TIGHT-SHALE BURGER: CO-DEVELOPMENT OF THE PIMIENTA SHALE OIL FORMATION AND JURASSIC-CRETACEOUS TIGHT RESERVOIRS ONSHORE THE SURESTE BASIN (MEXICO)

Bochkarev V.
PhD
Independent Upstream consultant, Mexico.
ORCID: 0009-0004-3642-6561
Bochkarev Ar.
PhD candidate, Gubkin Russian State University of Oil and Gas.
ORCID: 0009-0000-8526-3755
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Abstract

A Tight-Shale Burger concept is proposed — the first template, in Mexico (and worldwide), for simultaneous rather than sequential development of a source-rock interval and the adjacent tight reservoir it has charged. In the Sureste basin (the southeastern end of Veracruz state, the whole of Tabasco, and the western part of Campeche), the Tithonian Pimienta shale formation (Edzná) acts as the "patty," while the overlying Jurassic-Cretaceous tight reservoirs — Oxfordian sandstones of the Ek-Balam group, Kimmeridgian oolites of the Akimpech formation, and Lower Cretaceous fractured dolomites — act as the "buns," developed from a single wellpad and, where geometry allows, from a single horizontal wellbore. The central thesis: the economics of each of the two targets on its own is marginal, while combining them radically changes that economics through shared drilling and pad tie-in costs, diversification of the production profile, and infrastructure synergy. A differentiated completion design accounts for the difference in flow mechanisms (diffusion-matrix in the shale, fracture-dominated in the carbonate). A solution for flare-free utilization of sour associated gas is proposed: injection into depleted, oxidized Miocene sandstones, which serve simultaneously as underground gas storage and as a natural reactor for mineral hydrogen sulfide sequestration (a subsurface analogue of iron sponge). The applicability zone covers the southeastern tip of Veracruz state, the whole of Tabasco, and western Campeche (the latter predominantly a gas window). The approach's applicability beyond Mexico is shown — in the Maracaibo basin in Venezuela (La Luna formation). Target: a 4–6-fold increase in the region's onshore production by 2033–2035, to a level of 1.5–2 million bbl/d.

Keywords: Pimienta formation; Edzná; tight reservoirs; co-development; source rock; Tight-Shale Burger; Sureste basin; Salina del Istmo; Comalcalco; Reforma-Akal; Macuspana; differentiated completion; underground gas storage; mineral hydrogen sulfide sequestration; iron sponge; La Luna; Maracaibo.

1. The gap between a depleted surface and an undrilled depth

The Sureste basin and its four onshore structural provinces — Salina del Istmo, Comalcalco, Reforma-Akal, and Macuspana — stretching from the southern tip of Veracruz state through the whole of Tabasco to western Campeche, form one of the key oil and gas production regions of southeastern Mexico (Figure 1). It hosts both Miocene oil and condensate fields and substantial untapped potential in the deep Jurassic-Cretaceous section — and given the shared Late Triassic–Jurassic rift basement and the common Pimienta/Edzná source-rock interval, a similar "shale—tight reservoir" architecture is expected across all four provinces. This work details the concept using the Comalcalco sub-basin as the most thoroughly studied example, with direct applicability of the described solutions to the other three sub-provinces.

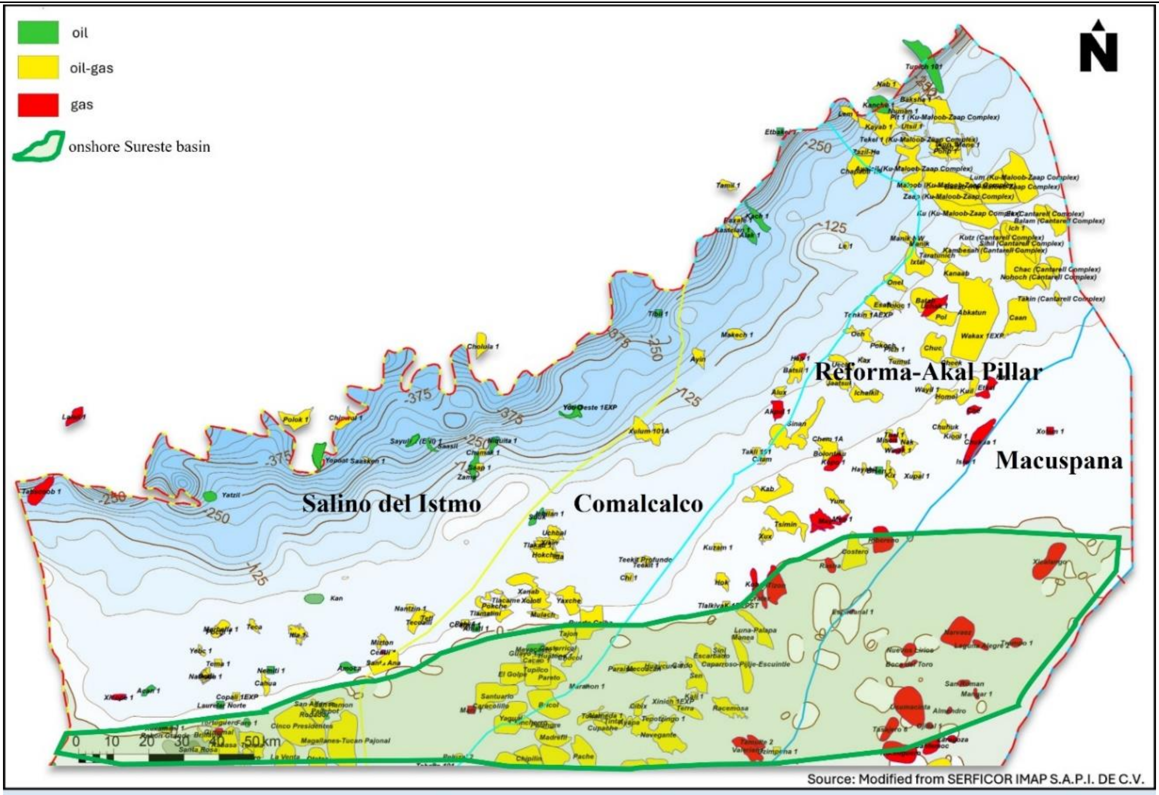


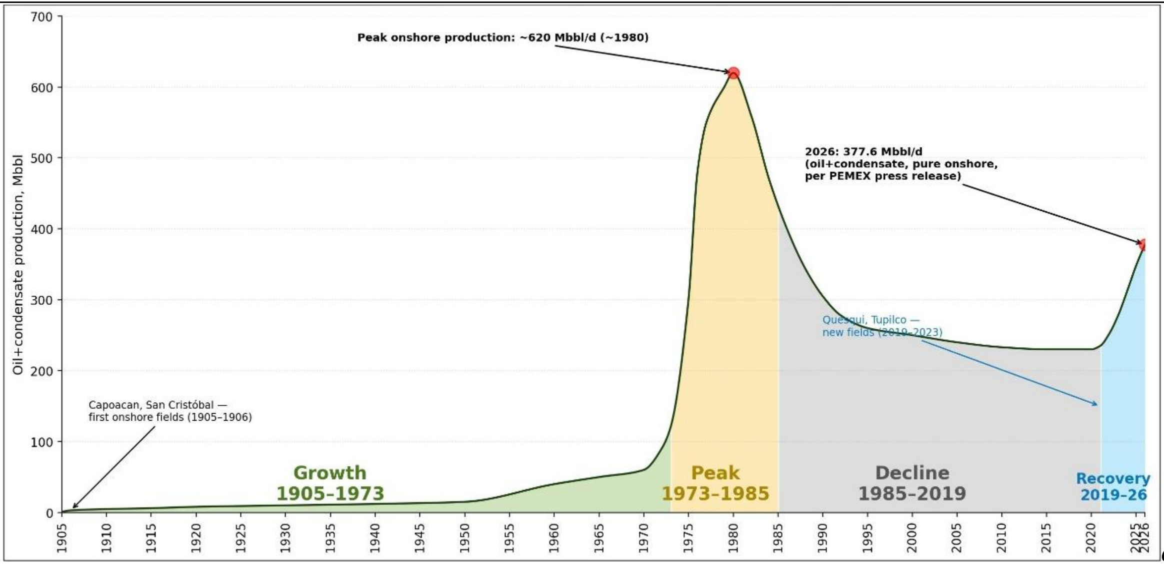
Figure 1. Overview map of the Sureste basin and its sub-basins (by open sources).

The oil and gas history of southeastern Mexico spans more than a century and a half. The first documented production attempts in Tabasco date back to the mid-19th century: in 1863, Father Manuel Gil y Sainz sank the San Fernando shaft near the village of Tepetitan, and in 1883 Dr. Simón Sarlat drilled his own well. Commercial oil production in the region, however, is conventionally dated from 1905–1906, when the Capoacan and San Cristóbal fields were brought on stream.

A qualitative leap occurred in the early 1970s. In 1971, the Pichucalco exploration well first penetrated reef and margin facies of the Cretaceous carbonate complex, proving the presence of a thick Cretaceous platform beneath the Tabasco plain [25]. Already in 1972, at a depth of roughly 4,200 m, a giant field was discovered, launching development of the Antonio J. Bermúdez complex in Reforma (the onshore part of the eponymous Reforma-Akal petroleum system) — one of the world's largest oil fields, with recoverable reserves of roughly 8 billion barrels of oil equivalent. The Puerto Ceiba field, brought online in 1982, belongs to the same geological cycle: its productive horizons — Upper Jurassic Kimmeridgian and Lower Cretaceous limestones at an average depth of about 5,000 m — are separated by an impermeable Tithonian interval (the stratigraphic analogue of the Pimienta formation), which in this section acts not only as the source rock but also as the fluid seal. This very alternation of the Pimienta shale and overlying carbonate bodies became one of the geological premises for the Tight-Shale Burger concept.

Many fields — Santuario, El Golpe, Caracolillo — were brought online in the 1960s–1970s. At the Santuario block, the two main fields had, by the early 2010s, been depleted to 73% (Santuario) and 90% (El Golpe); the Caracolillo field is fully depleted and was shut in 1992. Production came mainly from Miocene sandstones at depths of 1,000–2,500 m. By 2026, onshore production in Tabasco is well below its historical peak: most Miocene accumulations have entered late-stage operation, while the deep Jurassic-Cretaceous section remains essentially undrilled.

According to PEMEX data cited in a press release by the government of Tabasco state, in Q1 2026 net onshore oil and condensate production for Tabasco state was 377.6 thousand bbl/d, roughly 23% of national oil production (against a national average of 1.65 million bbl/d over the same period). This figure fundamentally excludes production from the offshore Litoral de Tabasco asset — a marine zone that PEMEX and government sources frequently lump together with Tabasco state statistics, leading to inflated estimates of "Tabasco production." A significant share of current onshore volume comes from the new Quesqui and Tupilco fields (discovered in 2019 and 2021, respectively) — predominantly gas-condensate assets; against this backdrop, the contribution of the traditional Reforma-complex fields (Samaria, Bermúdez, Bellota-Jujo, Cinco Presidentes), which delivered the state's peak onshore production in the late 1970s (roughly 550–620 thousand bbl/d), is currently estimated



at

200–260 thousand bbl/d (Figure 2).

Figure 2. Oil and condensate production in Tabasco state, 1905–2026.

It is precisely this gap — between depleted Miocene accumulations at the surface of the play and the essentially undrilled Jurassic-Cretaceous complex at depth — that forms the economic logic of Tight-Shale Burger co-development. Infrastructure, well stock, and a century of field experience already exist at the surface; the resource lies at depth beneath them. The concept links the two.

2. Geology, stratigraphy, and source-rock intervals of the Comalcalco sub-basin

2.1. Structural-tectonic framework

The Comalcalco sub-basin is one of four structural provinces of the Sureste basin (alongside Salina del Istmo, Reforma-Akal, and Macuspana), treated in this work as a single applicability zone for the concept owing to their shared Late Triassic–Jurassic rift basement. Continental red beds of the Late Triassic–Early Jurassic lie at the base of the section; during the Callovian, a Pacific marine transgression occurred, and under the resulting conditions of restricted circulation and elevated evaporation a thick evaporite sequence formed — the very salt whose tectonics (diapirs, salt pillows and walls, “rollers”) [12, 22] shaped almost all of the region's structural traps, including the Santuario block. Salt thickness in the Comalcalco sub-basin reaches 1,200 m. Carbonate deposition prevailed from the Late Jurassic to the Late Cretaceous, giving way to terrigenous deposition in the Paleogene amid the Laramide orogeny and formation of the fold-and-thrust structures of the Sierra Madre and the Chiapas range [21]. In the Middle Miocene (Serravallian), these structures were further deformed by lateral compression associated with movement of the Chortis block and subduction of the Cocos plate, followed by tilting to the north-northwest as salt was mobilized — it was this late-stage tectonics that formed the traps of the Miocene accumulations at Santuario and neighboring blocks (Figure 3).

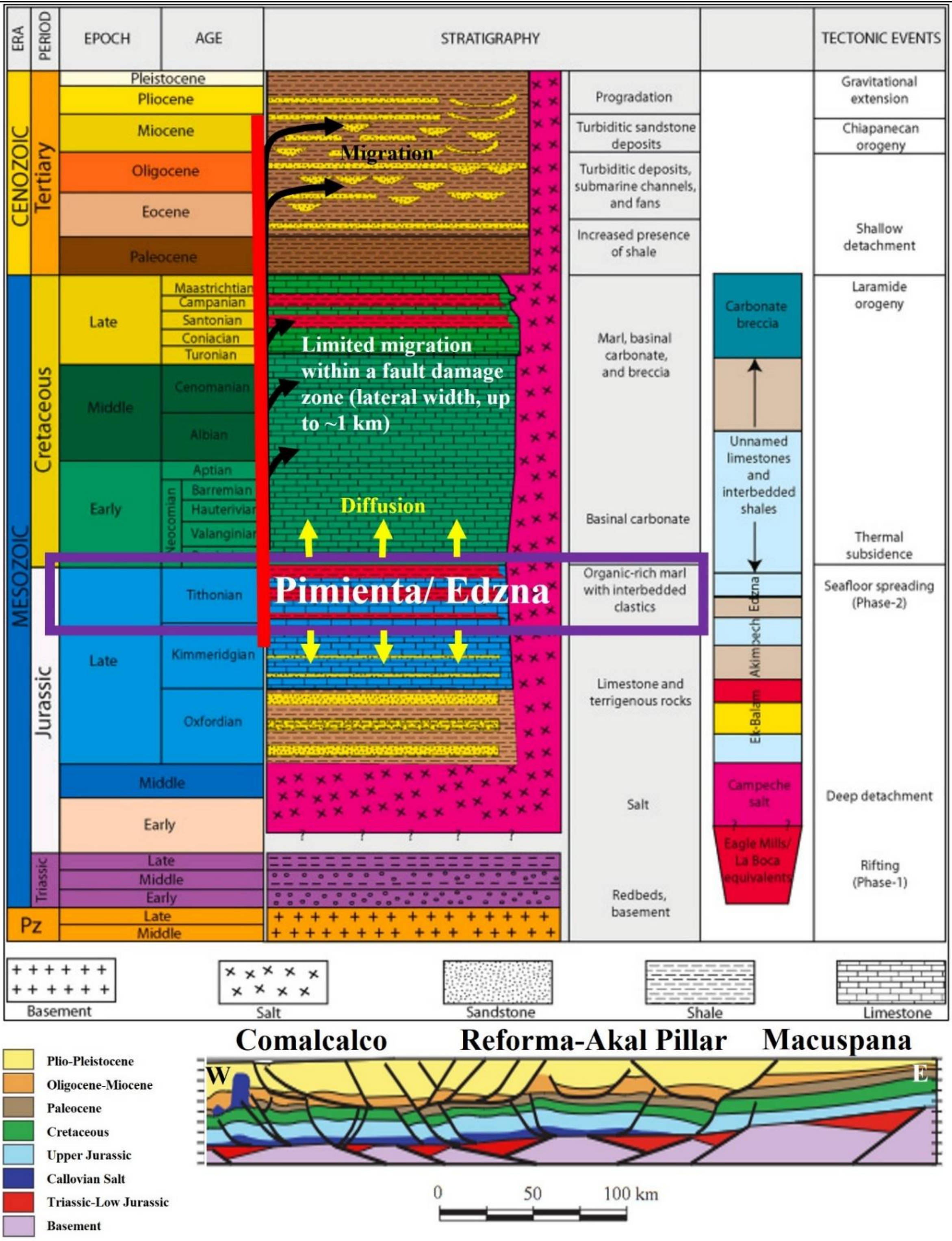


Figure 3. *Average lithostratigraphic section of the Sureste basin, showing the principal hydrocarbon migration mechanism from the Upper Jurassic source-rock formation (Pimienta/Edzná), and a regional sub-latitudinal cross-section across the Sureste basin (from open sources).*

2.2. Lithostratigraphy of the productive section

Formal lithostratigraphic names for the Comalcalco Jurassic-Cretaceous complex are scarce in the open literature — most PEMEX publications use the informal terms "Jurassic-Cretaceous Complex" (Complejo Jurásico-Cretácico) and "Cretaceous Breccia" (Brecha Cretácica). However, Comalcalco and Reforma-Akal are part of the single Sureste basin together with the Campeche shelf (the Cantarell, Sihil, and Ek-Balam complexes), where the stratigraphy is formalized in detail and can serve as the nearest regional reference for correlating the Santuario section.

From bottom to top, the reference section of the Sureste basin includes: Callovian salt (Sal Calloviana) at the base; the Oxfordian stage — eolian sandstones of the Bacab formation and the terrigenous-evaporite sequence of the Ek-Balam Group, comprising three members, the middle one of which, predominantly sandy, is the main reservoir at the eponymous Campeche shelf field; the Kimmeridgian — the Akimpech Formation, divided into four members, the uppermost of which, oolitic limestones, is the main tight-reservoir facies of the Kimmeridgian (an analogue of oolitic shoal bars); the Tithonian–Lower Berriasian — the Edzná Formation, the lateral and age-equivalent of the onshore Pimienta formation [20]: bituminous calcareous shales, the basin's main source-rock interval; the Cretaceous — dolomitized and intensively micro-fractured limestones, grading upward into a dolomitized breccia at the Cretaceous-Paleogene boundary; the Paleocene — the Cantarell and Abkatún formations, mudstones with a basal iridium-enriched ash layer (a marker of the Chicxulub impact event), acting as the regional seal; the Miocene — terrigenous deltaic sandstones, the productive interval of the Santuario, El Golpe, and Ogarrio fields.

2.3. The Pimienta / Edzná formation — the source-rock interval

The Pimienta formation (in its Campeche-shelf facies expression — the Edzná formation; Tithonian stage of the Upper Jurassic, locally grading into the Lower Berriasian) is the principal source-rock interval not only of the Comalcalco sub-basin but of the entire southern Gulf of Mexico, and is present in 4 Mexican states (Tamaulipas, Veracruz, Tabasco, and Campeche): according to a number of researchers [2, 5, 7, 18], it generated the hydrocarbons that filled practically all the giant onshore and offshore fields, including the heavy-oil fields of the Panuco–Ebano–Altamira blocks, the Golden Lane, Antonio J. Bermúdez, Cantarell, KMZ, and many others. Lithologically it is a black and dark-gray calcareous shale (carbonate mudstone) with interbeds of bituminous limestone and chert.

Key geochemical parameters (from regional analogue sections of the Gulf of Mexico): TOC averaging 3.0–4.5%, up to 5% in individual interbeds; kerogen predominantly Type II, of marine origin; gross interval thickness in the most thoroughly studied sections (Tampico-Misantla) reaches 300–500 m, with an organically enriched effective interval of 100–200 m; matrix permeability is extremely low — after secondary fracturing and diagenetic alteration it does not exceed a few hundred nanodarcies (up to ~300 nD), typical of carbonate-type shale formations, which necessitates hydraulic fracturing [2–8, 14, 17]. In Comalcalco, where the Pimienta/Edzná burial depth is substantially greater than in Tampico-Misantla, a higher thermal maturity is expected, and correspondingly a shift in the generated hydrocarbon composition toward light oil and condensate (Figure 4).

2.4. Jurassic-Cretaceous tight reservoirs

Below and partly within the Jurassic-Cretaceous section lie tight reservoirs comprising at least three productive levels: (1) Oxfordian terrigenous-carbonate deposits of the Ek-Balam group (a siliciclastic shelf bar); (2) Kimmeridgian oolitic shoal bars of the Akimpech formation, associated with structural highs — relicts of rift topography; (3) Lower Cretaceous dolomitized and fractured limestones. This very three-tier stack — Oxfordian sandstone, Kimmeridgian oolite, Cretaceous dolomite — has been documented as the reservoir sequence at the Sihil field (a neighboring block of the Cantarell complex) [23] and is regarded as a structural analogue of the section expected within the onshore part of Tabasco state.

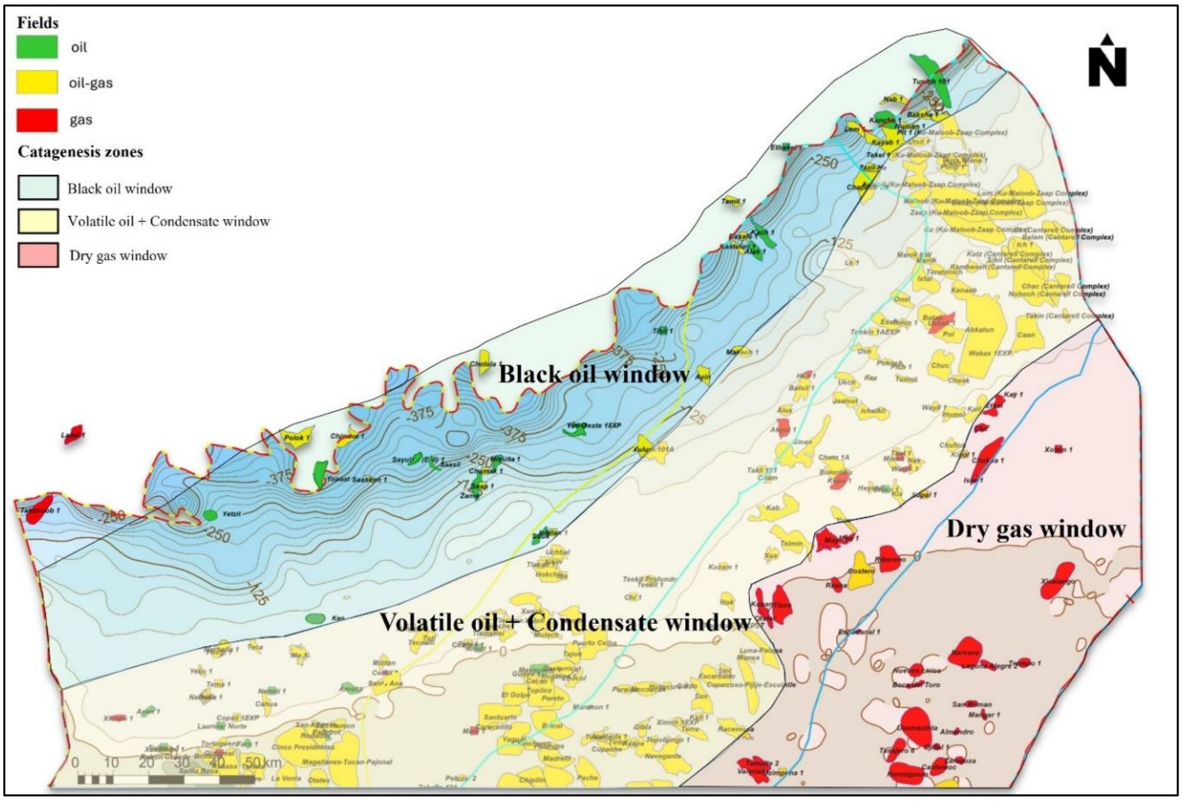


Figure 4. Catagenetic zonation of the Pimienta/Edzná source-rock formation within the Sureste basin.

Porosity in these reservoirs is predominantly secondary in origin — the result of dissolution, dolomitization, and intensive microfracturing [26]. Based on analogue Cretaceous sections in the region (the Poza Rica–Tampico trend), typical porosity values are 8–12% in grain-dominated facies [15, 24] and around 3%

in mudstones, while matrix permeability averages no more than 2 mD, rarely reaching a few hundred millidarcies owing to the fracture component. It is precisely this secondary (fracture) permeability that historically delivered the commercial rates of the giant Bermúdez, Catal, and Sitio-Grande fields — and it retains its defining role for the prospective tight targets of the onshore Sureste basin (southern Veracruz, Tabasco, and western Campeche).

Productivity of the Jurassic-Cretaceous complex has already been proven at a number of fields: Tupilco, Yaxché, Palangre, Chinchorro, Pareto, Mayacaste, Arrastradero, Tajón, Puerto Ceiba, Xanab, and others. At these fields, the Jurassic-Cretaceous complex yields light and medium oil at 33–45° API, consistent with the general characterization of the Mesozoic accumulations of the Reforma province as predominantly light-oil targets (Table 1).

Table 1. J

urassic-Cretaceous tight reservoirs of the Comalcalco sub-basin

Level	Age / lithology	Porosity type	Porosity / permeability	Analogue fields
I (upper)	Oxfordian deposits of the Ek-Balam group (siliciclastic shelf bars)	Primary + secondary	8–12% in grain-dominated facies	Sihil (Cantarell complex)
II (middle)	Kimmeridgian oolitic shoal bars of the Akimpech formation	Secondary (dissolution, dolomitization)	~3% in mudstones, matrix <2 mD	Reforma-Bermúdez (~8 billion bbl), Catal, Sitio Grande
III (lower)	Lower Cretaceous dolomitized and fractured limestones	Fracture (secondary)	Matrix <2 mD, fractures — a few hundred mD	Tupilco, Yaxché, Palangre, Chinchorro, etc. (33–45° API)

2.5. Traps, seals, migration

Traps in the Jurassic-Cretaceous complex are predominantly structural, associated with salt domes, diapirs, and fault-block highs, complicated by normal and thrust faults of the Laramide and Miocene deformation phases. At a number of fields (Puerto Ceiba), the internal seal between the Kimmeridgian and Cretaceous productive levels is the Tithonian Pimienta/Edzná itself — a thin but laterally persistent impermeable interval. The regional seal for the entire Mesozoic complex is provided by the Paleocene mudstones of the Cantarell and Abkatún formations, with an iridium-enriched ash layer at the base — a geochemical marker of the Chicxulub event [16], reliably traceable across the whole southern Gulf of Mexico section.

Hydrocarbons generated in the Pimienta/Edzná migrated upward along the fault and fracture system. In zones of active faulting, the most intensive saturation of tight reservoirs occurs across the full height of the section, including into the overlying Tertiary deposits. This migration mechanism is associated with the fault damage zone — a fracture-enhanced permeability halo whose lateral width, according to the literature, ranges from a few hundred meters up to ~1 km depending on fault displacement [1, 11]; within it, migration proceeds as through an ordinary fractured reservoir, while beyond its boundary the matrix remains tight and impermeable. In zones remote from faults, a diffusion-dominated migration mechanism prevails, and reservoir saturation takes on a more uneven, patchy character: saturation is concentrated mainly at the direct contact zone between the shale and the tight formation, while in the middle and upper part of the tight formation it is limited or entirely absent. This distribution directly determines the placement strategy for the first pads and horizontal wells, sub-parallel to the Chiapas fold system.

3. Tight-Shale Burger — a new development paradigm

The concept is named “Tight-Shale Burger” (or “Pimienta Burger”): the Pimienta shale formation acts as the “patty,” while the Upper Jurassic and Lower Cretaceous tight reservoirs act as the “buns,” forming a multi-layer hydrocarbon “burger” (Figure 5).

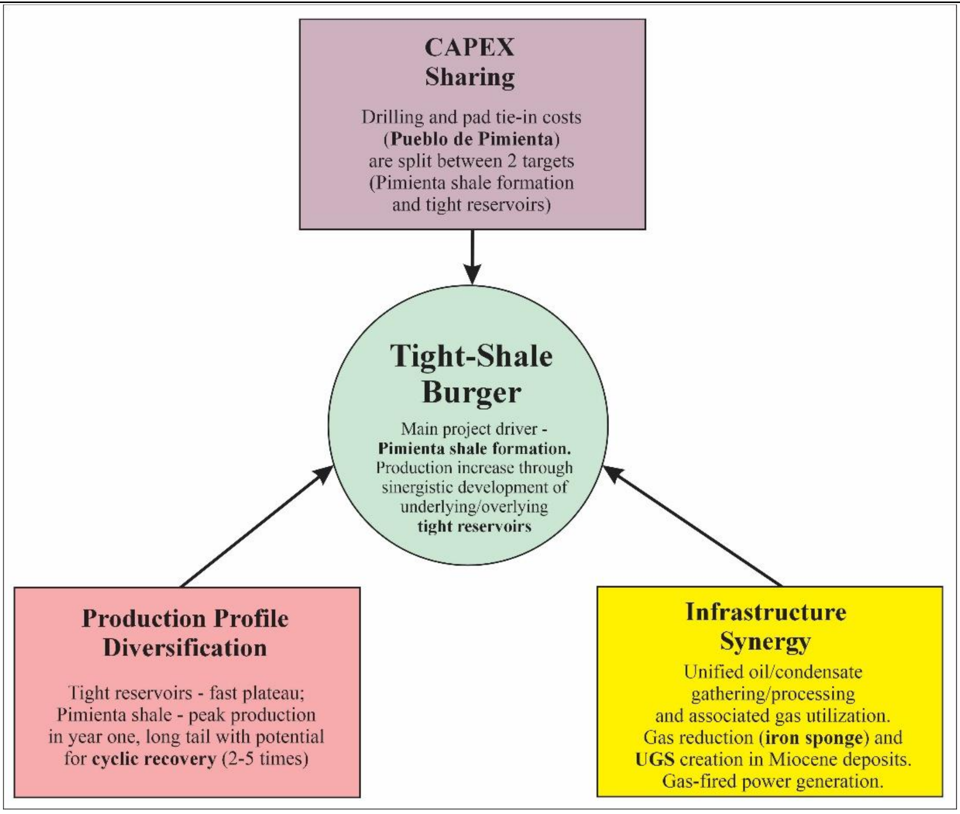


Figure 5. Architecture of the Tight-Shale Burger approach.

3.1. Why this is a new paradigm

In global practice, a source-rock shale and the adjacent reservoir it has charged are traditionally developed separately and sequentially — first as a conventional target (sometimes for decades), then, as a separate program, as an unconventional one. The classic example is the Eagle Ford–Austin Chalk system in Texas, USA: the thin, bituminous Cretaceous deposits of the Austin Chalk formation were developed as a conventional fractured reservoir starting in the 1970s, while the underlying Eagle Ford source-rock shale was not brought into development until 40 years later, with the advent of horizontal drilling and multistage fracturing, and is today regarded as a "hybrid petroleum system," with the Austin Chalk formation charged by fluids from the Eagle Ford shale interval along fractures [4, 8]. A similar logic applies to the Woodford/Mississippi Lime (SCOOP/STACK) system of the Anadarko basin.

Tight-Shale Burger takes this logic to a qualitatively new level: instead of sequential development of the source and the reservoir, it proposes their simultaneous co-development from a single pad from day one of the field's life. For southern Mexico, where Jurassic-Cretaceous tight targets such as Tupilco and Puerto Ceiba have already proven commercial productivity, while the Pimienta shale had previously not been considered a standalone target, this is the country's first systematic template for genuinely joint, rather than sequential, development of a shale formation and a tight reservoir.

3.2. Economic rationale of the "burger"

The key proposition underlying the concept's viability is as follows: the synergy of the two targets substantially increases the economic effectiveness of co-developing the shale and tight formations compared with developing them separately.

Isolated tight-carbonate lenses of the Kimmeridgian and Cretaceous, remote from major structures (targets of the Tupilco type), are characterized by limited productivity, often compartmented by fracture blocks; the matrix, away from faults, lacks oil saturation owing to the limited reach of diffusive migration from the Pimienta formation. Standalone development of such tight reservoirs will therefore have marginal economics.

Combining both targets in a single wellbore and a single pad changes the economics along three independent dimensions simultaneously:

- Capital cost sharing. Drilling, tie-in, and pad-construction costs are allocated not to one but to two productive targets — unit CAPEX per barrel drops multiple-fold, since the most expensive component (the wellbore, the pad, the infrastructure) is shared.
- Diversification of the production profile. The carbonate interval delivers a fast initial plateau (fracture permeability, immediate inflow); the shale delivers a peak followed by a sharp decline over 12–15 months, with potential for cyclic recovery. The combined profile is smoother and more predictable than that of either target on its own.
- Infrastructure synergy. A single gathering, processing, power-generation, and — critically — gas utilization system serves both targets. Pimienta's gas solves the energy-supply and injection problem for the entire pad.

It is precisely this triple synergy — not the productivity of either target on its own — that is the source of the concept's high profitability. Tight-Shale Burger is first and foremost an economic, and only then a technological, innovation (Figure 6, Table 2).

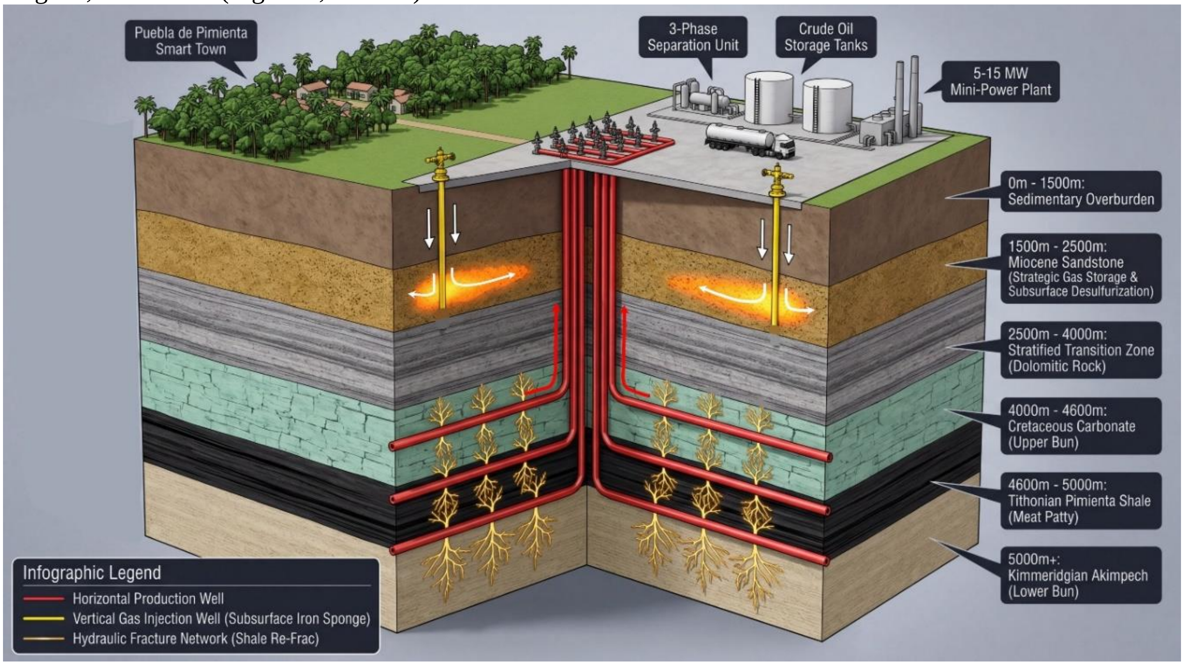


Figure 6. *Conceptual pad layout (Pueblo de Pimienta) for co-development of the shale and tight formations (Tight-Shale Burger)*

Table 2.

Triple economic synergy of Tight-Shale Burger

Synergy direction	Mechanism	Effect
Capital cost sharing	Drilling, tie-in, and pad-construction costs are allocated to two productive targets	Multiple-fold reduction in unit CAPEX per barrel
Diversification of production profile	Tight reservoirs — fast initial plateau; shale — peak production and sharp decline over 12–15 months, then a long “tail” with potential for cyclic recovery (re-frac)	Smoother, more predictable combined production profile
Infrastructure synergy	Unified gathering, processing, power-generation, and associated-gas utilization system	Pimienta's gas covers power supply and injection for the entire pad

3.3. Completion design

Flow mechanisms in the shale and in the tight reservoirs are fundamentally different — diffusion-matrix in the Pimienta versus fracture-matrix in the Jurassic-Cretaceous carbonates. Despite this, a single technological fracturing protocol is proposed for both targets (one fleet, one base fracturing fluid), with a single adjustable parameter — the presence or absence of an acid stage: it is not required for the Pimienta, while for the tight carbonates it is introduced to reactivate the existing natural fracture network. This is not two incompatible completion designs but a single protocol with a switchable parameter, which removes the question of sleeve and packer compatibility between intervals:

- Pimienta interval — 2,000-m horizontal wellbores are oriented parallel to the Chiapas fold system (maximum stress direction), with a dense grid of frac ports (plug-and-perf), reduced cluster spacing (18–25 stages), and increased proppant intensity, aimed at creating the well's own network of induced fractures in the low-permeability matrix. Horizontal wells are placed at the top and base of the shale formation to simultaneously cover both the shale and tight intervals, creating a production synergy with a high initial rate and a sustained plateau owing to cyclic development of the shale formation.
- Tight-carbonate interval — 2,000-m horizontal wells are placed at 2/3 of the reservoir thickness from its base for maximum coverage of the tight reservoir. A wider stage spacing (10–15 stages) with a hybrid (slickwater + acid) fracturing design is proposed, targeting both the creation of new fractures and the reactivation and cleanup of the existing natural fracture network (by analogy with practice at the Austin Chalk formation in the US). Well orientation is the same as in the shale formation.
- Within each wellpad, in addition to the synergy wellbores at the top and base of the Pimienta, dedicated calibration wells are drilled separately — one horizontal well into the shale formation and one into the tight reservoir, both in the middle of the respective formation, outside the contact zone. Their purpose is to determine the production capability of each target individually, so that the contribution of each formation to the combined rate of the synergy wellbores can be correctly assessed. Final pad layout: 20 wells into the Pimienta shale (10 at the top, 10 at the base) plus 16–20 wells into the tight reservoirs (calibration and coverage wells) — 36–40 horizontal wells per Pueblo de Pimienta in total.

4. Technical development parameters

The unit of development is the Pueblo de Pimienta wellpad cluster. Each Pueblo comprises 36–40 horizontal wells (20 into the Pimienta and 8–10 into each of 2 tight reservoirs), 2 km long, spaced 400 m apart. Horizontal wellbore orientation is chosen parallel to the Chiapas fault system (along the maximum horizontal stress direction, SHmax) to create an optimal fracture network transverse to the wellbore (Table 3).

Wellbore placement within the section is determined by structural position:

- At the areas of existing fields and structural highs, horizontal wells are drilled at the top and base of the Pimienta formation — this provides simultaneous coverage of both the shale interval and the adjacent tight reservoirs (full realization of the "burger").
- In inter-structural zones (between discovered fields), horizontal wells are placed in the middle of the Pimienta to minimize the risk of aquifer breakthrough [19] (aquifer presence in the tight reservoirs requires confirmation at the pilot stage).

Cyclic development of the Pimienta shale interval (shutting in wells after 36 months of continuous production for 2–3 weeks to stabilize the near-wellbore zone, followed by a re-frac) allows rates to be restored to 70–90% of initial values and additionally recovers hydrocarbons from the kerogen's unrealized generation potential (S2). The physical basis of this mechanism — removal of the pressure brake on generation upon drawdown — is presented separately by the authors and is the subject of a standalone work (Figure 7) [2–8].

5. Associated gas utilization: underground storage with mineral desulfurization

Co-development of the shale and tight formations will inevitably generate significant volumes of dissolved gas, which, at the early pilot stage — given the distance from gas-processing infrastructure — risk being flared. This is a direct loss of a marketable product and, at the same time, a regulatory and reputational risk (CO_2 and methane emissions). The proposed solution follows from the geology of the old Miocene fields themselves: injecting the surplus gas into depleted Miocene sand intervals, turning them into underground gas storage.

It is important to separate this solution into two levels, differing in technological maturity and risk.

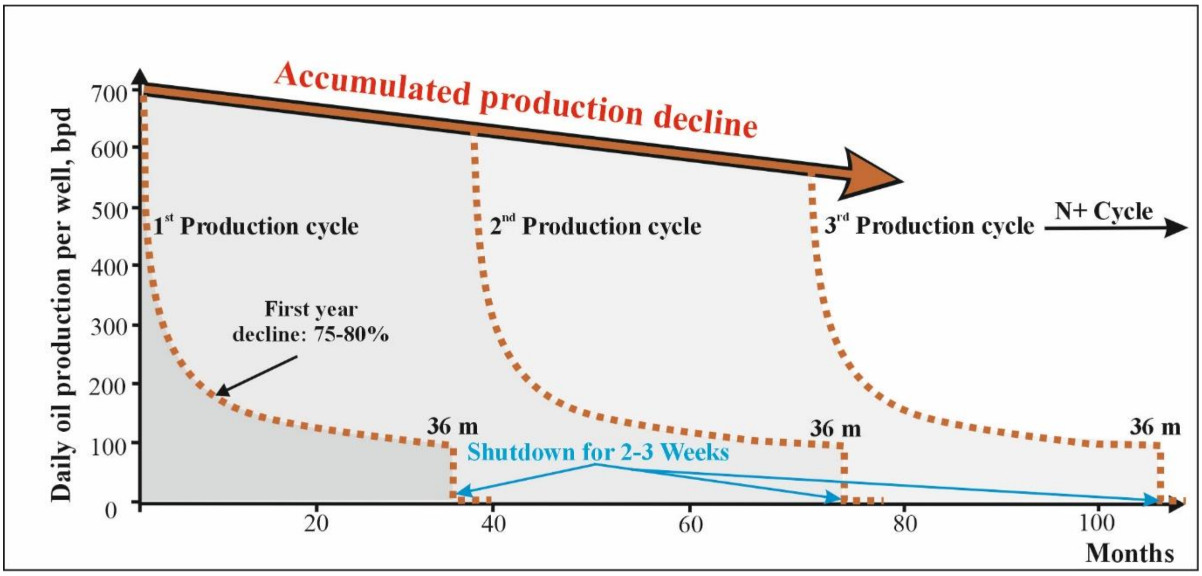


Table 3. Technical parameters of the Pueblo de Pimienta pad

Parameter	Value
Number of horizontal wells per pad	36–40
Horizontal wellbore length	2 km
Well spacing	400 m
Wellbore orientation	Parallel to the Chiapas fault system (along SHmax)
Section placement — field/high areas	Top and base of the Pimienta, plus placement at 2/3 thickness from the base within tight reservoirs (full "burger" realization)
Section placement — inter-structural zones	Middle of the Pimienta (reduces aquifer-breakthrough risk). Aquifer presence in tight reservoirs is verified during pilots.
Shale-interval development cycle	2–3-week shut-in + re-frac
Rate recovery after re-frac	70–90% of initial
Initial rate, shale well	400–800 bbl/d
Initial rate, tight well	500–1,200 bbl/d
Initial rate, wellpad	25–35 thousand bbl/d

Figure 7. The principle of cyclic development of shale formations [2, 5–7, 9].

5.1. Underground gas storage — a mature, low-risk foundation

Creating underground gas storage (UGS) in a depleted reservoir is a proven technology, applied worldwide for decades. The depleted Miocene sandstones of the Reforma-province fields, with their developed well stock and well-known geology, are ready-made assets for storing surplus gas (the Santuario field is 73% depleted, El Golpe 90%, Caracolillo fully depleted). Already at this level, the main objective is achieved: elimination of flaring and formation of a strategic gas reserve for subsequent power generation, petrochemistry, or export. This level contains no hypothetical assumptions and constitutes a reliable foundation for the solution.

5.2. Mineral hydrogen sulfide sequestration — a promising add-on

Part of the gas from the Pimienta formation contains sour components (H_2S, CO_2) — a typical feature of gases generated in a reducing, organic- and sulfate-rich (salt, anhydrite) setting. Instead of carrying this gas to a surface desulfurization unit (amine process), the concept proposes using the terrigenous Miocene reservoirs themselves as a natural polishing reactor.

Mechanism: in oxidized, near-surface, or previously oxygen-water-flushed intervals of the Miocene sandstones (near paleo gas-water contacts, in the updip parts of structures), iron is present predominantly in the trivalent form — within hematite-goethite film cements. On contact with hydrogen-sulfide-bearing gas, this oxidized iron is reduced, binding H_2S into stable sulfide minerals (mackinawite, later pyrite):

$$2Fe_2O_3 + 6H_2S \rightarrow 4FeS + 2S + 6H_2O$$

This is a direct subsurface analogue of the industrial “iron sponge” process, applied for decades to sweeten sour gas at the surface — only here the scrubber's role is played by the reservoir rock itself.

5.3. Static regime and the timescale of the effect

It is essential that the proposed scheme is not designed for a fast effect and is not a flow-through treatment. Gas is injected and deposited; the binding reaction proceeds in a static regime over years. It is precisely this regime that removes the main kinetic objections: slow diffusive mass transfer between the gas and the rock grains, as well as gradual passivation of the iron by the forming sulfide crust, are not obstacles where the process is allotted a decade-long timescale. Monitoring is simple and cheap: an annual gas sample from a monitoring well, plotting an H_2S concentration curve over time. A declining concentration confirms binding; stability disproves it.

5.4. Capacity limitation and mineralogical screening

The scheme's viability may face two possible limitations, which must be verified on available Miocene core:

First — the form of the iron. Published studies on underground gas storage also document the reverse process: pyrite already present in a reduced (mature, long in contact with hydrocarbons) reservoir may, conversely, serve as a source of H_2S rather than a sink for it [13]. The scheme's viability depends directly on the initial redox form of the iron: specifically oxidized forms (hematite/goethite), not reduced ones (pyrite/siderite), are required. This is checked by X-ray diffraction analysis of core to determine the iron speciation at the pilot stage of the project.

Second — binding capacity. The effect is limited by the amount of available trivalent iron: the total mass of sulfur that can be bound is finite and is determined by the mass of reactive Fe^{3+} per unit reservoir volume. For gas with a low H_2S content (fractions of a percent to a few percent), the capacity of a depleted sand body may suffice for very large gas volumes; for highly sour gas it will be exhausted faster. In other words, for fields with high H_2S content, this is about reducing the surface sulfur load, not fully replacing desulfurization under reservoir conditions. Capacity and passivation-rate assessment is performed by a core-flood column experiment with hydrogen-sulfide-bearing gas.

If the concept is confirmed, the benefit is clear: instead of flaring, a strategic underground gas reserve is formed; emissions and associated costs are reduced; capital costs for surface desulfurization are partly offset by using the existing well stock of depleted Miocene fields; and sulfur is bound mineralogically in the rock rather than being brought to the surface, requiring storage and disposal.

6. Incremental approach and placement of the first pads

The first Pueblo de Pimienta pads are placed only near faults, along which active vertical migration of hydrocarbons from the Pimienta occurs (Figure 8). In these zones, tight reservoirs are maximally saturated across the full height of the section, including into the overlying Tertiary deposits. The farther from the faults, the greater the role played by diffusive charging from the Pimienta — hydrocarbon distribution takes on an uneven, patchy character: saturation is concentrated mainly at the direct contact zone between the shale and the tight formation, while in the middle and upper part of the tight formation it is limited or entirely absent, which is indirectly confirmed by the development of similar tight reservoirs offshore the Gulf of Mexico (the Och, Pokoch, Ichakil, Jeatsul, Sinan, Chuc, and many other fields).

This placement implements the incremental principle common to the entire series of concepts: start in zones of maximum geological certainty (fault zones with proven saturation), confirm the technology and economics there, and only then extend development to zones remote from faults with diffusive saturation. Each subsequent step builds on a confirmed result from the previous one, not on an assumption. In inter-structural zones (outside the fields), the presence of an aquifer in the tight reservoirs must be confirmed to remove the risk to co-development of the shale and tight reservoirs (Figure 8).

Part of the produced dissolved gas is used on-site for power generation, and the remainder for injection into depleted Miocene structures to form an underground gas reserve, instead of surface desulfurization and flaring.

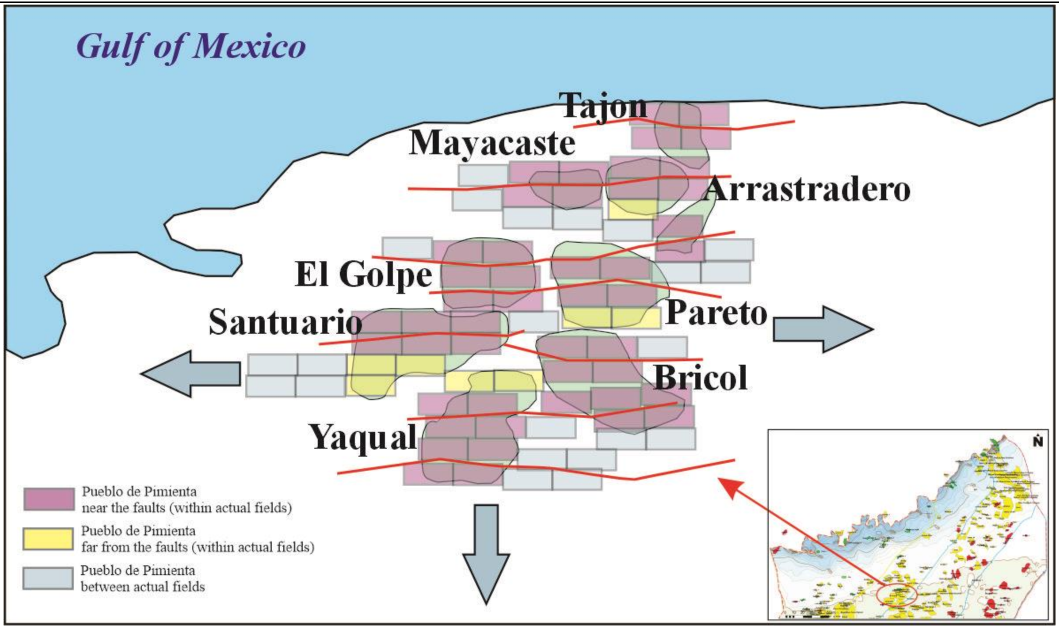


Figure 8. Drilling priority for Pueblo de Pimienta pads by position relative to faults within the fields of the Comalcalco sub-basin, illustrated by the Tajón, Mayacaste, Arrastradero, El Golpe, Pareto, Santuario, Bricol, and Yaqual fields.

7. Applicability of the approach beyond Mexico: the Maracaibo basin

The Tight-Shale Burger concept is not confined to the Sureste basin. Its direct structural analogue beyond Mexico is the Maracaibo basin (Venezuela), where the full "source—adjacent underlying carbonate—overlying sandy reservoir" configuration is reproduced.

Here, the Upper Cretaceous La Luna formation — the region's main source-rock interval, accounting for over 98% of the basin's reserves [27, 28] and, by geochemical parameters (TOC up to 9%, Type I–II kerogen, marine anoxia), close to the Pimienta formation — charged, along sub-vertical strike-slip faults, both the adjacent fractured Cretaceous carbonates (the La Paz, Mara, and Rosario fields — among the world's best-known fractured carbonate reservoirs) and the overlying Eocene-Miocene sandstones of the Bolívar coastal belt (Lagunillas, Bachaquero, Tia Juana, Cabimas).

It is significant that this analogy extends beyond the "burger" to the gas solution as well. The sand reservoirs of the Bolívar belt have been produced since the 1940s and are substantially depleted (more than 90%); this is a ready-made system of huge, depleted, oxidized sand reservoirs — a direct candidate for underground sour-gas utilization with mineral hydrogen sulfide sequestration, analogous to what is proposed for the depleted Miocene sandstones of the Reforma-province fields. Thus, in Maracaibo, two of the concept's three elements are simultaneously applicable: co-development of the source rock and adjacent tight carbonates, and mineral H_2S sequestration in the overlying depleted Miocene sandstones.

It is also worth noting the applicability of the mineral hydrogen sulfide sequestration solution to sour gas giants in other regions of the world. In particular, for the Tengiz field (Caspian region, Kazakhstan), with its high H_2S content, injection of sour gas into the nearly depleted Jurassic-Cretaceous North Buzachi field has previously been considered, where oxidized sandstones with high iron-compound content are capable of binding hydrogen sulfide mineralogically while simultaneously forming a gas reserve, and dissolution of the sour gas in Buzachi's heavy, biodegraded oil reduces its viscosity, giving an associated enhanced-oil-recovery effect. For gas with high H_2S content, this is about reducing the surface sulfur load; quantitative injection parameters are not considered in this work — only the applicability of the approach is presented.

8. Risks and solutions

The concept rests on a number of assumptions, each subject to verification. Below they are organized in a form suitable for pilot-program planning, with the corresponding solution indicated (Table 4).

1. Lack of direct data for Pimienta/Edzná in Comalcalco. The geochemical parameters presented are regional analogues. Solution: pilot drilling with core recovery, Rock-Eval, and determination of maturity and phase composition at specific wells.

2. Aquifer breakthrough in inter-structural zones. When wellbores are placed in the middle of the Pimienta outside structural highs (open fields), an influx of formation water is possible. Solution: hydrodynamic studies and trial production at the pilot before scale-up.

Table 4.

Concept risks and their solutions

No.	Risk	Mitigation
1	Lack of direct data for Pimienta/Edzná in Comalcalco — the geochemical parameters presented are regional analogues	Pilot drilling with core recovery, Rock-Eval, determination of maturity and phase composition
2	Aquifer breakthrough in inter-structural zones — formation-water influx possible where wellbores are placed outside structural highs	Hydrodynamic studies and trial production at the pilot

9. Potential and economic effect for Tabasco state

With successful piloting and scale-up of the approach, onshore production in Tabasco could be increased 4–6-fold relative to the current level already in the coming years. With cyclic development of the shale interval applied, cumulative production across the prospective clusters would grow 2–5-fold relative to a traditional depletion scheme.

Reaching a level of 1.5–2 million bbl/d by 2033–2035 will require the phased construction of approximately 150–200 Pueblo de Pimienta pads. These indicators are a project target, subject to refinement based on pilot-phase results; their achievability is determined above all by confirmation of the joint productivity of the shale and tight intervals at pilot pads (Table 2, Figure 8).

Table 5.

Target indicators for Tabasco state

Indicator	Value
Growth in Tabasco onshore production	4–6-fold relative to the current level
Growth in cumulative production under cyclic development	2–5-fold relative to a traditional depletion scheme
Target daily production level	1.5–2 million bbl/d by 2033–2035
Required number of Pueblo de Pimienta pads	~150–200

This growth gives the state a powerful development impulse: modernization of refining and petrochemistry, construction of water-treatment and desalination plants, growth of gas-fired power generation (including based on underground gas storage), tens of thousands of new jobs, and infrastructure and social projects. Significantly, this effect is achieved on territory with a century-long oil history and ready-made infrastructure — that is, with minimal added environmental burden and maximum use of the existing well stock and field base. It is also worth noting the high payback of shale projects implemented in the US, Canada, and Argentina [10].

10. Environmental and social component

The project's environmental component is not a compensatory obligation added to production but follows from its structure: development takes place on territory with a century-long oil history and ready-made infrastructure, which in itself minimizes new impact, while the project's cash flow, for the first time in decades, creates a funding source for programs that, absent production, have no funding vehicle.

10.1. Water-treatment and desalination plants: infrastructure for hydraulic fracturing and the region's social needs

A large-scale multistage fracturing program — across 150–200 Pueblo de Pimienta pads with 36–40 wells each — is, by definition, water-intensive. Supplying it with fresh water from the region's natural sources is problematic. The project's infrastructure therefore includes construction of two types of facilities, with different degrees of replication depending on the water source and logistics:

A desalination plant — a single, central facility in the city of Paraíso (a coastal municipality of Tabasco state, near the Dos Bocas terminal), distributing desalinated water via a pipeline network to the wellpads. Centralization is justified: clean water is transported by pipeline without contamination risk and without distance limitations.

Water-treatment plants (treatment and recycling of produced water/flowback) — at least three, at a rate of roughly one plant per 50–70 wellpads — unlike clean water, transporting contaminated flowback over long distances is impractical and carries additional environmental risk. Tentatively, by the geography of the Comalcalco sub-basin (the cities of Comalcalco, Cunduacán, Huimanguillo); the exact distribution among them will be refined against the actual pad-siting map at the pilot stage.

Significantly, the combined capacity of these plants is excessive relative to fracturing needs during inter-cycle periods and phases of reduced drilling activity. This surplus capacity will be directed toward water supply for coastal and inland municipalities of Tabasco — a region regularly facing both flooding and a shortage of quality drinking water. The network of water-treatment plants and the desalination plant become triple-purpose assets — industrial, municipal, and agricultural.

10.2. Restoration of lagoons and lakes

The coastal and inland part of Tabasco is a region of extensive wetlands, lagoons, and lakes, including the Pantanos de Centla system — one of the most important wetland complexes in Mesoamerica, holding biosphere reserve status since 1992 and protected under the Ramsar Convention as a wetland of international importance since 1995 (Site No. 733, area 302.7 thousand ha) — which have suffered oil contamination over a century of industrial production. Their cleanup and restoration is a task that, under current conditions, goes unsolved, since neither a dedicated budget nor an economic actor interested in funding it exists. Implementing the shale-and-tight co-development program creates both.

The water-body restoration program includes: survey and mapping of bottom and shoreline contamination; removal of historical oil lenses and oil-stained soils accumulated over a century of production; restoration of the hydrological regime and vegetation cover; a water-quality and biota monitoring program. Critically, the Tight-Shale Burger technology creates no new impact on these water bodies — development is conducted from existing field sites and deep horizontal wellbores — meaning the restoration work is not compensation for current damage but a pure improvement.

A formulation worth stating explicitly: the project does not require environmental compensation — it creates an environmental program that would otherwise never be implemented at all, since in the absence of production there is no actor in the territory capable of funding it.

10.3. Coastline and wetland monitoring

The project's field infrastructure — a distributed network of wellpads, power supply, and communications across the entire play — serves as a carrier for an environmental monitoring system whose creation as a standalone program would be incomparably more expensive. It provides for: monitoring of coastline condition and wetland dynamics (satellite and ground-based tracking of erosion, flooding, and mangrove-ecosystem degradation); monitoring of surface- and groundwater quality; and an early spill detection system, including for spills unrelated to the project — from the historical well stock and from third-party river traffic on the Grijalva and Usumacinta rivers. Tabasco regularly suffers from flooding, and the distributed hydrological and meteorological monitoring network has standalone value for the region, beyond the oilfield itself.

10.4. Flare-free gas utilization and the carbon loop

The project's environmental cornerstone is its gas solution (Section 5): associated and dissolved gas is not flared but injected into depleted Miocene sandstones serving as underground gas storage, with associated mineral binding of hydrogen sulfide in the rock. This eliminates both CO_2 and methane emissions from flaring and the accumulation of sulfur at the surface, while the well infrastructure of the depleted fields itself provides the foundation for a full carbon capture and storage (CCS) loop on the same asset base, forming underground gas storage for the region's future needs.

10.5. Social component

Southeastern Tabasco is a historic oil-producing district whose population has been tied to the industry for a century and has, in recent decades, watched it decline. Resuming development does not mean creating a new dependency but restoring employment lost in a region where the oil profession is traditional: tens of thousands of jobs in drilling, field operations, power generation, water treatment, and — as a separate track — in water-body restoration and monitoring programs, providing employment independent of the production cycle. Overall, the project returns to the territory not only production but also a functioning environmental, water, and monitoring infrastructure that would otherwise never have been built. The project's scale implies unprecedented employment (70–90%) of the population in its implementation and a reduction in social tension.

Conclusions

1. The Tight-Shale Burger concept is proposed — the first template, in Mexico (and worldwide), for simultaneous rather than sequential development of a source-rock interval (the Pimienta/Edzná shale — the “patty”) and the adjacent Jurassic-Cretaceous tight reservoirs it has charged (Ek-Balam Oxfordian sandstone, Akimpech Kimmeridgian oolite, Cretaceous fractured dolomite — the “buns”) from a single pad.

2. The resource potential of the Pimienta formation and its adjacent tight formations within the onshore Sureste basin is estimated by the authors at tens of billions of barrels.

3. The central thesis is economic, not technological: the synergy of developing the shale and tight formations makes the project highly profitable through three independent effects — shared capital costs across the two targets, diversification of the production profile (a fast carbonate plateau plus cyclic shale development), and infrastructure synergy, including gas utilization.

4. Flow mechanisms in the shale and in the tight reservoirs are fundamentally different — diffusion-matrix in the Pimienta versus fracture-matrix in the Jurassic-Cretaceous carbonates. Despite this, a single technological fracturing protocol is proposed for both targets (one fleet, one base fracturing fluid), with a single adjustable parameter — the presence or absence of an acid stage: it is not required for the Pimienta, while for the tight carbonates it is introduced to reactivate the existing natural fracture network.

5. Associated gas is utilized flare-free by injection into depleted Miocene sandstones serving as underground gas storage. The solution is split into two levels: formation of UGS — a mature, low-risk foundation that eliminates flaring and creates a gas reserve; mineral binding of hydrogen sulfide by the rock's oxidized iron (a subsurface analogue of iron sponge) — a promising add-on that shifts sulfur from a surface problem to a mineral-bound form in the reservoir. Mineral desulfurization is designed for a static regime and a decade-long timescale, which removes the kinetic objections (slow diffusion and passivation are not critical given the allotted time), and monitoring reduces to an annual H_2S measurement from a monitoring well.

6. Incremental placement of Pueblo de Pimienta pads: the first ones in fault zones with proven vertical saturation of the tight reservoirs, where geological certainty is greatest; extension to zones remote from faults with diffusive saturation only after the technology and economics are confirmed at the first stage.

7. The Tight-Shale Burger approach is applicable beyond Mexico. A direct analogue is the Maracaibo basin (Venezuela): the La Luna formation charges both adjacent fractured Cretaceous carbonates (La Paz, Mara, Rosario) and the overlying, 90%+-depleted sandstones of the Bolívar belt, reproducing both the

"burger" and a ready-made system for mineral H_2S sequestration. The desulfurization solution is also applicable to sour gas giants elsewhere (for example, the Tengiz–North Buzachi pair in the Caspian region, with an associated effect of reducing heavy-oil viscosity).

8. Target effect for Tabasco state: a 4–6-fold increase in onshore production relative to the current level, 2–5-fold growth in cumulative production with cyclic development of the Pimienta shale formation, reaching 1.5–2 million bbl/d by 2033–2035 with construction of 150–200 Pueblo de Pimienta pads. The project target will be confirmed by the pilot.

9. The environmental component follows from the project's structure rather than being added to it: development on territory with a century-long history and ready-made infrastructure minimizes new impact, while the cash flow creates, for the first time, a funding source for programs with no other vehicle — restoration of lagoons and lakes contaminated over a century (the Pantanos de Centla system), coastline and wetland monitoring, flare-free gas utilization. The desalination and water-treatment plants are designed comprehensively from the outset — not as facilities later adapted to the region's needs, but built from day one for a triple purpose: industrial (fracturing), municipal, and agricultural water supply. The project does not require environmental compensation — it creates an environmental program that could not otherwise be implemented.

Through the Pueblo de Pimienta system, Tight-Shale Burger transforms a territory with a century-long oil history, ready-made infrastructure, and seemingly exhausted potential into one of Mexico's most dynamic oil and gas regions of the 21st century. This is not only a technical innovation - the country's first template for simultaneous development of a source rock and adjacent tight reservoirs, complemented by flare-free gas utilization through natural subsurface desulfurization — but also a powerful driver of socio-economic development for the entire southeast of the country.

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