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Decarbonizing SAGD in Heterogeneous Ultra-Heavy-Oil Reservoirs: Barrier-Bypassing Well Patterns and Geomechanical Dilation Cut Steam Demand and CO₂ Emissions

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ABSTRACT

The shallow ultra-heavy oil reservoirs in Karamay, China are characterized by proximal braided-river continental settings, strong heterogeneity, well-developed interlayers, and multiple vertical flow barriers. The application of conventional dual-horizontal well SAGD (Steam-Assisted Gravity Drainage) technology in such reservoirs often results in slow steam chamber development and low oil drainage rates, limiting production performance and oil-steam ratio, and posing significant challenges for efficient reservoir development. To address these issues, this study conducted reservoir architecture analysis and detailed interlayer characterization to establish interlayer distribution patterns and better understand reservoir heterogeneity. Physical and numerical simulations were employed to investigate steam chamber growth and gravity drainage behavior under multiple flow barriers. Based on these insights, technical strategies for barrier breakthrough and flow improvement were developed. Several innovative well patterns and reservoir geomechanical dilation and stimulation techniques were proposed, including vertical-horizontal well combinations, dual-layer staggered configurations, and parallel-parallel linear arrangements. These approaches promote vertical steam chamber growth and enhance oil drainage rates, leading to the formation of an efficient three-dimensional drainage system. Field application in 109 SAGD well pairs demonstrated significant improvements, with oil production rates increased by 20%–40% and recovery factors enhanced by 10–15 percentage points, thereby lowering steam demand and associated CO₂ emissions. Drawing on a decade of integrated research and field application, this executive review distills transferable lessons that can accelerate and de-risk SAGD development in similarly heterogeneous ultra-heavy-oil reservoirs worldwide.

Key words: Highly heterogeneous; SAGD (Steam-assisted Gravity Drainage); Three-dimensional drainage system; Well pattern; Geomechanical reservoir dilation

Highlights

- Leverages more than a decade of field and laboratory experience in optimizing SAGD for strongly heterogeneous, ultra-heavy-oil reservoirs.
- Presents an integrated workflow that marries geology-specific 3-D well-pattern design with staged geomechanical dilation to breach shale barriers and extend steam chambers.
- Defines six archetypal interlayer–well configurations for proximal braided-river sands, providing a predictive framework for well placement and operating strategy.
- Uses a large true-triaxial physical model and CMG-STARs simulation to confirm a three-phase chamber evolution and fatigue-shear dilation zones 10–15 m from the injector.
- Field deployment on 109 well pairs raises oil rates by 20–40 %, lifts recovery by 10–15 percentage points, and trims SOR by ~40 %, cutting CO₂ emissions.

1. Introduction

China's shallow ($\leq 1000\text{m}$) ultra-heavy-oil reserve is estimated at $\sim 3 \times 10^9\text{ t}$ (≈ 21 billion bbl), or about 0.35 % of the $\sim 6 \times 10^{12}$ bbl of heavy-oil in place worldwide; Karamay's Fengcheng alone accounts for $\approx 0.25 \times 10^9\text{ t}$ (≈ 1.8 billion bbl), making it one of the country's largest single accumulations and a strategically important domestic supply node. The Jurassic ultra-heavy oil reservoirs in the Fengcheng Oilfield were deposited in proximal braided-river systems at depths of 170–700 m. The reservoirs are mainly composed of sandstone and gravelly sandstone, featuring a permeability variation coefficient (the ratio of the standard deviation of permeability to its mean) greater than 0.7 and an interlayer frequency of up to 2.6 layers per meter. Crude oil viscosity under reservoir conditions ranges from 1 to 5 million mPa·s. These geological characteristics result in strong reservoir heterogeneity and the widespread development of discontinuous shale/mud interlayers (flow barriers), which significantly hinder steam chamber development and gravity-driven drainage during Steam-Assisted Gravity Drainage (SAGD) processes (Sun et al., 2014; Li H.Y. et al., 2015).

Numerous studies have demonstrated that mudstone or shale interlayers significantly hinder SAGD performance by restricting steam-chamber growth, reducing effective drainage height, and increasing cumulative steam-to-oil ratio (cSOR). Early physical modeling showed that interlayers located directly or obliquely above well pairs reduce oil recovery and steam efficiency, and that vertical–horizontal well patterns outperform dual-horizontal configurations in such settings (Joshi, 1986). Numerical and data-driven studies further quantified these effects: Kumar and Hassanzadeh built 240 synthetic SAGD models with random shale barriers and showed that continuous interlayers occupying $\geq 80\%$ of the well length or positioned directly between injector and producer can reduce recovery by over 40%, while short barriers under 20% are relatively benign (Kumar and Hassanzadeh, 2021a). Their subsequent review highlighted the consistent effectiveness of solvent-assisted SAGD (ES-SAGD) in such conditions and emphasized the value of fast machine-learning-based screening tools (Kumar and Hassanzadeh, 2021b). Field observations and seismic monitoring confirm these findings, showing that steam chambers tend to stall in low-permeability zones with high clay content (Zhang et al., 2005; Tang and Shi, 1995; Lu et al., 2012; He et al., 2014; Sang et al., 2015; Shi et al., 2015; Liu et al., 2020; Sun et al., 2023). Several mitigation strategies have been proposed. Well pattern modifications, such as converting lower production wells into injectors and drilling new producers below interlayers, can improve vertical connectivity (Yang and Butler, 1992). Analytical models suggest that steady-state oil rates scale with the square root of permeability and drainage height, offering guidance for pad design (Heidari et al., 2009). Increasing steam injection rates or operating pressure has been shown to accelerate interlayer breakthrough and enhance steam-chamber development (Yang et al., 2013; Yuan, 2013). Non-conventional trajectories like the undulating UB-SAGD system have proven effective in physically breaching interlayers and improving recovery (Kim and Shin, 2020). In addition, geomechanical strategies such as staged dilation during start-up have been used to enhance permeability, reduce preheating time, and mitigate the effects of heterogeneity (Sun et al., 2012; Sun et al., 2021b). Additional investigations have also examined the impacts of reservoir heterogeneity and mudstone interlayers through numerical simulations and production data analyses (Chen et al., 2008; Shin and Choe, 2009; Dang et al., 2010; Li et al., 2011).

Canada's extensive commercial SAGD experience provides a practical benchmark for understanding interlayer effects and optimizing development strategies. Gates and Leskiw used 3D reservoir simulation of an Athabasca well pair to show that maintaining an inter-well sub-cool above approximately 20 °C is critical to avoid steam breakthrough and preserve trap control, thereby stabilizing cSOR between 2.4 and 2.7 m³/m³ (Gates and Leskiw, 2010). In a field-wide evaluation, Gates and Larter compared actual operating data against thermodynamic efficiency limits and found that most SAGD projects operate at SOR values of 2–4, more than three times the theoretical minimum, which limits energy return and increases carbon intensity to around 0.7 t CO₂ per m³ of bitumen (Gates and Larter, 2014). On the emissions side, Masnadi et al. validated the OPGEE life-cycle model using real data from the Foster Creek and Christina Lake projects, demonstrating that model-predicted carbon intensities agreed within 1–5% of field values and that steam and diluent management were the dominant sources of uncertainty (Masnadi et al., 2023).

Although decades of Canadian SAGD experience have generated valuable insights, few studies have simultaneously combined well-pattern optimization with active geomechanical dilation in shallow, continental, ultra-viscous reservoirs like Fengcheng. The present work fills that gap by introducing three key innovations: (i) a systematic classification of six interlayer–well configurations characteristic of proximal braided-river deposits; (ii) the first holistic evaluation—under true-triaxial laboratory conditions—of three fully three-dimensional well patterns plus two multilateral variants; and (iii) a coupled workflow that marries these patterns with staged geomechanical dilation to propagate shear dilation zone beyond shale barriers; (iv) field validation of the combined workflow on 109 SAGD well pairs. Together, these contributions provide the fundamental shift in development strategy needed to overcome Fengcheng’s extreme heterogeneity and pervasive flow barriers, distinguishing this study from prior single-aspect investigations.

We propose an integrated development approach. First, the mechanisms of steam chamber growth and gravity-driven drainage under multiple flow barriers are investigated. Six interlayer distribution patterns associated with well trajectories are identified through reservoir architecture analysis, and a three-dimensional physical model is constructed to clarify the flow mechanisms. Based on these insights, three types of three-dimensional well patterns—dual-layer staggered, parallel-parallel linear, and vertical-horizontal point-linear combinations—are developed, enabling effective barrier bypass and steam chamber growth. Field applications showed that these well patterns increased oil production rates by 20%–40% and recovery factors by 10%–15%. In addition, two types of multilateral SAGD well configurations were designed to further enhance gravity-driven drainage through multiple pathways, increasing oil production rates by approximately 10% and improving recovery factors by 2%–5%. Furthermore, considering the dilation behavior of weakly consolidated oil sands under low confining pressure, a large-scale true triaxial physical simulation platform (1050 mm × 410 mm × 410 mm) was constructed. This platform was used to study the coupling effects of three-dimensional well patterns and reservoir dilation in strongly heterogeneous formations. The results demonstrate that staged reservoir dilation reduces permeability differences along horizontal wells, mitigates interlayer impacts on inter-well flow, and facilitates breakthrough of overlying mudstone interlayers. The integration of reservoir dilation and new well patterns increase permeability by 0.1 to 3 times, expands the mobile fluid zone, and accelerates steam chamber growth and branch-assisted drainage, resulting in a production increase of approximately 20%. Numerical simulations clarified fluid-drainage behavior in these strongly heterogeneous reservoirs and guided the design of staged geomechanical dilation along horizontal wells; subsequent pilot tests on individual SAGD well pairs validated the concept, and full-field deployment—combining the optimized well patterns with staged reservoir dilation—has now been implemented on 109 well pairs. Collectively, the proposed workflow raised oil-production rates by up to 40 % and recovery factors by 15 %, demonstrating commercial viability for reservoirs previously deemed marginal.

This paper provides a high-level synthesis of our cumulative research findings and field experience in the Fengcheng ultra-heavy-oil reservoir. Section 2 traces the evolution of SAGD development in the field and defines the principal operational hurdles. Section 3 characterizes the geometry, petrophysics, and spatial distribution of interlayers that constrain steam-chamber growth. Section 4 distills the conception, laboratory verification, and pilot performance of three novel three-dimensional well patterns and two multilateral SAGD configurations devised to bypass flow barriers. Section 5 introduces the staged geomechanical dilation technology—supported by true-triaxial modelling and coupled geomechanical–thermal simulations—that upgrades reservoir properties and integrates seamlessly with the new well patterns. Section 6 summarizes full-field deployment on 109 well pairs, quantifying the resulting gains in steam utilization, production rate, and recovery factor. Finally, Section 7 consolidates the key lessons learned and discusses how the integrated workflow can inform SAGD development in other highly heterogeneous ultra-heavy-oil reservoirs.

2. Field Development History and Challenges

Since 2007 the Fengcheng Oilfield has advanced SAGD development in distinct phases, moving from comparatively favorable, low-viscosity/high-permeability Type-II sands to the more challenging, high-viscosity/low-permeability Type-III pay. The first pilot, launched in 2008 in Blocks Z32 and Z37, demonstrated commercial viability in Type-II reservoirs and was followed by full-scale

operations in 2012; a second pilot targeting Type-III reservoirs commenced in Block Z45 in 2013, and cumulative SAGD output surpassed one million ton by 2017. Reservoir quality, however, deteriorates markedly between the two facies: net pay thins from ~30 m to ~12 m, average permeability drops from 2.5 D to 0.7 D, and crude-oil viscosity at 50 °C rises an order of magnitude—from ~20 000 mPa s to ~200 000 mPa s—so peak oil rates per well pair in Type-III zones fall to roughly one-third of Type-II levels and oil–steam ratios halve. When benchmarked against Canadian marine oil-sands projects, Fengcheng’s Type-II reservoirs reside near the lower limit of commercial SAGD feasibility, whereas Type-III sands possess only one-quarter to one-third of the horizontal permeability typical of Canadian analogues. After accounting for additional shale interlayers that depress vertical permeability, Fengcheng’s vertical-to-horizontal permeability ratio (kv/kh) ratio is <0.1, far below the ~0.8 normally required for efficient SAGD in Alberta, Canada, underscoring the necessity for the enhanced well-pattern and geomechanical dilation strategies presented in this study (Table 1).

Table 1 Comparison of geological parameters of SAGD development projects in China and Canada

Region	Project/Reservoir	Porosity (%)	Permeability (mD)	Effective thickness (m)	Oil saturation (%)
Canada	UTF B	33	3000-5000	17-20	75-85
	Foster Creek	32	10000	25-35	50-85
	Burnt Lake	33	2000-3000	20	75-80
	Mackay River	33	3000-10000	15-25	70-84
	Christina Lake	33	3000-10000	25-35	79-83
	Hangingstone	33	6000	25-40	85
	Surmont	33	2000-10000	50	79-81
	Type-II ultra-heavy oil	30	1500-2500	14-30	69-76
Fengcheng Oilfield	Type-III ultra-heavy oil	28	700-1000	10-20	59-70

To address these challenges and extend the technical limits of SAGD applications in ultra-heavy oil reservoirs, continuous efforts have been made in three key areas: optimizing three-dimensional well patterns, reservoir dilation before SAGD operation, and improving balanced and efficient fluid production. These developments have led to the formation of a three-dimensional drainage system capable of overcoming multiple flow barriers. As a result, low-permeability barriers have been successfully bypassed, reservoir flow performance has been improved, and efficient development of low-grade ultra-heavy oil reservoirs has been achieved.

3. Reservoir Interlayer Characteristics and Distribution Patterns

The ultra-heavy oil reservoirs in the Fengcheng Oilfield contain two types of interlayers, distinguished by lithology and petrophysical properties. Lithologic interlayers are mainly composed of mudstone, silty mudstone, and calcareous sandstone, deposited as slack-water layers within point bars. These interlayers are poorly permeable, generally corresponding to oil stain zones, with porosity ranging from 1.8% to 6.0% and permeability from 0.5 to 10.0 mD. Petrophysical interlayers mainly consist of silty sandstone, muddy silty sandstone, and minor gravelly sandstone, formed by muddy fills within braided river channels. These interlayers have moderate permeability, typically corresponding to oil trace or oil stain levels, with porosity ranging from 15.8% to 18.0% and permeability from 100 to 120 mD.

Based on outcrop analogs of braided river deposits and using embedded modeling, multi-dimensional characterization, and dynamic constraints, a fine-scale geological model was established. The analysis shows that interlayer thickness ranges from 0.4 to 6.8 m, with an average of 1.3 m; interlayer length ranges from 57.2 to 790.8 m, averaging 167.7 m; and interlayer width ranges from 50.2 to 460.3 m, averaging 119.5 m. Most interlayers exhibit a lenticular (potato-shaped) distribution and are dominated by petrophysical interlayers, which account for approximately 68% of the total.

Based on interlayer position, geometry, size, and their relationship with horizontal wells, two types of interlayers and six typical distribution patterns were identified (Fig.1). The first type includes interlayers that develop between the injection and production wells, comprising three patterns: (A1) a single, large-area continuous interlayer; (B1) one relatively large interlayer combined with a partial-

shielding and a full-shielding interlayer above the injection well; and (C1) a small-scale interlayer with a larger full-shielding interlayer above the injection well. The second type includes interlayers located above the injection well, also comprising three patterns: (A2) a single full-shielding interlayer directly above the injection well; (B2) three interlayers above the injection well with progressively increasing coverage; and (C2) two offset partial-shielding interlayers overlain by a full-shielding interlayer at the top. The influence of these interlayers on steam chamber development decreases in the order of (A1) > (B1) > (C1) > (A2) > (B2) > (C2).

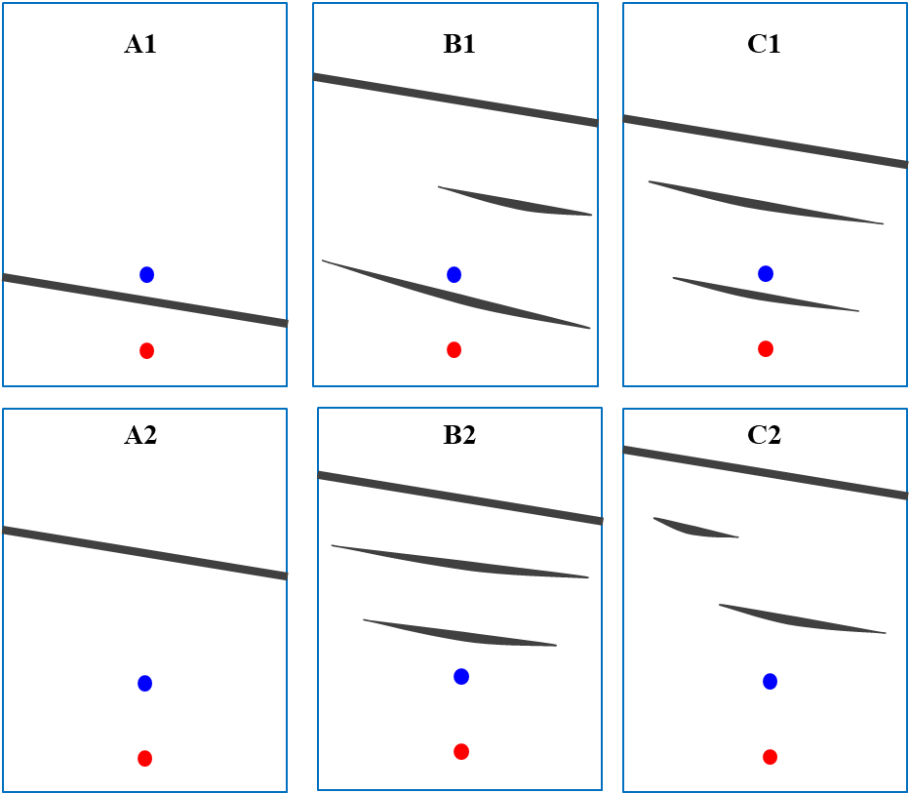


Fig. 1 Typical distribution patterns of interbedded barrier (Sun et al., 2021)

4.Three-Dimensional (3D) Well Patterns

4.1 Steam Chamber Development Characteristics under Multiple Flow Barriers

4.1.1 Three-Dimensional Lab Physical Modeling Study

At the PetroChina Research Institute of Petroleum Exploration and Development (RIPED) in Beijing we constructed a large-scale, three-dimensional physical model to isolate how shale interbeds govern steam-chamber evolution. The apparatus is a stainless-steel cylinder 1.0 m in diameter and 1.0 m high, rated for continuous steam injection at temperatures exceeding 250 °C and pressures up to 5 MPa. A slotted stainless-steel tube running axially through the model replicates the horizontal wellbore, while sand-pack and synthetic shale layers are built to the target porosity–permeability contrast measured in Fengcheng cores. Geometric, thermal, and fluid-property similarity criteria were applied rigorously so that key dimensionless groups (gravity number, mobility ratio, and Peclet number) match field conditions, ensuring that laboratory observations scale quantitatively to the reservoir. Embedded thermocouples and pressure taps provide full 3-D imaging of temperature and steam-saturation fronts, allowing us to track in real time how individual shale baffles suppress vertical rise, redirect lateral growth, and ultimately influence gravity-drainage efficiency. The physical model included three types of interlayers: two long and short interlayers (1#, 2#, and 3#) located above the injection well, and a short interlayer (4#) positioned between the injection and production wells. The lateral extent of the interlayers was set equal to the reservoir width, with the long interlayers representing broader and more influential barriers in the simulation. Fig 2. demonstrates the setting of interlayers in the 3D physical simulation model.

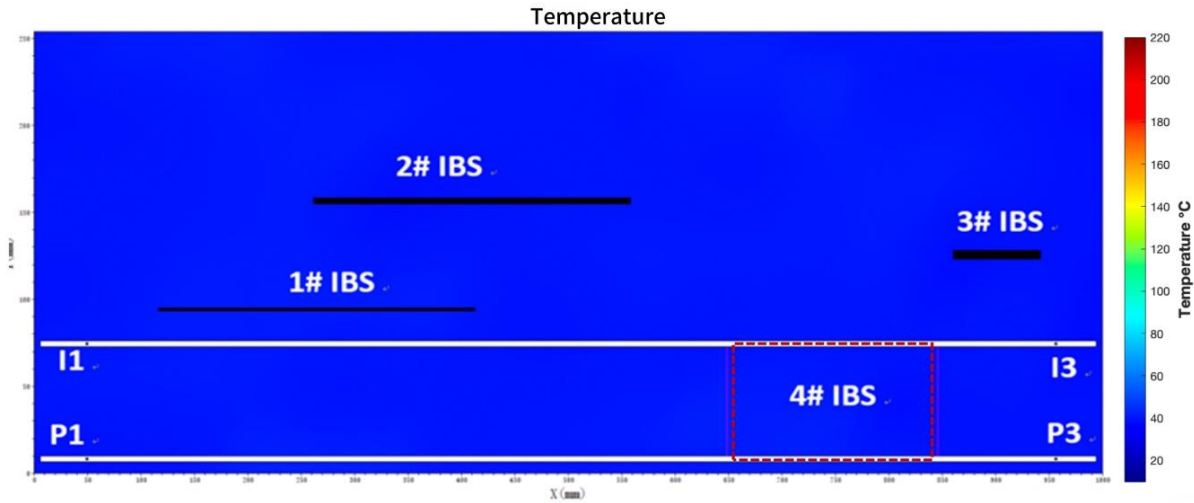
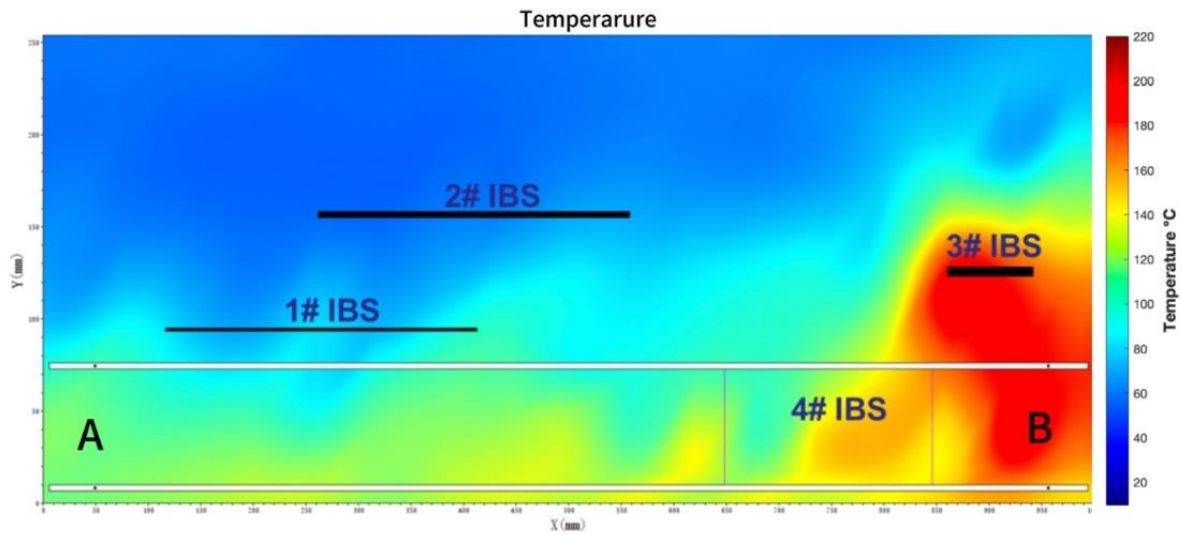
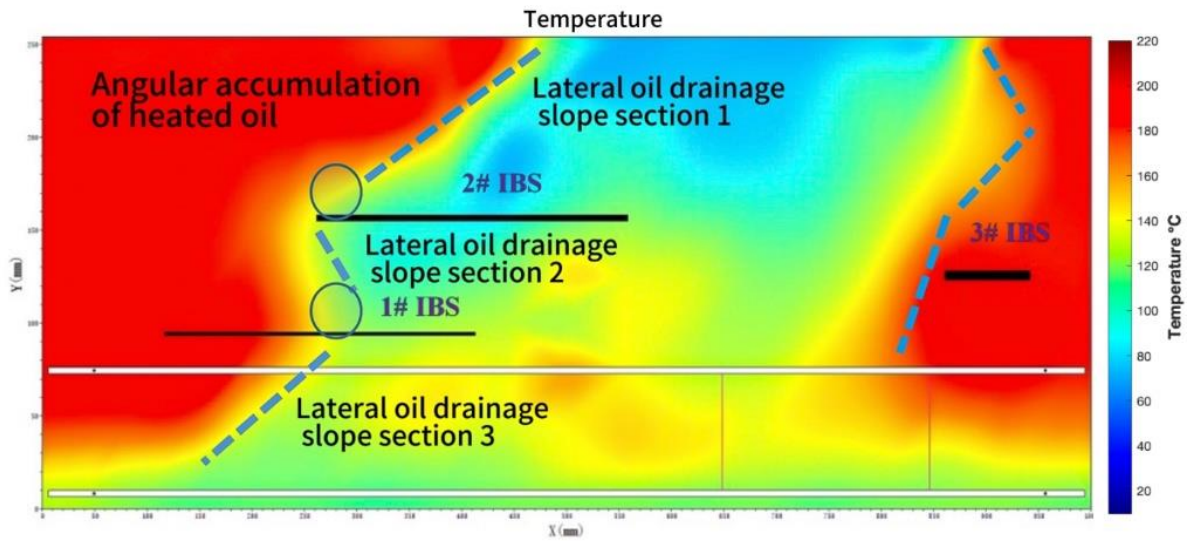


Fig. 2 Setting of interlayers in the 3D lab physical model (IBS stands for interbed shale)

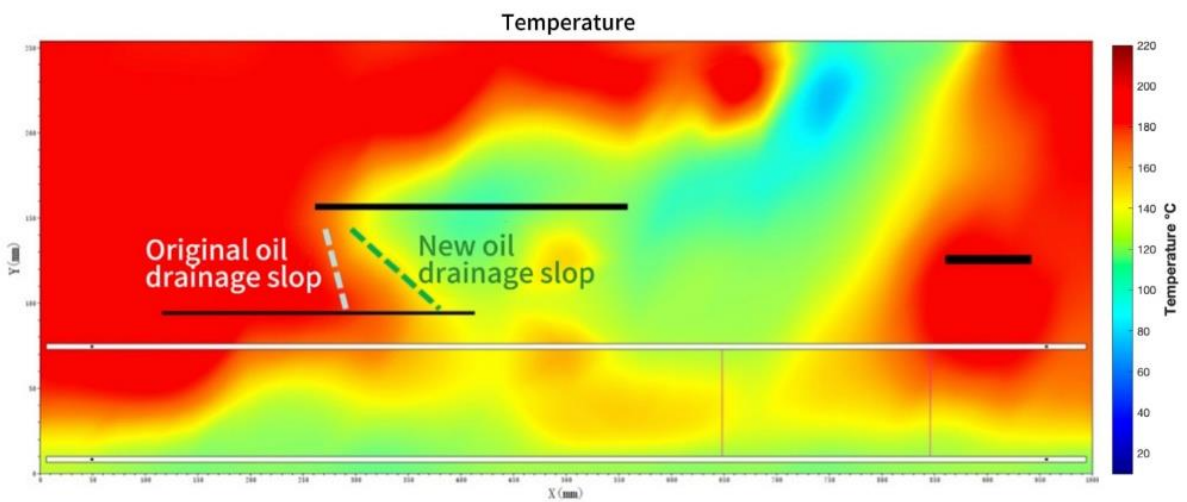
After circulation pre-heating elevated the inter-well average temperature to $\sim 110^{\circ}\text{C}$, a nascent steam chamber took shape at monitoring point B—the toe of the horizontal pair—while point A at the heel remained only weakly heated. Vertical communication was immediately throttled by Interlayer 4, which lies between the injector and producer, and upward chamber growth was capped by the short Interlayer 3 located above the injector (Fig. 3a). During early production, buoyant steam accumulated beneath Interlayer 3, then diverted laterally—a classic override response—until it reached an un-blocked interval where it could rise. This lateral detour established a new drainage slope above the barrier, and the steam chamber continued to feed heat into the strata overlying Interlayer 3, effectively neutralising its shielding effect. As the chamber advanced into the interval containing several stacked interbeds, each shale layer segmented the steam front, producing a staircase-like, multi-segment geometry along the wellbore (Fig. 3b). Continued injection allowed these discrete segments to elongate toward the heel, ultimately coalescing into a single continuous chamber that spanned the entire horizontal section (Fig. 3c). The experiment thus reveals a three-stage evolution under multiple flow barriers: (1) initial vertical suppression beneath the interbeds, (2) lateral diversion and slope formation above short barriers, and (3) longitudinal coalescence of previously isolated chamber segments—insights that explain why field steam chambers often appear patchy and discontinuous before eventually merging along the well trajectory. Therefore, under the influence of multiple flow barriers, steam chamber development in SAGD is characterized by vertical suppression and lateral diversion, while gravity-driven oil drainage exhibits angular accumulation and flow merging.



(a) Early stage of preheating



(b) Early production stage



(b) Late production stage

Fig. 3 Comparison of temperature distribution in different stages of 3D physical simulation SAGD

4.1.2 Numerical Simulation

To upscale the 3-D laboratory insights to field dimensions, we modelled steam-chamber evolution with CMG STARS, a fully coupled thermal-compositional simulator widely applied to SAGD. Geological layering, fluid PVT properties, and shale-interbed architecture were imported from the high-resolution Petrel model of Section 3, and local grid refinement to 0.5–1 m in the well vicinity preserved the key dimensionless groups—gravity number, mobility ratio, and Peclet number—that govern steam override and gravity drainage. The model was then history-matched to both the physical experiment and early production data, yielding a calibrated platform for subsequent sensitivity analysis.

Under uniform, barrier-free conditions the numerical model reproduces the classic fan-shaped steam chamber: steam rises directly above the injector and then flares outward, creating a smooth temperature isotherm that expands symmetrically along the well pair (Fig. 4a). Introducing a shale interlayer immediately above the injector arrests this vertical rise; steam is forced to migrate laterally until it finds a breach at the interlayer edge, after which it resumes upward propagation, yielding a stepped or “dog-leg” chamber profile (Fig. 4b). As additional interlayers are stacked, the cumulative baffle effect intensifies: each layer truncates the vertical trajectory, so successive steam pulses spend progressively more time spreading sideways, fragmenting the chamber into discrete segments and sharply reducing the heated pay thickness. The confined vertical growth also promotes higher local condensation, and the produced fluids emerge with elevated water saturation, a clear indicator of steam entrapment and inefficient gravity drainage.

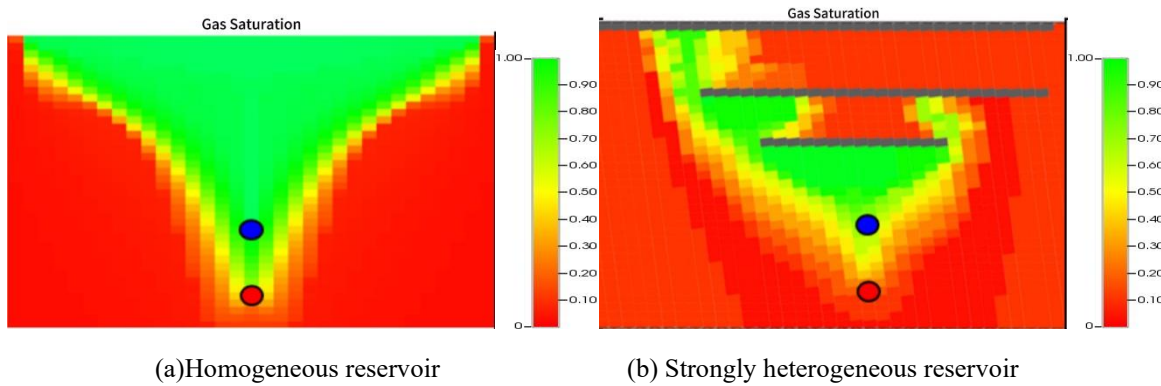
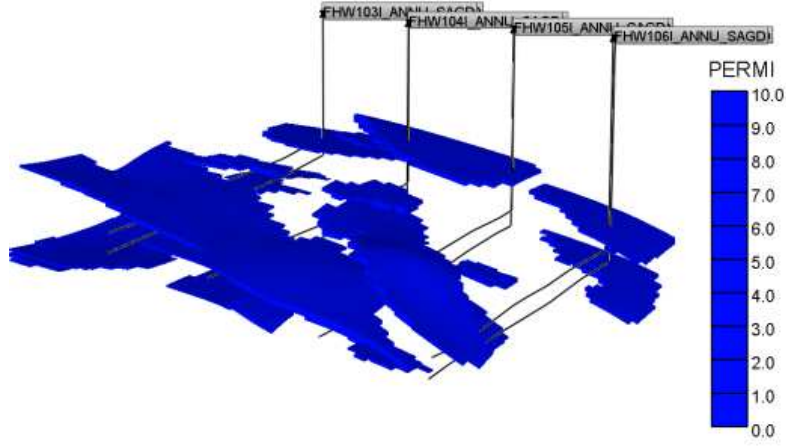
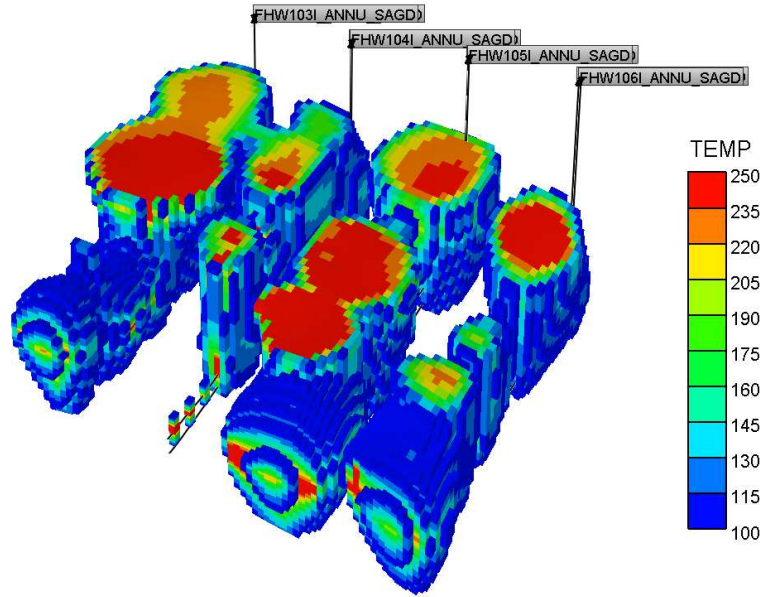


Fig. 4 Steam chamber development characteristics under different reservoir conditions, shown by gas saturation distribution

Fig 5 gives the SAGD simulation results in a real SAGD simulation project. Based on the heterogeneous geological model of the Z32 SAGD pilot area, steam chamber development was simulated. The results show that each well group contains interlayers of varying degrees, covering all six types of interlayer patterns described in the previous section (Fig. 5a). Under the influence of multiple interlayer types, the steam chambers of different well groups exhibit significant variations in width, height, and length. Within individual well groups, steam chamber development along the horizontal section is highly non-uniform. In some well segments, the steam chambers remain in the vertical expansion stage, while in others, lateral expansion has already occurred, with some chambers merging with those of adjacent well groups (Fig. 5b).



(a) Interlayer distribution characteristics (permeability field)



(c) Steam chamber development characteristics (temperature field)

Fig. 5 Steam chamber development in the SAGD pilot area of the Z32 block, Xinjiang Oilfield (as of December 2023)

4.1.3 Analytical Method Study

The influence of interlayer shielding on the recoverable reserves controlled by SAGD well groups was analyzed. For interlayers located above the injection well (Fig. 6), the effective recoverable reserves (N) consist of the reserves affected by the interlayer (N_2) and those unaffected by the interlayer (N_3), as shown in Equation (1). The calculation methods for the different reserve components are provided in Equations (2) to (4).

$$N = N_2 + N_3 \quad (1)$$

$$N_1 = l(H - h)W\phi S_{oi}\rho_{oi}/B_{oi} \quad (2)$$

$$N_2 = lhW\phi S_{oi}\rho_{oi}/B_{oi} \quad (3)$$

$$N_3 = (L - l)HW\phi S_{oi}\rho_{oi}/B_{oi} \quad (4)$$

An effective recoverable reserve coefficient (ε) is introduced and defined as follows:

$$\varepsilon = \frac{N}{N_1 + N_2 + N_3} \quad (5)$$

An effective recoverable reserve coefficient (ϵ) is introduced and defined as follows:

$$\epsilon = 1 - \frac{l}{L} \left(1 - \frac{h}{H}\right) \quad (6)$$

In the above equations: N is the geological reserves, t; L is the horizontal well length, m; l is the length of the interlayer along the horizontal well, m; H is the effective reservoir thickness, m; h is the interlayer thickness, m; W is the spacing between SAGD well pairs, m; ϕ is the porosity, fraction; S_{oi} is the initial oil saturation, fraction; ρ_{oi} is the crude oil density, t/m³; B_{oi} is the oil formation volume factor, dimensionless; ϵ is the effective recoverable reserve coefficient, dimensionless.

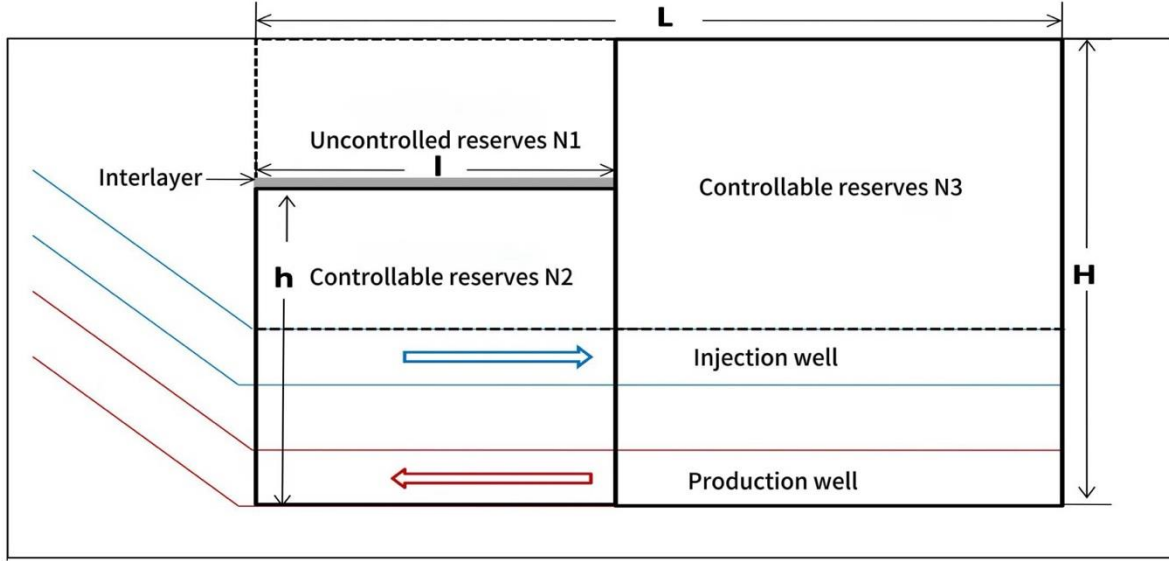


Fig. 6 Reserve control diagram of SAGD well pair with dual- horizontal wells

By substituting different interlayer lengths (l) and heights (h) into Equation (6), the relationship between interlayer dimensions and the effective recoverable reserve coefficient (ϵ) was determined, providing a quantitative assessment of the impact of interlayers on SAGD recoverable reserves. When the interlayer length accounts for 50% of the horizontal section length and the interlayer height accounts for 50% of the total effective thickness, the effective recoverable reserve coefficient is only 0.75. The results indicate that longer interlayers and lower vertical positions correspond to smaller values of ϵ (Fig. 7).

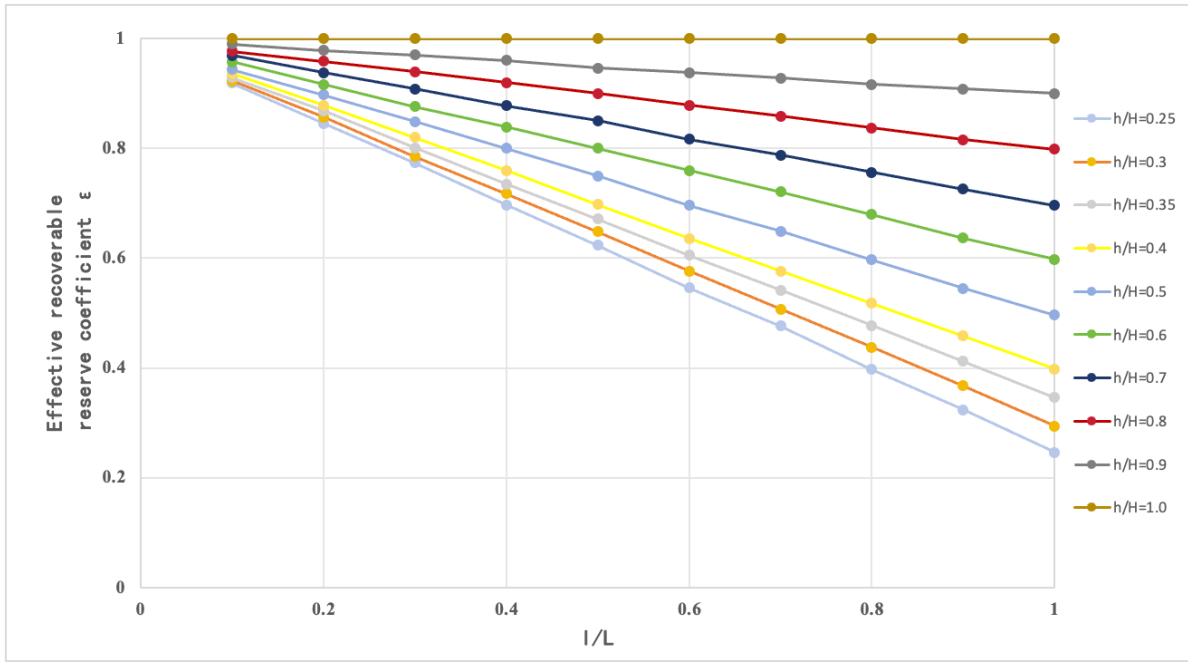


Fig. 7 Curves of interbedded barriers length and interbedded barriers height with effective productive reserve coefficient

For interlayers located between the injection and production wells, the impact on recoverable reserves along the horizontal section is more pronounced. In this case, the effective recoverable reserve coefficient can be expressed as follows:

$$\varepsilon = 1 - \frac{l}{L} \quad (7)$$

Where l is the interlayer length and L is the horizontal section length. This indicates that as the interlayer length increases, the proportion of recoverable reserves decreases correspondingly.

4.2 Well Pattern Optimization

Insights from the 3-D laboratory model and CMG STARS simulation in previous section showed that stacked shale interbeds choke vertical steam rise, fragment the chamber into isolated segments, and leave large volumes of pay unheated. Guided by these findings and early field results, we shifted from the conventional dual-horizontal-well layout to a suite of optimized well configurations expressly designed to sidestep flow barriers and re-establish continuous gravity drainage. By tailoring well spacing, orientation, and vertical positioning, these new patterns create alternative steam pathways, reconnect isolated compartments, and enlarge the effective drainage volume, thereby expanding recoverable reserves and boosting production performance. This section describes the design rationale, key geometric parameters, and field validation of these barrier-bypassing patterns.

4.2.1 Vertical-Horizontal SAGD Well Pattern

For the second type of interlayers, when the interlayer length above the injection well is less than 1/4 of the horizontal section length (L), a vertical-horizontal SAGD well pattern was proposed (Fig. 8). The study shows that this well configuration, which utilizes point-source steam injection from a vertical well to assist lateral displacement and linear oil drainage through dual horizontal wells, effectively addresses the problem of slow recovery and low utilization of oil above the interlayer. Field results indicate that the oil production rate in the block increased from 3.5% to 4.2% (Fig. 9).

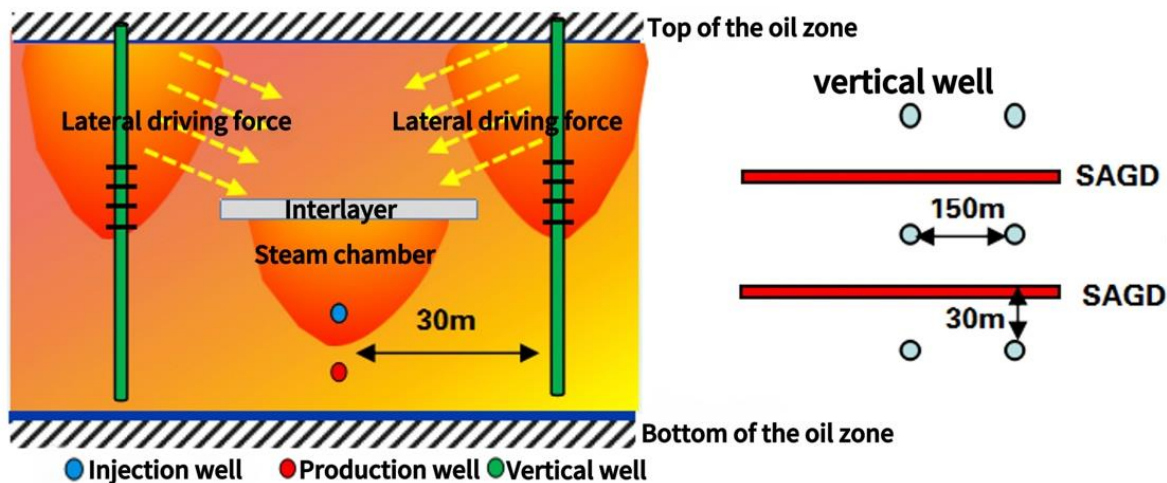


Fig. 8 Horizontal and vertical views of the vertical-horizontal SAGD well pattern

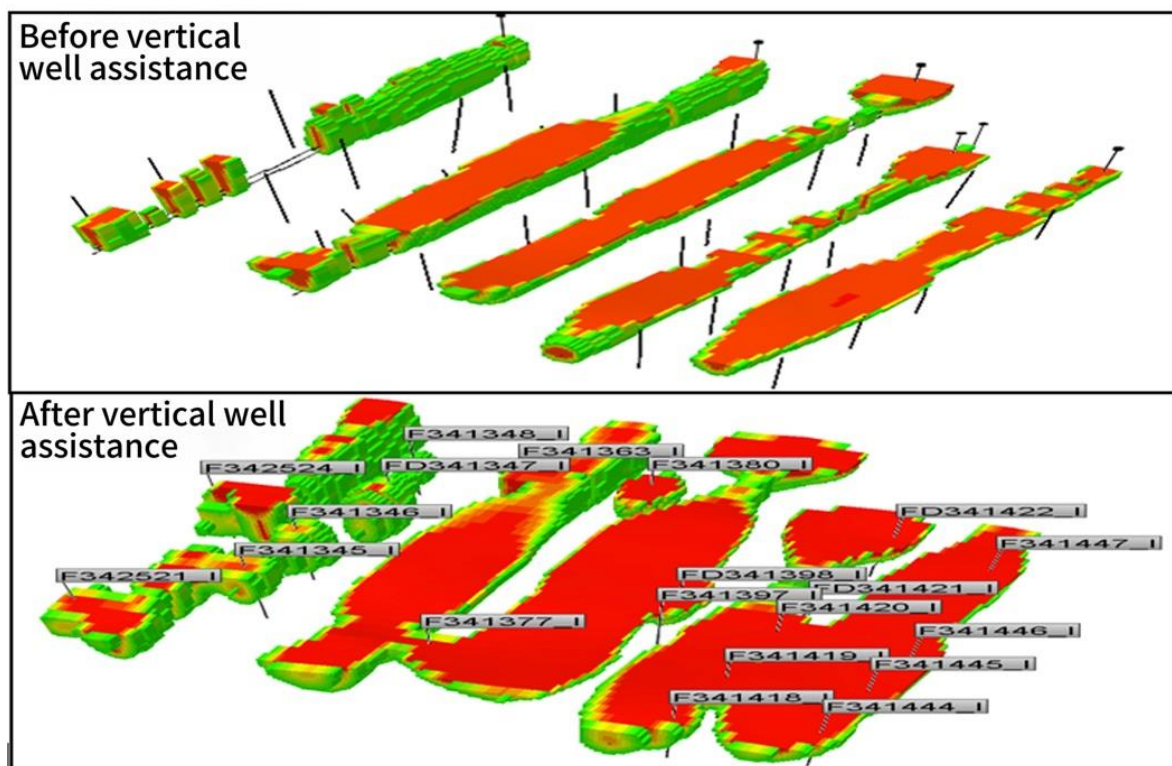


Fig. 9 Steam chamber development before and after applying the vertical-horizontal SAGD well pattern (temperature distribution)

4.2.2 Dual-Layer Staggered 3D SAGD Well Pattern

For the second type of interlayers, when the interlayer length exceeds 1/2 of the horizontal section length (L), a dual-layer staggered 3D SAGD well pattern was proposed (Fig. 10). In this configuration, the well groups above and below the interlayer are arranged in a staggered layout, enhancing the recovery of reserves and avoiding interference between well groups. The study shows that for reservoir zones where continuous interlayers are developed above the injection well, the dual-layer staggered 3D SAGD well pattern enables simultaneous development of large-scale flow barrier reservoirs. As a result, the oil production rate increased from 2.8% to 4.5%, and the recovery factor improved from 54% to 65% (Table 2).

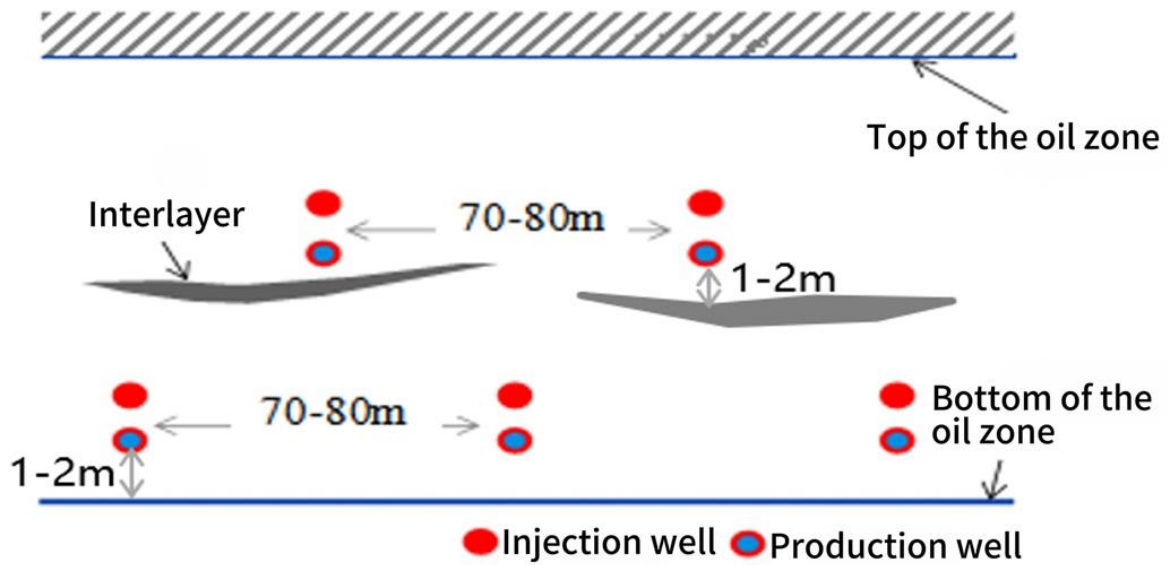


Fig. 10 Schematic diagram of the dual-layer staggered 3D SAGD well pattern

Table 2 Comparison of production performance between conventional and dual-layer staggered 3D SAGD well patterns

Pattern type	Plateau oil production (t·d ⁻¹)	Production- injection ratio	Oil-steam ratio	Oil production rate (%)	Recovery factor (%)
Conventional SAGD well pattern	37	0.90	0.21	2.8	54
Dual-layer staggered 3D SAGD well pattern	72	0.97	0.22	4.5	65

4.2.3 Parallel-Parallel Linear SAGD Well Pattern

For the second type of interlayers, when the interlayer length ranges between 1/4 and 1/2 of the horizontal section length (L), a parallel-parallel linear SAGD well pattern was proposed (Fig. 11). In this configuration, the auxiliary horizontal well is located in the middle of two SAGD well groups, with a horizontal section length approximately equal to that of the SAGD well pairs. The vertical position of the auxiliary horizontal well is parallel to the production wells in the SAGD well groups. The study shows that the “two injectors and three producers” horizontal well configuration increases the effective oil drainage pathways and enables the recovery of cold oil zones between well groups separated by discontinuous interlayers. As a result, the oil production rate in the block increased from 2.5% to 3.6%, and the recovery factor improved from 55% to 68% (Table 3).

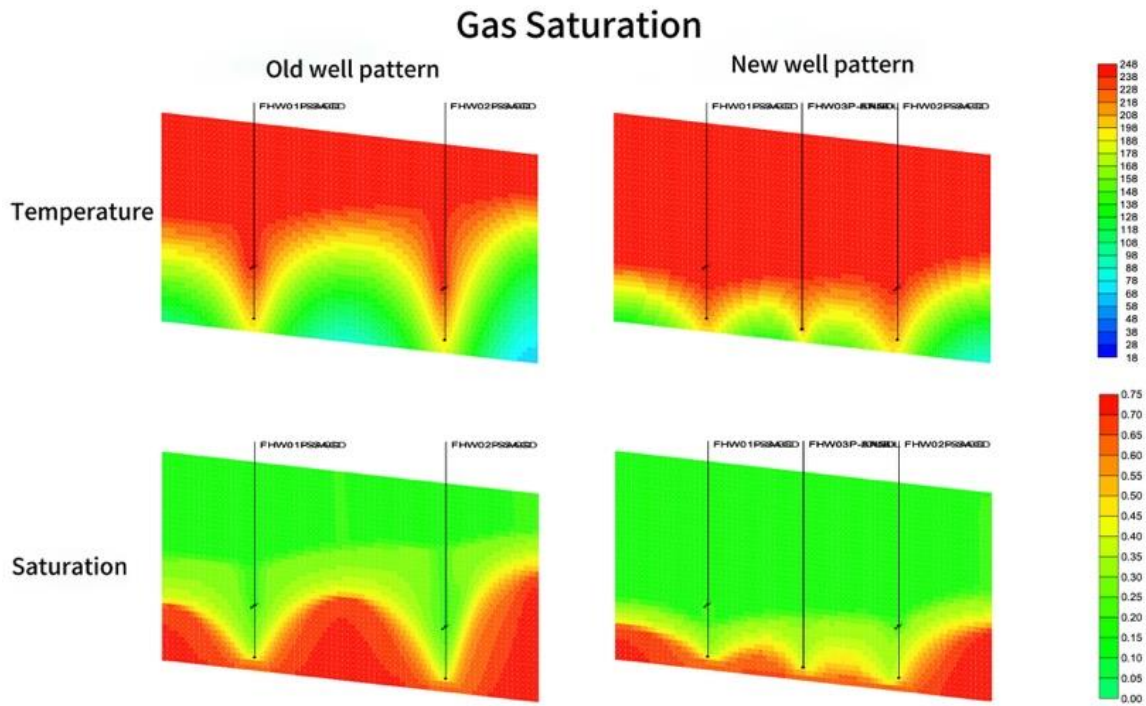


Fig. 11 Temperature evolution in the parallel-parallel linear SAGD well pattern

Table 3 Comparison of production indicators between conventional SAGD and horizontal well-assisted SAGD

Pattern type	Plateau oil production (t·d ⁻¹)	Production-injection ratio	Oil-steam ratio	Oil production rate (%)	Recovery factor (%)
Conventional SAGD well pattern	35	0.90	0.20	2.5	55
Horizontal-well-assisted SAGD	48	1.1	0.25	3.6	68

4.3 Multilateral SAGD Well Configuration

For the second type of interlayers, specifically the B2 and C2 distribution patterns, a multilateral SAGD technique (including primary and secondary branches or so-called “fish bone” SAGD) was proposed to break through interlayer barriers and enhance gravity drainage through multiple flow paths (Fig. 12). Compared with conventional SAGD operations, the multilateral SAGD approach, combined with reservoir dilation techniques, increases the steam sweep area of the branches, heats the surrounding reservoir, and establishes oil drainage pathways above the interlayers (Fig. 13). As a result, the peak oil production rate increased by 1.3 times (Fig. 14).

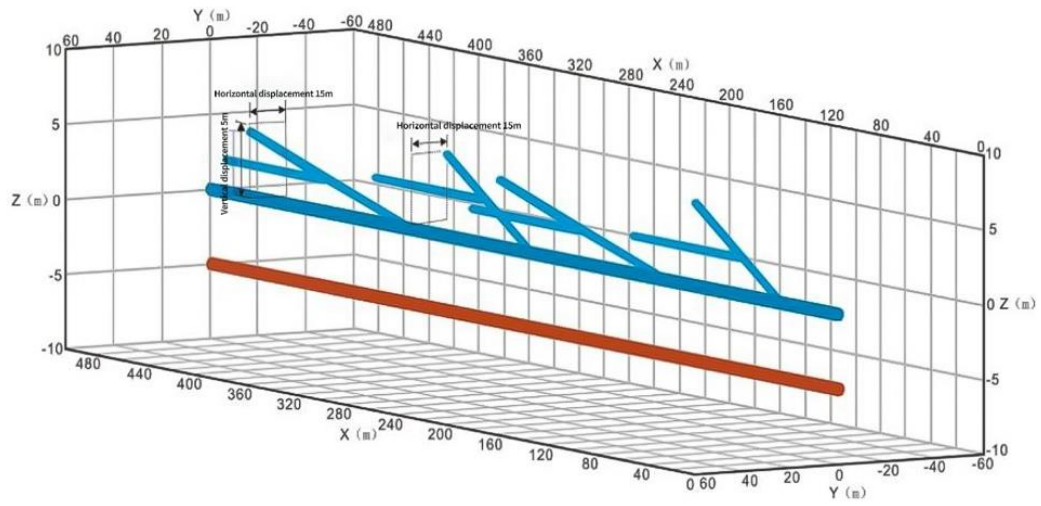


Fig 12. Diagram of two-stage multi-branch SAGD well pattern

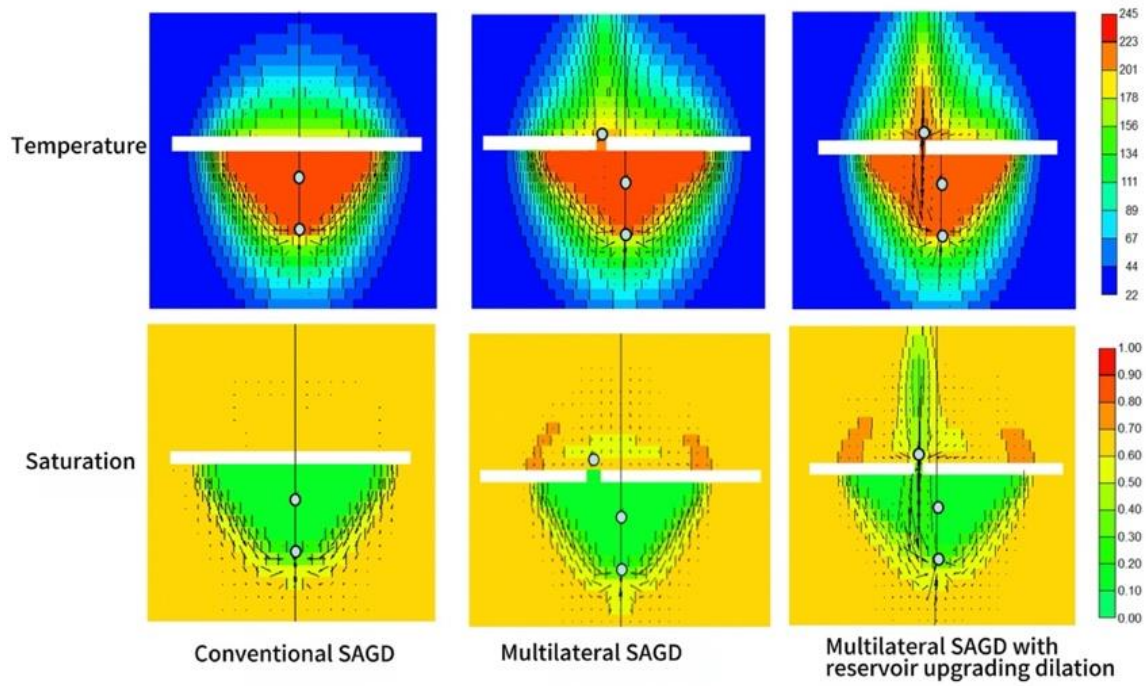


Fig. 13 Comparison of steam chamber development characteristics (temperature and oil saturation distribution) among conventional SAGD, multilateral SAGD, and multilateral SAGD with reservoir upgrading dilation

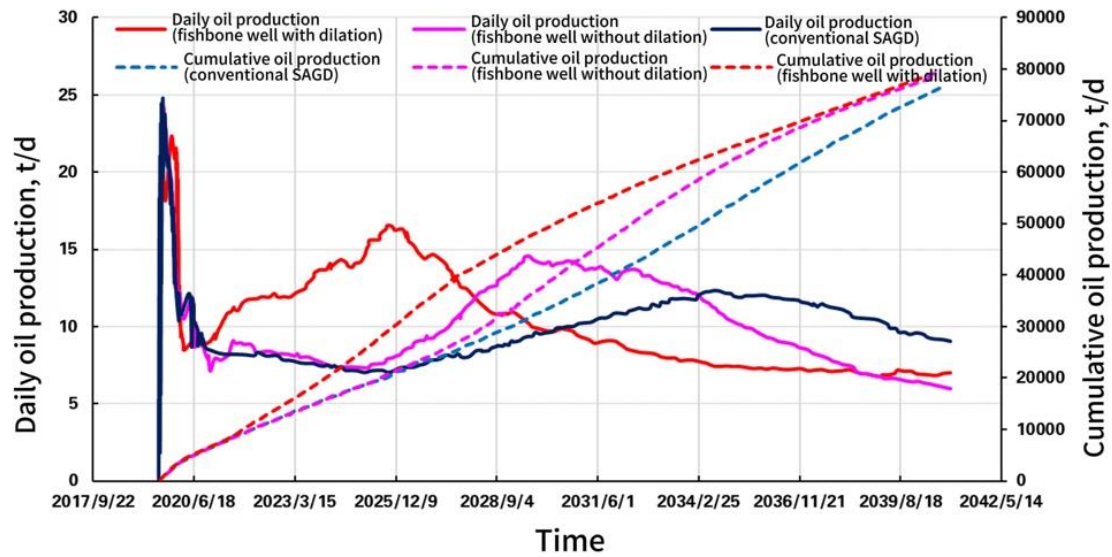


Fig. 14 Production comparison curves under different development strategies

5. Geomechanical Reservoir Dilation

5.1 Geomechanical Dilation to Boost the Reservoir Permeability and Breakthrough Shale Interlayers

Laboratory and simulation results showed that the three-dimensional well patterns struggle when several shale interbeds lie both between and above the SAGD well pair; vertical steam advance stalls and large pockets of cold pay remain undrained. A complementary tactic is therefore required. In unconsolidated oil-sands—such as the McMurray Formation in Alberta, Canada—operators have long exploited geomechanical dilation: short, high-pressure fluid injection cycles temporarily raise pore pressure above the minimum principal stress and below reservoir fracturing pressure, inducing shear slip and grain separation that boost porosity and permeability by one to several times. Similar “dilation start-up” pilots were introduced to Xinjiang’s Fengcheng field in the mid-2010s (Sun et al., 2021), where they successfully created a hydraulic conduit between the injector and producer and cut the circulation pre-heating period. Their drawback, however, was a limited vertical reach—dilation concentrated mainly in the pay sand sandwiched between the two horizontals and did little to breach the overlying interbeds that restrict steam-chamber lift during the production phase.

Building on the original “dilation start-up” concept, we have developed an integrated reservoir-dilation and stimulation workflow that meshes seamlessly with the barrier-bypassing well patterns outlined in Section 4. Staged high-pressure injections are timed and positioned to coincide with vertical–horizontal hybrids, dual-layer staggered arrays, parallel–parallel layouts, and “fish-bone” SAGD pairs, allowing the resulting shear bands to propagate both upward and laterally, slice through multiple shale interbeds, and reconnect otherwise isolated flow compartments. A tailored sequence of working fluids—hot water, polymer slurries, and other temporary-plugging agents—emulates the zonal-isolation logic of hydraulic fracturing, directing dilation precisely where permeability enhancement is most needed and evening out flow along the horizontal sections. The goal is to create a larger, more uniform three-dimensional dilated envelope that abbreviates start-up and sustains steam-chamber growth over the entire production life. As of 2025, more than 30 Fengcheng well pairs have been stimulated with this method, and its effectiveness has been confirmed through extensive true-triaxial large-scale physical modelling, coupled reservoir–geomechanical simulations, rock-mechanics triaxial testing, and field minifrac measurements of in-situ stress.

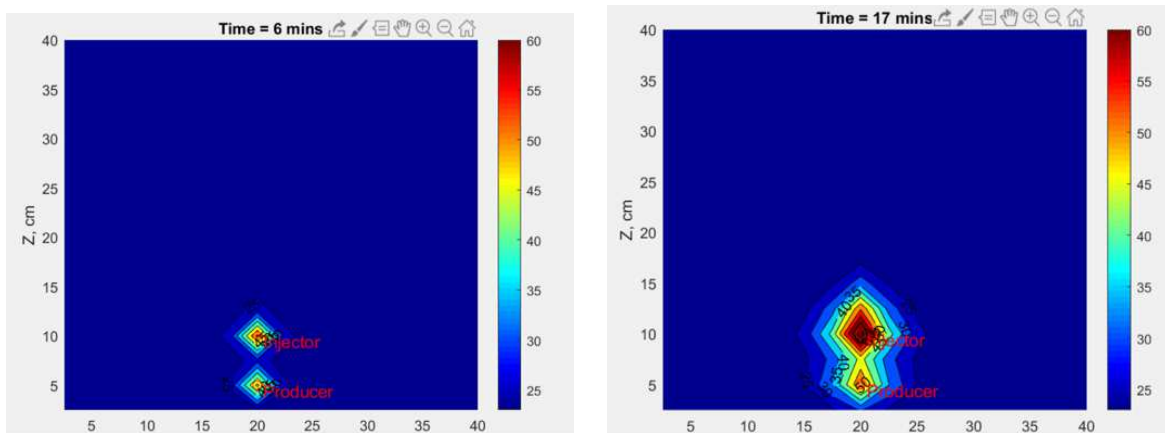
5.2 Geomechanical Properties and In-Situ Stresses

Triaxial core tests and minifrac analyses show that the Fengcheng oil-sands are weak and unconsolidated: unconfined compressive strength is < 2 MPa, Young’s modulus 0.6–0.9 GPa, cohesion 0.4–0.8 MPa, and internal friction angle 29–31°. At burial depths of 170–

500 m the reservoir is governed by a normal-faulting stress regime ($\sigma_v > \sigma_{Hmax} > \sigma_{hmin}$), with the maximum horizontal stress (σ_{Hmax}) trending NW–SE (azimuth $\approx 130\text{--}140^\circ$). Minifrac data place the minimum horizontal stress gradient (σ_{hmin}) between 0.014 and 0.016 MPa m⁻¹, while σ_{Hmax} and the vertical stress gradients average ~ 0.020 MPa m⁻¹ and ~ 0.022 MPa m⁻¹, respectively. Because σ_{hmin} is low, elevating pore pressure by only 2–3 MPa above the in-situ gradient is sufficient to trigger shear slip and grain dilation. Stepwise pressure ramps conducted under these conditions produce a complex dilation zone whose volumetric strain peaks at $\sim 7\%$, and whose radial reach averages 10–15 m—compared with the 6–8 m typically achieved by conventional SAGD start-up cycles (Sun et al., 2021; Wang et al., 2022). By propagating dilation zone both upward and laterally, the treatment breaches multiple shale interbeds, balances permeability along the horizontal well, and establishes low-resistance drainage pathways, thereby outperforming earlier dilation-only approaches and markedly enhancing production from strongly heterogeneous ultra-heavy-oil reservoirs.

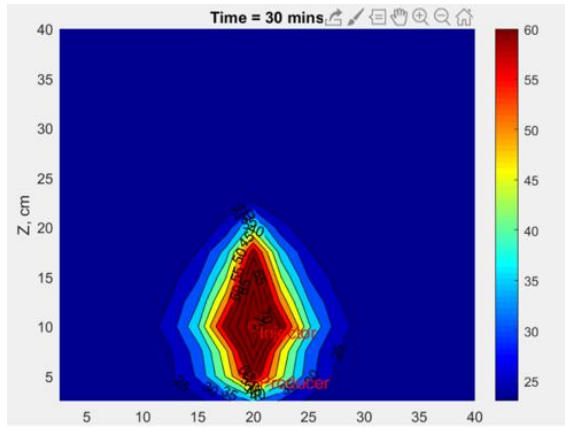
5.3 Large-Scale True Triaxial Physical Model for Geomechanical Dilation on SAGD Wells

The cornerstone of our dilation workflow is a 105 cm $\times$ 41 cm $\times$ 41 cm true-triaxial physical model that replicates the low-stress environment and weak grain bonding of Fengcheng oil sands under field-representative pore-pressure and temperature conditions (Wang et al., 2021). Independent servo frames apply and maintain the three principal stresses while steam, hot water, or steam-plus-gas is injected through a slotted “horizontal well.” Dozens of embedded fiber-optic temperature sensors, pressure transducers, and 3-D digital image–correlation markers capture the coupled thermal, hydraulic, and mechanical response in real time, allowing direct visualization of dilation fronts and fracture initiation. The model faithfully reproduces field stress paths ($\sigma_v > \sigma_{Hmax} > \sigma_{hmin}$) and records shear-induced dilation zone propagation under controlled pressure ramps, providing a laboratory analogue for staged high-pressure injections. Results confirm that cyclic pressurization to 1–1.5 MPa above σ_{hmin} initiates micro-shear slip, generating volumetric strains up to 7% and permeability gains of 3 times. The dilated zone extends 10–15 cm (field-scaled to $\approx 10\text{--}15$ m) from the wellbore and, crucially, propagates vertically through synthetic shale interbeds, demonstrating the feasibility of mechanically breaching flow barriers. When the model incorporates branch-well geometries from our multilateral designs, dilation zones coalesce, forming a continuous high-permeability sheath that accelerates steam-chamber symmetry and reduces start-up time by more than 50%. Fig. 15 gives an example results of the large scale SAGD dilation physical model in which the hot water and polymer were used for the dilation and the dilation zone is monitored by 120 temperature sensors. These findings underpin the field-scale success of staged dilation in 109 Fengcheng SAGD well pairs and validate the integration of geomechanical stimulation with 3-D well-pattern optimisation for heterogeneous ultra-heavy-oil reservoirs.

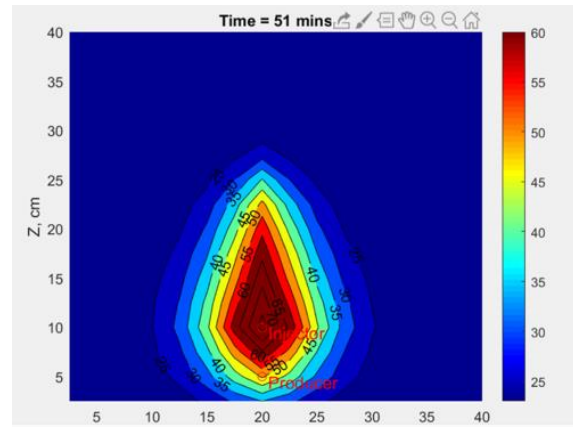


(a) Low-pressure conditioning stage

(b) Inter-well reservoir dilation stage



(c) Reservoir dilation stage using polymer



(d) reservoir stimulation

Fig. 15 The dilation zone detected in large scale SAGD physical model (temperature distribution)

5.4 Field Implementation of Staged Geomechanical Dilations on Oilsands Reservoir

Since 2020, The staged geomechanical dilation on different SAGD well patens were routinely executed in the field. A normal geomechanical dilation process consist of the following stages (Fig. 16):

Low-pressure conditioning stage: Low fluid pressure was applied to the reservoir surrounding the wellbores, increasing the water saturation near the wells and improving reservoir property homogeneity. At this stage, dilation zones of 1–2 meters were formed around both the injection and production wellbores. 2. Dilation stage between SAGD well pairs: By increasing the injection volume, the bottom-hole pressure was further raised, and the expansion zones around the injection and production horizontal wells were enlarged. Expansion zones of 2–3 meters were formed near the wellbores, and a distinct temperature field was established between the wells.

Temporary-plugging and uniform-dilation stage: Once an initial dilation envelope has been created along the horizontal leg, mechanical and petrophysical heterogeneity can leave large undilated segments, producing uneven injectivity and poor steam conformance. To equalize the response, a temporary-plugging sequence is executed: a slug of high-viscosity polymer (or other thermally degradable diverting agent) is injected at low rate to seal the already dilated, high-permeability intervals; hot water is then re-injected at elevated pressure, forcing the dilation front to propagate into the previously undisturbed, low-permeability segments. The polymer breaks down or is flushed as the new dilation zone forms, after which the cycle can be repeated—polymer plug, pressurize, flush—until distributed temperature sensing (DTS) and downhole thermocouple data show a continuous, uniform temperature rise along the entire wellbore, confirming that a near-homogeneous three-dimensional dilation sheath has been achieved. This staged diversion strategy ensures that permeability enhancement and fracture density are balanced along the well, maximizing steam-chamber symmetry and long-term production efficiency (Sun et al., 2021; Wang et al., 2022).

Cyclic Reservoir Dilation: Both injector and producer were pulsed at elevated rates, subjecting the oil-sand to repeated high-pressure loading and unloading. Each cycle triggered fatigue-induced shear along grain contacts, progressively unzipping the matrix and driving a dilated fracture network 10–15 m upward from the injector—an interval that conventional steam cannot effectively access.

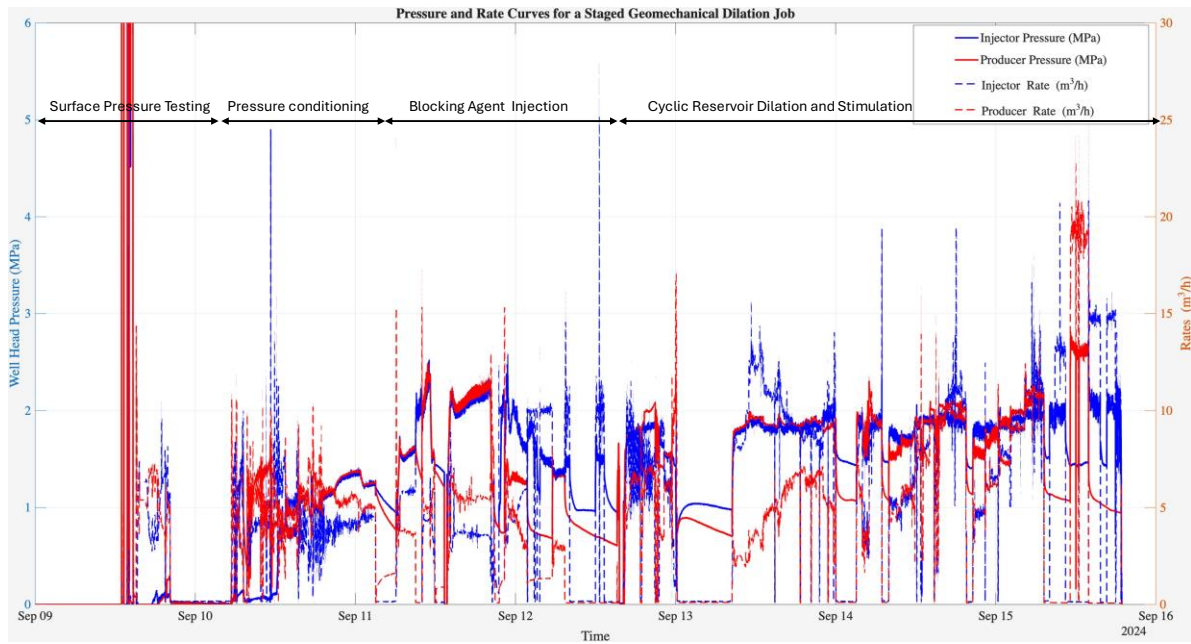


Fig. 16 A field example of staged dilation on SAGD well in Fengcheng ultra-heavy oilsands reservoir

5.5 Staged Dilation on Multilateral SAGD Wells

For reservoirs with strong heterogeneity and well-developed interlayers, multilateral wells (or fish bone SAGD) can promote rapid steam chamber expansion and address the issue of residual oil retention above the interlayers. A two-step staged preconditioning process combined with pulsed dilation effectively mobilizes the branch sections of the injection horizontal wells. Fig. 17 illustrates the results from large scale physical model. In the first step of staged preconditioning, the injection pressure is set at 4,000 kPa for 30 minutes, while in the second step, the injection pressure is increased to 5,500 kPa for 20 minutes. Compared with conventional SAGD, this approach achieves faster preheating. During field implementation, the pore pressure preconditioning time and the working fluid volume of multilateral horizontal wells are significantly greater than those of conventional rapid and uniform SAGD startup, resulting in a wider expansion sweep area and more favorable expansion effects (Fig. 17).

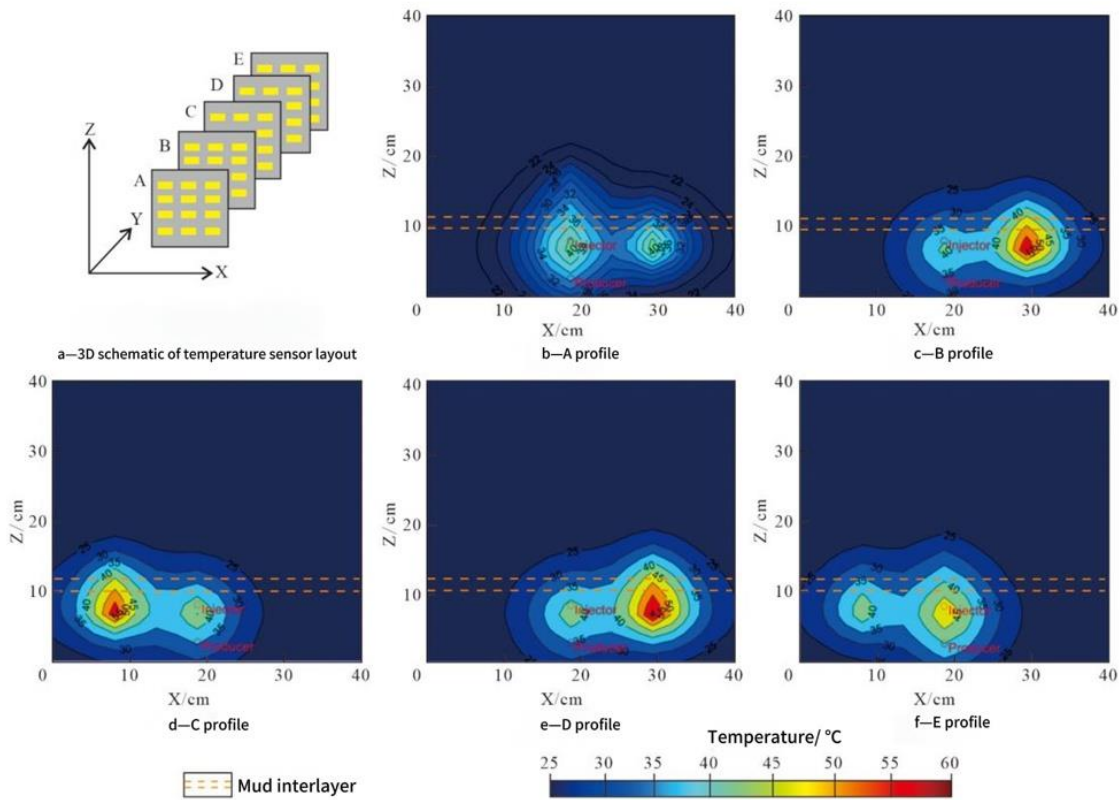


Fig.17 Temperature distribution along the horizontal section of the large-scale physical model during multilateral SAGD reservoir dilation

5.6 Coupled Geomechanical Numerical Simulation

Based on the reservoir rock mechanical and petrophysical parameters as well as the hydraulic dilation characteristics of oil sand reservoirs, coupled geomechanical numerical simulations were conducted using a finite element geomechanical expansion model (ABAQUS) and a thermal recovery simulator (CMG-STARs). The results (Meng et al., 2023) indicate that after dilation, the porosity around the well group increased by 2%, permeability increased by 0.1 to 3 times, and the maximum volumetric expansion ratio reached 1%–2.5%. When the permeability contrast exceeds 4, staged dilation using temporary plugging is required. In this approach, polymers with different viscosities are injected to achieve zonal blocking and expansion along the horizontal section, first improving the low-quality reservoir zones and then expanding the high-quality zones, thereby achieving more uniform expansion along the horizontal well. Compared with conventional rapid preheating techniques, the upgraded reservoir expansion technology provides a more uniform expansion effect, improves thermal communication, and enhances overall development performance (Fig. 18).

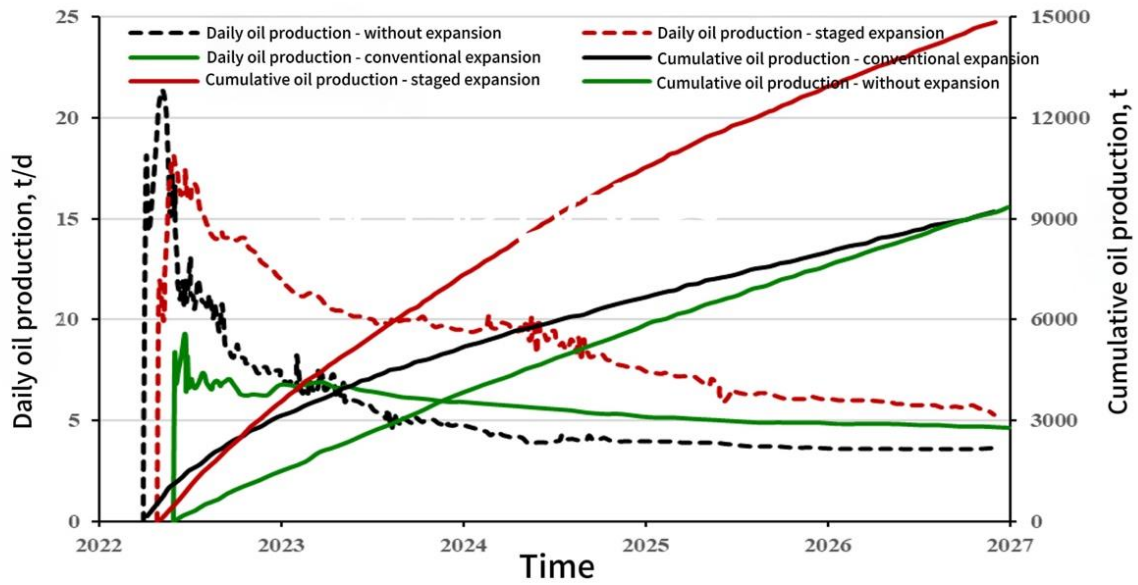


Fig. 18 Comparison of SAGD performance with different upgrading dilation modes in typical well pairs

6. Field Application Results

Industrial-scale roll-out of SAGD in the Fengcheng Oilfield now totals 278 producing well pairs—108 of them drilled in the three-dimensional configurations presented here—lifting annual output to ~1.2 Mt of ultra-heavy oil that was previously considered uneconomic. By promoting faster steam-chamber lift and a more uniform heat sweep, these patterns have lowered cumulative steam-to-oil ratio (SOR), trimmed the natural-gas demand for steam, and delivered a tangible cut in CO₂ emissions while boosting ultimate recovery. Field performance of each configuration and the allied reservoir-upgrading workflow can be distilled as follows:

1. **Vertical-horizontal pattern** – +10 % final recovery with a 1 % uplift in group production rate;
2. **Parallel-parallel pattern** – 1.5× daily oil rate and an 80 % improvement in oil-to-steam ratio;
3. **Dual-layer staggered (3-D) pattern** – production-rate gain from 3.2 % to 5.7 % and recovery factor raised from 56.7 % to 68.4 %;
4. **Multilateral pattern** – 1.25× steam-injection capacity and 1.3× oil rate versus adjacent conventional wells;
5. **Reservoir dilation and stimulation technology** – pre-heat duration cut by 50 % and total steam consumption lowered by 40 %.

Collectively, these results confirm that the integrated well-pattern and geomechanical-dilation strategy not only unlocks stranded heterogenous reserves but also advances the field toward lower-carbon, water-efficient heavy-oil recovery.

7. Conclusions

Fengcheng’s Jurassic ultra-heavy-oil play—shallow, continentally deposited, and shale interlayers—has long been regarded as “borderline developable.” Early SAGD pilots in the mid-2000 s suffered from sluggish steam-chamber lift, fractured heat fronts, and steam-to-oil ratios that rendered Type-III oil sands uneconomic. The root causes were extreme viscosity ($1\text{--}5 \times 10^6$ mPa s), a permeability-variation coefficient > 0.7 , and vertical-to-horizontal permeability ratios below 0.1—all of which stifled vertical steam rise and gravity drainage. Against this backdrop, the present paper provides a high-level synthesis of fifteen years of integrated research and field practice aimed at overcoming those barriers.

This study presents the first end-to-end development workflow that couples geology-specific well-pattern optimisation with staged geomechanical dilation for shallow, continentally deposited ultra-heavy-oil reservoirs. We (i) classified six archetypal interlayer–well configurations that control steam conformance in Fengcheng’s braided-river sands; (ii) used large-scale 3-D physical modelling and

calibrated CMG-STARS simulation to decode the three-stage evolution of steam chambers beneath stacked shale baffles; (iii) translated these insights into three barrier-bypassing, fully three-dimensional well patterns plus two multilateral variants; and (iv) synchronised each layout with a multi-fluid, high-pressure dilation sequence that propagates shear bands 10–15 m from the wellbore and breaches multiple interbeds. Field pilots on 30 well pairs verified a 20–40 % uplift in oil rate, a 10–15 percentage-point rise in ultimate recovery, a 50 % cut in start-up time, and a 40 % reduction in cumulative steam-to-oil ratio.

Industrial adoption has now extended these methods to 108 of the 278 SAGD well pairs in Fengcheng, lifting annual output to ~1.2 Mt and materially lowering natural-gas consumption and associated CO₂ emissions. By demonstrating that productivity gains and decarbonization can be achieved simultaneously—even in reservoirs with kv/kh < 0.1 and viscosity > 10⁶ mPa s—this work delivers a transferable blueprint for heavy-oil developments worldwide. Its novelty lies in the holistic integration of three-dimensional well architecture, laboratory-validated flow mechanics, and mechanically tuned dilation, bridging the gap between isolated research advances and commercial-scale performance.

Author contributions

Xinge Sun: Conceptualization, Project administration. **Chihui Luo:** Visualization, Formal analysis, Software. **Lanxiang Shi:** Formal analysis, Investigation, Validation. **Shengfei Zhang:** Validation, Data curation, **Jingyu Huang:** Writing – original draft, Writing – review and editing. **Bin Xu:** Methodology

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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