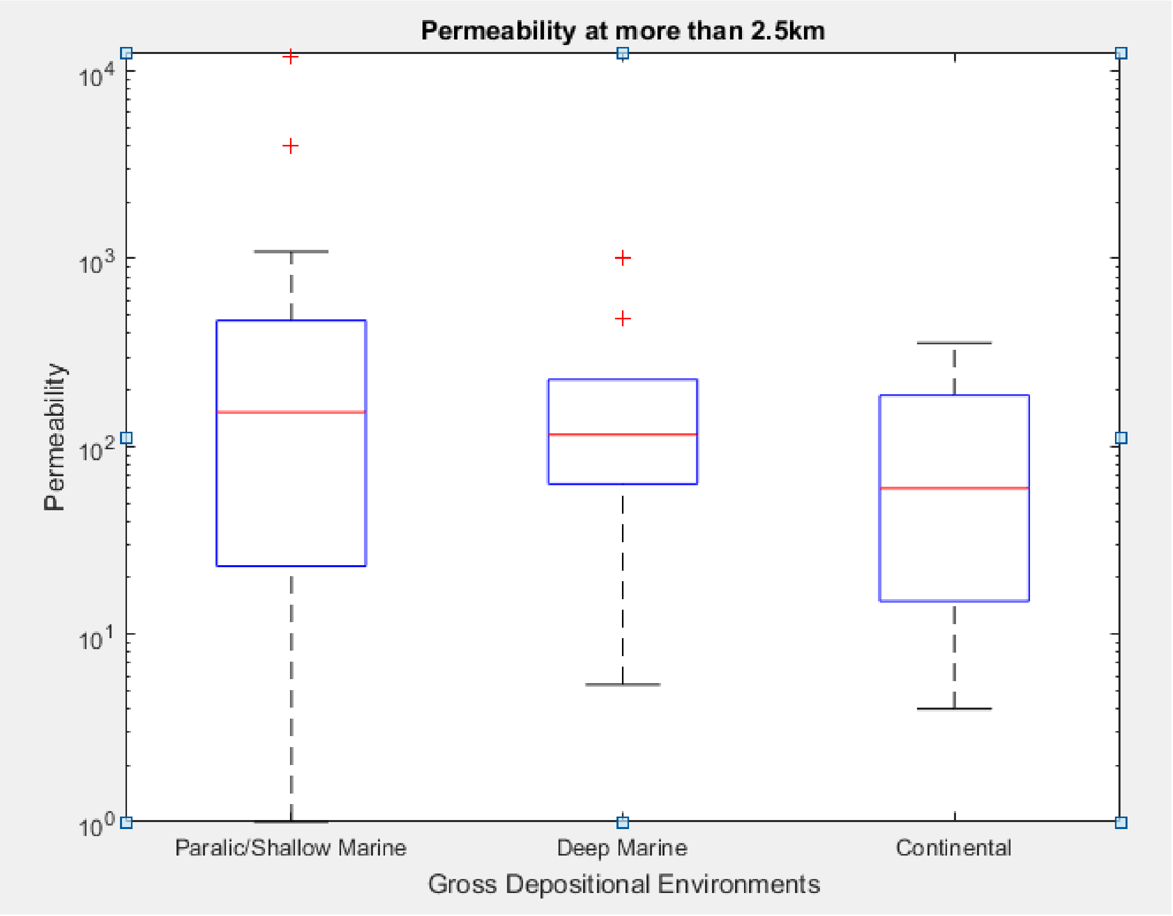
Most important parameters



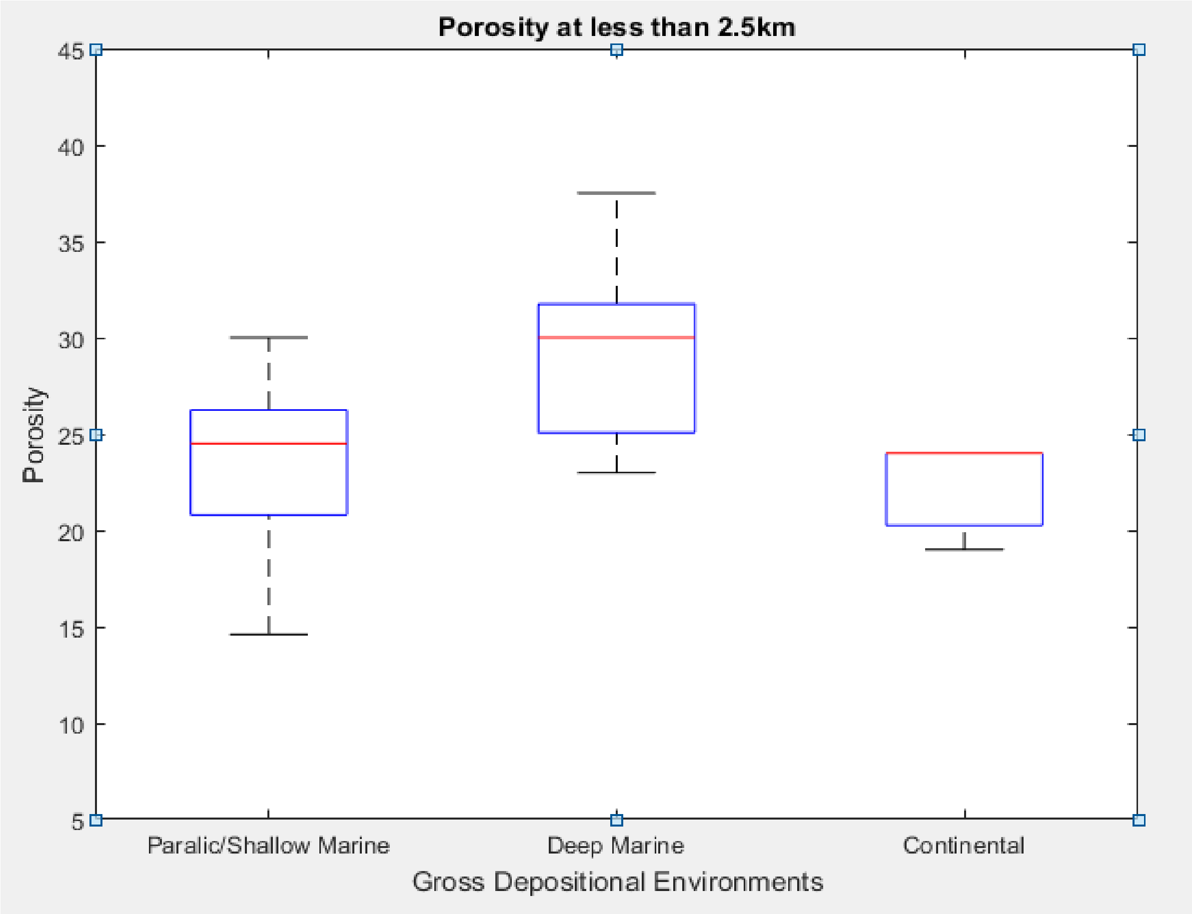
1) Reservoir Depth (PC1)	9) Original oil in place (PC2)
2) Average Porosity (PC1)	10) Pay area (PC2, PC3)
3) Initial Pressure (PC1)	11) Production Strategy (PC3)
4) Initial Temperature (PC1)	12) Fault compartment (PC3)
5) Average Permeability (PC1)	13) Stratigraphic Heterogeneity (PC4)
6) Gross Depositional Environment (PC2)	14) Diagenetic impact (PC7)
7) Trap Type (PC2)	
8) Reservoir Bulk Rock Volume (PC2, PC3)	

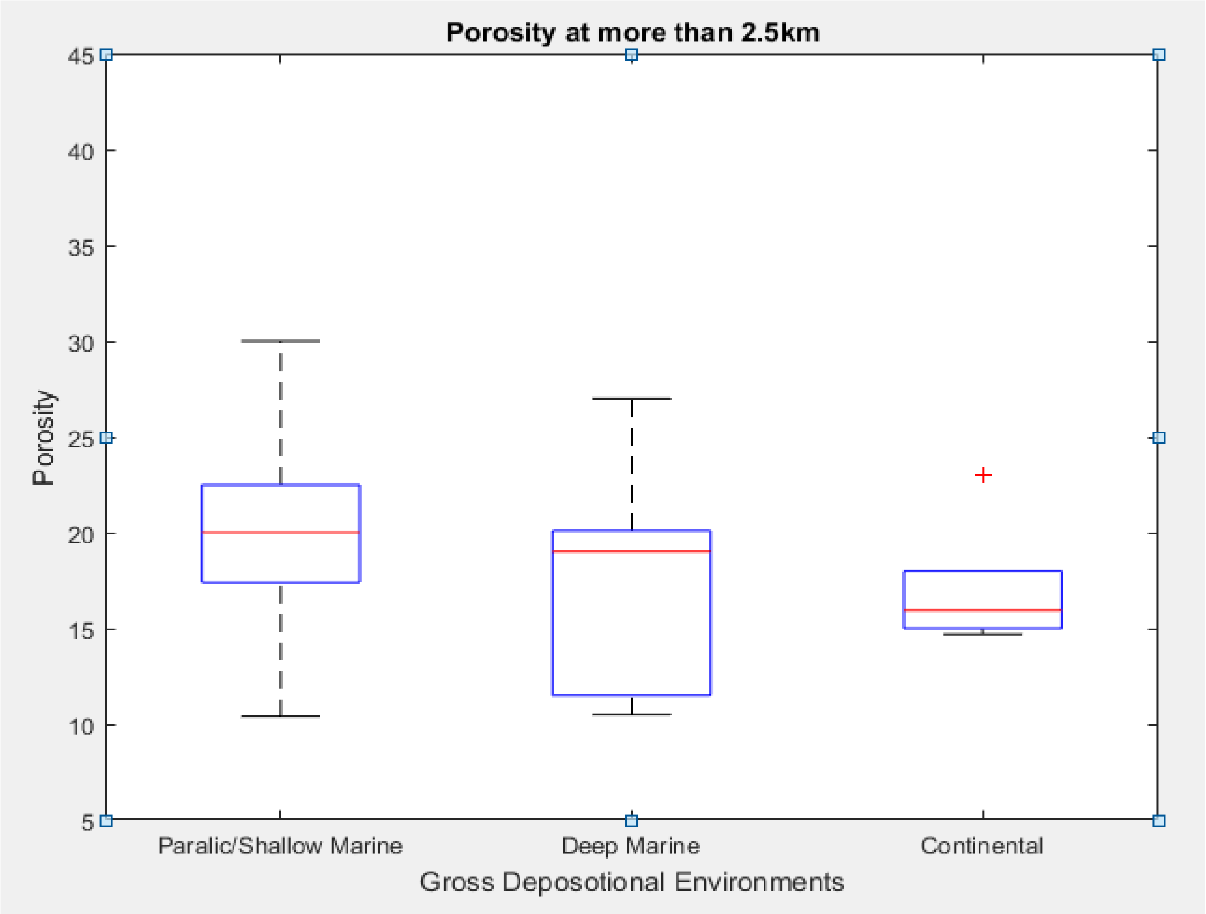
Exploring the importance of depth its control on permeability





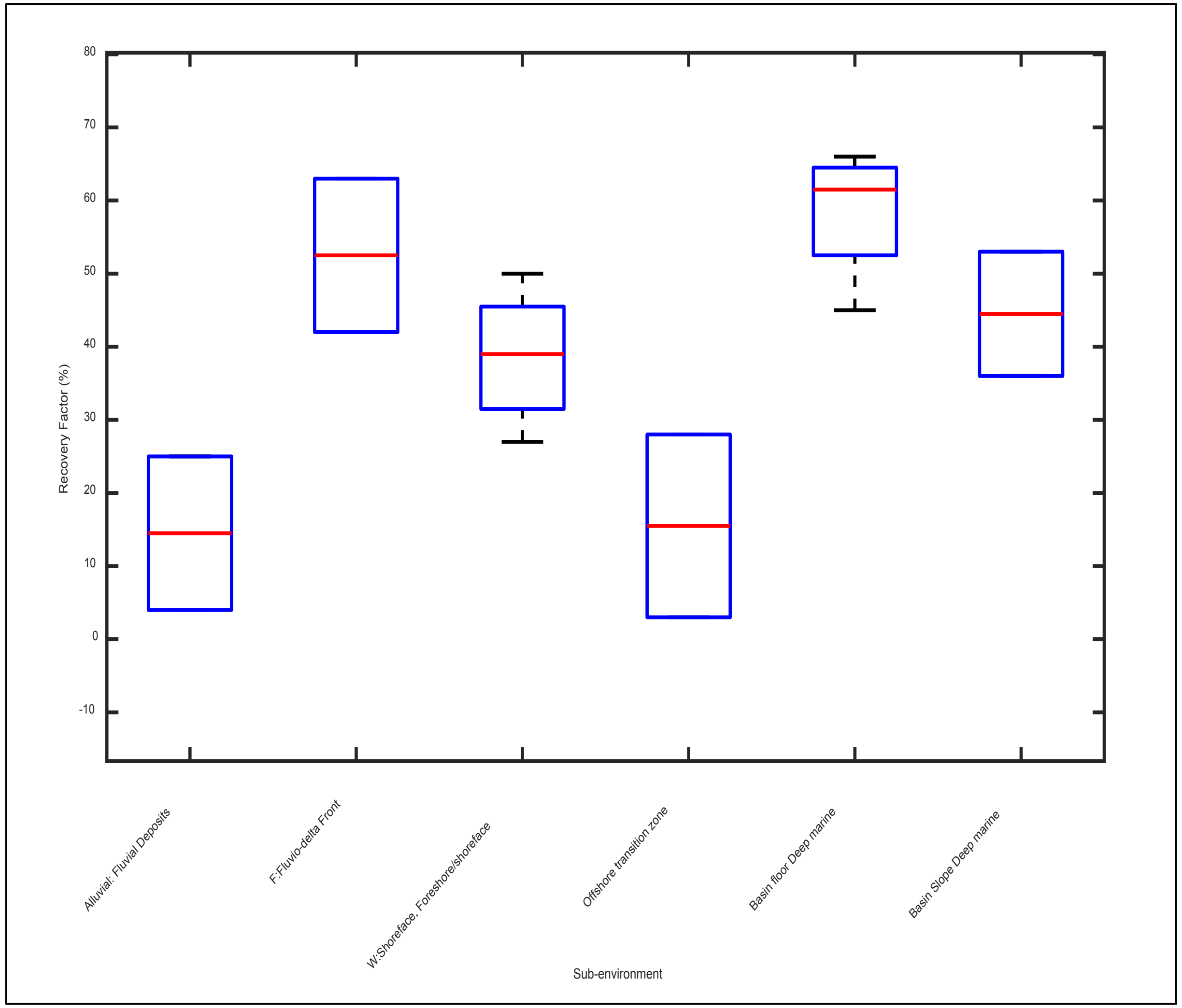
Exploring the importance of depth its control on Porosity



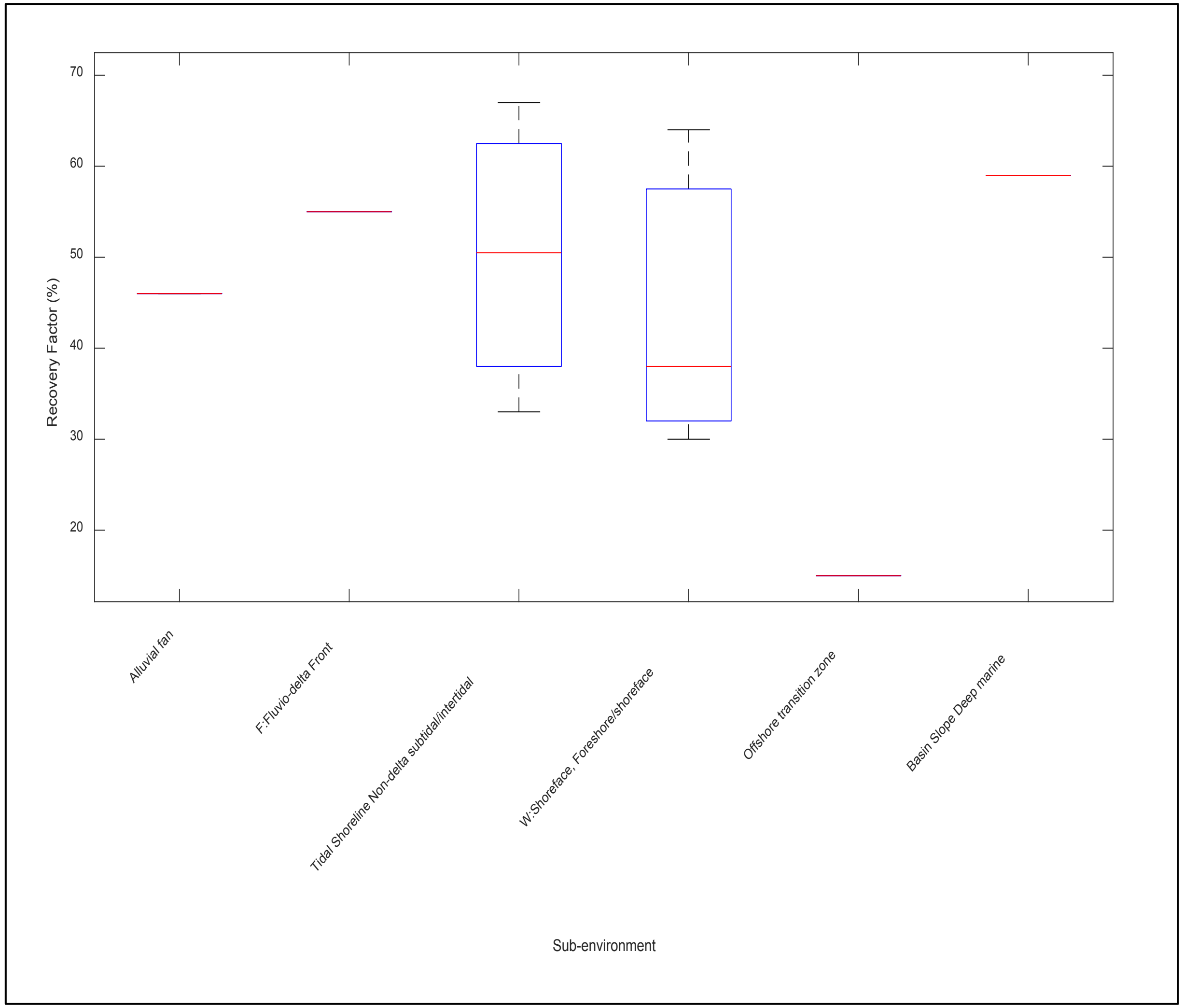


Recovery as a function of dominant depositional sub-environments

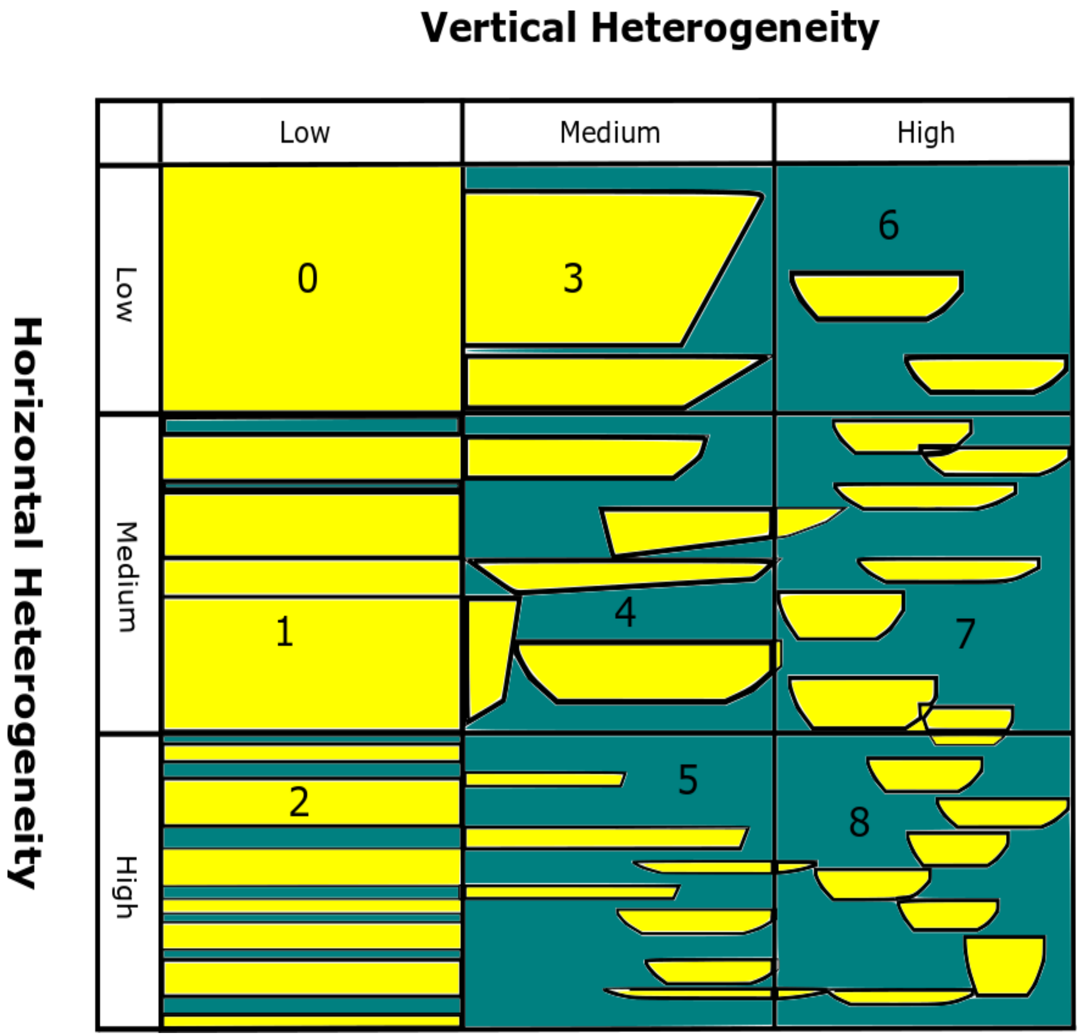
Reservoirs produced by pressure depletion



Reservoirs produced by water injection



Stratigraphic Heterogeneity Scale



(modified after Tyler and Finley, 1999)

1 = Alvheim, Balder, Blane, Cod, Frigg, Grane, Glitne, Hemdal, Jotun, Oselvar, Volund

2 = Brage, Fram, Lille Frigg, Oseberg Sor, Skirne, Heidrun, Gullfaks sor, Ula Vale, Troll, Svalin

3 = Oseberg, Trym, Volve, Huldra, Mikkel

4 = Tune, Snore

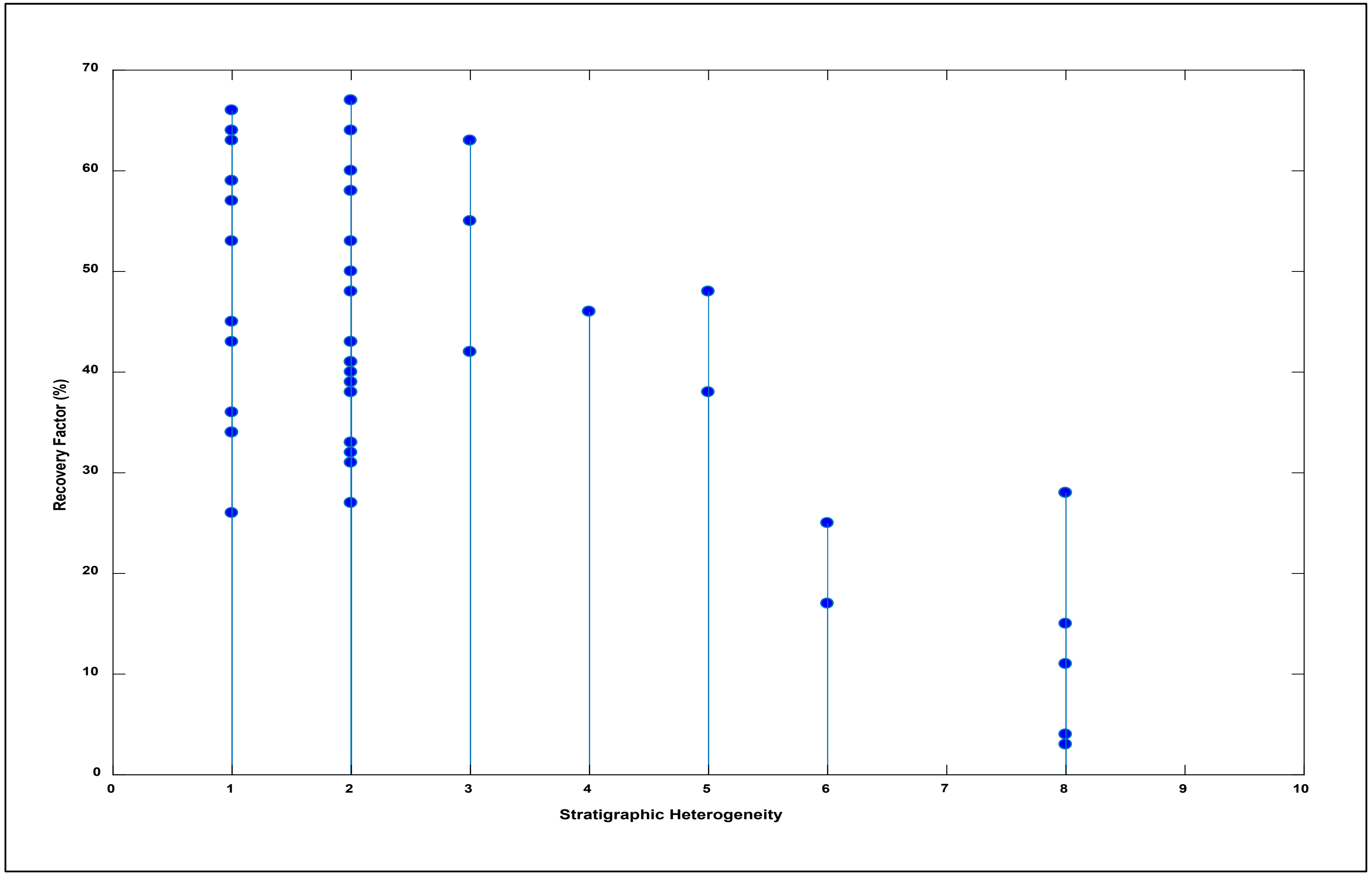
5 = Gullfaks Sor, Gullfaks

6 = Embla, Froy

7 = Gungne, Sigyn

8 = Brynhild, Gaupe, Gjoa, Mime, Yme

Recovery against stratigraphic heterogeneity



Conclusion

- Principal component analysis (PCA) reveals that gross depositional environment and sedimentological related parameters dominate the first four principal components.
- Fluid properties parameters, API density and water saturation are unexpectedly among the less important parameters.
- Delta front deposit, wave-dominated shoreface deposit, tidal non-delta reservoirs, alluvial multistorey stacked deposits and deep marine reservoirs have strong oil recovery. Whereas;
- Offshore/transition zone reservoirs and alluvial: fluvial meandering channel deposits have weak oil recovery.

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