Cusiana Field: Understanding the Reservoir and Improving Depletion History*

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Abstract

Cusiana is a mature onshore oil field which is producing from a Late Cretaceous sandstone reservoir, known as the Guadalupe Formation, and two Early Tertiary sandstone reservoirs: the Paleocene Barco Formation and the Miocene Mirador Formation. Cusiana development has been challenging: the hydrocarbon is compositionally complex and the reservoir highly heterogeneous. This peculiar combination of oil, gas and water flowing through matrix rocks of variable permeability and along an intricate network of faults and natural fractures in an active tectonic environment has led to undesirable fingering effects in the fluid flow.

Early gas and water breakthrough has forced modifications to the original development plan. Well designs have been changed, as has injection support strategy, both in terms of fluid type and injection points. These modifications have often been successful in slowing production decline and in some cases have allowed previously shut-in wells to be returned to production.

This presentation illustrates the geological interpretations that justified the early development plan and shows how dynamic data was used to update the geological interpretation allowing depletion strategy to be optimized. Cusiana was discovered in 1992. In less than 20 years the Cusiana operation has moved from discovery, through appraisal, development and ultimately depletion management. This fast evolution with constant acquisition of new static data and abundant high quality dynamic data has enabled the geoscientists and engineers to change interpretations and modify development plans. These 18 years of history are best described in 4 distinct periods: 1992 to 1997, 1998 to 2004, 2005 to 2008, and 2009 to present (2010).

Cusiana 1992 to 1997

The field was originally described as a simple asymmetric hanging-wall anticline. Over 50% of the reserves occur in the upper Eocene Mirador reservoir, which comprises stacked incised valley deposits. Additional, deeper reservoirs include estuarine sandstones of the Paleocene Barco Formation and the shallow-marine Santonian-Campanian Upper Guadalupe Sandstone.

At this time the peculiar petrophysical properties of the reservoir were first recognized. Despite low porosity of less than 10% in most of the reservoir, good permeability is retained. This is because the reservoirs are pure quartz-cemented arenites. Authigenic clays and carbonate cements which typically reduce the permeability in other reservoirs are absent here.

The prevalent understanding at this time was that matrix permeability, rather than fracture permeability, provided the high deliverability of Cusiana reservoir (Cazier et al., 1995). The impact of natural fractures on fluid flow was initially underestimated. Regarding reservoir pressure support mechanism, gas expansion and aquifer support were expected. However, reservoir simulation work indicated that very high liquid hydrocarbon recoveries should be achievable from all reservoirs by re-injecting produced gas to maintain reservoir pressure and to vaporize residual oil (Cazier et al., 1995). This description also anticipated poor reservoir connectivity and early water and gas breakthrough at producers as serious risks.

Fast-track development was sanctioned in 1993 based on the following scheme: Reinjection of all produced gas at the crest of the reservoir, primary drilling concluded by year-end 1998 at 640-acre spacing, and a water disposal well in the shallower sandy units. Two gas injection phases were focused on the main Mirador reservoir while the secondary Barco and Guadalupe reservoirs were developed under primary depletion, relying on gas expansion and aquifer influx for pressure support.

This initial period was characterized by high oil rates with individual wells producing over 10,000 bopd. Indeed one well recorded a peak rate of 35,000 bopd. At the same time high oil decline started to be evident due to scale deposits and water breakthrough. The Barco and Guadalupe reservoirs also showed significant pressure depletion.

Cusiana 1998 to 2004

During this period the initial development program was completed. Four fundamental concepts were changed from the original reservoir understanding:

1) Based on the integration of high-resolution biostratigraphy, sedimentology, geochemistry and fracture studies, together with pressure and tracer data, it was concluded that a simpler reservoir description would be more successful in describing fluid movement than the earlier sedimentologically-based descriptions.

2) Long-term testing was used to demonstrate field-wide connectivity, allaying previous concerns over reservoir compartmentation.

3) Aquifer support was interpreted as insufficient to provide adequate pressure support.

4) A new 3D seismic survey and well data re-interpretation revealed that structural complexity was greater than originally interpreted with a complex frontal imbricate. This resulted in a higher original oil-in-place estimate due to multiple oil-water contacts (Warren et al., 2001).

Based on the new interpretation, an update in the development program was required. A down structure water injection programme was implemented to enhance oil recovery in Barco and Guadalupe; a horizontal and multilateral well program was started in Barco and Guadalupe; an infill program was initiated in the Mirador; and by adding perforations, the Mirador and Barco gas caps were used to naturally gas lift Barco and Guadalupe wells with high water cut.

Peak production of 310 mbopd was achieved in 1998 during the late development phase. Once the drilling development program was completed, production decline rates accelerated. Water production and high gas oil ratios (GOR) in unexpected areas of the field forced production intervals, and in many cases whole wells, to be shut in. The evolution of gas and water production did not follow the even piston like behavior predicted; rather, these fluids were clearly fingering through the reservoir.

Horizontal wells were particularly disappointing; these wells were quickly killed by water production due to channeling along fracture corridors. Although the water injection strategy provided pressure support, no response in oil production was observed. In fact, production decline showed no response even when water injection was increased or suspended. The main mechanism used to control production decline during this time was infill well drilling and an aggressive well workover program that included natural gas lift using shallower reservoirs.

Cusiana 2005 to 2008

Detailed revision of the static information closely tied with the dynamic data revealed that strong interaction between multiple sources of heterogeneity controlled fluid flow. It was demonstrated that fingering flow was controlled by high permeability layers connected by natural fracture corridors. The effect was reinforced by baffling caused by low permeability rocks, particularly at sandstone body boundaries, and by the same fracture corridors that exhibit very low permeability perpendicular to the fracture orientation.

A key learning was that reservoir connectivity is dynamic, and changes with pressure as fractures open and close. Additionally, originally sealing faults began to leak as large pressure differentials were established across them. Micro-seismicity was used in combination with dynamic data to observe and map these activities.

In addition to fault analysis, the vertical communication between reservoirs was also evaluated and explained by means of communication behind pipe and through abandoned wells. This new interpretation suggests that fluid flow in the Cusiana Field is controlled by:

- Arrangement and contrast in matrix permeability rather than simple averages.
- Fault and fractures and the strong contrasts between permeability along them versus across them.
- Dynamic behavior of fractures and fault seal due to pressure differences.
- Reservoir operations that unintentionally create vertical communication pathways between reservoirs.

This new understanding was integrated with previous knowledge in reservoir models. Using these models, it was predicted that incremental recovery could be achieved by a new strategy incorporating:

- Gas injection in all reservoirs to take advantage of multiple mechanisms (miscibility, mass transfer, pressure support and lifting).
- Movement of gas injection points to the structure's flank to create pressure baffles (that reduce aquifer entry) and move some hydrocarbon components from the oil rim behind producers to the produces located updip.
- Multiple gas injection points with smaller injection rates, to increase flexibility to modify injection paths preventing gas injection channeling. Additionally, smaller injection rates increase the gas injection travel time creating opportunities to contact lower quality reservoirs with high oil saturations.

The new strategy was implemented quickly as the mechanisms had already been shown to be effective in the Mirador reservoir. Additionally, costs and implementation time were reduced by reusing the old water injection lines and previously shut in wells.

This strategy showed remarkable benefits. Production decline rate was reduced. Several wells previously shut in due to high water cut or uneconomical GOR were put back on production. Well work and infill projects also became more attractive with this gas injection strategy.

Even though gas volumes available for injection have been reduced due to gas sales and other commercial issues, the strategy is still providing an efficient reservoir management lever to control production decline.

Cusiana 2009 to Present (2010)

The growing gas market in Colombia and other commercial issues is constantly reducing the gas volume available to support oil production. This, plus the obvious oil and water production are quickly reducing the reservoir pressure. To slow pressure decline, a new strategy has been implemented to inject water in the mid-flank area, where high efficiency in gas injection has left low remaining oil saturations. This water injection strategy compliments the gas injection strategy allowing more gas injection to be redirected from the structure’s crest to the flank, where it is showing higher benefits.

Currently, the expansion of the water injection strategy to include crestal injection is under evaluation. This will allow more gas injection to be moved to other field areas and help slow reservoir pressure decline as gas sales rates are increased.

References

Cazier, E .C., A.B. Hayward, G. Espinosa, J. Velandia, J.F. Mugniot, and W.G. Leel, Jr., 1995, Petroleum geology of the Cusiana Field, Llanos Basin foothills, Colombia: AAPG Bulletin, v. 79/10, p. 1444-1463.

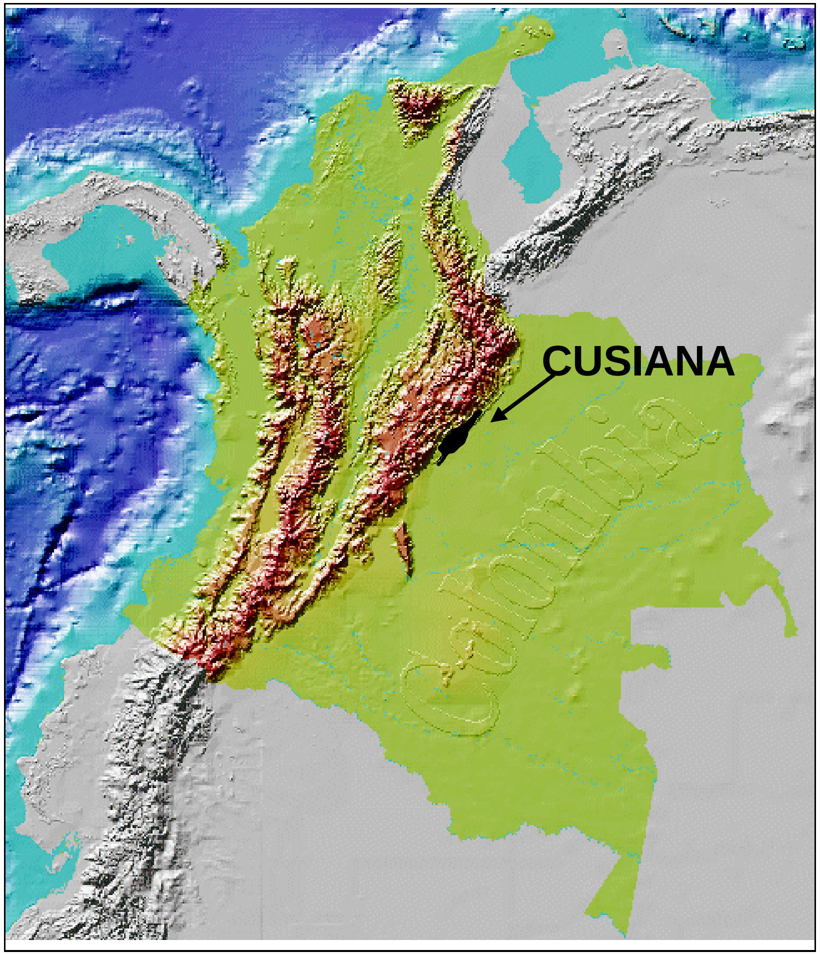
Warren, E.A. and A.J. Pulham, 2001, Anomalous porosity and permeability preservation in deeply buried Tertiary and Mesozoic sandstones in the Cusiana Field, Llanos Foothills, Columbia: JSR, v. 71/1, p. 2-14.

All fields have a large range of heterogeneity, but only a part of it is relevant for the field operation, and this depends on your production goals and the technology used.

Cusiana Field: Understanding the Reservoir and Improving Depletion History

Luis E Soto
September14, 2010

Cusiana General



The Cusiana Field is located in the Llanos Foothills on the Eastern Cordillera of the Andes, in Colombia.

It was discovered in 1988 by well Cusiana-1. An appraisal program concluded in the declaration of field commerciality in 1993.

Full field production started in 1995.

3 Clastic reservoirs:

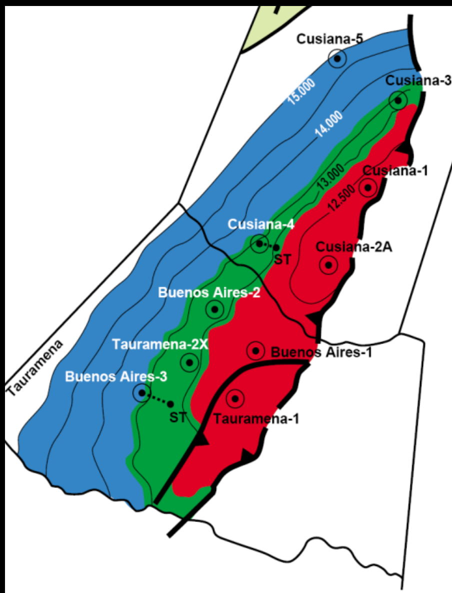
- Mirador (Eocene) 66% STHIIP
- Barco (Paleocene) 15% STHIIP
- Guadalupe (Cretaceous) 19% STHIIP

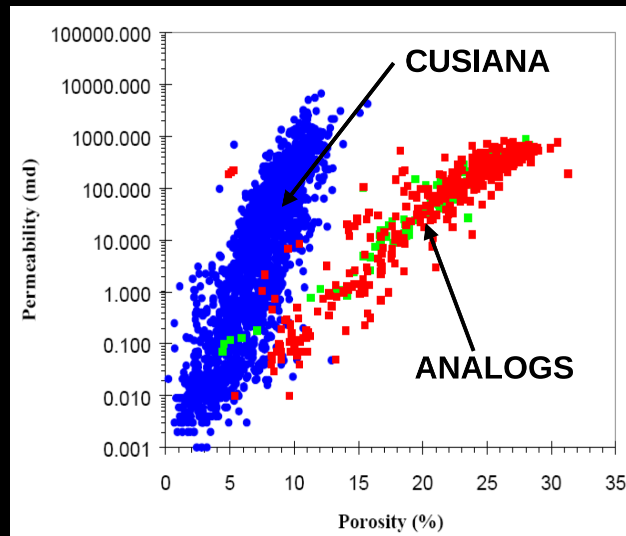
Fluids:

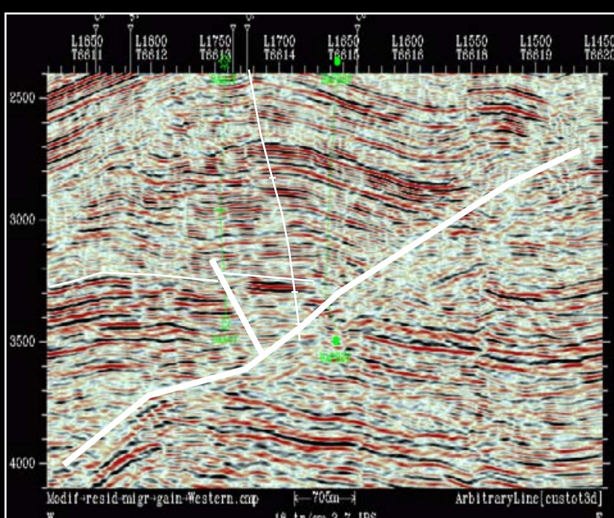
700 ft hydrocarbon column. Volatile oil/42API and Lean Gas Condensate

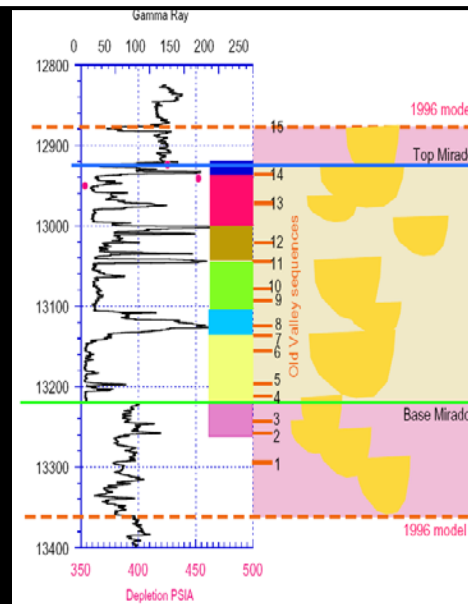
3TCF GIIP & 1,770 MM Liquid Hydrocarbon IIP

Discovery









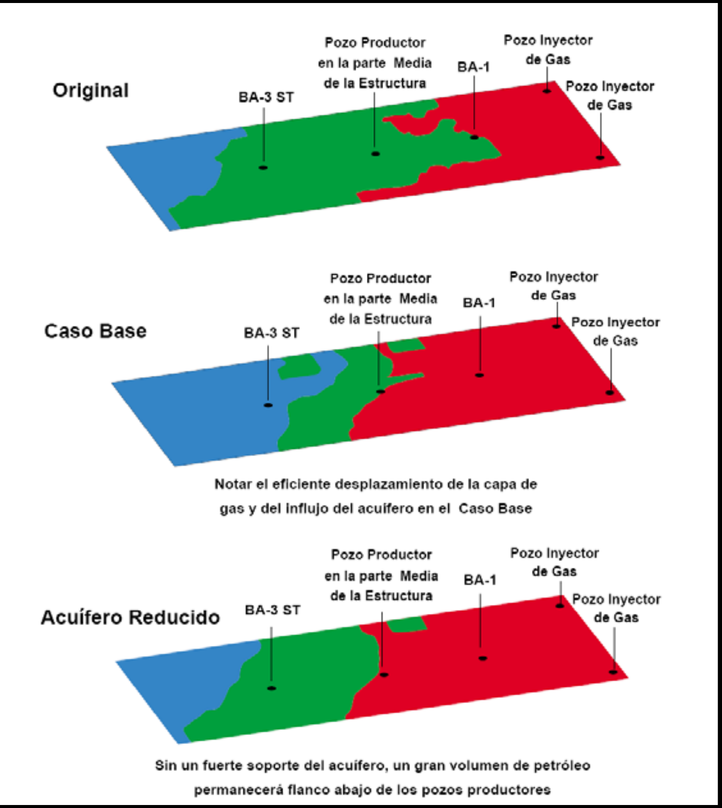
➢Data

- Existing well (Decelerated no commercial Gas in the 70s)
- 2D seismic

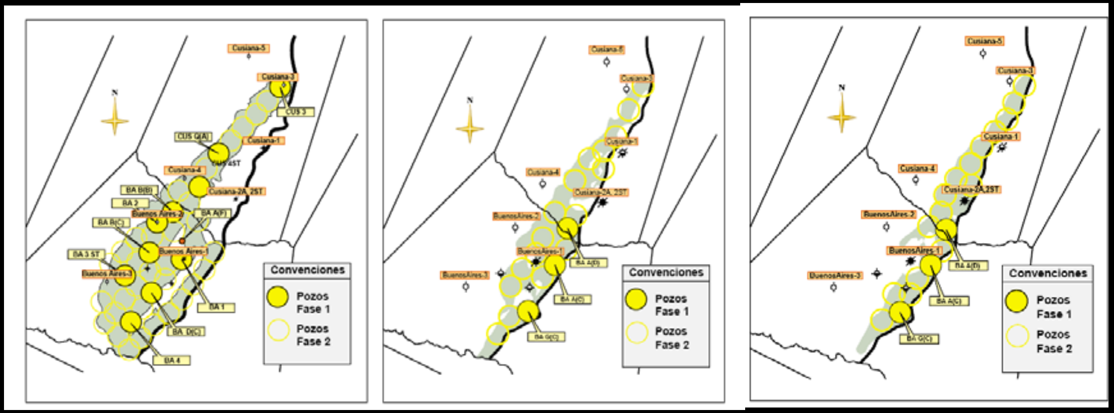
➢Interpretation

- Structure: Asymmetric anticline limited by thrust fault at east
- Fractures: Expected very limited fluid flow contribution
- Stratigraphic: Mirador incise valley model
- Rock quality: Very high permeability preservation
- Reservoir communication: Good N–S communication. Barco and Guadalupe connected. Mirador separated tank

Initial Development Plan



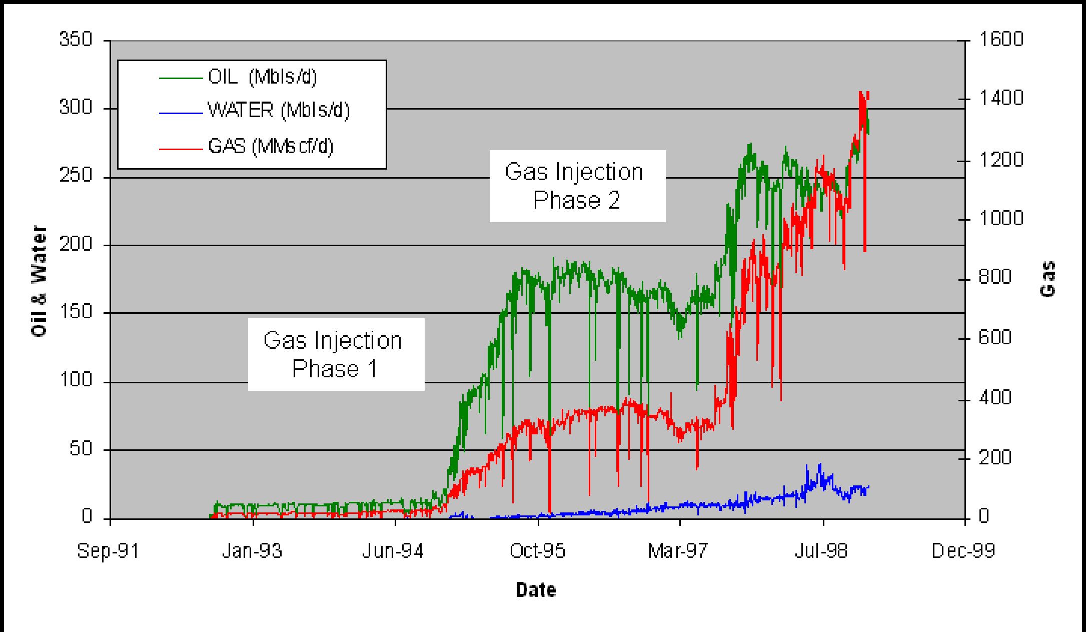
Efficient gas expansion and aquifer support was interpreted

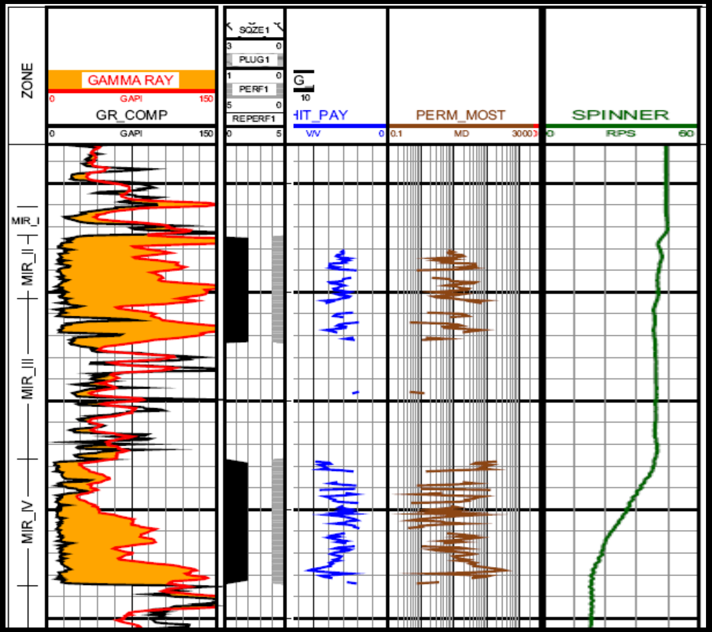


- 80 to 100 Producer wells (320 acre-spacing)
- Crestal gas injection wells
- Shallow water disposal wells
- Natural lifting mechanism
- Pad S shape wells

Two gas injection phases were focused in the main reservoir Mirador and the secondary reservoirs were developed under pressure support of the natural mechanism gas expansion and aquifer support.

1992 to 1997 Reservoir Response





PHASE	Oil Production	Gas injection
1992 LTT	12 Mbopd.	25 MMstcpd
1994 Ph 1	180 Mbopd.	365 MMscfd
1997 Ph 2	310 Mbopd	955 MMscfd

This initial period was characterized by high oil rates with wells producing over 10,000 bopd each, and one with amazing record of 35,000 bopd.

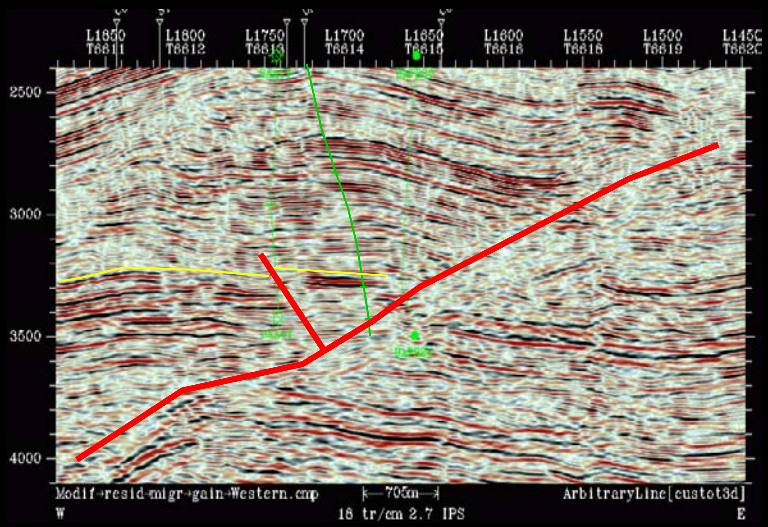
Main contribution is from matrix permeability

Scale deposits reduce productivity

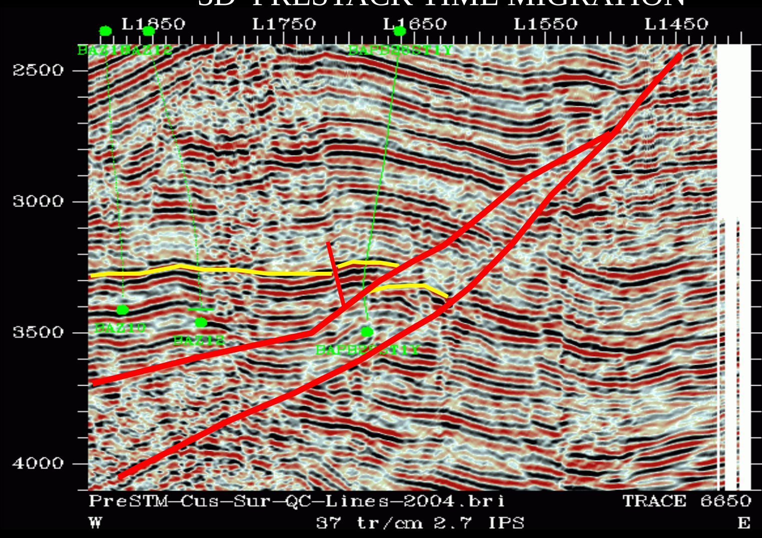
High oil decline stat is evidence of scale deposit and water breakthrough. Barco and Guadalupe showed significant pressure drop

1997 to 2004 Reservoir Response

2D POSTSTACK TIME MIGRATION



3D PRESTACK TIME MIGRATION



- **Development Issues**

- Water displacement less efficient than expected

- Fast pressure depletion in Barco & Guadalupe

- OOIP reduced

- Very expensive wells

- Lifting problems in high water cut wells

- Scale deposits reduce well productivity

- **Additional data**

- Static: 3D Seismic, more wells, cores

- Dynamic: pressure, production, logs

- **Reservoir interpretation revision**

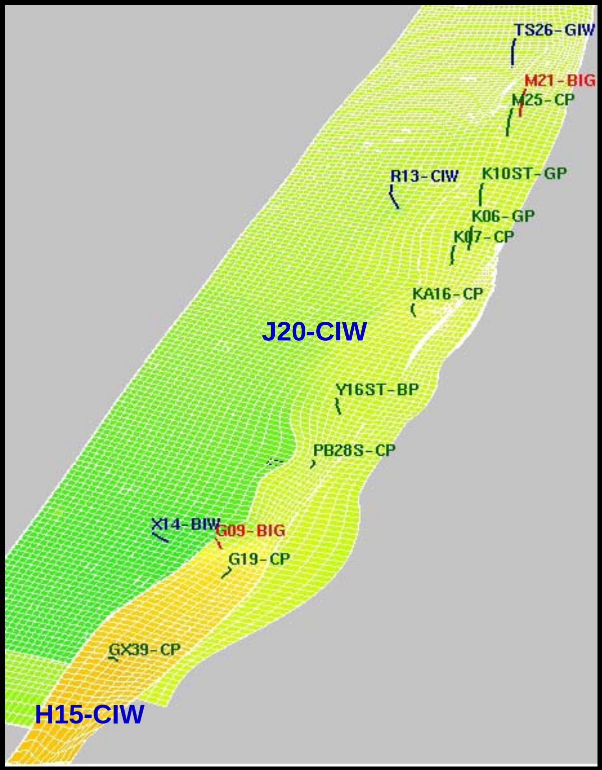
- New stratigraphic model

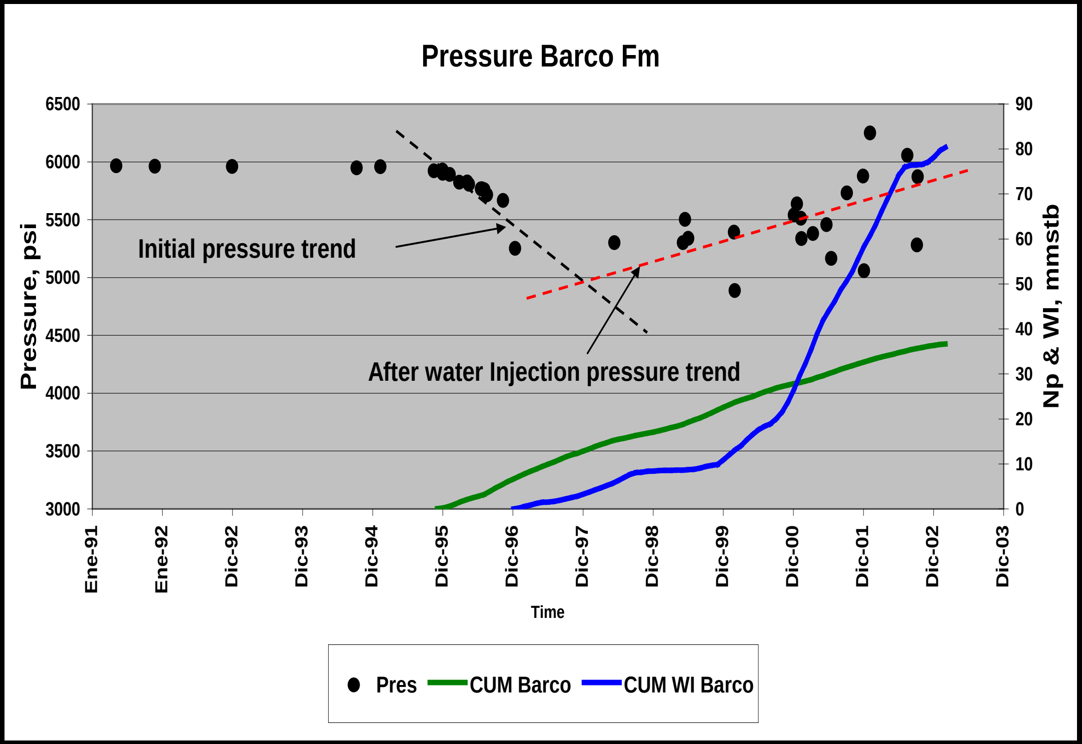
- Structural complexity increased

- Reservoir connectivity confirmed

- Aquifer strength significantly reduced

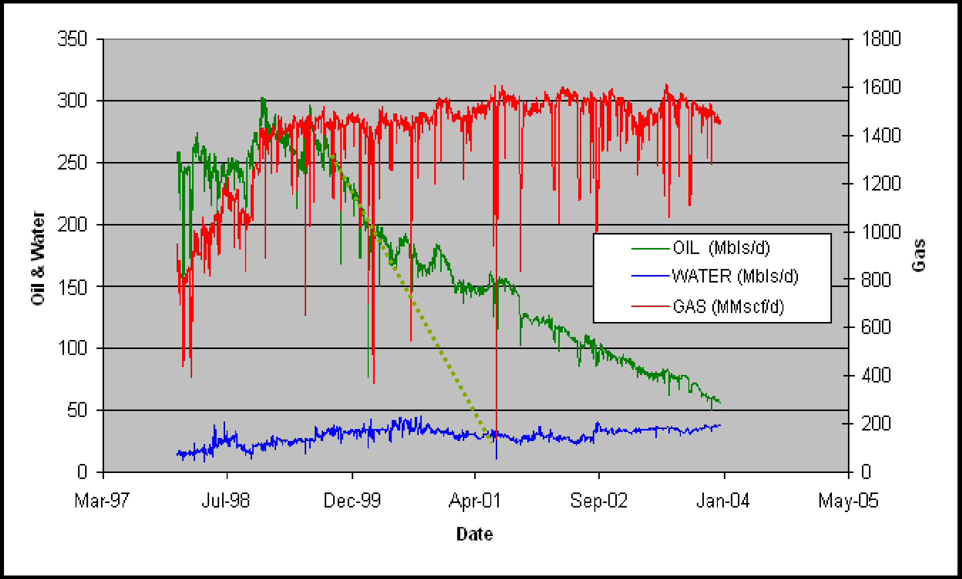
1997 to 2004 Update Development Plan

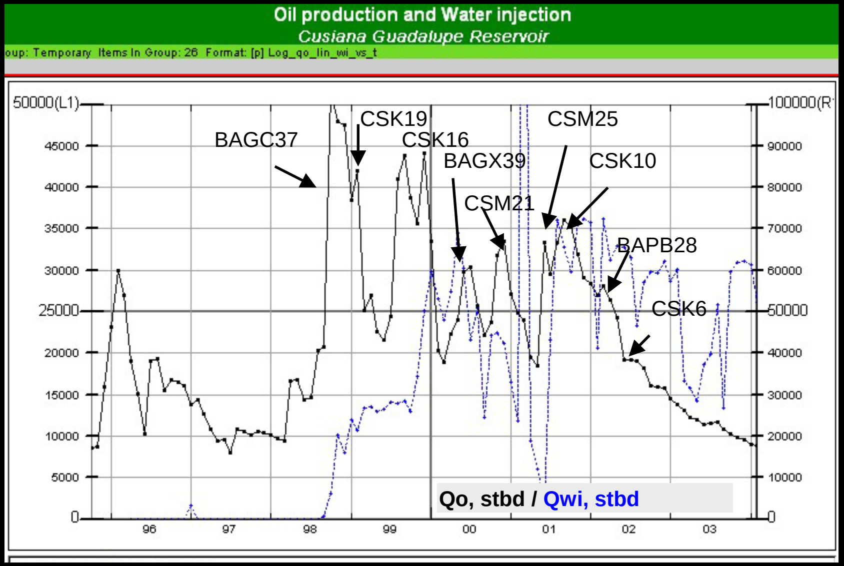




- **Down structure water injection program to enhance oil recovery in Barco and Guadalupe.**
- **Horizontal and multilateral well program in Barco and Guadalupe to reduce drilling costs**
- **Mirador and Barco gas cap was used to assist lifting in Barco and Guadalupe wells with high water cut.**
- **Aggressive scale understanding studies**
- **Mirador infill program**

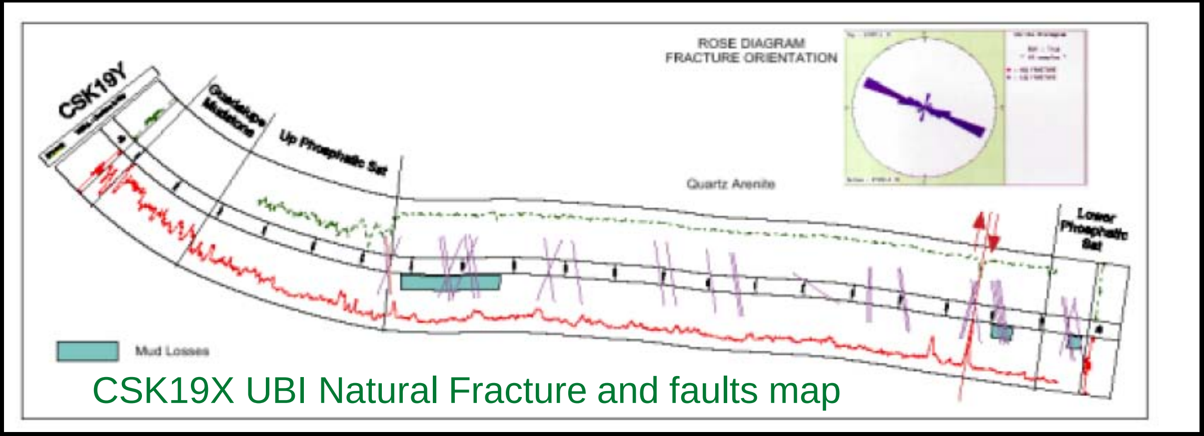
1997 to 2004 Reservoir Responds





Peak production of 310 Mbopd was achieved in 1998 during the late development phase.

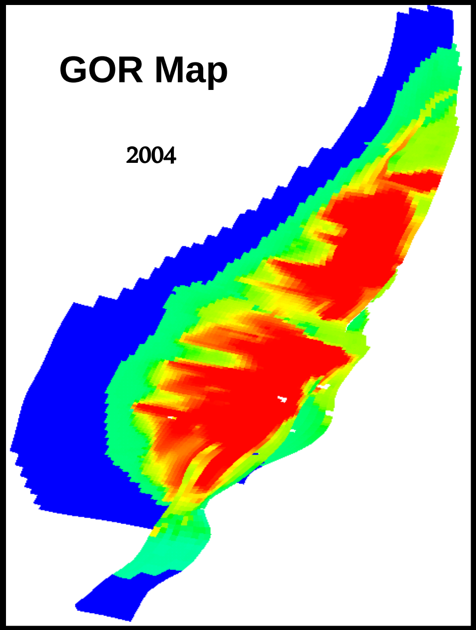
The water injection strategy was very efficient providing pressure support but, it was not observed any responds in oil production.



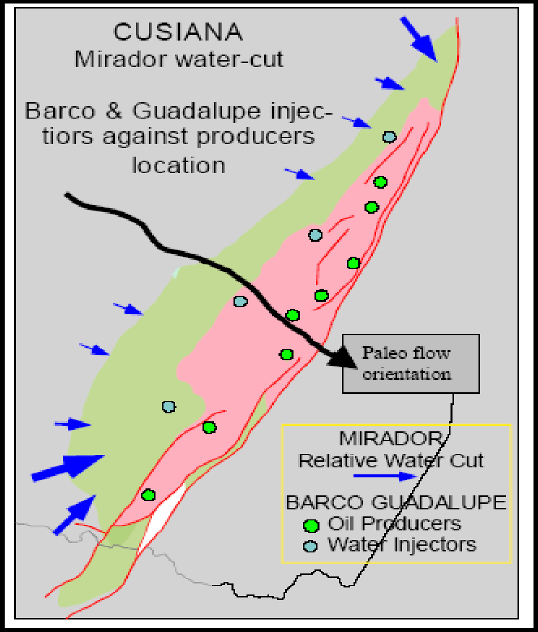
CSK19X UBI Natural Fracture and faults map

Horizontal wells put initial very high oil rated (up to 37 Mbopd) but, bring water very quickly resulting uneconomic project

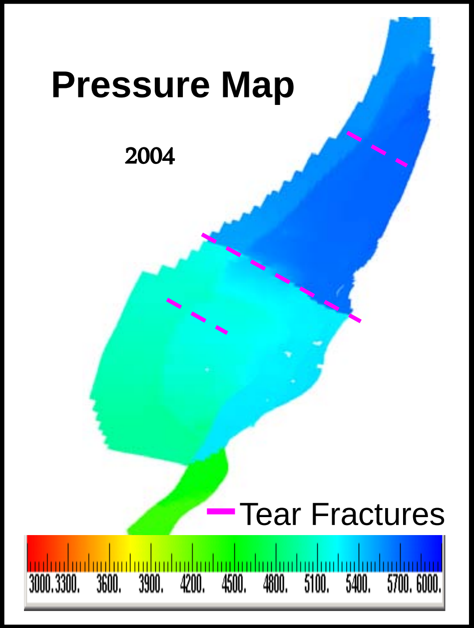
1997 to 2004 Reservoir Responds



Gas injection fingering dramatically increased GOR, forcing shut-in of some wells



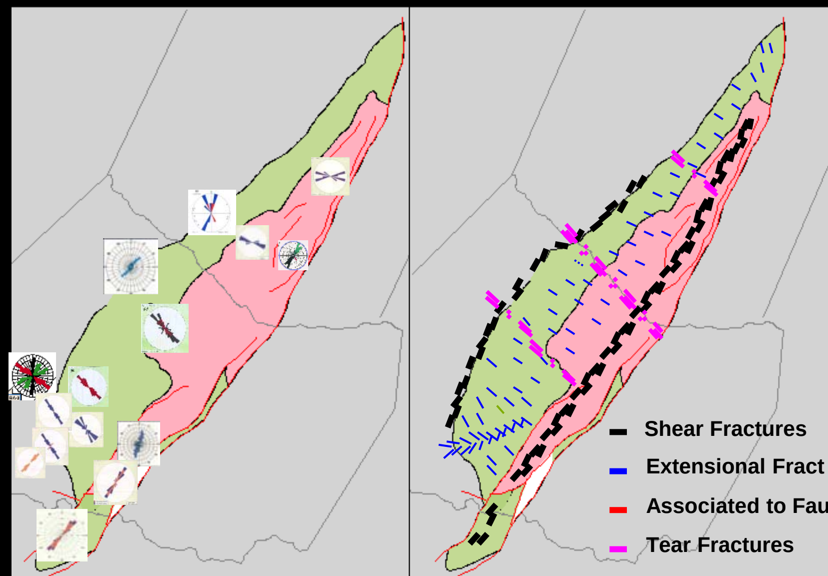
Water breakthrough in all reservoirs does not follow easy to interpret path



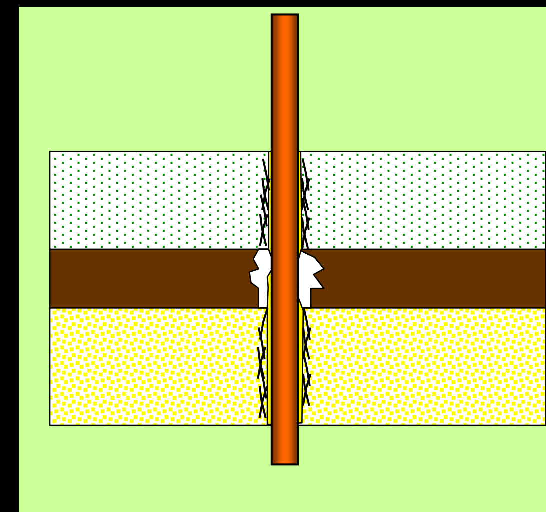
Initially undetected pressure baffles start to become evident and originally sealing faults starts to allow flow across them

2004 – 2009 Heterogeneities Studies:

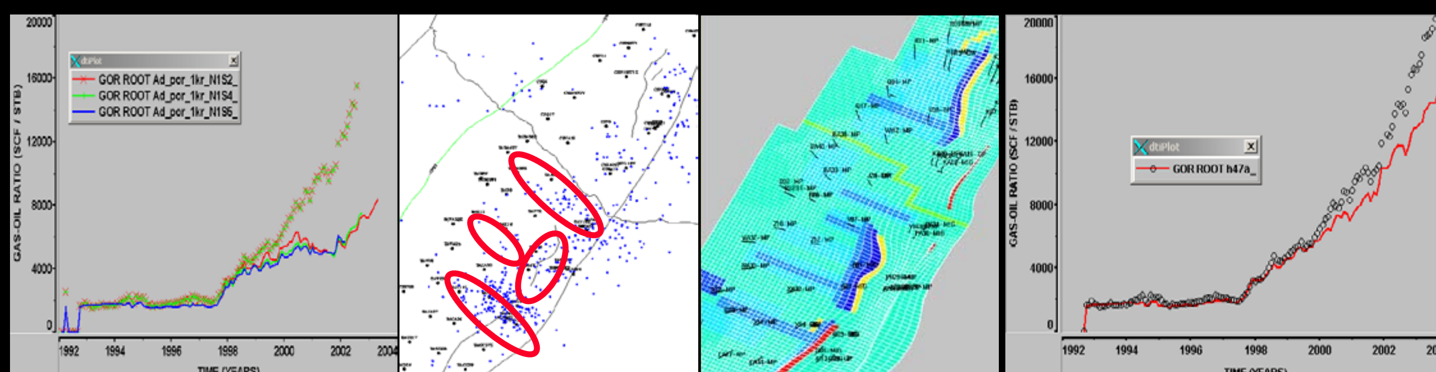
All scales of Heterogeneity
Pore
Lamine
Sand Body
Depositional system



Conceptual fractures model



Created Connectivity

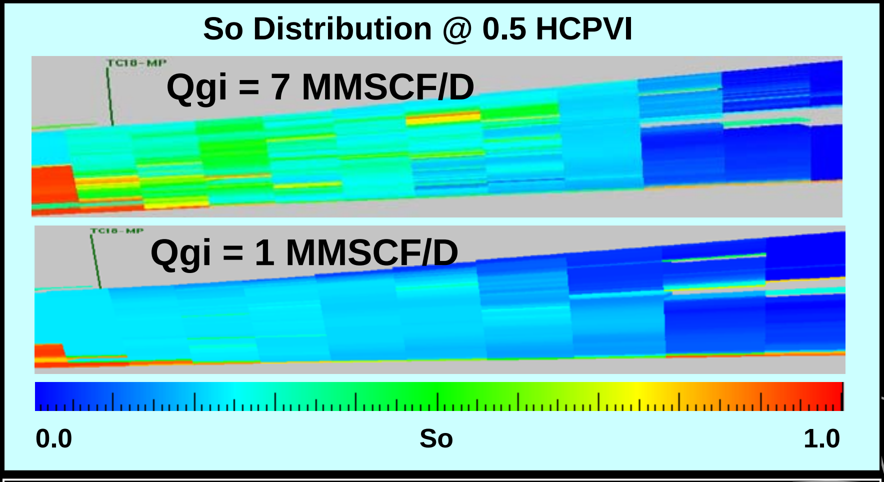


Capturing natural fracture reactivation strongly improved fluid flow modeling

Heterogeneities controlling sweep efficiency

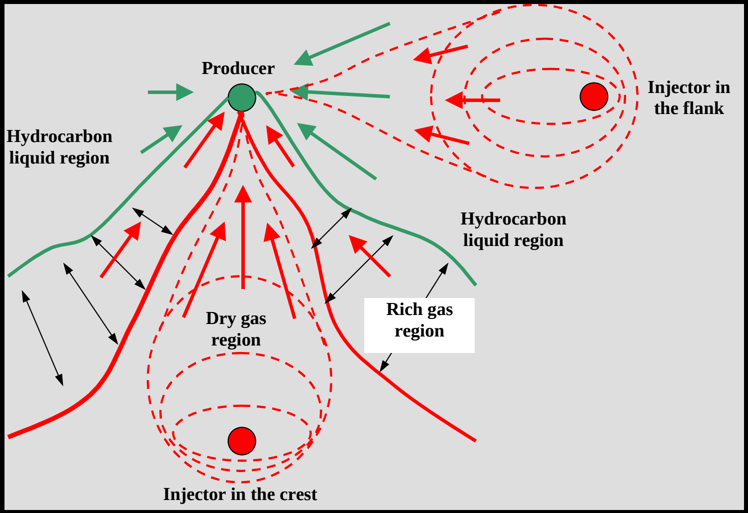
Lamination and fractures create permeability contrast that controls the fluid flow patterns.

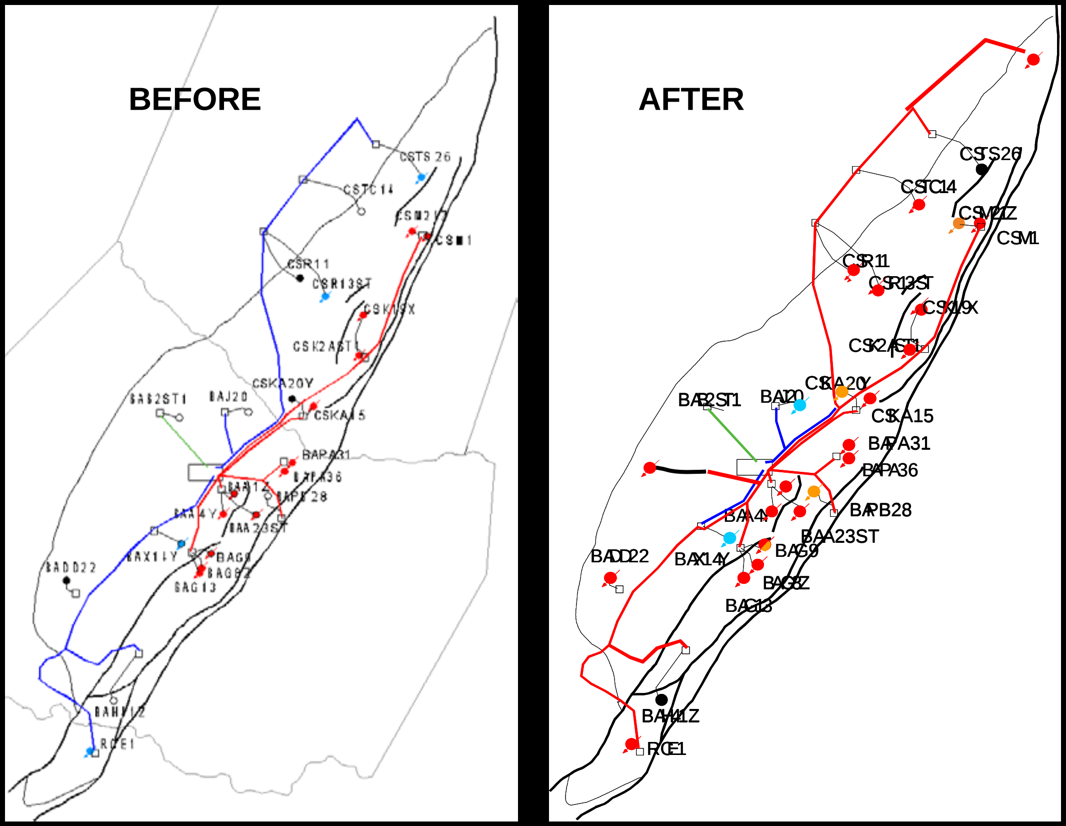
Oxidation shows flow patterns that reflect variations in permeability similar to those observed in cores. Dissimilarity in color intensity is a function of the amount of flow in each rock segment.



Flow velocity highlights permeability contrasts promoting fingering and reducing the sweep efficiency.

2004 to 2009 Update Development Plan

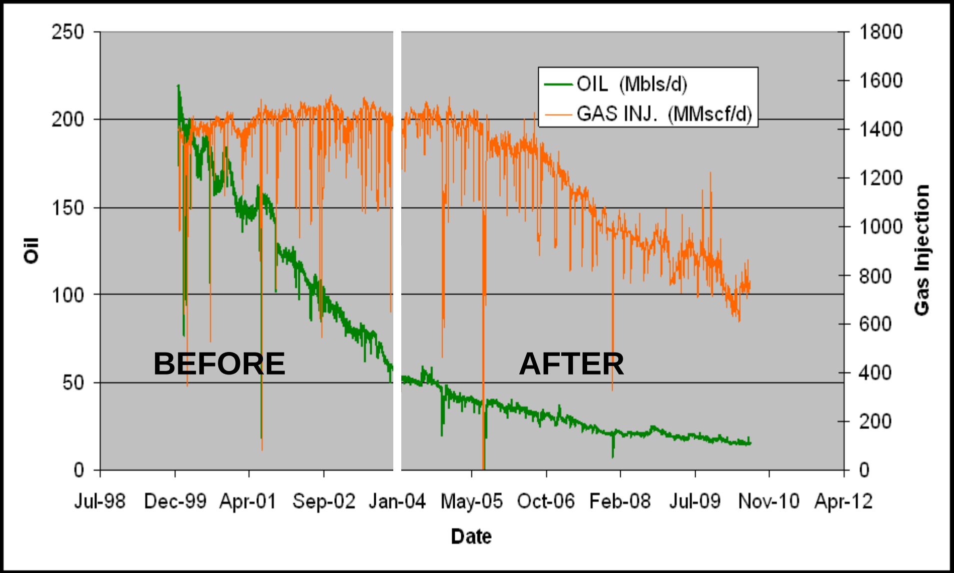


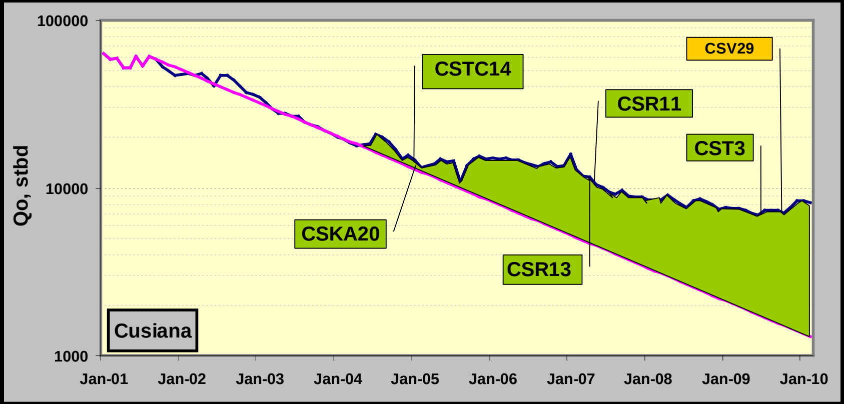


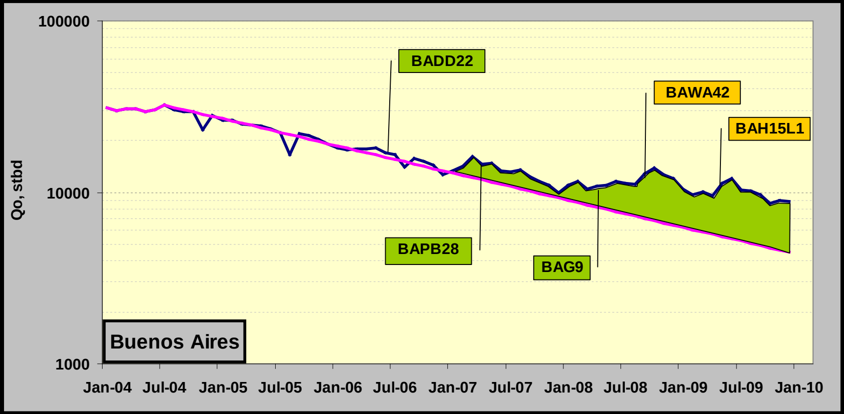
- Gas injection in all reservoirs
- Move gas injection point to down flank and producers up dip
- Low injection rate to avoid quick gas injection corridors evolution
- Increase injection points to preserve total gas injection volume and add manageability

Over $300 Million dollars in water injection lines and shut-in wells were rehabilitated

2004 to 2009 Reservoir Responds







Strategy outcome remarkable benefits:

Reducing production decline.

Several wells previously shut-in due to high water cut or uneconomical GOR were put back online, recovering significant investments. Well work and infill projects acquire higher potential with this gas injection strategy.

Water entry was reduced.

Some areas of the field not only reduced oil decline, but are showing incline production

2009 up Today (2010)

➢ Current Conditions

•Down Flank Gas injection still being implemented and showing good results.

• Gas volume available to support oil production is being reduced due to growing gas market in Colombia and other commercial issues.

➢ Update Development Plan

• Continue gas injection redistribution to down-flank areas

• Water injection in mid-Mirador flank areas, where high efficiency in gas injection has left low remnant oil saturation to improve reservoir pressure.

• Currently, it is under evaluation and expansion of the water injection strategy to the structure's crest, this will allow more gas to move towards other field areas and in preparation of the coming additional gas sales.

• Implementation of cheaper drilling technologies: Through Tubing Rotary Drilling (TTRD)

Conclusions

Development plan updates are required due to changes in the range of heterogeneity that matter for your field production goals

There is always something new:

Data, Technology, IDEAS