Gulf Keystone Petroleum

Using Intersect and DELFI to make development decisions quickly

September 2019

The Shaikan Field

Field Overview

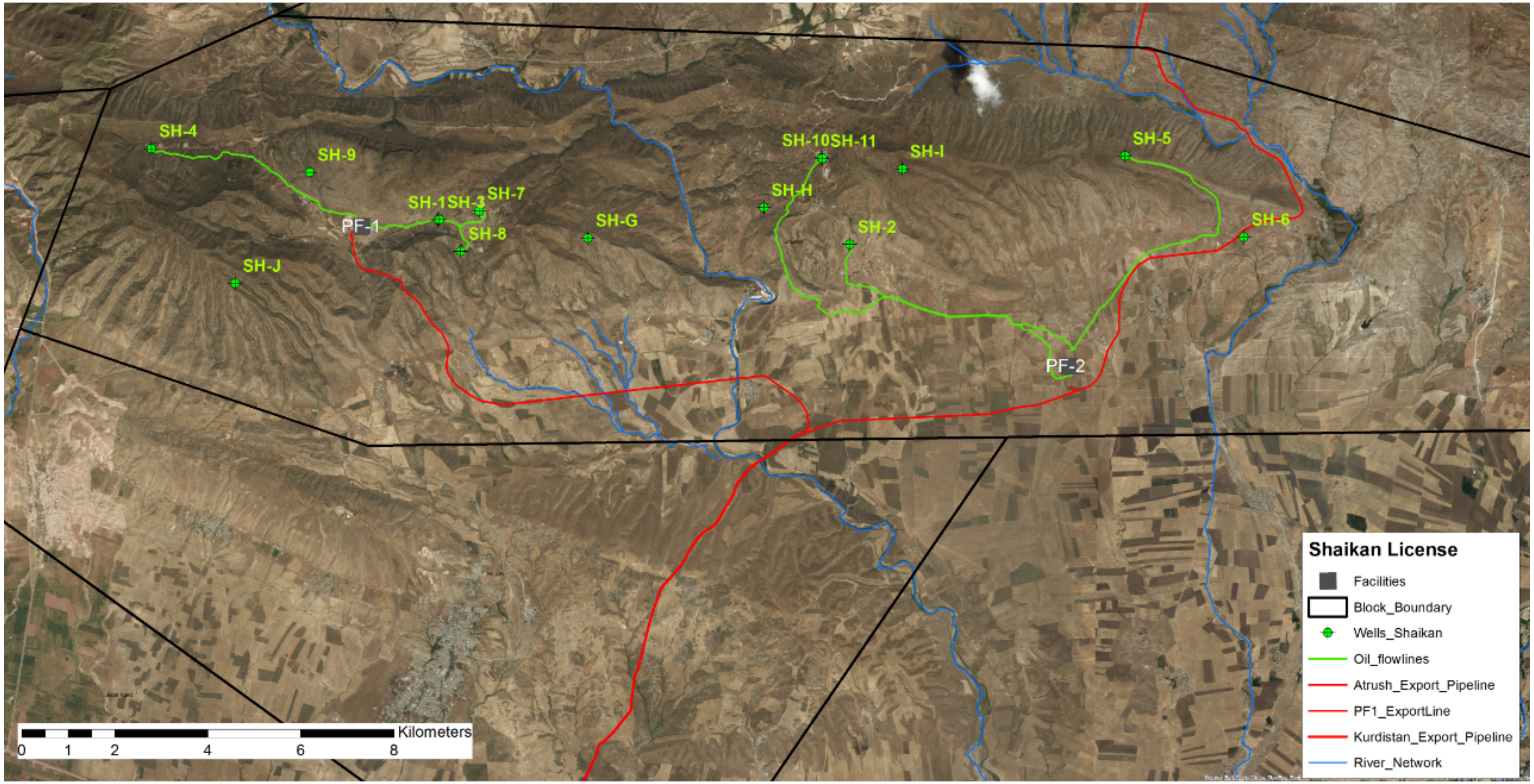
- Located c.60km north-west of Erbil at the north-west end of the Zagros Fold-belt
- Giant fractured carbonate oil field currently producing medium/heavy oil from Jurassic reservoir
- One of the largest fields in Kurdistan by reserves and production
- Development plan
  - Current production from Jurassic only
  - Only ~10% of ultimate reserves produced to date
  - Phased future development with further Jurassic wells, artificial lift, plant expansion and gas re-injection
  - Pilot development of Triassic reservoirs

Key Facts

- **Gulf Keystone interest**: 80%
- **Partner**: MOL 20%
- **Discovered**: August 2009
- **Production start**: July 2013
- **STOIIP (Jurassic):** ~3500 MMstb
- **2P reserves:** 591 MMstb*
- **Reservoir depth (Jurassic):** 300 – 1450 mTVDSS
- **Geology:** Fractured carbonate (limestone, dolomite, anhydrite)
- **Production mechanism:** primary depletion
- **Surface facilities:** PF-1 and PF-2 processing plants, with pipeline export
- **Current production rate:** ~40 Mstb/d from 9 wells
- **Cumulative oil recovery to date:** 64 MMstb

** Source: ERC Equipoise. CPR volume estimates of 615 MMstb as at 31 December 2016, adjusted for 12.9 and 11.5 MMstb production in 2017 and 2018 respectively*

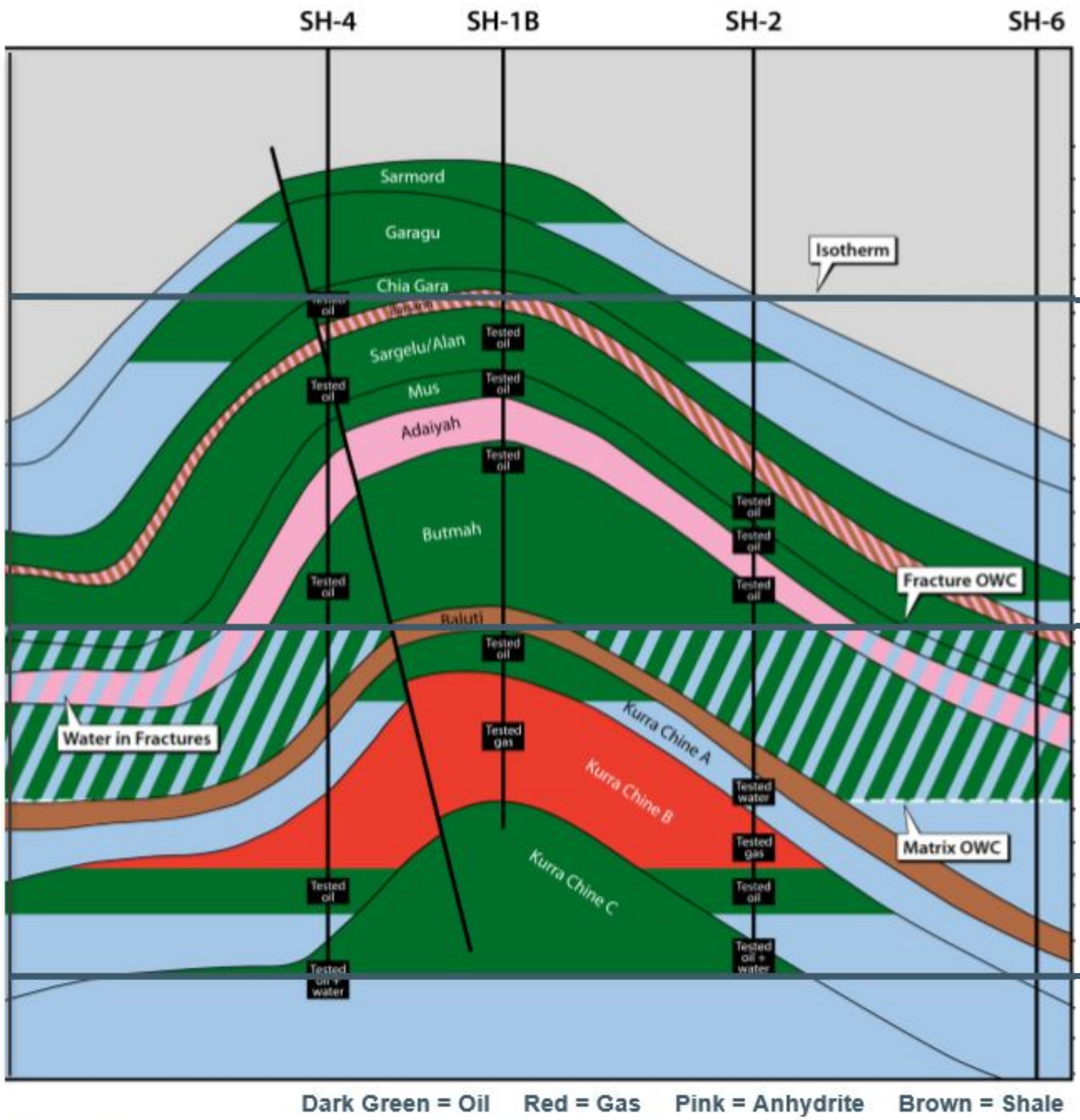
Shaikan Field Satellite Image



- Two production facilities, each with a nameplate capacity of 20 Mstb/d
- Nine production wells, without artificial lift
- PF-2 pipeline operational since July 2018
- PF-1 pipeline recently completed

Note: Well locations, pipeline routes and licence boundary are approximate

Subsurface Schematic Cross-Section



Cretaceous reservoir

Very heavy or bituminous oil

Jurassic reservoir

Heavy oil with 14 - 20° API

Unusually thick hydrocarbon column – c.950m

Triassic

Light oil with 38-43° API and gas condensate

Reservoir Modelling Challenges

- Full-field geological model of Upper and Lower Jurassic reservoir recently constructed in PETREL, incorporating matrix properties from log and core, and fracture properties upscaled from fine-scale Discrete Fracture Network (DFN) model
- Fine layering scheme required to preserve heterogeneity
- Static geological model grid and layering preserved in associated dynamic simulation model
- Several elements combine to result in a complex simulation model:
  - **Dual porosity** formulation required to fully capture fracture and oil recovery processes
  - Total cell count (matrix + fractures) of over 2 million cells, of which about **0.5 million are active**
  - Compositional gradient requires **"API Tracking"** option in Black Oil fluid model
  - **Low fracture porosity** (average <0.5%)
  - **High permeability contrast** (<1 mD matrix vs >1000 mD fractures)
  - Detailed **six-year production history** with daily records of BHP for nine wells
  - Introduction of gas re-injection results in **very rapid saturation changes** in fracture cells

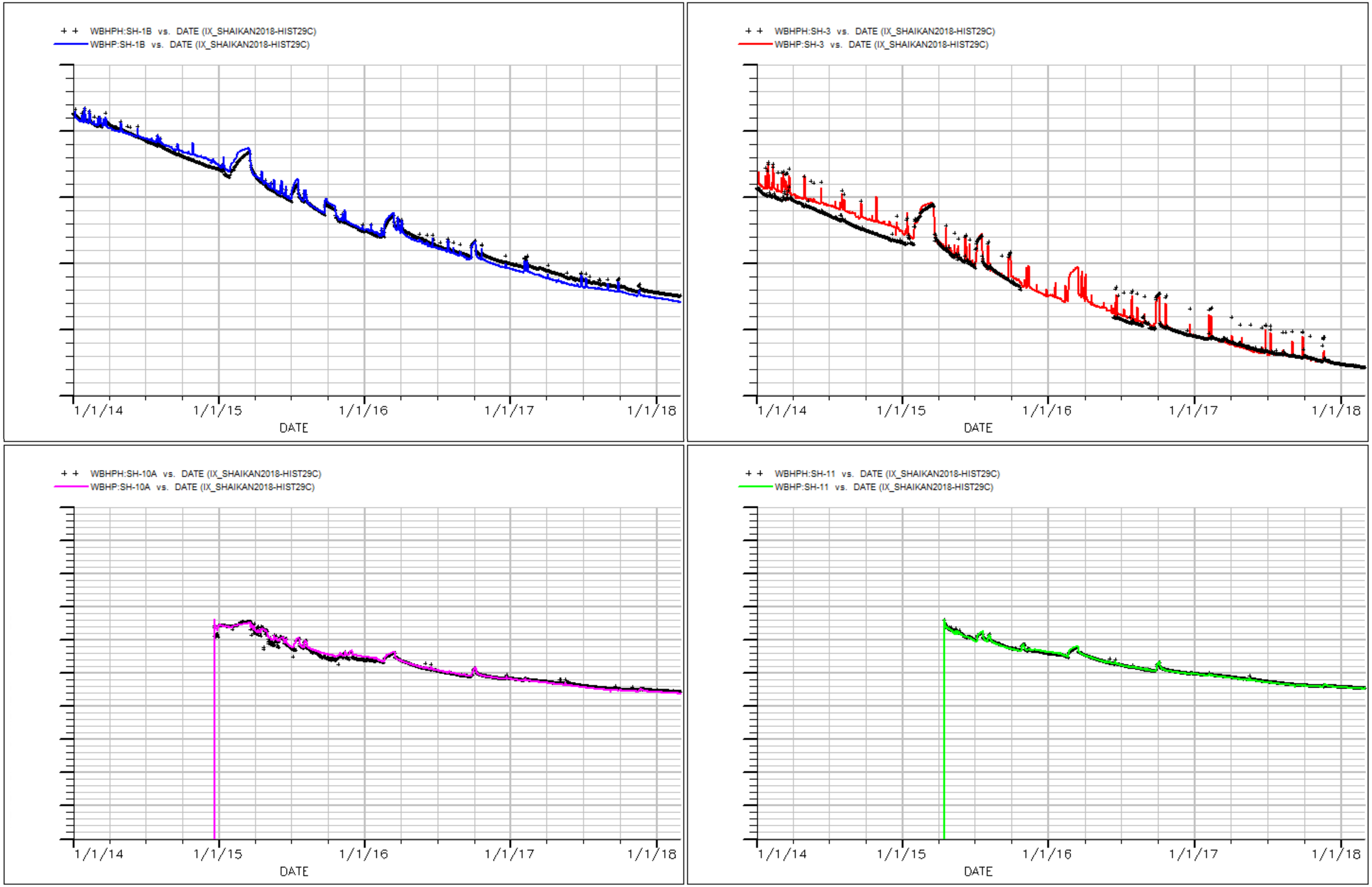
- Full history-match simulation run takes 6 - 7 hours in ECLIPSE…

Improving Simulation Run Times

- Reliable history-match was required to correctly "calibrate" the Shaikan simulation model before it could be used for production forecasting and development planning
- Long simulation run times encountered with ECLIPSE made history-matching exercise time-consuming and disjointed
- Predictive simulations with gas re-injection presented additional numerical problems in ECLIPSE and extended run times further

- Alternative simulators were considered and tested in-house before ultimately choosing INTERSECT as most suitable software for simulation for all Shaikan models
  - Run times **reduced by a factor of 4 – 5**
  - ECLIPSE results **exactly reproduced** by INTERSECT
  - **Almost all ECLIPSE functionality** available in INTERSECT
  - MIGRATOR allows existing ECLIPSE models to be **easily converted** to INTERSECT
  - INTERSECT **output available in ECLIPSE format** for post-processing

Example Well BHP History-Match Plots

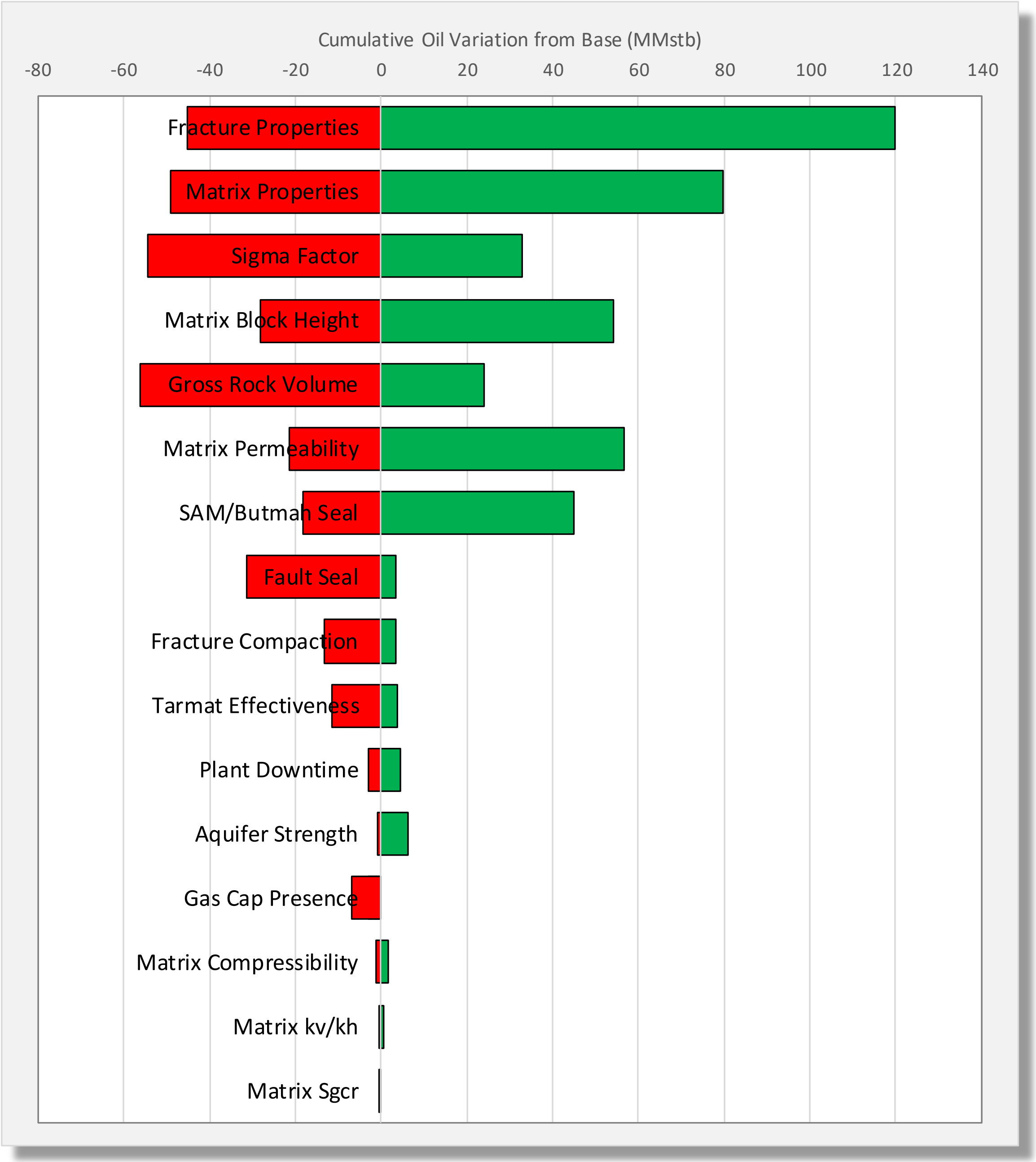


Uncertainty Study

- Use of INTERSECT allowed a good deterministic history-match to be achieved to all wells within a reasonable timeframe, and the prior rigorous calibration of the DFN model meant only minor global tuning of reservoir properties was required to achieve the match
- However, the manual process of history-matching yields only **one non-unique solution**. Clearly, with only nine wells producing from such a large field, and only 10% of reserves recovered, there remains significant uncertainty in any subsequent production forecast derived from this single deterministic model

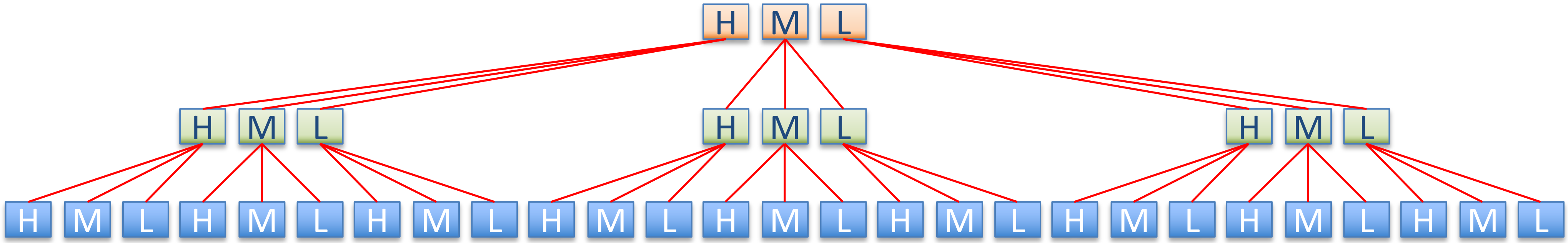
- Hence an "Uncertainty Study" was proposed with a number of objectives:
  - To identify the most important uncertainties and risks
  - To capture subsurface uncertainty in Shaikan static and dynamic models
  - To bracket probabilistically the STOIIP and reserves ranges
  - To generate a number of equi-probable history-matched simulation models
  - To derive probabilistic production forecasts for current Field Development Plan
  - To identify representative P90 / P50 / P10 forecast cases for further optimisation

Sensitivity Analysis "Tornado Chart"



Experimental Design

- To examine all possible combinations of all independent uncertainties would require a "full factorial" approach. Example for 3 variables and 27 combinations:



- Choosing seven independent variables, each with high / mid / low values, would require **2187 separate simulation runs!**
- Experimental Design adopts a "fractional factorial" approach to cover the full uncertainty space with the minimum number of combinations
- The **"Box-Behnken"** design requires only **57 simulation runs** for seven variables

“Box-Behnken” Design Tables

3 Factors

Block	Run	A	B	C
1	1	-1	-1	0
	2	1	-1	0
	3	-1	1	0
	4	1	1	0
2	5	0	-1	-1
	6	0	1	-1
	7	0	-1	1
	8	0	1	1
3	9	-1	0	-1
	10	1	0	-1
	11	-1	0	1
	12	1	0	1
Base	13	0	0	0

4 Factors

Block	Run	A	B	C	D
1	1	-1	-1	0	0
	2	1	-1	0	0
	3	-1	1	0	0
	4	1	1	0	0
2	5	-1	0	-1	0
	6	1	0	-1	0
	7	-1	0	1	0
	8	1	0	1	0
3	9	-1	0	0	-1
	10	1	0	0	-1
	11	-1	0	0	1
	12	1	0	0	1
4	13	0	-1	-1	0
	14	0	1	-1	0
	15	0	-1	1	0
	16	0	1	1	0
5	17	0	-1	0	-1
	18	0	1	0	-1
	19	0	-1	0	1
	20	0	1	0	1
6	21	0	0	-1	-1
	22	0	0	1	-1
	23	0	0	-1	1
	24	0	0	1	1
Base	25	0	0	0	0

5 Factors

Block	Run	A	B	C	D	E
1	1	-1	-1	0	0	0
	2	1	-1	0	0	0
	3	-1	1	0	0	0
	4	1	1	0	0	0
2	5	-1	0	-1	0	0
	6	1	0	-1	0	0
	7	-1	0	1	0	0
	8	1	0	1	0	0
3	9	-1	0	0	-1	0
	10	1	0	0	-1	0
	11	-1	0	0	1	0
	12	1	0	0	1	0
4	13	-1	0	0	0	-1
	14	1	0	0	0	-1
	15	-1	0	0	0	1
	16	1	0	0	0	1
5	17	0	-1	-1	0	0
	18	0	1	-1	0	0
	19	0	-1	1	0	0
	20	0	1	1	0	0
6	21	0	-1	0	-1	0
	22	0	1	0	-1	0
	23	0	-1	0	1	0
	24	0	1	0	1	0
7	25	0	-1	0	0	-1
	26	0	1	0	0	-1
	27	0	-1	0	0	1
	28	0	1	0	0	1
8	29	0	0	-1	-1	0
	30	0	0	1	-1	0
	31	0	0	-1	1	0
	32	0	0	1	1	0
9	33	0	0	-1	0	-1
	34	0	0	1	0	-1
	35	0	0	-1	0	1
	36	0	0	1	0	1
10	37	0	0	0	-1	-1
	38	0	0	0	1	-1
	39	0	0	0	-1	1
	40	0	0	0	1	1
Base	41	0	0	0	0	0

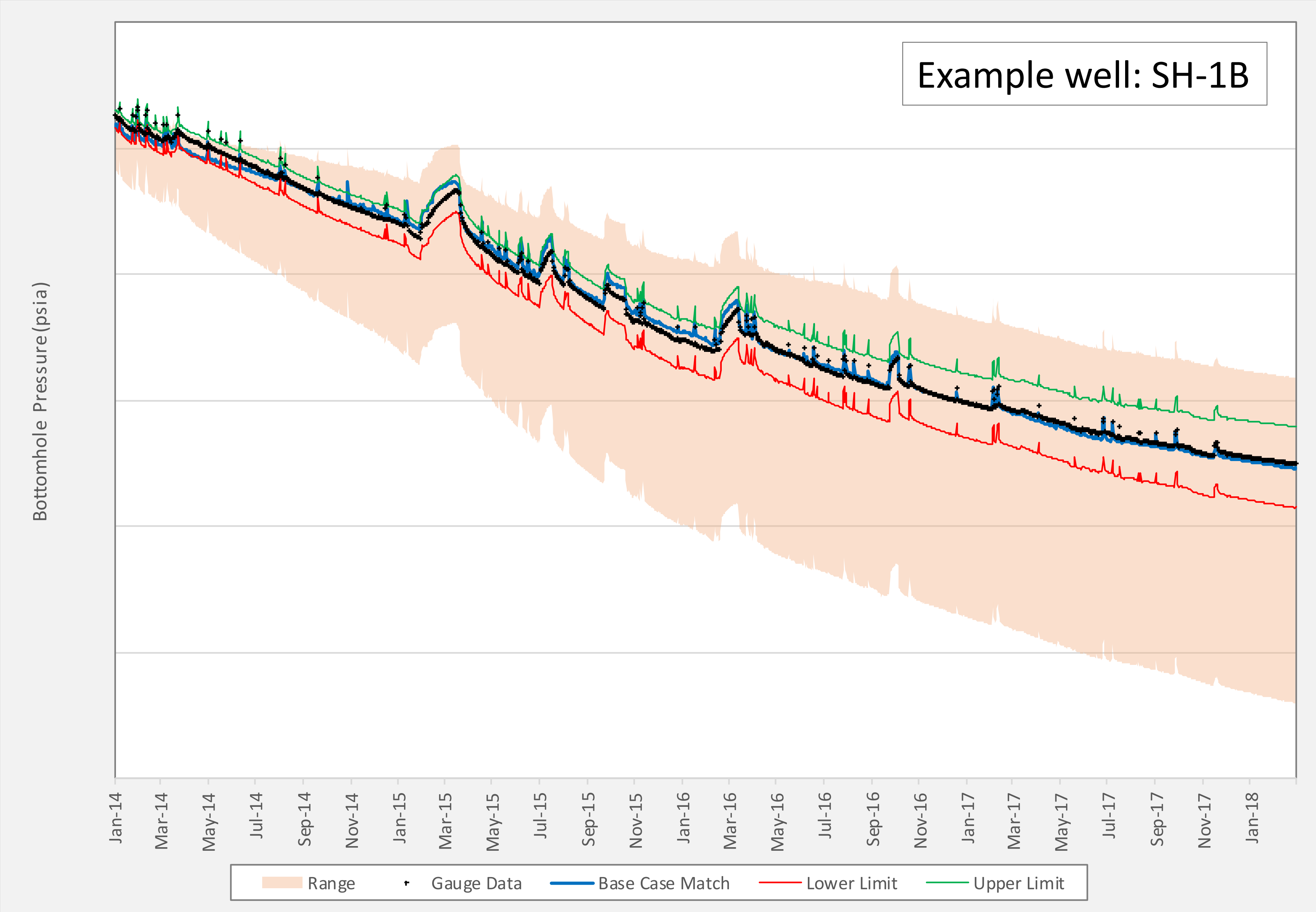
6 Factors

Block	Run	A	B	C	D	E	F
1	1	-1	-1	0	-1	0	0
	2	1	-1	0	-1	0	0
	3	-1	1	0	-1	0	0
	4	1	1	0	-1	0	0
	5	-1	-1	0	1	0	0
	6	1	-1	0	1	0	0
	7	-1	1	0	1	0	0
	8	1	1	0	1	0	0
2	9	0	-1	-1	0	-1	0
	10	0	1	-1	0	-1	0
	11	0	-1	1	0	-1	0
	12	0	1	1	0	-1	0
	13	0	-1	-1	0	1	0
	14	0	1	-1	0	1	0
	15	0	-1	1	0	1	0
	16	0	1	1	0	1	0
3	17	0	0	-1	-1	0	-1
	18	0	0	1	-1	0	-1
	19	0	0	-1	1	0	-1
	20	0	0	1	1	0	-1
	21	0	0	-1	-1	0	1
	22	0	0	1	-1	0	1
	23	0	0	-1	1	0	1
	24	0	0	1	1	0	1
4	25	-1	0	0	-1	-1	0
	26	1	0	0	-1	-1	0
	27	-1	0	0	1	-1	0
	28	1	0	0	1	-1	0
	29	-1	0	0	-1	1	0
	30	1	0	0	-1	1	0
	31	-1	0	0	1	1	0
	32	1	0	0	1	1	0
5	33	0	-1	0	0	-1	-1
	34	0	1	0	0	-1	-1
	35	0	-1	0	0	1	-1
	36	0	1	0	0	1	-1
	37	0	-1	0	0	-1	1
	38	0	1	0	0	-1	1
	39	0	-1	0	0	1	1
	40	0	1	0	0	1	1
6	41	-1	0	-1	0	0	-1
	42	1	0	-1	0	0	-1
	43	-1	0	1	0	0	-1
	44	1	0	1	0	0	-1
	45	-1	0	-1	0	0	1
	46	1	0	-1	0	0	1
	47	-1	0	1	0	0	1
	48	1	0	1	0	0	1
Base	49	0	0	0	0	0	0

7 Factors

Block	Run	A	B	C	D	E	F	G
1	1	0	0	0	-1	-1	-1	0
	2	0	0	0	1	-1	-1	0
	3	0	0	0	-1	1	-1	0
	4	0	0	0	1	1	-1	0
	5	0	0	0	-1	-1	1	0
	6	0	0	0	1	-1	1	0
	7	0	0	0	-1	1	1	0
	8	0	0	0	1	1	1	0
2	9	-1	0	0	0	0	-1	-1
	10	1	0	0	0	0	-1	-1
	11	-1	0	0	0	0	1	-1
	12	1	0	0	0	0	1	-1
	13	-1	0	0	0	0	-1	1
	14	1	0	0	0	0	-1	1
	15	-1	0	0	0	0	1	1
	16	1	0	0	0	0	1	1
3	17	0	-1	0	0	-1	0	-1
	18	0	1	0	0	-1	0	-1
	19	0	-1	0	0	1	0	-1
	20	0	1	0	0	1	0	-1
	21	0	-1	0	0	-1	0	1
	22	0	1	0	0	-1	0	1
	23	0	-1	0	0	1	0	1
	24	0	1	0	0	1	0	1
4	25	-1	-1	0	-1	0	0	0
	26	1	-1	0	-1	0	0	0
	27	-1	1	0	-1	0	0	0
	28	1	1	0	-1	0	0	0
	29	-1	-1	0	1	0	0	0
	30	1	-1	0	1	0	0	0
	31	-1	1	0	1	0	0	0
	32	1	1	0	1	0	0	0
5	33	0	0	-1	-1	0	0	-1
	34	0	0	1	-1	0	0	-1
	35	0	0	-1	1	0	0	-1
	36	0	0	1	1	0	0	-1
	37	0	0	-1	-1	0	0	1
	38	0	0	1	-1	0	0	1
	39	0	0	-1	1	0	0	1
	40	0	0	1	1	0	0	1
6	41	-1	0	-1	0	-1	0	0
	42	1	0	-1	0	-1	0	0
	43	-1	0	1	0	-1	0	0
	44	1	0	1	0	-1	0	0
	45	-1	0	-1	0	1	0	0
	46	1	0	-1	0	1	0	0
	47	-1	0	1	0	1	0	0
	48	1	0	1	0	1	0	0
7	49	0	-1	-1	0	0	-1	0
	50	0	1	-1	0	0	-1	0
	51	0	-1	1	0	0	-1	0
	52	0	1	1	0	0	-1	0
	53	0	-1	-1	0	0	1	0
	54	0	1	-1	0	0	1	0
	55	0	-1	1	0	0	1	0
	56	0	1	1	0	0	1	0
Base	57	0	0	0	0	0	0	0

Filtering “Box-Behnken” Cases via History-Match

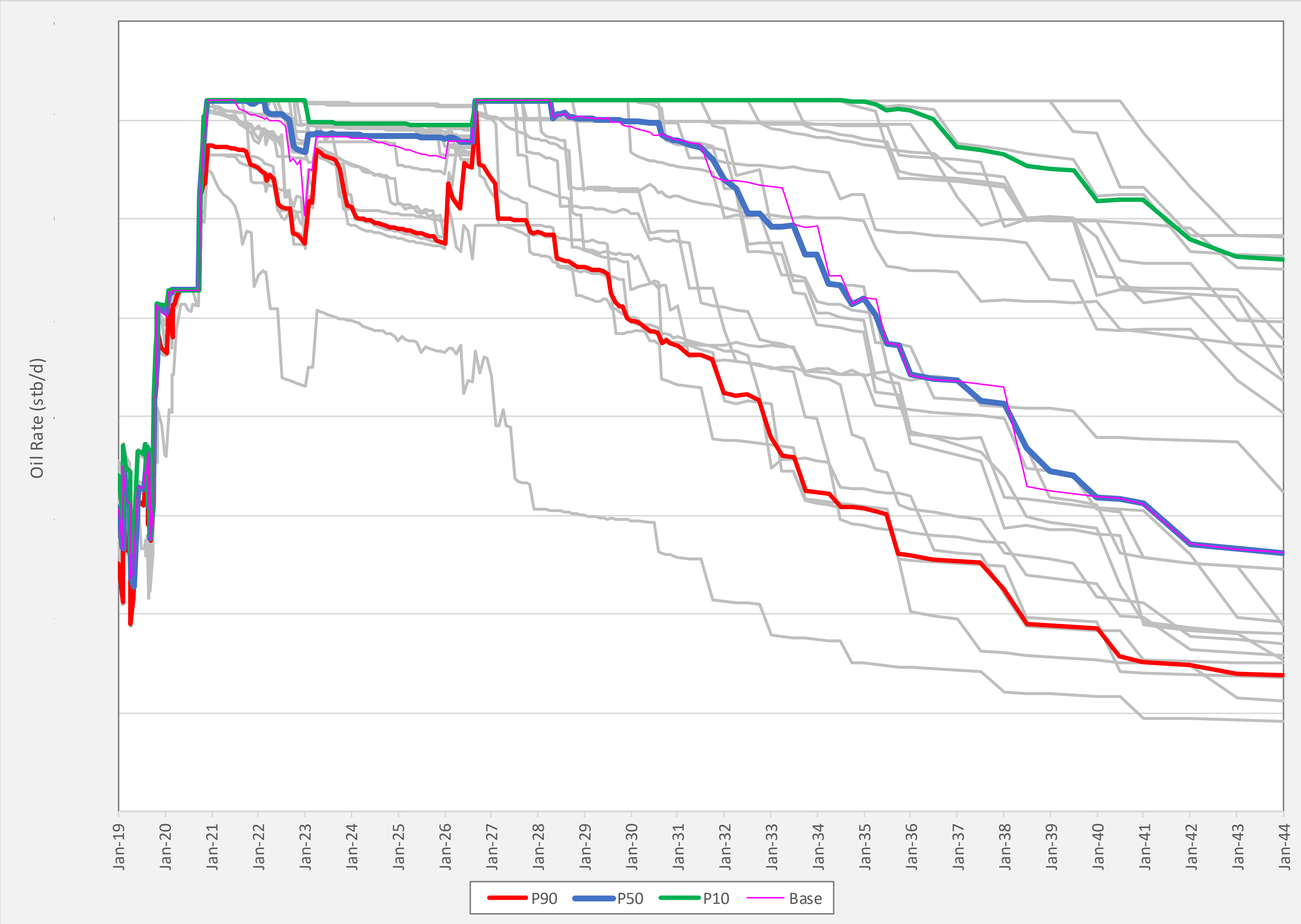


Uncertainty Study Summary

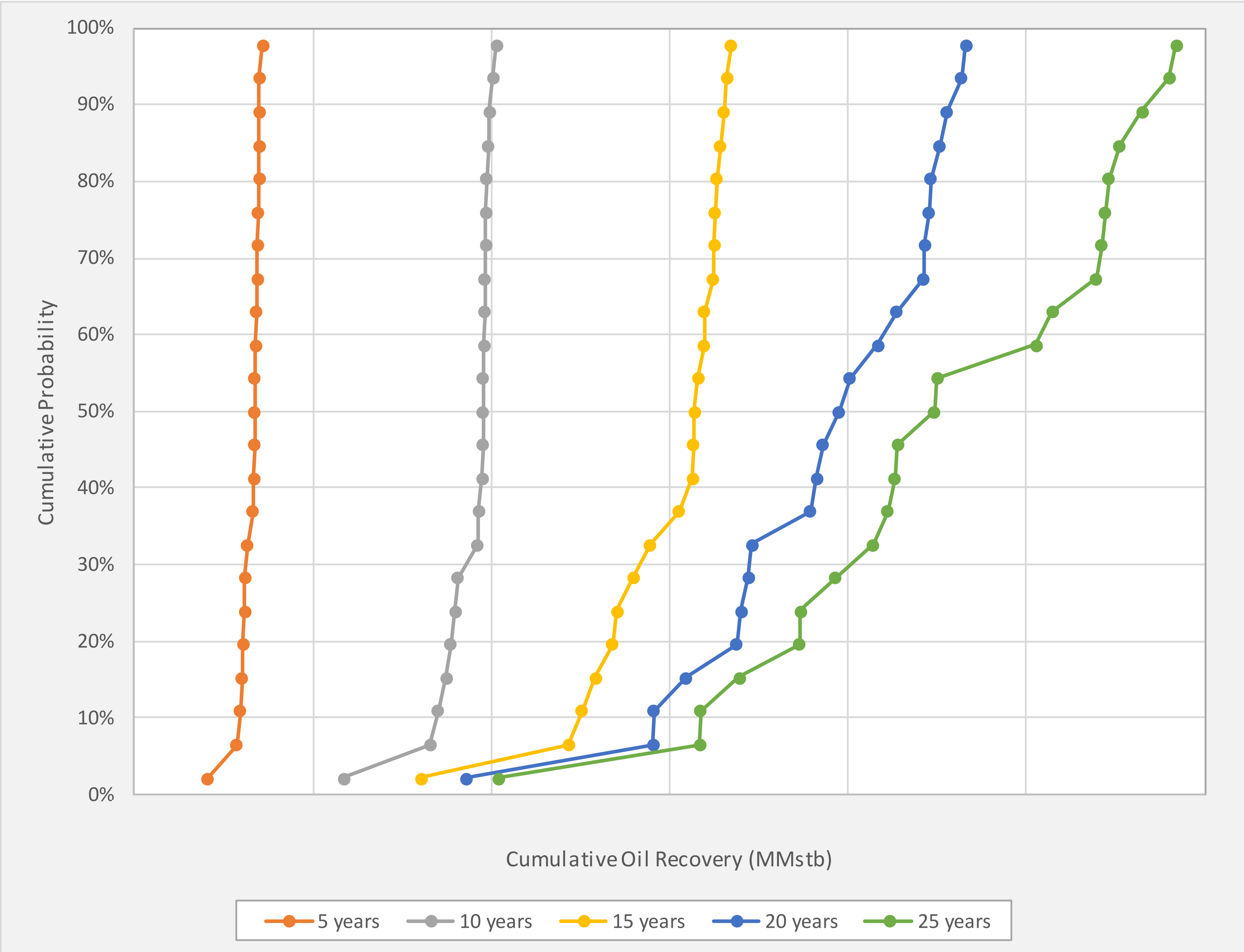
1. Identify 16 key reservoir uncertainties and assign high / mid / low values (or scenarios) to each variable
2. Run "sensitivity analysis" of predictive simulations with each variable set to its low & high value in turn
3. Rank variables in "tornado chart" according to the impact of their uncertainty on ultimate oil recovery, and select the top seven
4. Use "Box-Behnken" experimental design approach to define 57 fractional-factorial cases to cover entire uncertainty space
5. Run history-match simulations for all 57 cases and filter the cases according to an overall "tolerance" on the BHP match for each well
6. Total of 23 cases were within tolerance for all nine wells

- Full 25 year production forecasts simulated for all 23 filtered cases, both with and without gas re-injection, giving total of **46 simulation runs**
- Each predictive simulation takes **10 – 12 hours** in INTERSECT using 16 processors on a single high-spec workstation
- **DELFI cloud computing service** used to complete all 46 simulations within a few days, meeting study objectives and **achieving delivery within project deadline**

Production Forecasts for 23 Filtered Cases



S-Curves for Cumulative Oil Recovery



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Conclusions and Further Work

1. Excellent history-match to well performance in large fractured carbonate oil field achieved, with crucial element being fracture properties upscaled from DFN model.
2. Non-unique deterministic solution and early production stage dictated that a probabilistic approach to production forecasting should be adopted.
3. Sensitivity Analysis allowed the key reservoir uncertainties to be identified and ranked.
4. Experimental Design techniques allowed the number of possible combinations of uncertainty variables (and hence simulation runs required) to be minimized in a fractional-factorial design.
5. Filtering of resulting simulation output allowed only adequately matched cases to be passed for predictive simulation.
6. Final set of 23 matched cases define range of valid production forecasts and allowed synthetic P90 / P50 / P10 profiles to be derived.
7. Selected cases will now be used to optimize and refine the drilling programme in the Shaikan Field Development Plan.
8. INTERSECT simulator and DELFI cloud computing service were **essential** in enabling large number of complex simulation runs to be completed in a reasonable timeframe, and the study results to be delivered on time.


Thank you