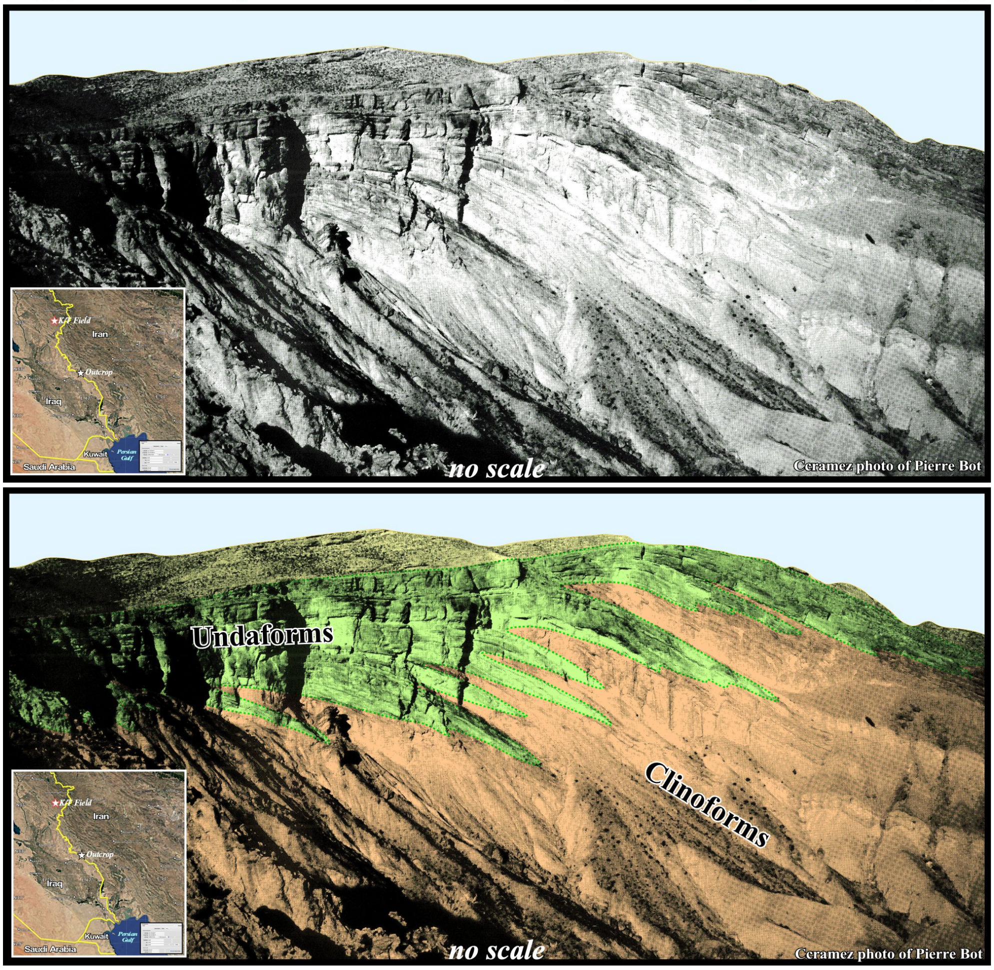
Oligocene Carbonate Reservoir
Case-Study from Northern Iraq
Regional Geological Framework

(Implications for Seismic Interpretation and Petroleum Exploration)

Oligocene Undaforms and Clinoforms

East **(Lower Asmari Formation, Iran Onshore)** West



Ccramez, May 2026

Caption of the cover

This photograph, taken by Pierre Bot during a Total field excursion in onshore Iran in the 1980s, illustrates an exceptional outcrop analogue of the Lower Asmari Formation and its Oligocene progradational carbonate system. Although the exact location of the outcrop is only approximately known, the exposure clearly shows the transition between shallow-water carbonate undaforms and deeper muddy clinoforms deposited during Oligocene marine ingression associated with the warm interglacial phases accompanying the early stages of Antarctic glaciation.

This outcrop is considered broadly equivalent, in both age and depositional facies, to the Oligocene reservoir interval of the Case-Study Petroleum System in southeastern Iraqi Kurdistan. In the study field, potential reservoir-rocks (Rrs) are interpreted to occur preferentially within the shallow-water carbonate facies and may have been significantly enhanced by fracturing, fracture corridors, karstification, dolomitization, and other diagenetic processes.

The exposure also demonstrates a fundamental geological characteristic of progradational carbonate systems: facies boundaries are oblique to chronostratigraphic surfaces. The characteristic inverted-S geometry of the depositional profile illustrates the spatial distribution of the shallow-water undaform, slope clinoform, and deeper-water fondoform depositional environments existing contemporaneously within the carbonate system. The diachronous nature of the depositional architecture results from the progressive basinward migration of these environments during progradation. Consequently, lithological boundaries (facies lines) do not coincide with time-equivalent surfaces (chronostratigraphic lines).

This observation is of major importance for the geological interpretation of the case-study petroleum system. It implies that reservoir distribution, connectivity, and trap geometry cannot be accurately predicted solely from structural maps of chronostratigraphic horizons. Instead, petroleum accumulations are more likely controlled by the structural configuration of facies-defined reservoir bodies and their associated fracture systems. The figure therefore illustrates not only the regional geological context of the study reservoirs, but also the fundamentally theory-laden nature of seismic interpretation and petroleum-geological modelling.

Executive Summary

This memorandum analyses the geological global context of the Oligocene reservoir-rocks (Rrs) of the case-study petroleum system in southeastern Iraqi Kurdistan and discusses its implications for seismic interpretation, volumetric evaluation, and petroleum exploration.

The study demonstrates that the interpretation of the case-study petroleum system cannot be reduced to a purely inductive reading of seismic data. On the contrary, the geological interpretation is fundamentally guided by prior geological concepts derived from:

- **regional tectonics,**
- **sequence stratigraphy,**
- **carbonate depositional systems,**
- **climatic evolution,**
- **glacio-eustatic sea-level fluctuations,**
- **and paleogeographic reconstruction.**

Particular emphasis is placed on the Eocene–Oligocene Transition (EOT) and the onset of major Antarctic glaciation, which generated large-amplitude glacio-eustatic sea-level fluctuations during the Oligocene. These conditions strongly favoured the development of extensive progradational carbonate systems along the northeastern margin of the Arabian Plate, characterised by the depositional association of undaforms, clinoforms, and fondoforms.

The memorandum argues that the Oligocene interval of the case-study petroleum system should not be interpreted as a simple layer-cake chronostratigraphic succession. Instead, the potential reservoir-rocks (Rrs) are interpreted as diachronous facies-control-led carbonate bodies generated by the progressive basinward migration of depositional environments during carbonate progradation. Consequently, facies boundaries are ex-pected to be oblique to chronostratigraphic surfaces, implying that structural maps drawn on time-equivalent seismic horizons may not accurately represent the true geo-metry and continuity of the reservoir-rocks.

The study further demonstrates that the presently available merged legacy 3D seismic dataset does not possess sufficient vertical and lateral seismic resolution to directly individualise the likely thin and heterogeneous reservoir-rocks developed within the Oligocene carbonate interval. This limitation has major petroleum consequences.

On the one hand, insufficient seismic resolution may produce resource overestimation through:

- **false continuity,**
- **false structural closure,**
- **and overestimated reservoir connectivity.**

On the other hand, it may produce resource underestimation by failing to identify:

- ✦ **hidden reservoir-rocks,**
- ✦ **sub-seismic pay zones,**
- ✦ **fracture corridors,**
- ✦ **karstified intervals,**
- ✦ **or facies-controlled stratigraphic traps.**

Consequently, the memorandum emphasises that seismic interpretation in complex carbonate petroleum systems is intrinsically theory-laden. The geological meaning of seismic reflections does not emerge directly from the seismic data themselves, but rather from the interaction between:

- ➡ **prior geological conjectures,**
- ➡ **regional geological knowledge,**
- ➡ **sequence-stratigraphic concepts,**
- ➡ **depositional models, and**
- ➡ **the observational constraints provided by the seismic image.**

The tentative interpretation of the legacy 3D seismic Inline 5876 crossing the study structure illustrates this principle particularly well. The same seismic dataset may generate significantly different geological interpretations depending upon the conceptual framework adopted by the geoscientist.

The memorandum concludes that meaningful seismic interpretation in complex carbonate petroleum systems such as the case-study is impossible without prior geological knowledge. It also emphasises that high-quality seismic reprocessing, amplitude-preserving workflows, seismic inversion, azimuth-preserving imaging, fracture characterisation, and integrated geological interpretation are essential for reducing the epistemological gap between seismic representation and actual geological complexity.

Abstract

This memorandum examines the geological global context of the Oligocene reservoir-rocks (Rrs) of the case-study petroleum system in southeastern Iraqi Kurdistan and evaluates its implications for seismic interpretation and petroleum exploration. The study integrates regional geological information derived from:

- **Cenozoic climatic evolution,**
- **glacio-eustatic sea-level fluctuations,**
- **sequence stratigraphy,**
- **paleogeography,**
- **carbonate depositional systems, and**
- **Zagros tectonics.**

Particular attention is given to the Eocene–Oligocene Transition (EOT) and the onset of major Antarctic glaciation, which induced repeated sea-level fluctuations responsible for the development of extensive Oligocene progradational carbonate systems along the northeastern margin of the Arabian Plate.

Within this framework, the Oligocene interval of the csae-study petroleum system is interpreted as consisting of diachronous facies-controlled carbonate bodies rather than laterally con-tinuous chronostratigraphic units. The depositional model predicts that:

- **facies boundaries are oblique to chronostratigraphic surfaces,**
- **reservoir-rocks are strongly heterogeneous, and**
- **hydrocarbon accumulations are controlled not only by structural closure but also by facies architecture, depositional geometry, fracture systems, and diagenetic evolution.**

The memorandum further analyses the epistemological implications of limited seismic resolution in complex carbonate petroleum systems. It demonstrates that the presently available merged legacy 3D seismic dataset of the study field is insufficient to directly resolve the detailed geometry of the potential reservoir-rocks, thereby obliging the geoscientist to introduce significant geological inference into the interpretation and volumetric evaluation.

The study distinguishes between:

- **positive petroleum consequences associated with resource overestimation through false continuity or false closure, and**
- **negative petroleum consequences associated with resource underestimation through hidden reservoir-rocks and sub-seismic pay zones.**

A tentative geological interpretation of legacy 3D seismic Inline 5876 is presented as a practical illustration of the fundamentally theory-laden nature of seismic interpretation in petroleum geology. The study argues that seismic interpretation should not be viewed as a passive observational activity, but rather as a process of conjectures and refutations in which geological hypotheses are continuously tested against observational constraints.

The memorandum concludes that meaningful seismic interpretation in complex carbonate reservoirs requires the continuous interaction between prior geological knowledge and observational data, and that advanced seismic reprocessing, inversion, fracture characterisation, and integrated geological interpretation are essential for reducing geological uncertainty and improving exploration and development decisions.

1)Introduction

Geological Knowledge as an A Priori Framework for Petroleum Exploration

Petroleum exploration is not a purely inductive activity in which geological knowledge emerges passively from the accumulation of observational data. On the contrary, geological interpretation is fundamentally guided by prior geological concepts and theoretical models that precede the observation itself. In petroleum geology, seismic reflectors, well logs, outcrops, production data, structural maps, and geophysical attributes do not possess an intrinsic meaning independent of interpretation. Their geological significance depends upon an *a priori* conceptual framework within which the observations are organised, compared, and critically evaluated

The case-study petroleum system of southeastern Iraqi Kurdistan provides an instructive example of this epistemological reality. The interpretation of the study oil field did not originate from isolated seismic observations alone, but from the integration of regional geological knowledge derived from sedimentology, sequence stratigraphy, tectonics, paleogeography, carbonate depositional systems, climatic evolution, and geological analogues observed throughout the Zagros Fold–Thrust Belt and neighbouring regions of Iran and Iraq.

The geological framework summarised in Figure 1 constitutes the initial set of working hypotheses guiding the interpretation of the case-study petroleum system. These hypotheses are not arbitrary assumptions; they are geological conjectures derived from independent regional observations and established geological principles. Their scientific value resides precisely in the fact that they generate predictions that can subsequently be corroborated, refined, or falsified by subsurface data.

One of the fundamental hypotheses concerns the climatic and eustatic evolution of the Cenozoic, which allows a regional understanding of sea-level fluctuations during the deposition of the study reservoir interval/s (R) — hydraulically connected petroleum-bearing interval or pressure/production unit, which may include both porous and non-porous rocks — and its associated reservoir-rocks (Rrs) — individual porous and permeable rock bodies within the reservoir (R) that are capable of storing and transmitting hydrocarbons.

Such understanding is essential for the development and production analysis of the K/T field because eustatic sea level is not only a parameter of the climate system, but also one of the principal controls on sedimentation. Variations in eustatic sea level, together with tectonic subsidence, govern the evolution of the available depositional space (shelf accommodation) and therefore strongly influence the geometry, facies distribution, and stacking pattern of sedimentary bodies.

In fact, the Earth's climate has experienced an overall long-term cooling trend since, at least, the beginning of the Cenozoic. This cooling evolution is punctuated by three major cooling steps during which the cooling rate increased significantly:

(i) the Late Eocene–Early Oligocene transition (approximately 36 Ma),
(ii) the Middle Miocene cooling step (approximately 15,5 Ma), and
(iii) the Late Pliocene cooling step (approximately 3,0 Ma).

The first of these corresponds to the onset of major Antarctic glaciation during the Eocene–Oligocene Transition (EOT). The Middle Miocene event is associated with a

still incompletely understood climatic transition, whereas the Late Pliocene step corresponds to the expansion of the Northern Hemisphere ice sheets.

From a sedimentological and petroleum-geological perspective, the critical point is that the glacial and interglacial cycles associated with these climatic cooling phases generated major glacio-eustatic sea-level fluctuations. These fluctuations controlled alternating lowstand and highstand geological conditions and strongly influenced the development of carbonate platforms and progradational depositional systems.

During the warmer interglacial periods, deglaciation induced relative sea-level rises (marine ingressions), favouring the development of carbonate factories and the growth of the progradational carbonate platforms, particularly within Earth's equatorial and sub-tropical regions

Geological Setting of the Studied Oligocene Carbonate Reservoir

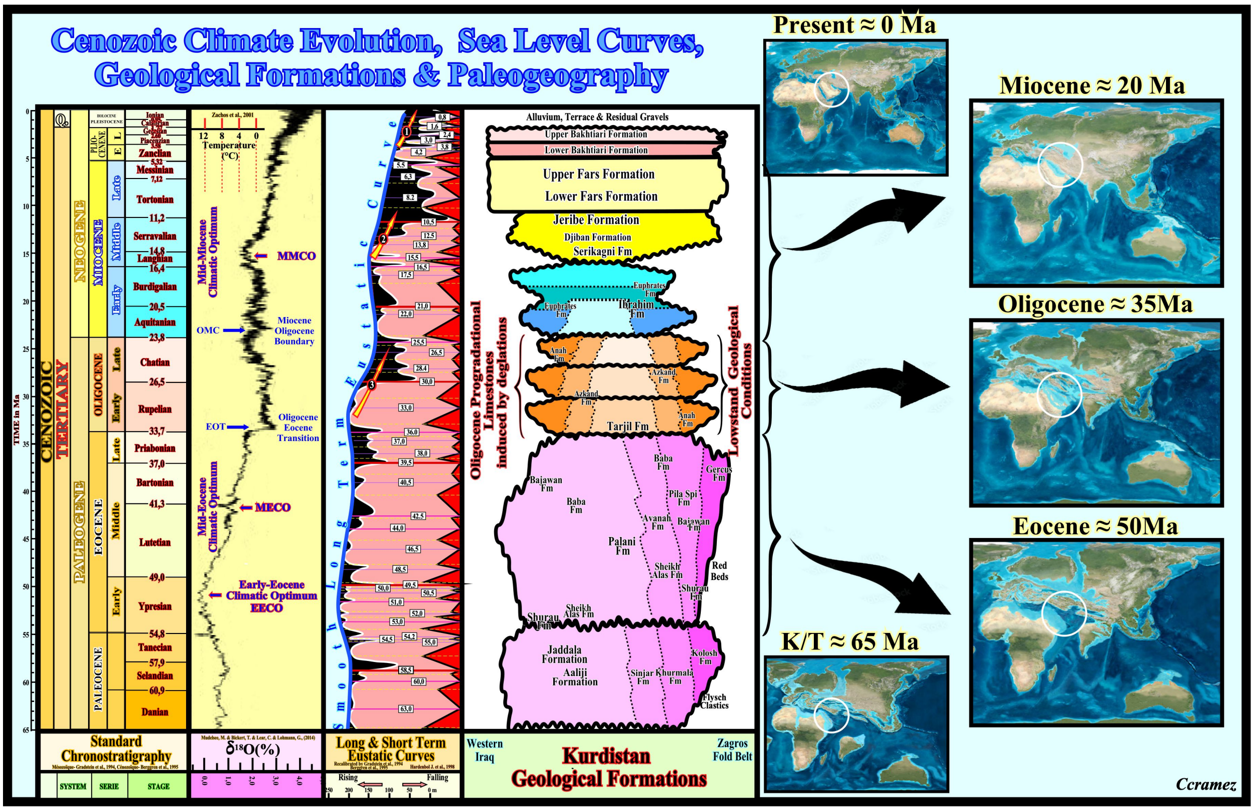


Figure 1 — Geological Setting of the Studied Oligocene Reservoir-Rocks (Rrs).
This figure summarises the principal geological information available prior to detailed interpretation. It illustrates the regional tectonic, stratigraphic, and structural framework that constrains and guides the geological interpretation of the investigated Oligocene carbonate reservoir. It illustrates how regional geological understanding precedes and conditions the observation and interpretation of seismic, well, stratigraphic, sedimentological, and structural data. The figure integrates several independent but genetically related geological datasets, including: (1) Cenozoic climatic evolution, (2) long- and short-term eustatic sea-level variations, (3) the regional chronostratigraphic framework, (4) the stratigraphic succession of the Kurdistan geological formations, and (5) the paleogeographic evolution of the Middle East from the Paleocene to the present day. Together, these datasets provide the regional geological framework within which the Oligocene carbonate reservoirs (R) of the studied oil field were deposited and subsequently deformed. Particular emphasis is placed on the Eocene–Oligocene Transition (EOT) and the onset of major Antarctic glaciation, which induced large-amplitude glacio-eustatic sea-level fluctuations throughout the Oligocene, as well as on the persistently equatorial to subtropical paleogeographic position of the Middle East during the Cenozoic. Together, these climatic and paleogeographic conditions strongly favoured the development of extensive carbonate depositional systems along the northeastern margin of the Arabian Plate. This is particularly true during lowstand time intervals, when relative sea level falls below the depositional coastal break/shelf break inherited from the preceding

highstand systems tract of the previous sequence-cycle. Such conditions promoted basinward progradation and generated the characteristic association of shallow-water undaforms, slope clinoforms, and deeper-water fondoforms interpreted within the Oligocene interval of the case-study petroleum system. This regional geological model constitutes an essential working hypothesis guiding the interpretation of the subsurface data; a) Lower Fars detachment, b) tectonic decoupling, c) disharmonic deformation, and d)mismatch between shallow and deeper structures. It predicts that the Oligocene reservoir/s interval (R) is not composed of simple layer-cake chronostratigraphic units, but rather of diachronous facies bodies in which facies boundaries are oblique to time-equivalent surfaces. Consequently, reservoir geometry, connectivity, and trap distribution are expected to be controlled not only by structural deformation, but also by the spatial organisation and progradation of carbonate depositional environments. The figure therefore illustrates the fundamentally theory-laden nature of geological observation in petroleum exploration: geological knowledge does not emerge from isolated observations alone, but from the critical interaction between prior geological conjectures and new observational data capable of corroborating, refining, or falsifying these interpretations.

This paleogeographic context is especially important because the Iraqi Kurdistan region remained located within tropical to subtropical paleolatitudes throughout the Cenozoic, following the breakup of the Pangea supercontinent approximately 200–180 Ma ago during the Late Triassic to Early Jurassic. Such paleoclimatic and paleogeographic conditions were highly favourable for the development of extensive carbonate depositional systems along the northeastern margin of the Arabian Plate.

The Oligocene reservoir-rocks (Rrs) of the case-study petroleum system are interpreted within this broader climatic and depositional framework. They are closely related to the onset of Antarctic glaciation and are interpreted to have developed preferentially within shallow-water carbonate undaform depositional environments. These carbonate bodies were bounded and locally modified by erosional surfaces, i.e., unconformities generated during relative sea-level falls with glacial maxima.

Such erosional and subaerial exposure surfaces may have significantly enhanced the petrophysical properties of the potential reservoir-rocks (Rrs) through dissolution, karstification, meteoric diagenesis, and related weathering processes. However, the precise mechanisms, geometry, and reservoir impact of these weathering and diagenetic processes remain incompletely understood and require detailed geological, petrophysical, and seismic investigation.

This depositional model implies, *a priori*, several important geological and petroleum consequences:

- ➡ **First, the Oligocene carbonate reservoir-rocks (Rrs) cannot be interpreted as a simple layer-cake succession composed of laterally continuous chronostratigraphic units. Instead, each potential reservoir interval (R) is expected to consist of diachronous facies bodies generated by the progressive basinward migration of depositional environments during progradation. Consequently, the facies boundaries defining the potential reservoir-rocks (Rrs) are expected to be oblique to chronostratigraphic surfaces. This implies that the geometry and spatial distribution of the reservoir-rocks cannot be accurately represented solely by structural maps drawn on time-equivalent seismic horizons. As a result, structural closure mapped on chronostratigraphic horizons may neither represent the true geometry of the porous reservoir-rocks nor the actual geometry of hydrocarbon trapping.**
- ➡ **Second, this depositional architecture predicts strong lateral and vertical heterogeneities within the reservoir interval/s (R). Potential reservoir-rocks (Rrs) are expected to develop preferentially within shallow-water carbonate facies, particularly within grain-supported shoal, reef, back-reef, and platform-margin environments associated with the undaform domain. In contrast, muddier clinoform**

and fondoform facies are expected to exhibit poorer reservoir properties. Furthermore, reservoir quality may be significantly modified after deposition by fracturing, fracture corridors, stylolitisation, dolomitization, karstification, dissolution, and other diagenetic processes, which may either enhance or reduce reservoir connectivity and storage capacity.

➡ **Third, the geological model predicts that structural geometry alone cannot adequately define petroleum traps and reservoir connectivity within the case-study petroleum system. Since the individual reservoir-rocks (Rrs) are both facies-controlled and diachronous, structural maps drawn on chronostratigraphic horizons may not accurately represent the true geometry and spatial distribution of the reservoir-rocks. Consequently, petroleum accumulations are expected to depend not only on structural closure, but also on the spatial organisation, continuity, compartmentalisation, and deformation of the facies-defined reservoir bodies and their associated fracture systems.**

➡ **Fourth, if the available seismic data allow geoscientists to identify and map the facies boundaries — for instance through 3D seismic inversion, multi-attribute analysis or advanced seismic attributes— the corresponding structural maps may provide a relatively accurate representation of the geometry and distribution of the most likely reservoir-rocks (Rrs).**

➡ **Fifth, if the available seismic data do not possess sufficient vertical and lateral seismic resolution to individualise these facies boundaries, and only approximate chronostratigraphic horizons can be mapped reliably, the geoscientist is obliged to introduce numerous geological approximations into the volumetric evaluation.**

Consequently, in order to estimate the potential hydrocarbon resources trapped within the Oligocene reservoir interval/s (R), the geoscientist generally proceeds, as follows:

A) He initially assumes the presence of a single broad Oligocene reservoir interval (R), even though several distinct reservoirs may actually exist within the interval and may not be hydraulically connected.

B) At the same time, he generally assumes that the trap configuration is predominantly structural, typically corresponding to a tentative four-way dip closure mapped on chronostratigraphic seismic horizons. Consequently, the initial volumetric evaluation commonly simplifies the geological complexity of the system by treating potentially compartmentalised and facies-controlled reservoir-rocks (Rrs) as be-longing to a single continuous reservoir unit.

C) He constructs a structural map of the top Oligocene horizon, within which the presence of a broader reservoir interval (R) is assumed, although the individual reservoir-rocks (Rrs) cannot be directly resolved seismically.

D) Using this structural map, he estimates the most likely closed area within which hydrocarbons may potentially accumulate.

E) Since the potential reservoir-rocks (Rrs) cannot be directly individualised, he introduces an assumed net-to-gross pay ratio (NTG pay), corresponding to the ratio between the thickness of productive reservoir-

rocks (net pay) and the total thickness of the interval considered (gross interval):

$$\text{NTG pay} = \frac{\text{Net Pay Thickness}}{\text{Gross Interval Thickness}}$$

F) Ultimately, he estimates the hydrocarbon-in-place resources using either a deterministic or probabilistic volumetric estimation methods taking into account:

- the closed area;
- the gross reservoir thickness;
- the net-to-gross ratio;
- the porosity;
- the hydrocarbon saturation, and
- the formation volume factor (FVF), which relates the hydrocarbon volumes at reservoir conditions to volumes at standard surface conditions.

Consequently, if the geometry and distribution of the actual reservoir-rocks (Rrs) are poorly constrained, the volumetric evaluation may contain significant geological uncertainty, even when sophisticated deterministic or probabilistic calculation methods are employed.

1.1) The Epistemological Consequences of Limited Seismic Resolution

Obviously, the hypothesis that available seismic data do not possess sufficient vertical and lateral seismic resolution to individualise these facies boundaries—which is presently the case for the merged legacy 3D dataset of the case-study petroleum system—has important positive and negative petroleum consequences.

From a petroleum-geological perspective, these consequences are not merely technical.

They directly affect the estimation of:

- ➡ hydrocarbon-in-place resources,
- ➡ reservoir continuity,
- ➡ trap geometry,
- ➡ field compartmentalisation,
- ➡ development strategy, and ultimately,
- ➡ the economic value attributed to the petroleum system.

More importantly, these consequences illustrate a fundamental epistemological problem in petroleum exploration — the distinction between the actual geological reality of the subsurface and its seismic representation ».

In practice, seismic data never constitute a direct image of geology itself. Seismic sections are physical representations of contrasts in elastic proper-ties filtered by:

- acquisition geometry,

- **bandwidth limitations,**
- **wave propagation effects,**
- **processing assumptions,**
- **noise attenuation procedures,**
- **migration algorithms, and**
- **intrinsic limits of seismic resolution.**

Consequently, seismic interpretation is never a purely objective or inductive reading of "raw data." Instead, it is fundamentally dependent upon prior geological concepts, depositional models, and interpretative assumptions. In In Popperian terms, seismic interpretation corresponds not to a passive accumulation of observations, but rather to a continuous process of conjectures and refutations, that is to say:

a **continuous process of conjectures and refutations**

This epistemological limitation becomes particularly important in complex carbonate petroleum systems such as K/T, where the critical geological objects controlling hydrocarbon accumulations — namely the individual reservoir-rocks (Rrs), fracture corridors, stylolites, karstified intervals, facies boundaries, and small-scale compartmentalisation — frequently occur at scales below conventional seismic resolution.

Under such conditions, the geoscientist is obliged to replace direct observation by indirect geological inference. The interpretation therefore depends increasingly on:

- **sedimentological concepts,**
- **sequence-stratigraphic models,**
- **carbonate platform analogues,**
- **well information,**
- **petrophysical interpretation,**
- **structural geology, and**
- **regional geological understanding.**

This situation generates two opposite but equally important petroleum consequences.

1.1.1) Positive Petroleum Consequences: *Resource Overestimation by "False Continuity" or "False Closure"*

Limited seismic resolution may artificially increase the apparent continuity of the reservoir system. In such situations, several isolated, poorly connected, or compartmentalised reservoir-rocks (Rrs) may be incorrectly interpreted as belonging to a single continuous reservoir interval (R). Likewise, structural closure mapped on chronostratigraphic seismic horizons may create the illusion of a large and laterally continuous hydrocarbon accumulation, whe-

This phenomenon may be described as false continuity or false closure

reas the actual facies-con-trolled reservoir-rocks may:

- ➡ pinch out laterally,
- ➡ become tight or cemented,
- ➡ be water-bearing,
- ➡ be disconnected hydraulically,
- ➡ or even disappear entirely within portions of the mapped closure.

This phenomenon may be described as:

Under these conditions, volumetric calculations may artificially over-estimate:

- ➡ gross rock volume,
  - ➡ net pay continuity,
    - ➡ reservoir connectivity,
      - ➡ drainage efficiency, and ultimately
        - ➡ the estimated hydrocarbon-in-place resources and recoverable reserves.

Similarly, seismic data with insufficient resolution may fail to identify:

- ✦ stylolite barriers,
- ✦ tight carbonate intervals,
- ✦ small-scale fault compartmentalisation, or
- ✦ diagenetic heterogeneities,

thereby creating an overly optimistic image of reservoir continuity and production performance.

From a management perspective, such interpretations may generate:

- ➡ overestimated reserve expectations,
  - ➡ oversized development plans,
    - ➡ inappropriate well placement,
      - ➡ unrealistic production forecasts, and
        - ➡ erroneous economic evaluations.

1.1.2) Negative Petroleum Consequences: *Resource Underestimation by "Hidden Reservoir-Rocks" or "Sub-Seismic Pay"*

Paradoxically, the same lack of seismic resolution may also produce the opposite effect:

a significant underestimation of hydrocarbon resources

Thin but highly productive reservoir-rocks (Rrs) may remain entirely below seis-mic detectability. This is particularly important in fractured carbonate systems such as K/T, where economically significant reservoir intervals may consist of:

- ➡ thin porous shoal bodies,
  - ➡ fracture corridors,
    - ➡ karstified zones,
      - ➡ dolomitized intervals, or

➡ **highly fractured carbonate beds, whose thicknesses remain below conventional seismic resolution.**

Such geological bodies may therefore constitute:

hidden reservoir-rocks, or sub-seismic pay zones

In addition, facies-controlled stratigraphic traps or combined structural–stratigraphic traps may remain undetected if the geological interpretation relies exclusively on chronostratigraphic seismic horizons. Under such conditions, the mapped structural closure may represent only a partial and simplified image of the actual petroleum system geometry.

Similarly, several independent reservoirs (R) may occur outside the tentatively assumed structural closed area defined on chronostratigraphic surfaces. This situation is particularly important in progradational carbonate systems, where the distribution of the potential reservoir-rocks (Rrs) is controlled primarily by depositional facies architecture rather than by purely structural geometry.

Consequently, porous and permeable carbonate bodies associated with shallow-water undaform depositional environments may extend laterally beyond the mapped structural closure, or may occur as isolated stratigraphic or combination traps not directly visible on conventional structural maps. In such cases, economically significant hydrocarbon accumulations may remain undetected if the interpretation is restricted to simple four-way dip structural closures mapped on time-equivalent seismic horizons.

This has major petroleum implications because:

- ➡ **potentially productive reservoirs may not be included within the volumetric evaluation,**
- ➡ **important hydrocarbon accumulations may remain undrilled,**
- ➡ **field compartmentalisation may be underestimated,**
- ➡ **and the true petroleum potential of the system may therefore be significantly underestimated.**

From an exploration/development perspective, this may result in:

- ☑ **conservative volumetric estimates,**
- ☑ **missed drilling opportunities,**
- ☑ **underdeveloped compartments,**
- ☑ **and significant overlooked hydrocarbon resources.**

Thus, in complex facies-controlled carbonate systems such as the Kurdamir/Topkhana petroleum system, the absence of an apparent structural closure on chronostratigraphic maps does not necessarily imply the absence of hydrocarbon accumulations.

1.1.3) Epistemological Implications

Thus, limited seismic resolution does not merely introduce statistical or computational uncertainty into the volumetric evaluation. It fundamentally affects the geological representation of the petroleum system itself.

The seismic image may:

- **create the illusion of reservoir continuity where none exists, or**
- **conceal economically important reservoir-rocks that remain be-low seismic detectability.**

In other words, the issue is not simply one of imperfect measurement, but rather one of the relationship between:

- **geological reality, and**
- **its seismic representation.**

Consequently, seismic interpretation in complex carbonate petroleum systems should not be viewed as a passive observational activity, but rather as a process of critical geological reasoning, in which prior geological hypotheses are continuously confronted with observational evidence capable of corroborating, refining, or falsifying them.

This is precisely why:

- ☑ **high-quality seismic reprocessing,**
- ☑ **amplitude-preserving workflows,**
- ☑ **azimuth-preserving imaging,**
- ☑ **seismic inversion,**
- ☑ **fracture characterisation, and**
- ☑ **integrated geological interpretation**

are essential for the K/T petroleum system.

Their objective is not merely to produce visually cleaner seismic sections, but rather to reduce the epistemological gap between the seismic representation and the actual geological complexity of the subsurface.

2) Theory-Laden Observation in Petroleum Geology

Tentative Interpretation of a Legacy 3D Seismic Line

Before analysing the seismic interpretation itself, it is important to briefly recall the regional geological and structural context of the Kurdamir/Topkhana (K/T) petroleum system.

The geological map illustrated in Figure 2 shows the location of the complex buried anticline structure with which is associated the Kurdamir/Topkhana Oil Field within southeastern Iraqi Kurdistan and the position of the seismic line detail crossing the field.

The Kurdamir/Topkhana structure is located within the northwestern segment of the Zagros Fold–Thrust Belt, along the northeastern margin of the Arabian Plate. Re-

gionally, the area is characterised by elongated NW–SE-oriented anticlines associated with thin-skinned tectonics above the regional Lower Fars detachment level.

However, unlike many neighbouring fields of southeastern Iraqi Kurdistan — such as Kirkuk, Chemchemal, or Taq Taq — the Kurdamir/Topkhana structure does not correspond to a well-expressed surface anticline. On the contrary, the K/T petroleum system is interpreted as a predominantly buried anticlinal structure, developed at depth beneath a much more subdued surface expression. Con-sequently, the structural closure responsible for the hydrocarbon accumulation is not directly observable at surface and must be inferred principally from seismic and subsurface data.

SE Iraqi Kurdistan (Geological Map & Fields)

(Ccramez, adapted from D. G. of Geological Survey & Mineral Investigation, Baghdad, 1986)

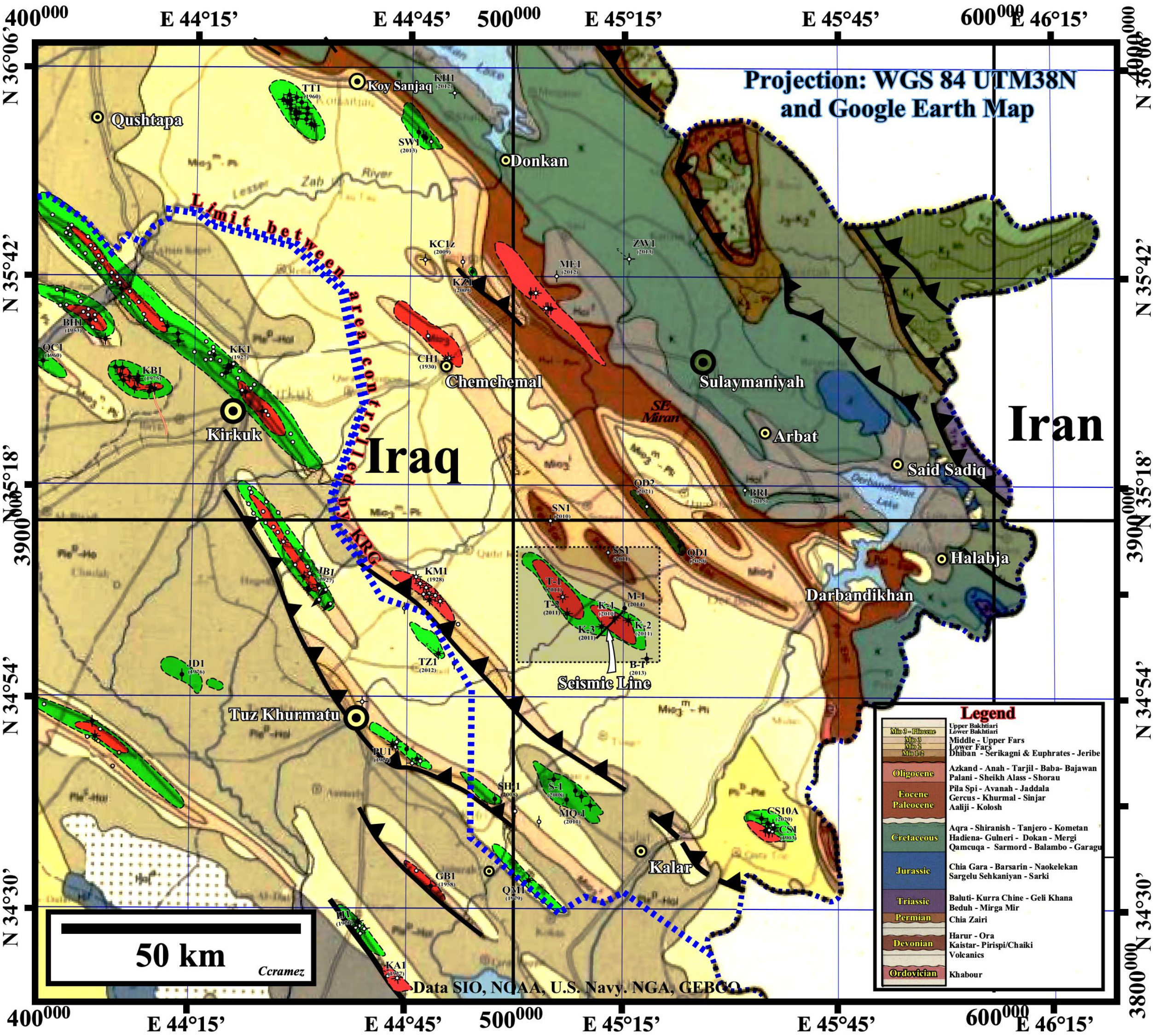


Figure 2 — Geological Map & Fields of SE Iraqi Kurdistan. This figure illustrates the principal geological structures, petroleum fields, and tectonic framework of southeastern Iraqi Kurdistan, located within the northwestern segment of the Zagros Fold–Thrust Belt. The region encompasses, approximately, the transition from the Foothill Zone of the Zagros Belt toward the adjacent low-relief foreland basin domain. Geomorphologically, the area is characterised by a well-developed system of linear to curvilinear ridges and intervening valleys, reflecting the surface expression of NW–SE-trending anticlines and synclines generated by regional compressional tectonics. These topographic lineaments are particularly well developed within the northeastern sector of the study area (Sulaymaniyah–Halabja region), where tight and elongated ridges correspond mainly to resistant carbonate formations forming the cores of folded structures.Toward the southwestern and southern sectors of the region (Kirkuk–Tuz Khurmatu–Kifri area), the topographic relief progressively decreases, and the landscape transitions into a more subdued and gently undulating

morphology characteristic of the foreland basin domain. In these areas, fold amplitudes generally decrease, and the structures become broader and less clearly expressed at surface. The regional drainage network is strongly structurally controlled, with several river courses locally aligned either parallel or transverse to the fold axes. In several locations, the occurrence of water gaps, deflected streams, and structurally controlled valleys indicates the continuing influence of tectonic deformation on landscape evolution. Overall, the figure clearly demonstrates that the regional topographic lineaments provide a reliable proxy for the underlying subsurface structural trends, underlining the importance of fold geometry in controlling both regional geomorphology and hydrocarbon trapping within the Zagros petroleum province. From a structural and petroleum-systems perspective, the distribution of the oil and gas fields clearly follows the regional NW–SE structural grain associated with the fold-thrust architecture. Major producing trends — including the Bai Hassan–Kirkuk–Jambur trend, as well as the alignments extending toward Chemchemal, Kurdamir/Topkhana, Khor Mor, Pulkhana, Miran, and Qara Dagh — are spatially associated with elongated anticlinal structures, confirming the strong structural control exerted on hydrocarbon accumulation throughout the region. The map also highlights the coexistence of oil fields, gas fields, and gas-condensate accumulations, organised into several major petroleum provinces: (i) Kirkuk Area — a mature supergiant petroleum province characterised by large structural closures, dense well control, and extensive production infrastructure; (ii) Central Corridor (Chemchemal–Kurdamir/Topkhana) — characterised predominantly by major gas and gas-condensate accumulations, including the case-study petroleum system; (iii) Eastern Belt (Miran–Bina Bawi–Qara Dagh) — consisting mainly of gas-prone structures located closer to the frontal zones of the Zagros Fold–Thrust Belt. Particular attention should be paid to the cade-study structure, located within the central corridor. Unlike many neighbouring fields expressed by prominent surface anticlines, the studied structure is interpreted as a predominantly buried anticlinal structure, whose principal hydrocarbon accumulations are not directly associated with a major surface topographic high. The field is interpreted to contain two principal gas-cap culminations, corresponding approximately to the northern and Tsouthern culminations, separated by an intermediate structurally lower zone. On the figure: 1- the dotted blue line separates the area controlled by the Regional Government of Iraq (RGI/KRG) to the north from the area controlled by the Central Government of Iraq (CGI/ICG) to the south; and 2- the grey rectangle, centred around the buried Kurdamir/Topkhana structure, indicates the location of the 3D seismic Inline 5876 segment tentatively interpreted in geological terms within the present memorandum.The figure therefore provides the essential regional geological, structural, and petroleum-system framework required for understanding the tentative geological interpretation of the legacy 3D seismic data discussed in the following sections.

In addition, as illustrated, the case-study petroleum system is interpreted to contain two major gas-cap culminations, corresponding approximately to the northern and southern culminations, separated by a structurally lower intermediate zone. Whether these culminations belong to a single hydraulically connected reservoir system or to partially compartmentalised reservoir domains remains one of the important geological and development questions of the field.

This regional and structural context is critical because it strongly conditions the geological interpretation of the seismic data. The geoscientist does not interpret the seismic line in an epistemological vacuum. On the contrary, the interpretation is guided from the outset by:

- **➡ the regional tectonic framework,**
- **➡ the buried anticlinal geometry,**
- **➡ the known petroleum occurrences,**
- **➡ the assumed Oligocene progradational carbonate depositional model, and**
- **➡ the existence of potential gas-cap culminations within the structure.**

Figures 3 and 4 illustrate particularly well the fundamentally theory-laden nature of seismic interpretation in petroleum geology. Figure 3 shows an uninterpreted segment of the merged legacy 3D seismic dataset crossing the case-study petroleum system, whereas Figure 4 presents a tentative geological interpretation of the same seismic line.

At first sight, the uninterpreted seismic section appears to consist merely of a set of seismic reflections organised in broad anticlinal geometries. By itself, however, the seismic image does not directly reveal:

- ✦ the geological age of the reflectors,
- ✦ the depositional environments,
- ✦ the reservoir distribution,
- ✦ the sequence boundaries,
- ✦ the facies architecture,
- ✦ the fluid content,
- ✦ or the petroleum significance of the observed geometries.

3D Inline 5876 of Studied Oil Field

(uninterpreted)

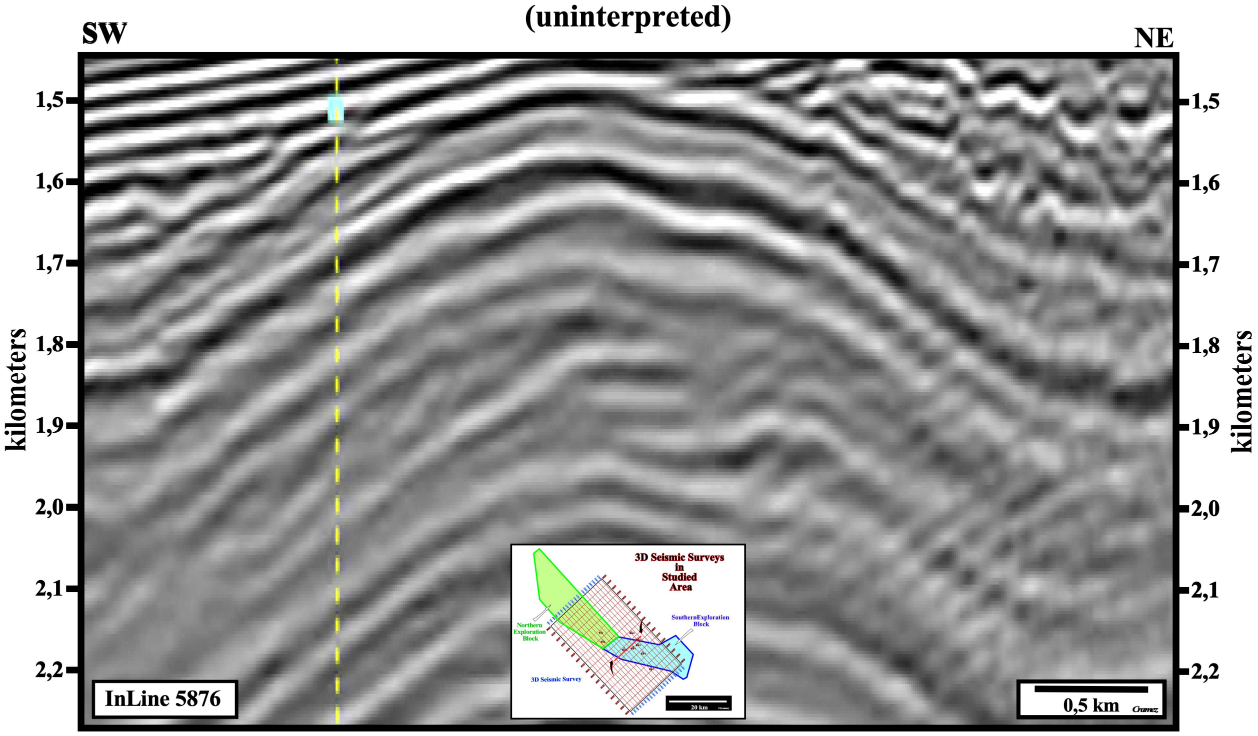


Figure 3 — Uninterpreted segment of the Legacy 3D Seismic Inline 5876. This figure shows an uninterpreted segment of the merged legacy 3D seismic Inline 5876 crossing the case-study petroleum system in southeastern Iraqi Kurdistan. The seismic line is oriented approximately SW–NE and traverses the central part of the buried studied anticlinal structure, whose location within the different merged 3D seismic surveys is indicated in the inset map. At first sight, the seismic image appears to consist merely of a series of continuous to semi-continuous seismic reflections organised in a broad anticlinal geometry. However, in its uninterpreted form, the seismic section does not directly reveal: (i) the geological age of the reflectors, (ii) the depositional environments; (iii) the location of potential reservoir-rocks (Rrs); (iv) the distribution of fluids; (v) the existence of sequence boundaries; (vi) the geometry of facies bodies; (vii) or the actual petroleum significance of the observed seismic configurations. Consequently, the seismic image by itself does not constitute a direct observation of geological reality, but rather a physically filtered representation of acoustic impedance contrasts within the subsurface. The figure therefore illustrates a fundamental epistemological principle of petroleum geology: Seismic Observations Are Intrinsically Theory-Laden. The geological meaning of the seismic reflections depends critically upon the prior geological concepts, depositional models, tectonic assumptions, and sequence-stratigraphic framework introduced by the geoscientist before and during the interpretation process. In the present memorandum, the interpretation of this seismic line is strongly guided by the previously established regional geological model of the case-study petroleum system, including: a) an Oligocene progradational carbonate depositional system, b) major glacio-eustatic sea-level fluctuations associated with the onset of Antarctic glacia-tion, c) the development of carbonate undaforms, clinoforms, and fondoforms, and d) the existence of diachronous facies-controlled reservoir-rocks bounded by sequence-stratigraphic surfaces. With-in such a geological framework, reflector terminations, geometrical relationships, and seismic con-figurations may be tentatively reorganised into meaningful geological objects capable of generating testable hypotheses concerning: 1- reservoir distribution, 2- facies geometry, 3- trap configuration, 4- fracture development, 5- reservoir connectivity, and 6- hydrocarbon accumulation. The figure also illustrates the important limitations associated with the present merged legacy seismic dataset. Although the seismic data image the broad structural geometry of

the buried studied anticline reasonably well, the available vertical and lateral seismic resolution remain insufficient to directly individualise the likely thin and heterogeneous reservoir-rocks (Rrs) developed within the Oligocene carbonate interval. Consequently, the interpretation of the petroleum system necessarily relies upon significant geological inference and conceptual modelling. This seismic line therefore constitutes an instructive example of the continuous interaction between: A) prior geological knowledge, B) seismic observations, and C) tentative geological interpretation, that characterises petroleum exploration within complex carbonate reservoirs such as the Kurdamir/Topkhana petroleum system.

These geological meanings emerge only after the introduction of a prior geological framework capable of transforming the seismic reflections into interpretable geological objects.

In the present case, the tentative interpretation shown in Figure 4 was strongly guided by the previously established regional geological model summarised in Figure 1. In particular, the interpretation assumes:

- **an Oligocene progradational carbonate system,**
- **major glacio-eustatic sea-level fluctuations associated with Antarctic glaciation,**
- **the development of carbonate undaforms, clinoforms, and fondoforms,**
- **diachronous facies geometries,**
- **and the existence of sequence boundaries associated with relative sea-level falls.**

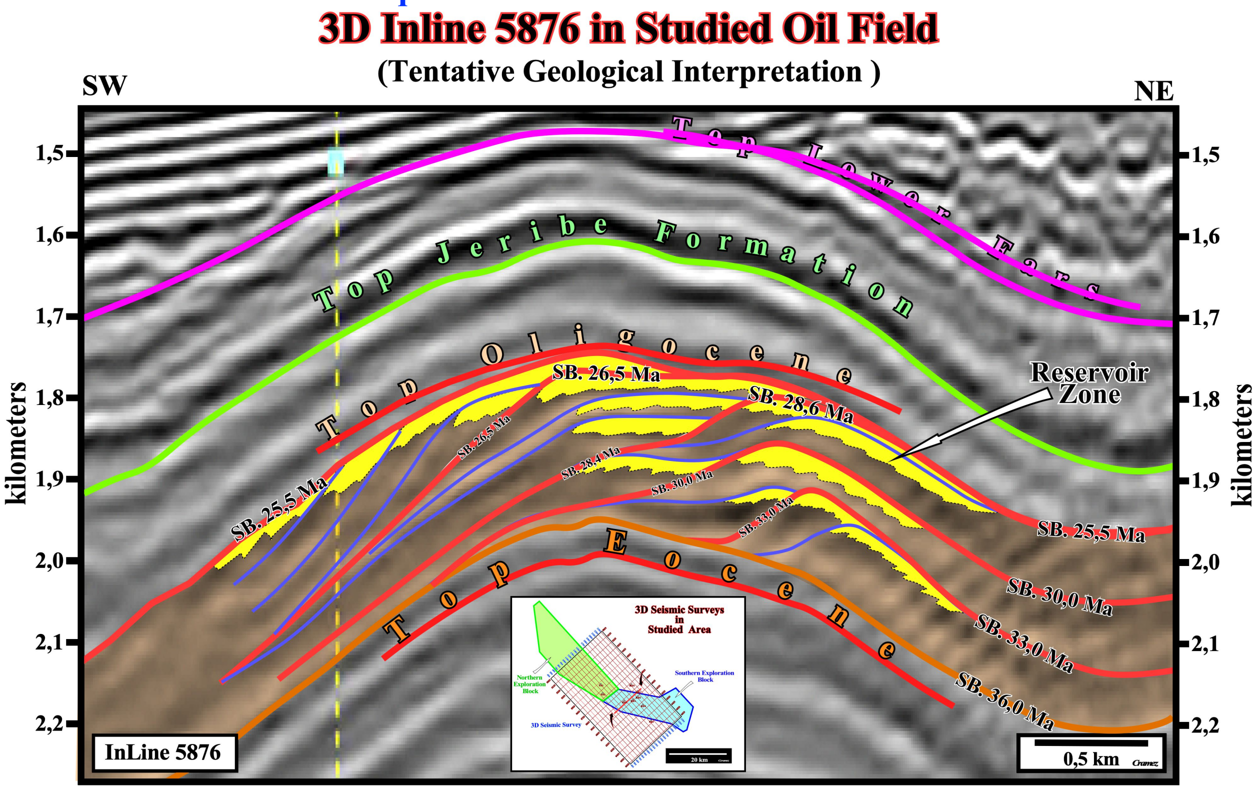


Figure 4 — Tentative Geological Interpretation of the Legacy 3D Seismic Inline 5876 Segment. In this figure, the seismic line is oriented approximately SW–NE and traverses the central part of the buried studied anticlinal structure.The interpretation is strongly guided by the previously established regional geological framework, particularly: (i) the assumed Oligocene progradational carbonate depositional model,(ii) the influence of glacio-eustatic sea-level fluctuations associated with the onset of Antarctic glaciation, and (iii) the expected development of carbonate undaforms, clinoforms, and fondoforms within the Oligocene interval. Several tentative sequence boundaries (SBs) are interpreted within the Oligocene interval, including horizons tentatively associated with approximately: 36,0 Ma, 33,0 Ma, 30,0 Ma, 28,6 Ma, 26,5 Ma, and 25,5 Ma relative sea-level events.The ages assigned to these sequence boundaries represent tentative regional chronostratigraphic correlations and should not be interpreted as precise chronometric datings of the seismic surfaces themselves. These interpreted surfaces are not directly observable geological entities, but rather geological hypotheses inferred from: a) reflector geometries, b) onlap/downlap relationships, c) sequence-stratigraphic concepts, d) regional chronostratigraphic understanding, and e) the

assumed depositional model. The figure also highlights a tentative "Reservoir Zone" interpreted preferentially within the shallow-water Oligocene carbonate interval. Within the conceptual framework proposed in this memorandum, this interval is considered the most likely location for the development of potential reservoir-rocks (Rrs) associated with undaform depositional environments. However, the actual geometry, continuity, thickness, and connectivity of these reservoir-rocks remain uncertain because they are generally below the effective vertical and lateral seismic resolution of the presently available merged legacy 3D seismic dataset. The interpreted geometry suggests a broad buried anticlinal structure, overlain by the Jeribe Formation and the Lower Fars Formation, and deve-loped above deeper Eocene units. The interpretation also suggests that the Oligocene interval may consist of several diachronous facies-controlled carbonate bodies, rather than a single laterally continuous layer-cake reservoir.Consequently, the figure illustrates the fundamentally theory-laden nature of seismic interpretation in petroleum geology. The geological meaning attributed to the seismic reflections does not emerge directly from the seismic image itself, but from the interaction between: 1- prior geological conjectures, 2- regional geological knowledge, 3- sequence-strati-graphic concepts, 4- depositional models, and 5- the observational constraints provided by the seismic data. This interpretation must therefore be regarded as a tentative geological conjecture rather than as a definitive representation of geological reality. Its scientific value resides precisely in its capacity to generate testable predictions concerning: A) reservoir distribution, B) facies geometry, C) trap configuration, D) fracture development, E) reservoir connectivity, and F) hydrocarbon accumulation within the Kurdamir/Topkhana petroleum system. The figure therefore provides a practical illustration of one of the central epistemological principles developed in this memorandum: in complex carbonate petroleum systems, meaningful seismic interpretation is impossible without prior geological knowledge

Once these geological assumptions are introduced, the seismic line becomes considerably easier to interpret. Reflector terminations, geometrical relationships, onlap/downlap configurations, and broad anticlinal geometries can then be tentatively organised within a coherent depositional and structural framework.

Thus, the interpreted seismic section does not result from a purely inductive extraction of geological information from the seismic data themselves. Rather, it results from the continuous interaction between: A) prior geological conjectures, B) regional geological knowledge, C) sequence-stratigraphic concepts, D) depositional models, and E) the observational constraints provided by the seismic image.

In Popperian terms, the geological interpretation therefore precedes, organises, and conditions the seismic observation itself. The seismic reflections do not "speak for themselves." Their geological meaning emerges only after they are integrated within a prior conceptual and geological framework.

For instance, the tentative interpretation shown in Figure 4 identifies several potential sequence boundaries (SBs) within the Oligocene interval, including horizons tentatively associated with approximately: 36,0 Ma, 33,0 Ma, 30,0 Ma, 28,6 Ma, 26,5 Ma, and 25,5 Ma relative sea-level events.

These interpreted surfaces are not directly "visible" in the seismic data as objectively given geological entities. Rather, they represent geological hypotheses inferred from:

- **➡ reflector geometries,**
- **➡ regional chronostratigraphic understanding,**
- **➡ sequence-stratigraphic relationships, and**
- **➡ the assumed progradational carbonate depositional model.**

Similarly, the interpreted "Reservoir Zone" shown in Figure 4 does not correspond to a directly observable reservoir body. It represents a geological inference suggesting that potential reservoir-rocks (Rrs) may preferentially occur within specific shallow-water carbonate facies associated with the progradational Oligocene interval, particularly within the interpreted undaform depositional environments.

This example clearly demonstrates that the same seismic dataset may generate significantly different geological interpretations depending upon the conceptual framework adopted by the geoscientist.

A geoscientist interpreting the seismic data within a purely structural framework may perceive the Oligocene interval mainly as a relatively continuous anticlinal closure. Conversely, a geoscientist working within a progradational facies-controlled depositional model may interpret the same interval as a complex association of diachronous carbonate bodies controlled by:

- ➡ **depositional architecture,**
- ➡ **facies migration,**
- ➡ **relative sea-level fluctuations, and**
- ➡ **sequence stratigraphy.**

Consequently, the seismic data themselves do not uniquely determine the geological interpretation. The observational meaning of the seismic image depends fundamentally upon the geological hypotheses introduced before and during the interpretation process.

This does not imply that all interpretations are equally valid. On the contrary, geological interpretations must ultimately be tested against independent observations capable of corroborating or falsifying the proposed geological model. In the K/T petroleum system, such tests may include:

- ✦ **well correlations,**
- ✦ **petrophysical data,**
- ✦ **pressure communication,**
- ✦ **production behaviour,**
- ✦ **core observations,**
- ✦ **seismic inversion,**
- ✦ **fracture-sensitive attributes, and**
- ✦ **future seismic reprocessing.**

Assuming interval velocities of approximately 4000–5000 m/s and dominant seismic fre-quencies of approximately 30–40 Hz within the Oligocene interval, the effective vertical seismic resolution is expected to be on the order of 25–35 m (λ/4 criterion). Consequently, many individual reservoir-rocks (Rrs), fracture corridors, stylolitic barriers, and karstified intervals may remain below direct seismic detectability.

The present interpretation must therefore be regarded as a tentative geological conjecture rather than as a definitive representation of geological reality. Its scientific value resides precisely in its capacity to generate testable predictions concerning:

- ☑ **reservoir distribution,**
- ☑ **facies geometry,**
- ☑ **trap configuration,**
- ☑ **fracture development,**
- ☑ **reservoir connectivity, and**
- ☑ **hydrocarbon accumulation.**

Figures 3 and 4 therefore illustrate one of the central epistemological principles of petroleum geology: geological observation is never theory free. In complex carbonate

petroleum systems, meaningful seismic interpretation becomes possible only through the continuous interaction between prior geological knowledge and observational data.

(3) Main conclusions

1)

The case-study petroleum system demonstrates that petroleum exploration and seismic interpretation are fundamentally theory-laden activities. Geological observations do not possess an intrinsic meaning independent of interpretation, but derive their significance from prior geological concepts, deposition-al models, and tectono-stratigraphic hypotheses.

2)

The Oligocene interval of the case-study petroleum system should not be interpreted as a simple layer-cake succession composed of laterally continuous chronostratigraphic units. Instead, the potential reservoir-rocks (Rrs) are interpreted as diachronous facies-controlled carbonate bodies generated by the progressive basinward migration of depositional environments during carbonate progradation.

3)

The Oligocene carbonate depositional systems of the case-study petroleum system are closely related to the onset of major Antarctic glaciation during the Eocene–Oligocene Transition. Repeated glacio-eustatic sea-level fluctuations strongly influenced:

- **carbonate platform development,**
- **progradational geometries,**
- **sequence-boundary generation,**
- **and the spatial distribution of potential reservoir-rocks.**

4)

The geometry and continuity of the reservoir-rocks cannot be accurately predicted solely from structural maps drawn on chronostratigraphic seismic horizons because facies boundaries are expected to be oblique to time-equivalent surfaces.

5)

Hydrocarbon accumulations within the case-study petroleum system are expected to depend not only on structural closure, but also on:

- **depositional facies architecture,**
- **facies migration,**
- **fracture systems,**
- **diagenetic evolution,**
- **and reservoir compartmentalisation.**

6)

The presently available merged legacy 3D seismic dataset does not possess sufficient vertical and lateral seismic resolution to directly individualise the likely thin and heterogeneous reservoir-rocks developed within the Oligocene interval.

7)

Insufficient seismic resolution may generate two opposite classes of petroleum errors:

- **resource overestimation through false continuity and false structural closure, and**
- **resource underestimation through hidden reservoir-rocks and sub-seismic pay zones.**

8)

In complex carbonate petroleum systems such the case-study, seismic continuity does not necessarily imply:

- **reservoir continuity,**
- **hydraulic communication,**
- **or petrophysical homogeneity.**

Similarly, structural closure mapped on chronostratigraphic horizons does not necessarily correspond to actual reservoir closure.

9)

The tentative geological interpretation of the legacy 3D seismic Inline 5876 demonstrates that the same seismic dataset may generate significantly different geological interpretations depending upon the conceptual framework adopted by the geoscientist.

10)

The geological interpretation proposed in this memorandum must therefore be regarded as a tentative geological conjecture rather than as a definitive representation of geological reality. Its scientific value resides in its capacity to generate testable predictions concerning:

- **reservoir distribution,**
- **facies geometry,**
- **trap configuration,**
- **fracture development,**
- **reservoir connectivity,**
- **and hydrocarbon accumulation.**

11)

Meaningful seismic interpretation in complex carbonate petroleum systems requires the continuous interaction between:

- **prior geological knowledge,**
- **seismic observations,**
- **sequence-stratigraphic concepts,**
- **depositional models, and**
- **observational constraints capable of corroborating or falsifying the proposed geological hypotheses.**

12)

High-quality seismic reprocessing, amplitude-preserving workflows, azimuth-preserving imaging, seismic inversion, fracture characterisation, and integrated geological interpretation are essential for reducing the epistemological gap be-

tween the seismic representation and the actual geological complexity of the Kurdamir/Topkhana petroleum system.

13)

Consequently, future exploration and development decisions within the case study petroleum system should not rely exclusively on structural mapping of chrono-stratigraphic horizons, but must integrate seismic reprocessing, inversion, fracture-sensitive attributes, depositional modelling, and continuous geological hypothesis testing.