Multidisciplinary Approach, Key Factor in the Development of Complex Stratigraphic Fields in Colombia, Case Study: Llanito Field*

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Abstract

Llanito District is located in the Middle Magdalena Basin, Colombia. It has 306 wells and a cumulative production of 76.8 MMBO rated at December 2009. Their production comes from the Tertiary Mugrosa and Colorado Clastic Formations with a complex of potential zones to be drained.

The development of this district began in 1945 with the discovery of the Galan Field by Tropical Oil Company and during their operation the Llanito Field was discovered by Ecopetrol (first discovery of the company). As a part of the second development of the Llanito Field, in 1985, Gala Field was discovered.

Important technological advances had been carried on in this district, like fresh and brine waterflooding pilots in Galan Field. Their good results led to the implementation of waterflooding projects in the neighboring Casabe Field, one of the most important fields of Ecopetrol. In 2004, the third development of Llanito began with the perforation of 50 wells and later 3D seismic acquisition and interpretation in 2009.

Based on the 3D seismic interpretation aided with a multidisciplinary approach of the new information acquired it was possible to accomplish the following tasks:

- A new structural model. - Identification of new potential zones based on the combination of seismic inversion, sedimentological studies, and production test interpretation.
- Petrophysical model calibration with the new wells drilled and a better risk assessment in the selection of zones to be perforated.
- A new reserve incorporation strategy was implemented by the perforation of wells with RNPPr and RNPPo classification reserves.
- Near field prospect identification focused in deeper Cretaceous Formations.
- Optimization in well architecture design, lifting equipment, and production monitoring activities.

- With the aid of the previous items and the lifting cost re-evaluation, it was possible to optimize the economics of the field and led an aggressive portfolio with future activities for several years.
- OOIP updated with an increment of 47%.

Impacts and Benefits:

- Increment in Production, Better OOIP Calculation, and Technological Innovation in 3D Seismic interpretation tools.

Introduction

It is common in Colombia to think about old fields that seem like mature fields. Several important fields like La Cira Infantas and Casabe, discovered in the first half of the twentieth century have taught us how the impact of the 3D seismic and modern drilling and completion techniques aided with acquisition of a complete suite of well logs, could led to redevelop the fields obtaining important oil recoveries. In some cases reaching the initial peak production that they had in the first stages of primary development.

The Llanito District contains the Llanito, Gala Cardales, and Galan Fields, and historically has had important key milestones as follows:

- Discovery of the Galan Field in 1945 by Tropical Oil Company, and in 1952 their development by newly Ecopetrol (Now known as Ecopetrol S.A.).
- In 1960, Discovery of the Llanito Field (first discovery of Ecopetrol).
- Discovery of the Gala structure in 1985 and important technological advances like pilot projects of waterflooding with brine and fresh waters, based on these results waterflooding in the Casabe Field took place.
- In 2004, beginning of the third development of Llanito District with fifty wells drilled.
- From 2007 to 2009, acquisition and interpretation of Llanito 3D seismic volume.

These key dates in the active life of the district have an impact in the cumulative curve of oil production where it is easy to associate the high peaks with the development stages (Figure 1).

General Aspects

Llanito District is located in the north part of the Middle Magdalena Valley Basin (MMVB) between the Cimitarra and La Salina faults. (Figure 2). The main structure that composes the field is an asymmetric anticline, with its main axis trending in a SW – NE direction with structural closure in their flanks based on observations of wildcat wells drilled in the frontiers of the structure (Figure 3). The field's northern limit is controlled by the plunge of the anticline. Galan Field has no geologic limit in the southern part because it belongs to the northern part of the Casabe Field (Figure 4).

Galan Field is structurally controlled in the south by the northern part of the Dextral strike-slip Casabe Fault that has a SW-NE trending direction. Based on the seismic interpretation it is concluded that the reactivation mechanism of this fault cuts all the Cretaceous and Tertiary time sequences (Figure 5).

An important anticline with a north-east trend is associated with the main strike-slip fault, with minor anticline and syncline folds developed in "echelon" axes plunging to the north controlled mainly by antithetic faults (Figure 6). This zone is referred as an *extreme deformation zone* (Kim et al., 2004) that has as characteristic growing longitude and spacing of minor faults as going away from the master fault. It is common to find in this kind of structural setting - a combination of horsetail splay and antithetic faults (Figure 7).

The change in the structural setting regime associated with a master strike-slip fault is presented in the north sector of Galan Field, with direct impact from the Cardales Field to the north.

Stratigraphic Interpretation

Most of the wells in this area have drilled a sequence of clastic sedimentary rocks of fluvial environment from Tertiary to Quaternary ages that rests unconformably over marine Cretaceous rocks (Figure 8).

Based on electrofacies interpretation and core description of available wells in the area it could be possible to define the depositional environments for the oil-bearing sands of the Mugrosa Formation as meandering channel rivers - identifying subenvironments like channels, channel fills, crevasse splays, and floodplain deposits. The main oil accumulation is located in channel fill sands and crevasse splays (Figure 9).

The stratigraphic model in this area is complex due to successive interbedding between sands and clays, exhibiting for instance in the Mugrosa B zone a multilayer behavior inside the zones of interest (Figure 10) making it very difficult to establish a unique Oil Water contact.

In order to obtain a detailed stratigraphic model as input to the static model, a high resolution well log interpretation focusing in the oil-bearing sands to obtain as a result 18 units with their corresponding facies interpretation and net sand distribution maps (Figure 10).

Petrophysical Interpretation

The petrophysical model uses mainly as input a GR, neutron, density, and true resistivity logs. Based on the methodology established a model could be obtained capable of identifying rock types based on the well log responses. A key part to elaborate the model was the core analysis of the wells available in the field and their tie with the well log curves of those wells.

This model was applied to the wells without cores obtaining as a result a good confidence and showing high lateral and vertical heterogeneity in the petrophysical properties in the strat column.

The model is in constant updating via production test of newer wells, and with the addition of the conductivity log with a cutoff of 250 MMOH (blue curve on the right in Figure 11), where values lower than that and that meet other criteria could be considered as an oil bearing sand with water saturation lower than 50% (black flags in the second column from right to left, Figure 11).

Some of the particularities present in the Llanito Field are the salinity of formation water, ranking from 25,000 ppm up to 35,000 ppm of chlorides. Other aspect regards high resistivity clays composed by illite, smectite, and caolinite a challenge to the team in order to deal with those clays in the drilling phase because they exhibit a fast ionic destabilization when they are in open hole exposure putting at risk the well’s integrity.

Another important aspect is the high content of clay in the sands and the high irreducible water saturation, components that reflect an inverse resistivity pattern with a very low true resistivity in oil-bearing sands (lower than 2 ohm.m in some cases) making it difficult to establish a cutoff between oil and water producing sands. The common expression of a high peak of true resistivity pay zone could be possible in sands with Rock Type 1 with excellent reservoir properties like 150 mD of permeability and greater than 15% of effective porosity.

These kind of issues make the acquisition of data important regarding geological description, oil shows, and drilling parameters in real time in order to make a complete analysis to select the candidate zones in each new well and the design of a workover interval test in existing wells (Figure 12).

The topics covered before plus the stratigraphic complexity makes it possible to drill infill wells spaced 250 meters from each other and finding oil-bearing sands with near-to-original reservoir pressures contacting different channels to the neighbors’ wells (Figure 13).

Near to 80 wells have been drilled in the third development of the district and almost all of them have a complete suite of modern electrical logs acting as a valuable input to feed the petrophysical model and give them a confidence close to 80% in the prediction of oil producing zones.

In the same way, static pressure test logs have been acquired in several wells in order to determine the reservoir pressure and give the confidence to perforate oil producing zones in the Llanito and Gala-Cardales fields and to obtain a pressure gradient to determine depleted zones through the fields and new zones associated with new oil producing intervals from not yet contacted channels (Figure 14 and Figure 15).

Reservoir and Engineering Analysis

By year 2010, with the seismic interpretation of the seismic 3D volume concluded and the structural model of the district established, an integrated analysis with reservoir and production departments has been done increasing the OOIP 47% with a Recovery Factor updated to 7%. This gives the opportunity to generate projects with the objective to reach a recovery factor of 25% associated with reducing space infill program and designing of secondary recovery projects like selective waterflooding programs. These project that took place in the 80’s in the Galan Field and recovered 1.8 MMBEO by the effect of waterflooding. This project was concluded to understand better the lateral continuity of the sands and evaluate operational problems like well collapses and casing and tubing corrosion.

The scope of this project was the producing sands of the Colorado Formation in the southern part of Galan Field, now occupied by the oil refinery of Barrancabermeja (Figure 16). The results of this project was increasing the oil production by secondary recovery effects (Figure 17, gap between brown and yellow curves), with general characteristics like naftenic type oil with an API gravity of 18.4° (Table 1).

Development Strategies of Llanito District

A key aspect to establish the strategies to develop the district was the structural model updated with the 3D seismic volume, based on that, the team evaluated new prospective zones not yet drained and incorporated in the OOIP calculations.

The strategies began in 2004 with the perforation of 30 wells spread in different sectors of Llanito, Gala, Cardales, and Galan fields, with a special scope in Cardales Field, which before this drilling campaign had only one well and after, five wells with good results in terms of oil production.

With the acquisition of the seismic 3D volume in 2007 and the consequent processing and interpretation in 2008 and 2009 respectively, aided with the results of 20 wells drilled from 2007 to 2009, led to turn the strategy and evaluate new areas with potential to be developed based in the compartments analyzed from reservoir and production points of view.

The multidisciplinary work between reservoir, engineering, and production teams allowed the establishment of drilling projects via multiple fiscal years, with an overall view of all the alternatives present in the area and ranking them as proved, probable, and possible reserves, in order to give them a better perspective from an economical point of view.

Cardales Field Case

An important advance in the development of the static model of the Llanito area was the evaluation of the Cardales Field. Since the updated structural model proposes a north displacement of the main W-E normal fault that controls the southern block, making prospective the north block of this area (Figure 18 and Figure 19).

Based on that, in late 2010 a well was drilled in the northern block of Cardales, showing good oil-bearing sands with original reservoir pressure (Figure 20), encouraging the advance of the development of lower blocks in these kind of structures (blue and fucsia wells in Figure 19).

Moreover, after seismic interpretation the area between Northern Galan and Cardales sector and determining subtle structural changes in this block and integrating a complete reservoir and production analysis of the wells surrounding this block, it was possible to propose several wells with an injection pattern purpose (Figure 21 and Figure 22).

Waterflooding Pilots in Llanito District

Within the field development strategy in the Llanito District and considering the last updated OOIP achieving increase recovery factor, two pilots were proposed in the Llanito and Galan fields with the main objective to test the effectiveness of the water injection in the Mugrosa Formation, considering its high heterogeneity and depositional environment.

Assuming successful case of waterflood pilots in the exposed areas (Figure 23 and Figure 24) simulations were performed of the injection response in producing multilayer along the field, reaching a projection to drill 334 injector and producer wells which are subject to surface feasibility (Figure 25) from 2015 to 2016 in order to increase the production of the asset (Figure 26).

Llanito Field Gas Project

As part of the alternatives for making viable economic asset, we evaluated certain arenas with gas shows in old wells, which at the time were not assessed as commercial considering they were part of the early development of the field, the 60's, whose priority was the liquid hydrocarbon.

An inventory of wells with gas manifestations and a high resolution correlation of these sand bodies were made to determine their areal extent and to quantify the gas reserves associated (Figure 27 and Figure 28).

Based on these results, a perforation program was made in a pilot well in order to determine the amount of gas that could accumulate and its characteristics, obtaining an initial production of 2-MCFD of dry gas mainly methane. This led to the establishment of a project in which we are evaluating the potential of more wells to prove and make additional perforations in order to be able to use these gas reserves, whether for sale to a third party or as a source for self-generation electricity, one of the main challenges working in this field.

Waterflood Project in Galan Field

From the results of the pilots of secondary recovery in the Galan Field conducted in the 80's and as part of the strategy of incorporation of reserves in the field, an interdisciplinary analysis was established that would make possible the water injection in the Galan Field.

Given that much of the field is occupied by the urban municipality of Barrancabermeja and the oil refinery of Ecopetrol, various analytical simulations were performed over the main producing sands in the field in the available areas that may be exploitable, (Figure 29 and Figure 30).

As a result, 130 well locations were evaluated, which had to be evaluated in different deviation scenarios from the surface locations available, including low flood zones that share cluster with the Cardales South Sector, extensions to existing locations, and areas agreed with refining department for infill drilling inside the refinery to recover primary reserves.

Environmental Aspects

An important aspect to consider for the development of this asset was surface restrictions, which specifically in the Northern Galan – Cardales Sector are flooding in low areas near the swamp of San Silvestre. In order to boost the drilling of the proposed wells it was necessary to implement new technology techniques to design cluster locations of 28 and 14 wells, which, under a model of large-scale economy can achieve more competitive prices in the market, thus generating projects aimed at the incorporation of reserves and an increasing production (Figure 31 and Figure 32).

Drilling Aspects

Wells drilled as part of the third development of the Llanito District has a final depth of approximately 7800 ft (TVDSS) and have a Type S profile, comprising a vertical section from surface, a KOP approximately at 1500 ft, and EOB at 4500 ft to going afterwards vertically from the producing formation of interest until TD.

Most wells have two sections, an upper section of 13-3/8" with casing 9-5/8" to about 1000 ft (MD), and the final section with a hole of 8 ½" with a production casing of 7". Ditch samples are acquired throughout the well, following the current regulations for sampling purposes and final disposal by the ANH (Figure 33).

Production Aspects

Similarly, the multidisciplinary approach implemented in the field had an impact in the production team, optimizing the mechanical pumping systems to unconventional systems more effective route, under estroques per minute and lower power consumption, seeking to reduce the mean time between failures and reduce the lifting cost, improving the OPEX and hence the economy of incremental projects to be developed.

Activities were also conducted such as productivity analysis in the wells to prevent the pressure at surface, application of technologies for reducing pressure in the annular, and measurable production increases by optimizing mechanical pumping system with high gas/oil ratio and low productivity, reaching pumping efficiencies from 40% to 70% (Figure 34).

Finally, a more detailed technical and financial analysis has been conducted of the results of stimulation work performed in order to refocus the same, leading to greater effectiveness and impact on the well production (Figure 35).

Final Considerations

The multidisciplinary work between different strategic areas of the company has contributed positively to the maturation of the projects within a massive contract scheme, allowing select different options on the market to ensure the implementation and technical feasibility of building facilities and new drilling methodologies with high-end drilling equipment impacting in time savings and investment. In turn, the multi-year planning project scheme generates added value for service companies, executing time extended contracts ensuring the learning curve impacts directly on efficiency and time in implementation of the projects.

One of the key issues to the success in this kind of project is giving value to information assets, this applies to fields with a great story that needs to be collected properly, validate and adjust to not make similar mistakes in future projects, calibrate the learning curve and to see with fresh eyes the implementation of new technologies and methodologies to assess the risks implementing pilots and extending to macro projects to meet its development as a mature field, and can be economically profitable in the long term for companies as Ecopetrol S.A.

Acknowledgements

The authors thank Ecopetrol S.A. for allowing the publication of this paper. Also, recognize all the hard work to the multidisciplinary team involved in the modeling and development of the Llanito asset, the group of specialists who contribute with their expertise to the implementation of best practices and innovative ideas, and professionals who are no longer in company but left an imprint of his work in basins such as Middle Magdalena Valley Basin, to which the asset belongs.

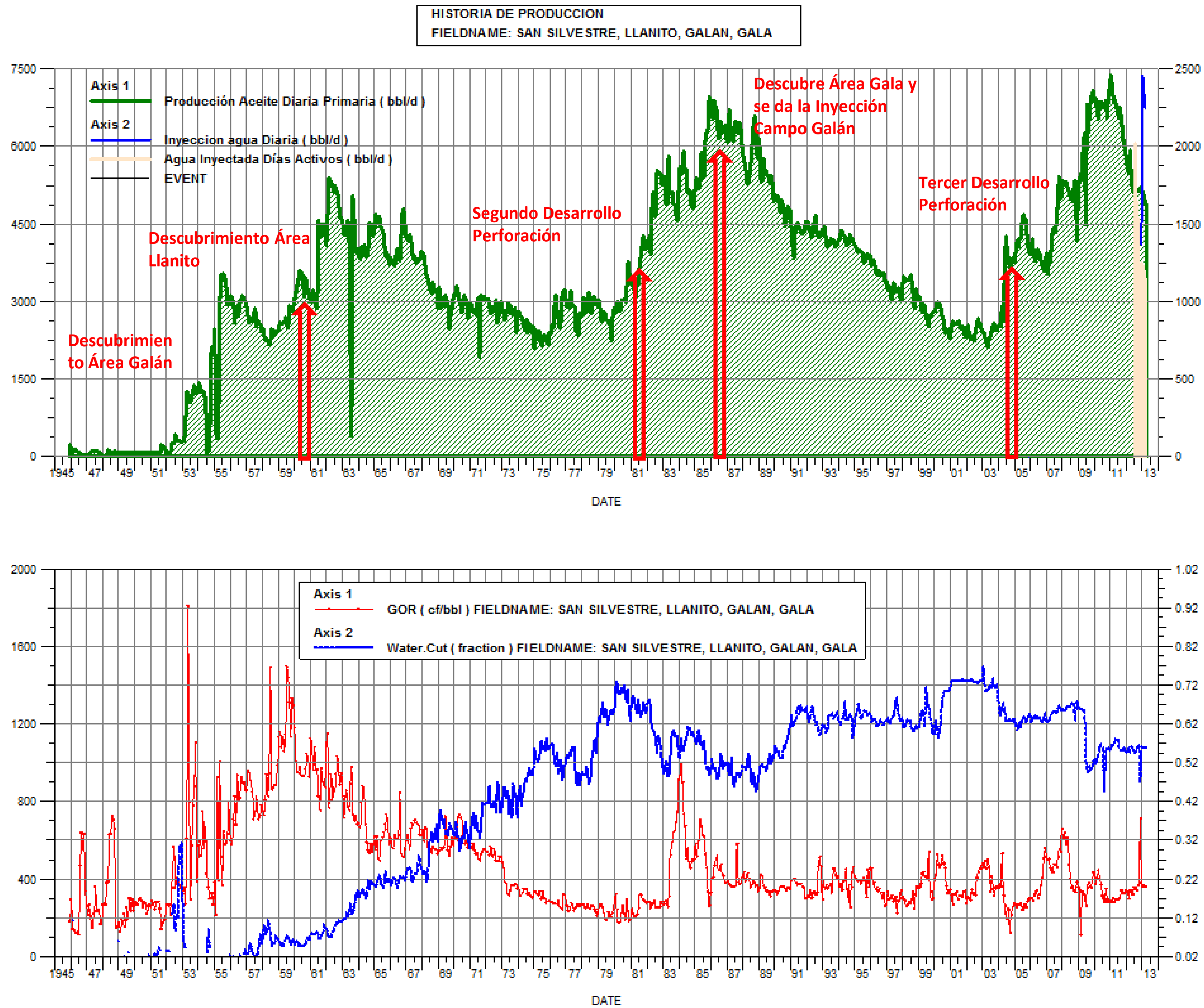


Figure 1. Oil Production Curve of Llanito District.

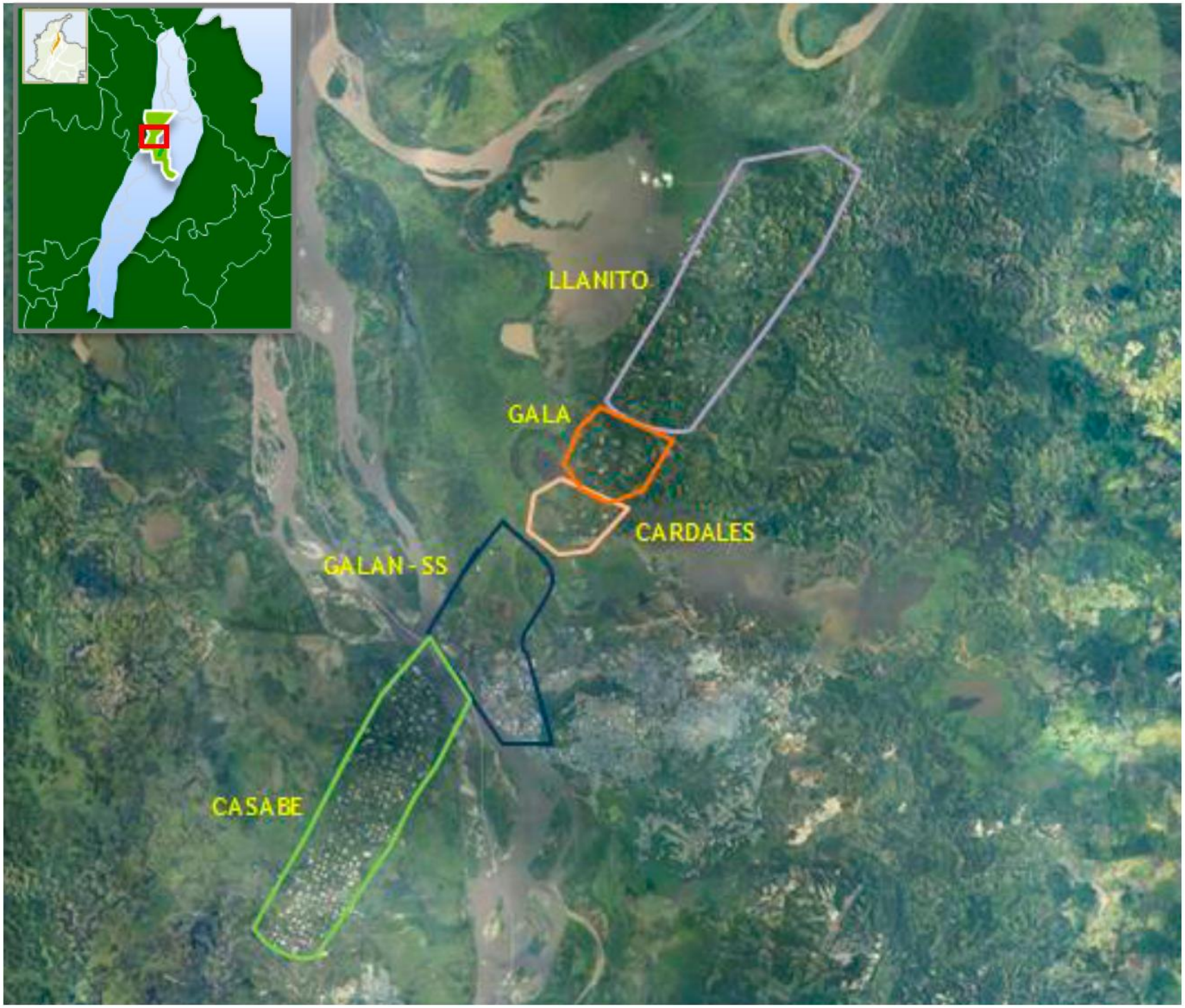


Figure 2. Geographic Location of Llanito District.

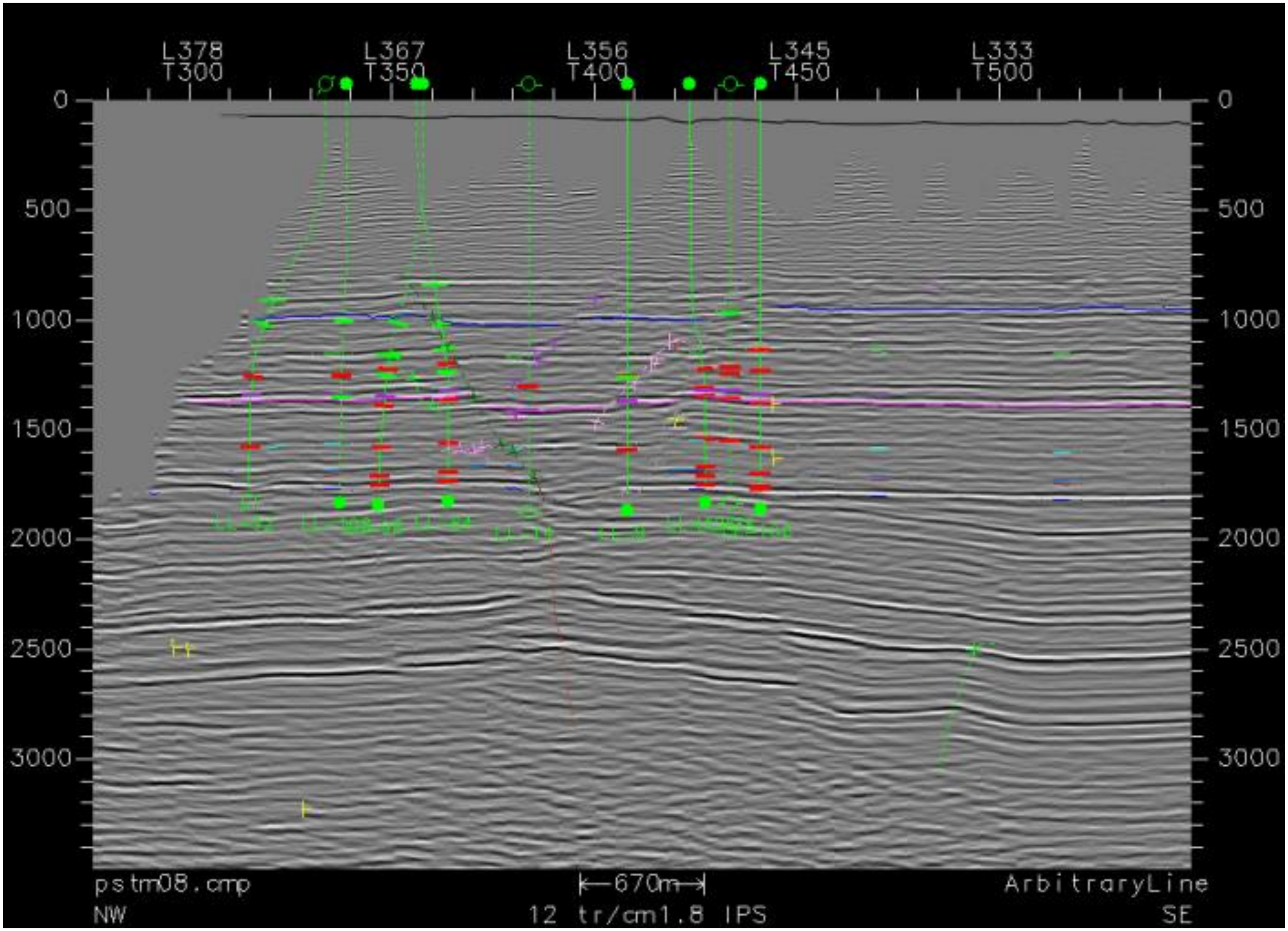


Figure 3. East and West Closure of Llanito Field, Inline section.

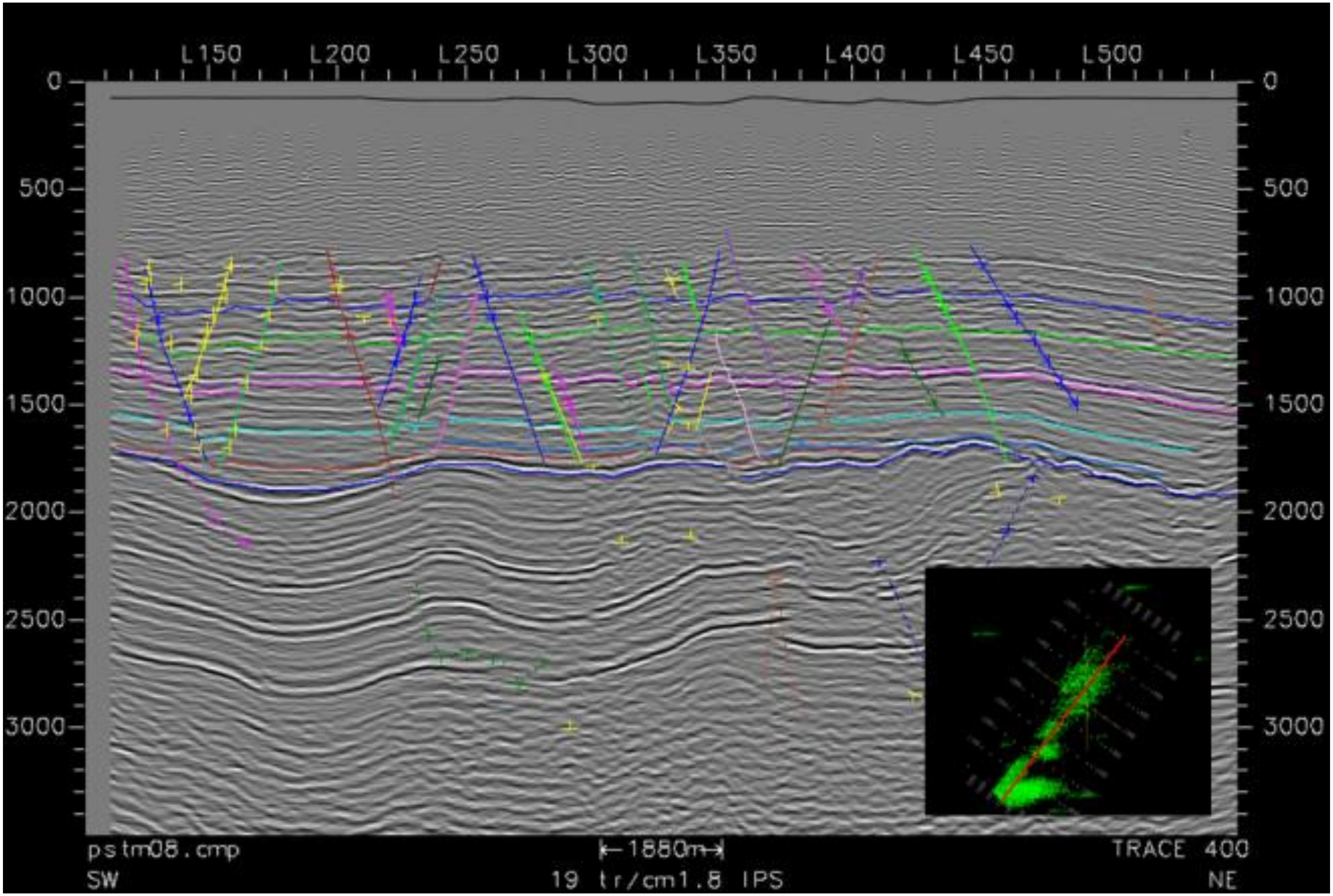


Figure 4. Northern closure of Llanito Field (right side of the image) and Galan Field (left side of the image). Xline.

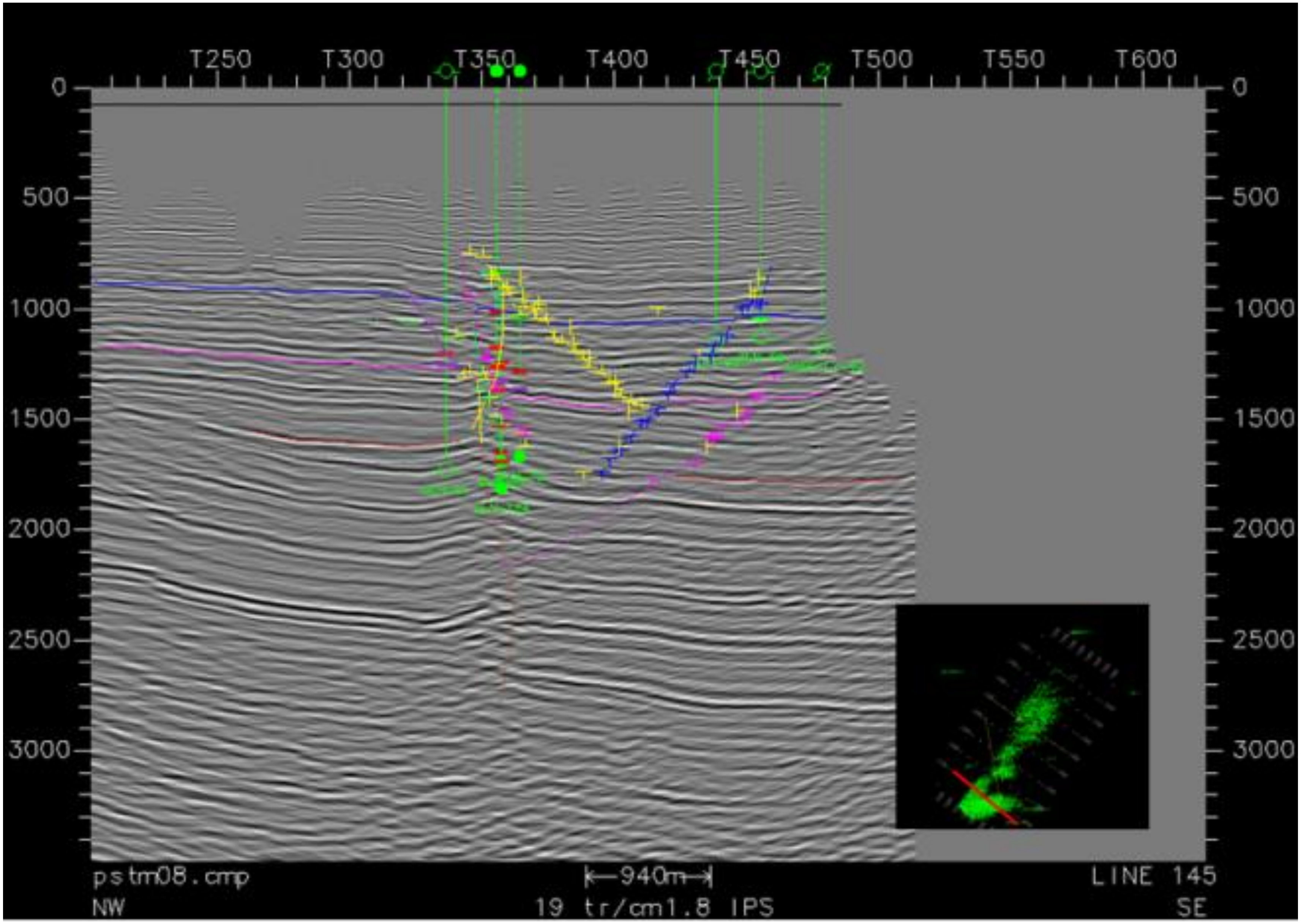


Figure 5. Reactivation of dextral strike slip fault in Galan Field.

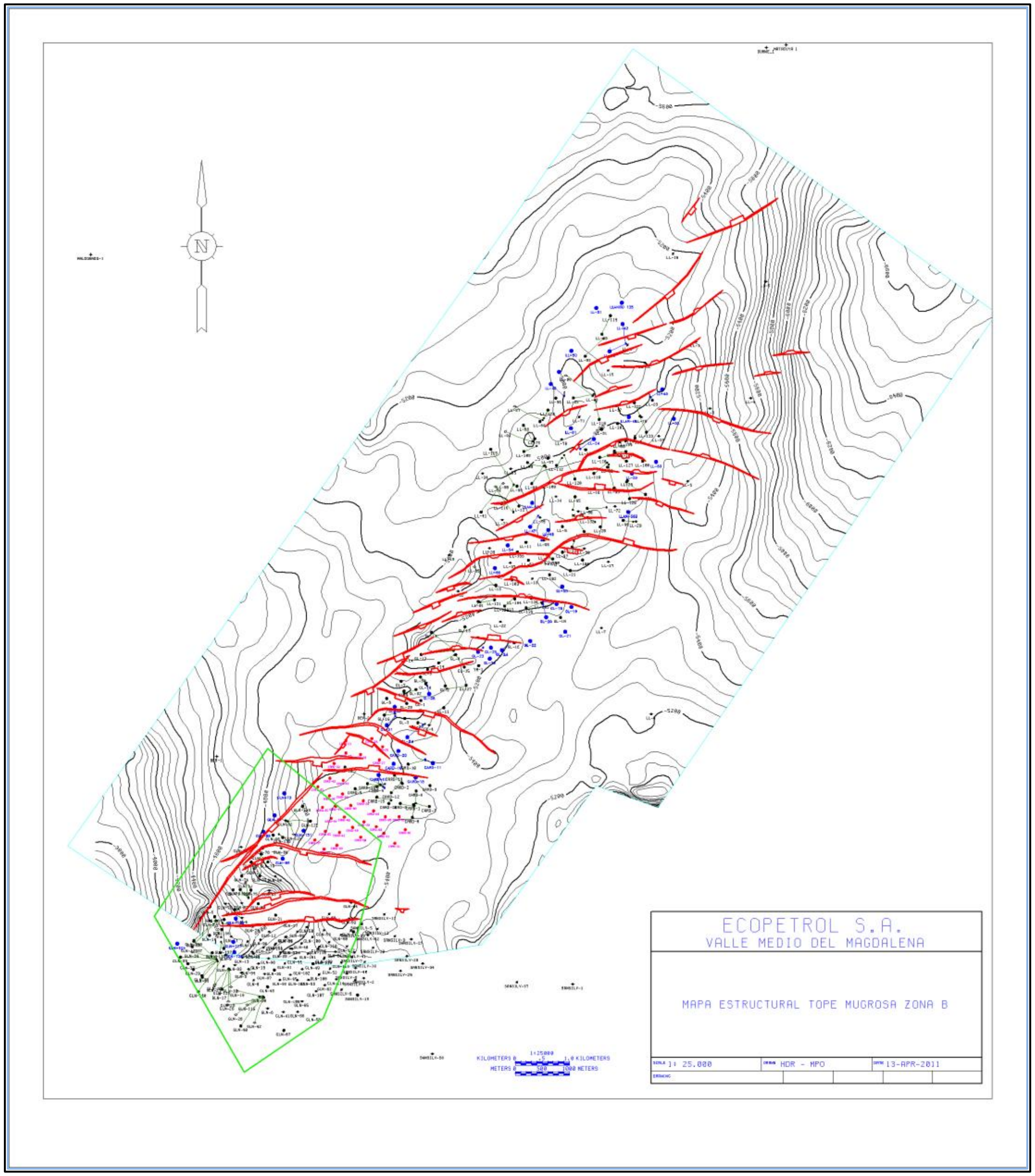


Figure 6. Structural map of Mugrosa B zone in Llanito District.

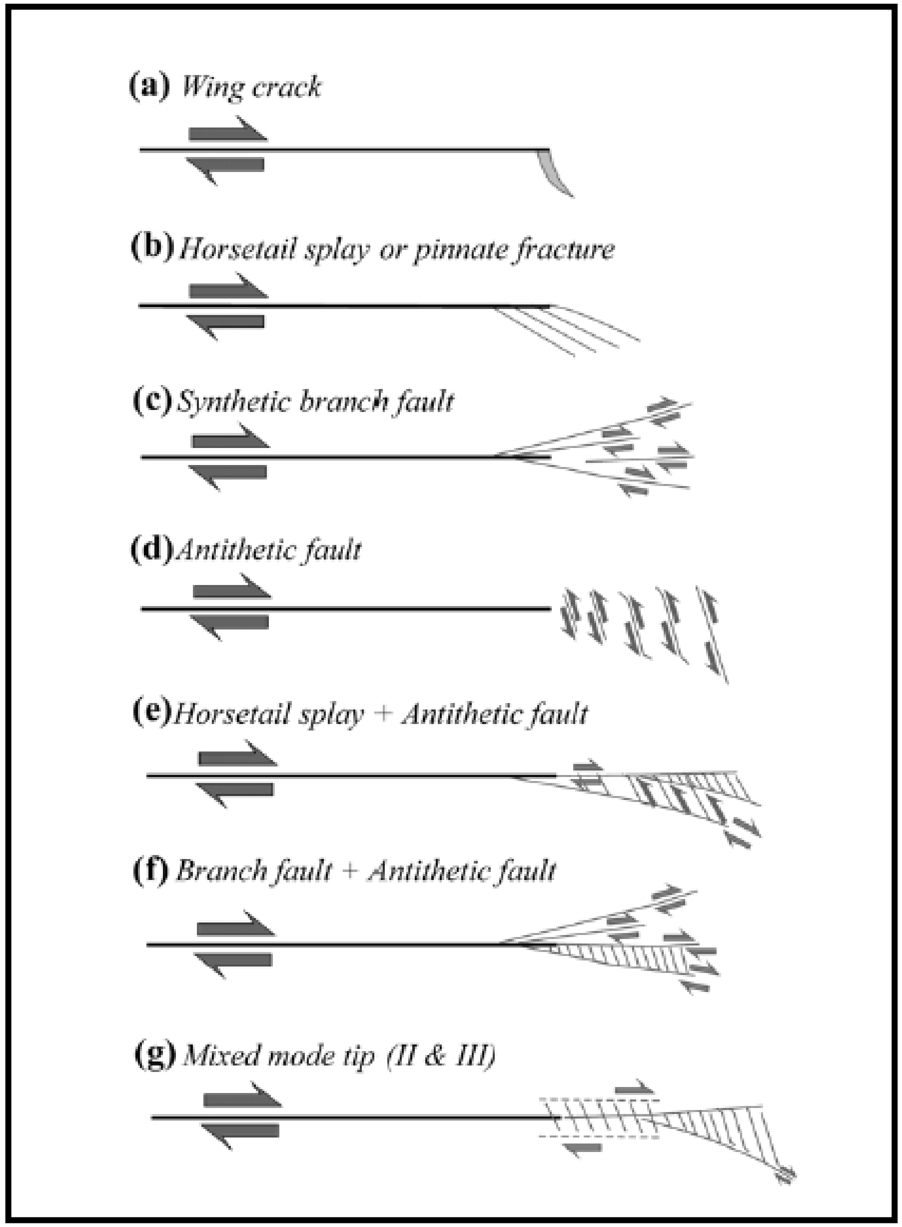


Figure 7. Scheme of main fault type zones in extreme of strike-slip faulting.

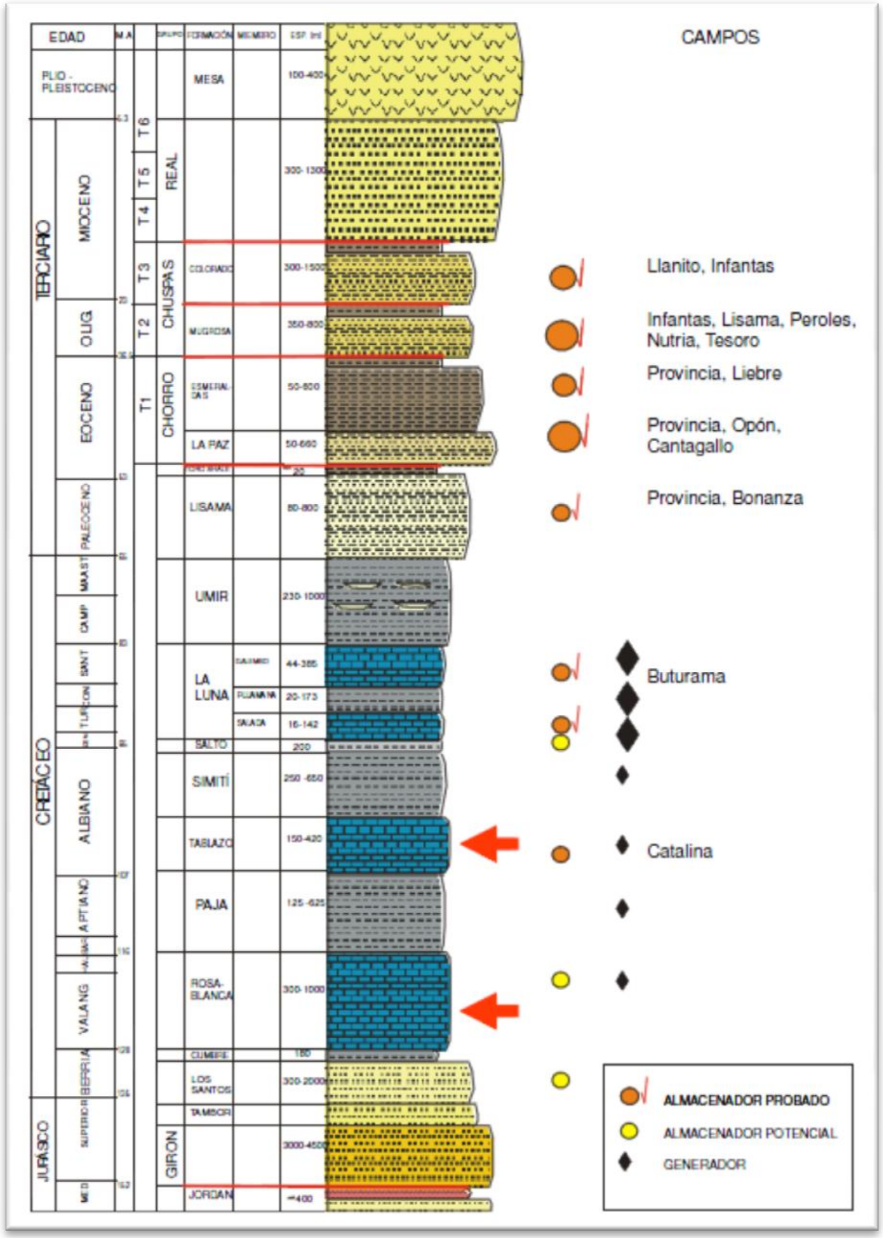


Figure 8. Stratigraphic Column of Middle Magdalena Valley Basin.

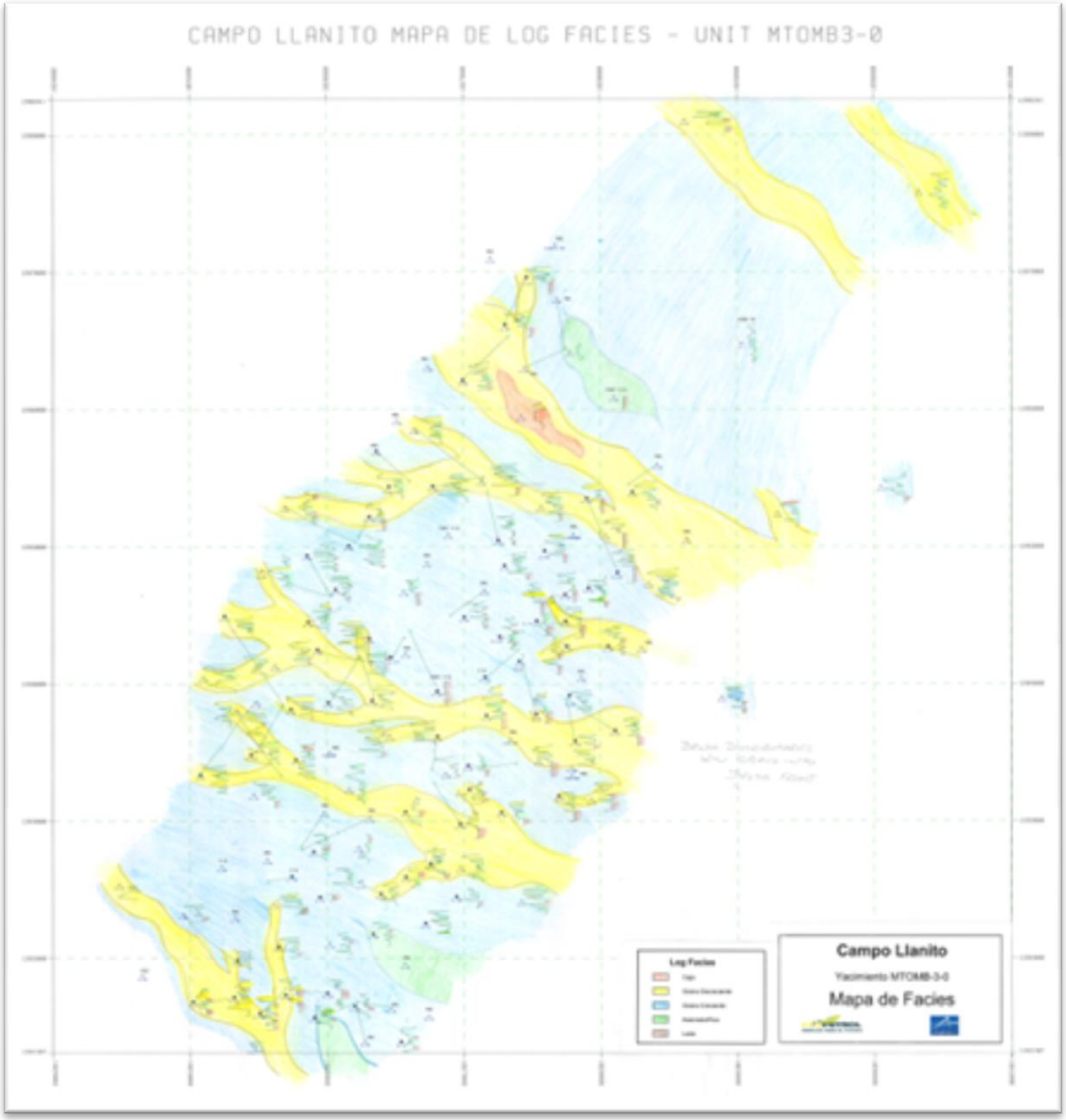


Figure 9. Facies map of B3-0 unit in Llanito Field.

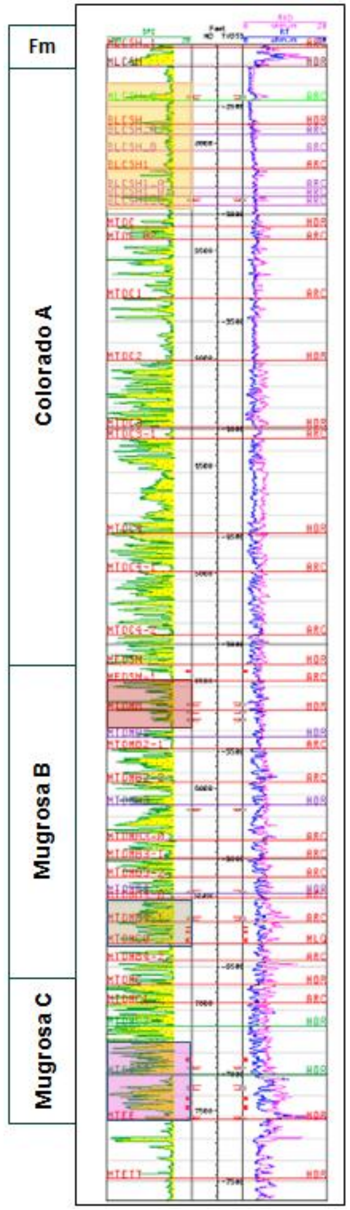


Figure 10. Producing zones in Type Well (Left, SP log – Right, resistivity curves).

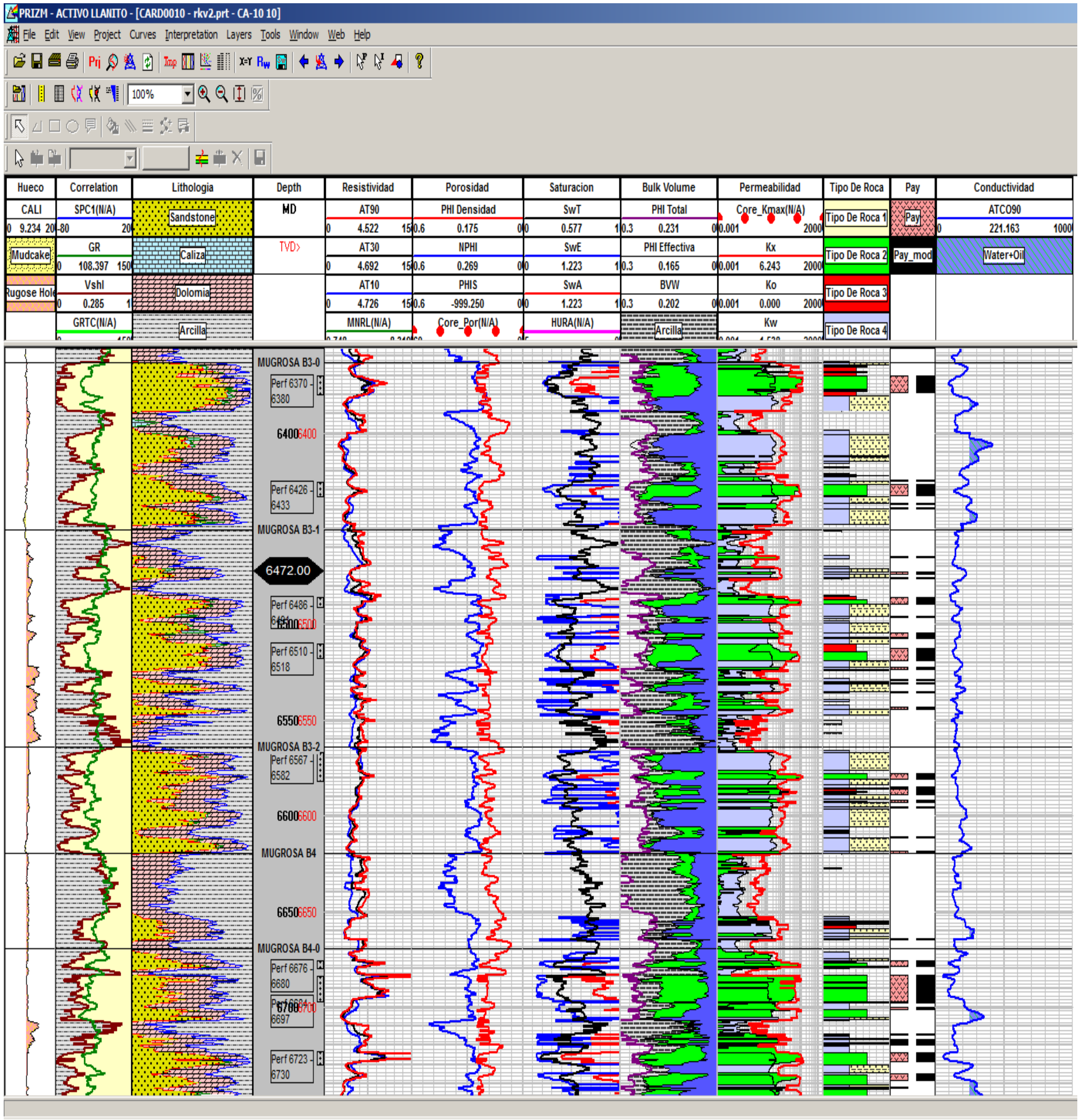


Figure 11. Petrophysical model of Llanito Field.

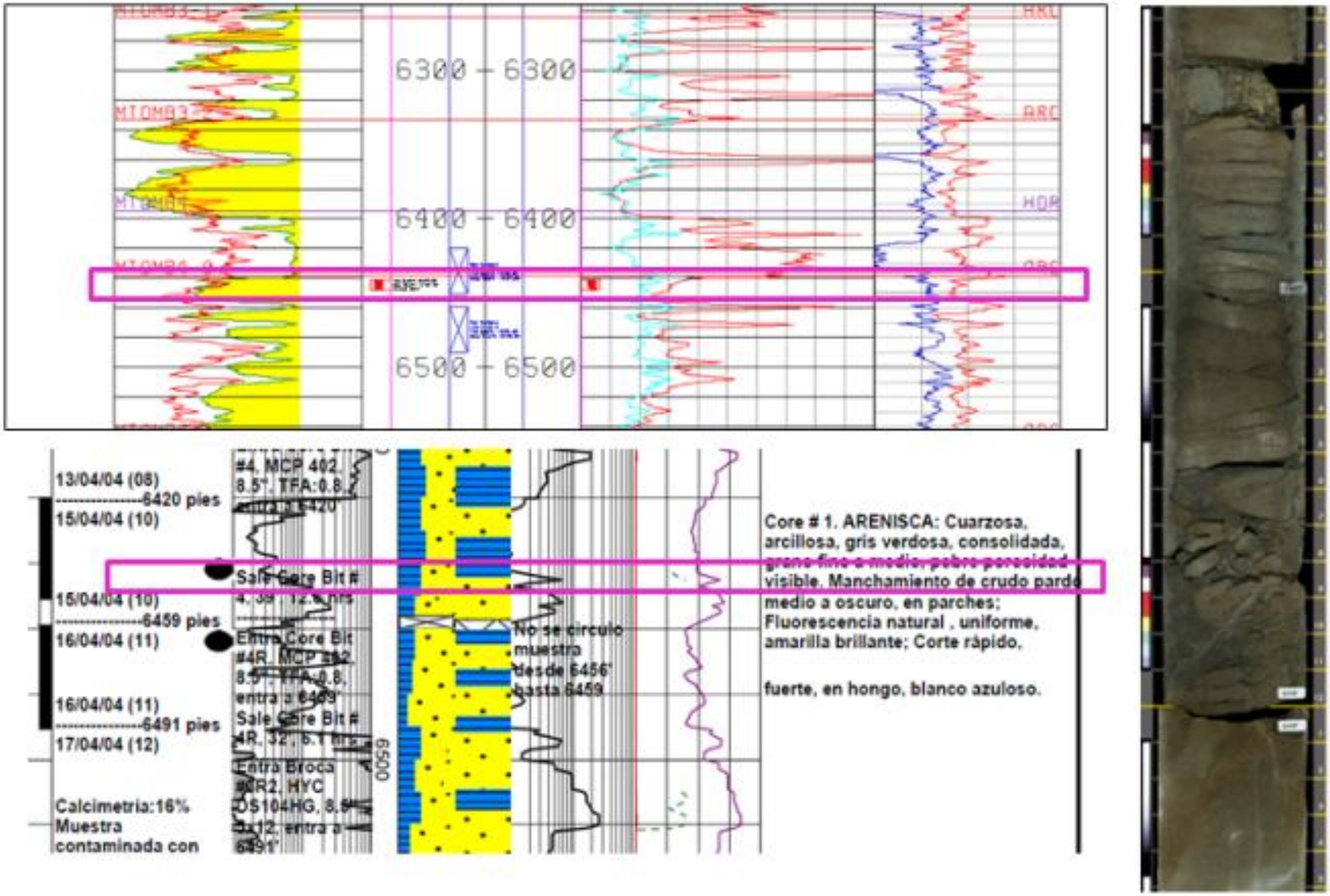


Figure 12. Typical log analysis of low resistivity pay zone (second track from right to left), with core description and oil shows.

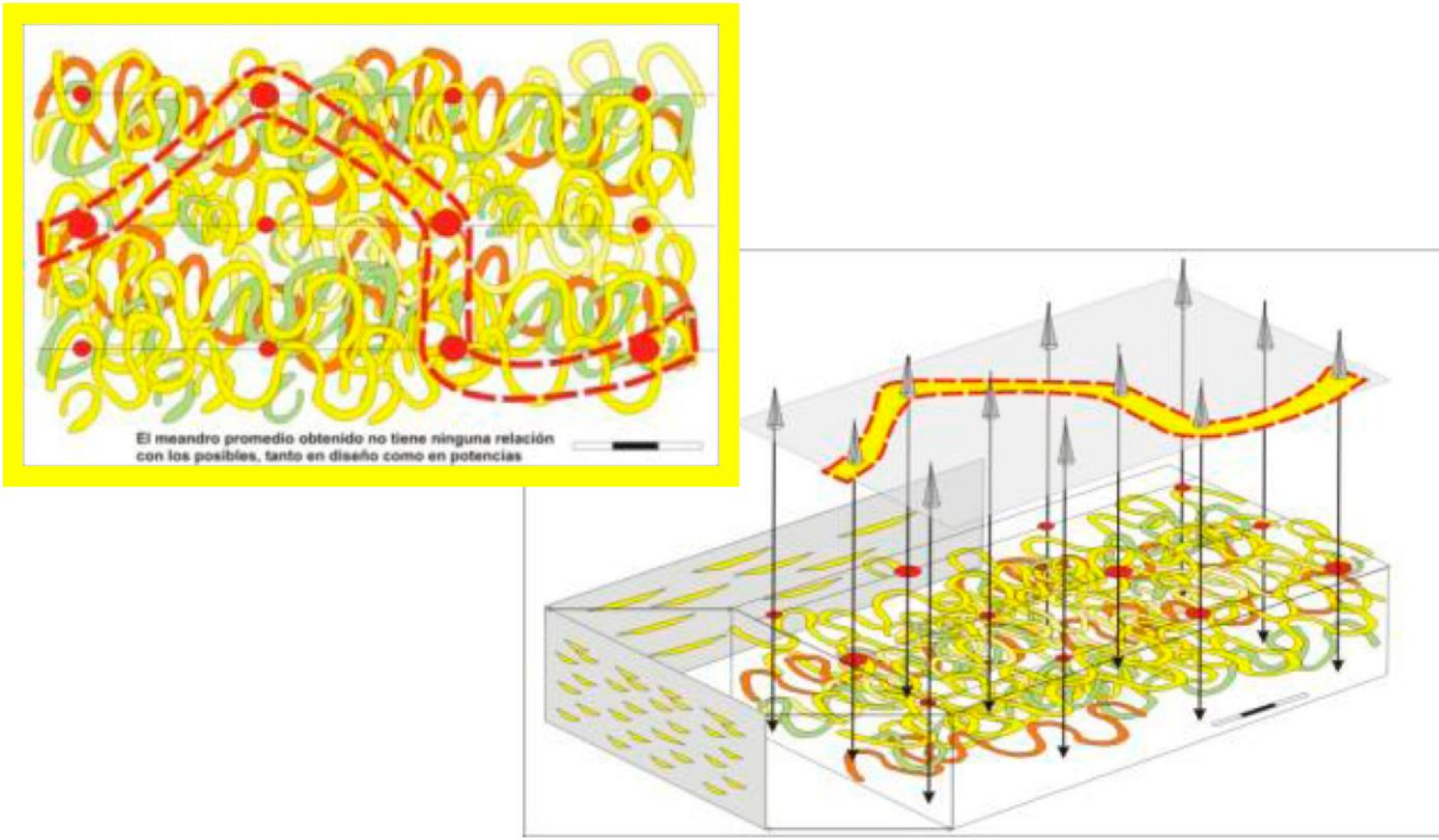


Figure 13. Schematic model of interrelated channels adopted by Llanito District (modified from Cross and Ramon).

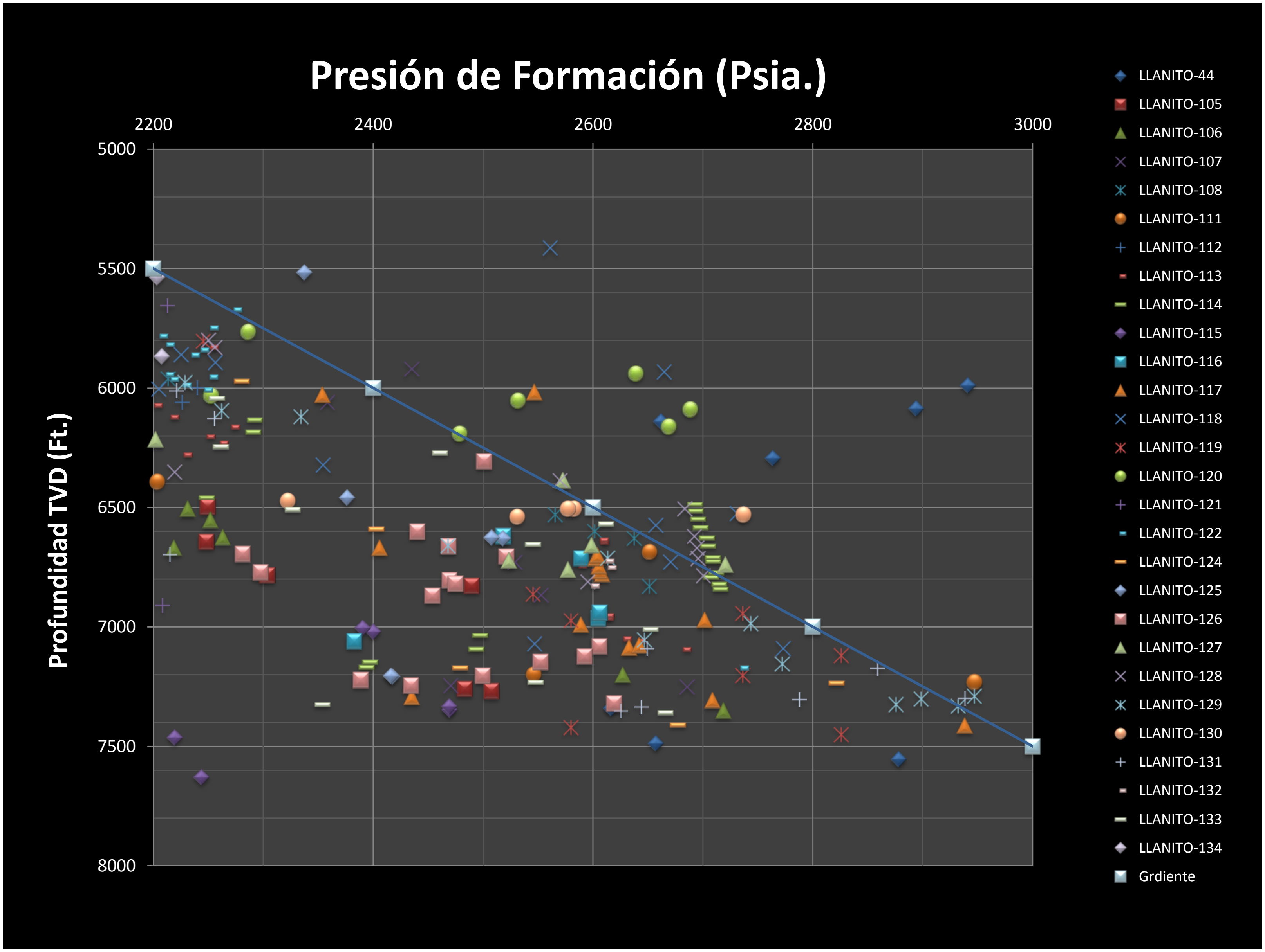


Figure 14. Pressure analysis Llanito Field.

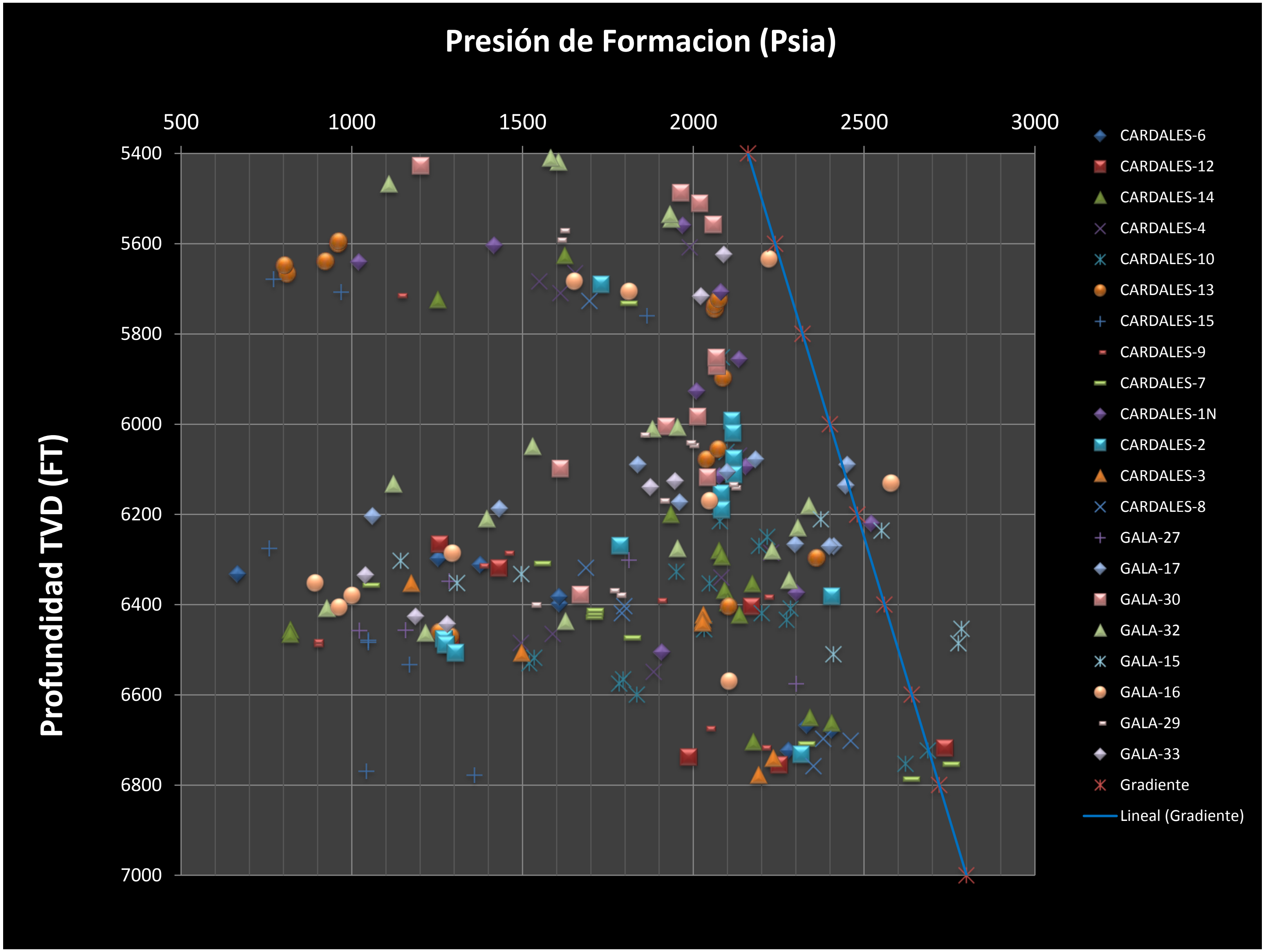


Figure 15. Pressure Analysis Gala Cardales Field.

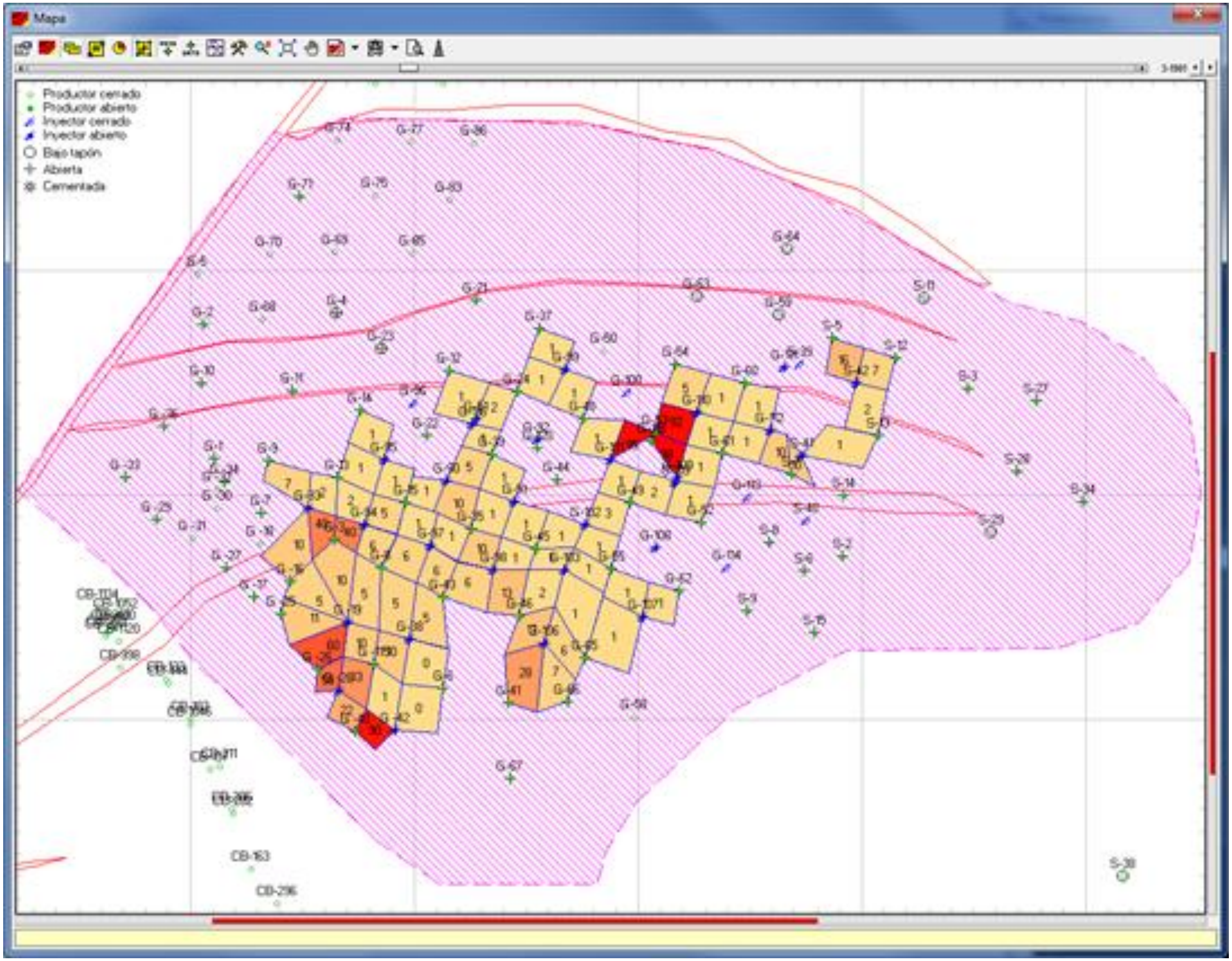


Figure 16. Influence area of waterflooding program in Galan Field.

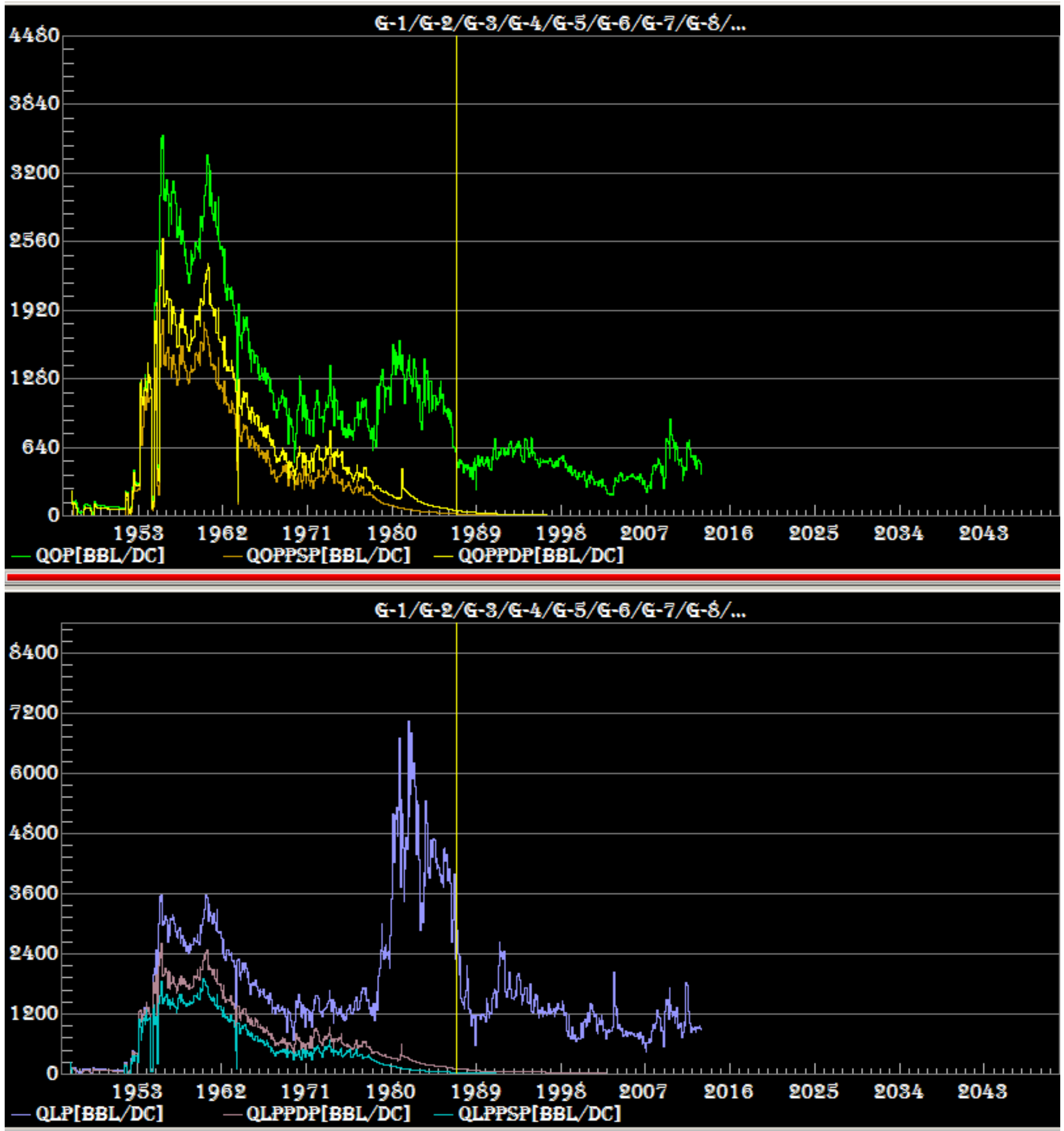


Figure 17. Upper part - Waterflooding effect in Oil recovery; Lower part - cumulative water production during the waterflooding period.

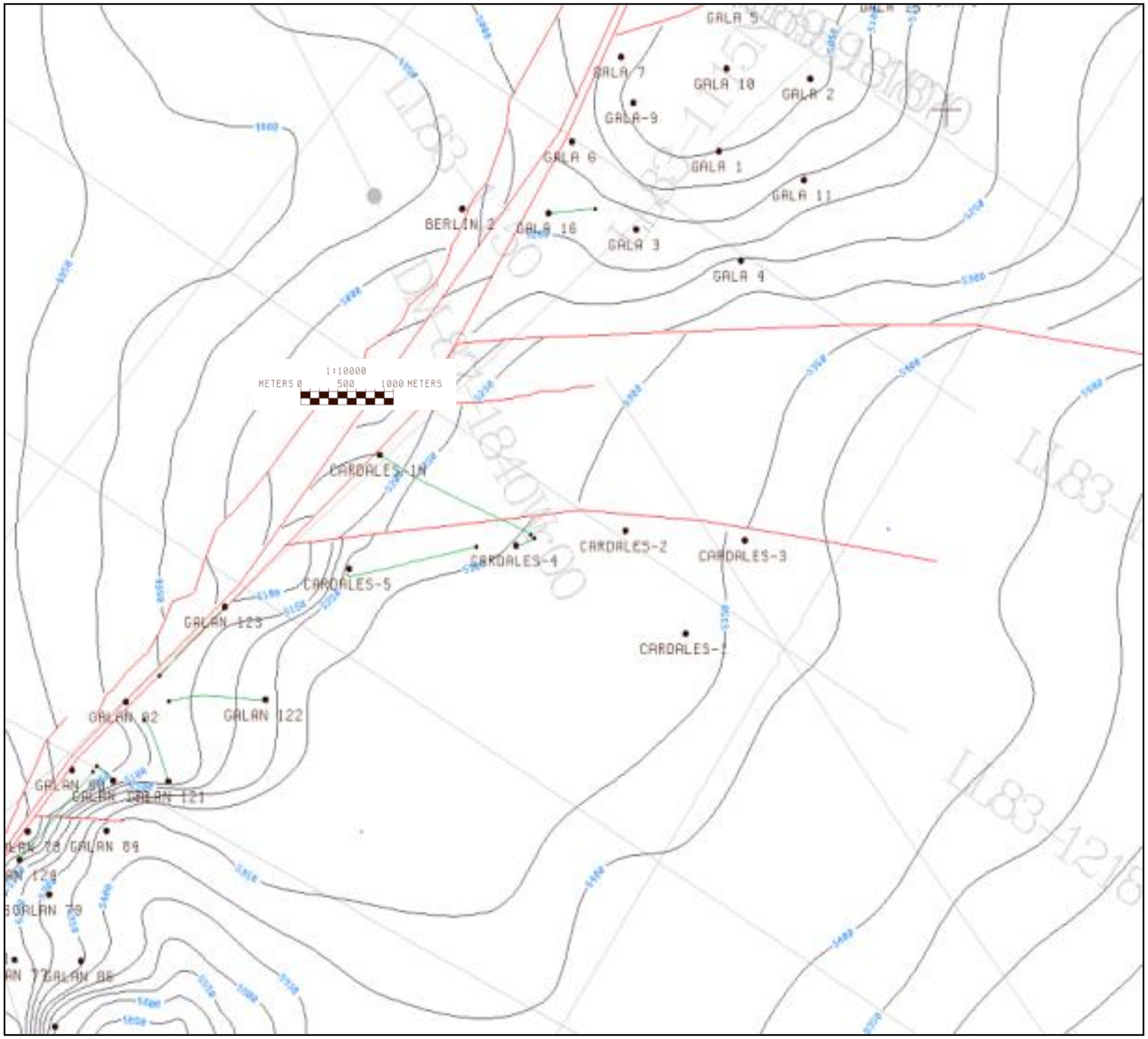


Figure 18. Former structural model in Northern Galan - Cardales Sector.

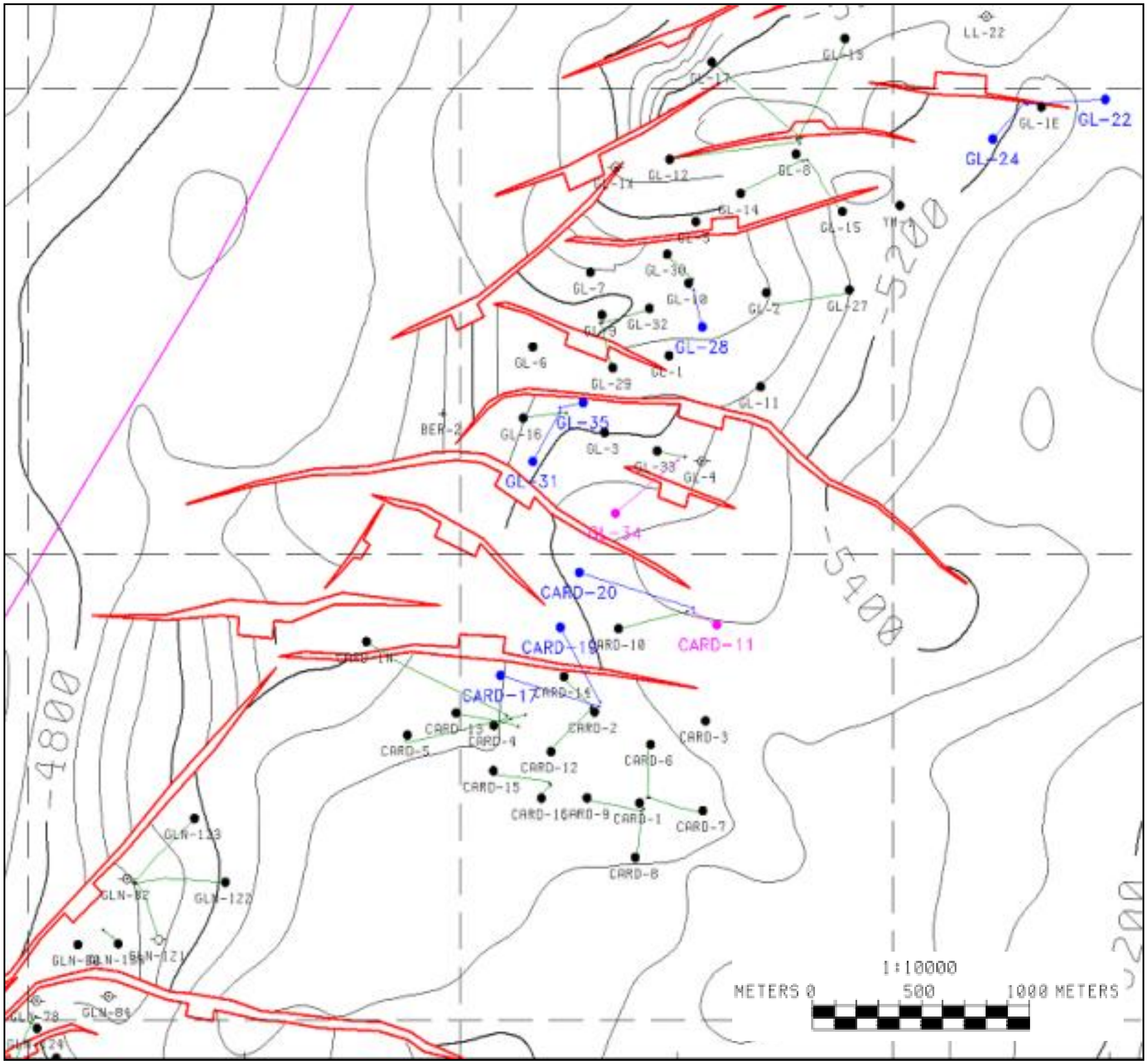


Figure 19. Updated structural model in Northern Galan and Cardales Sector.

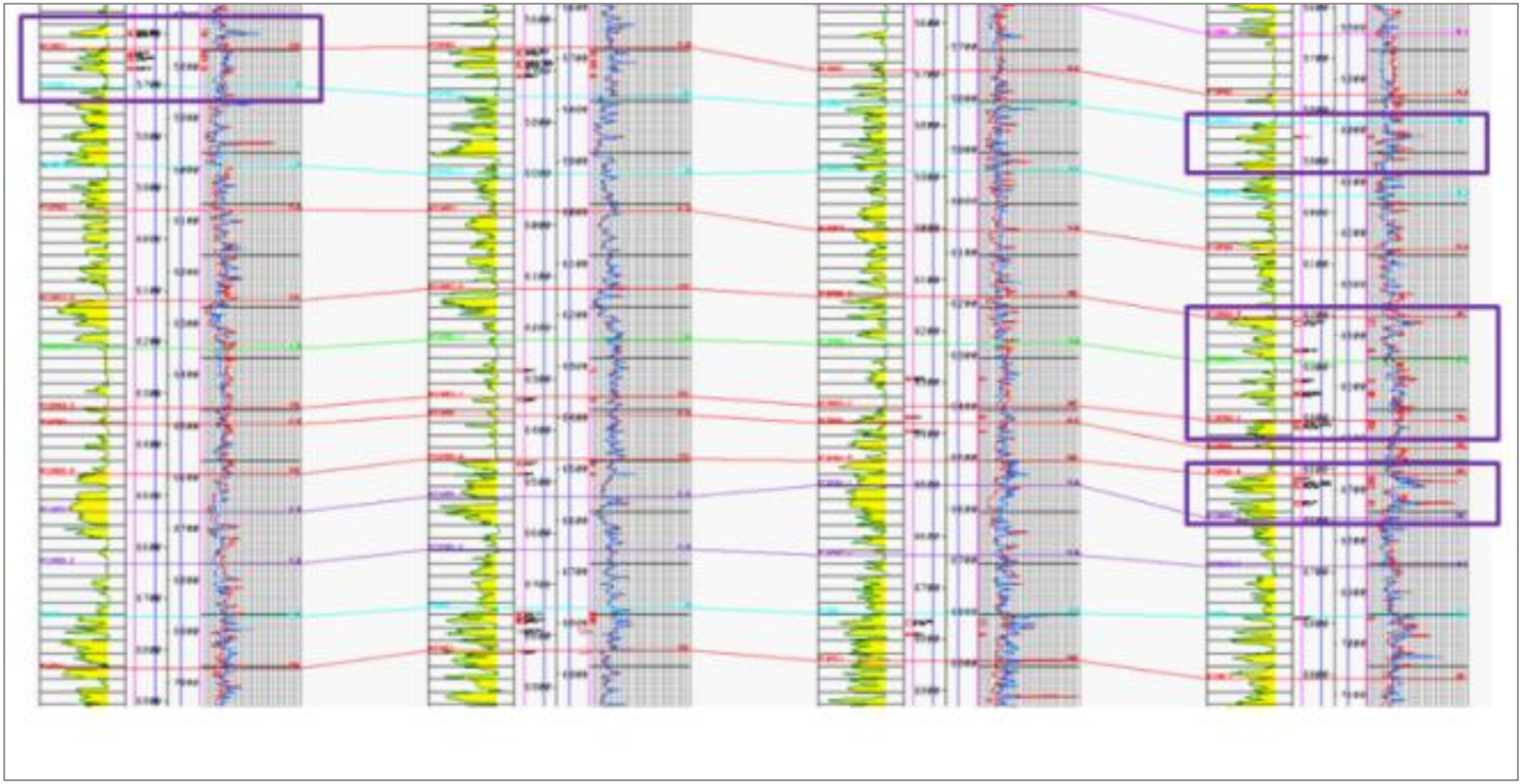


Figure 20. Good pay zones discovered in the lower block of Cardales Area (first well to the right).

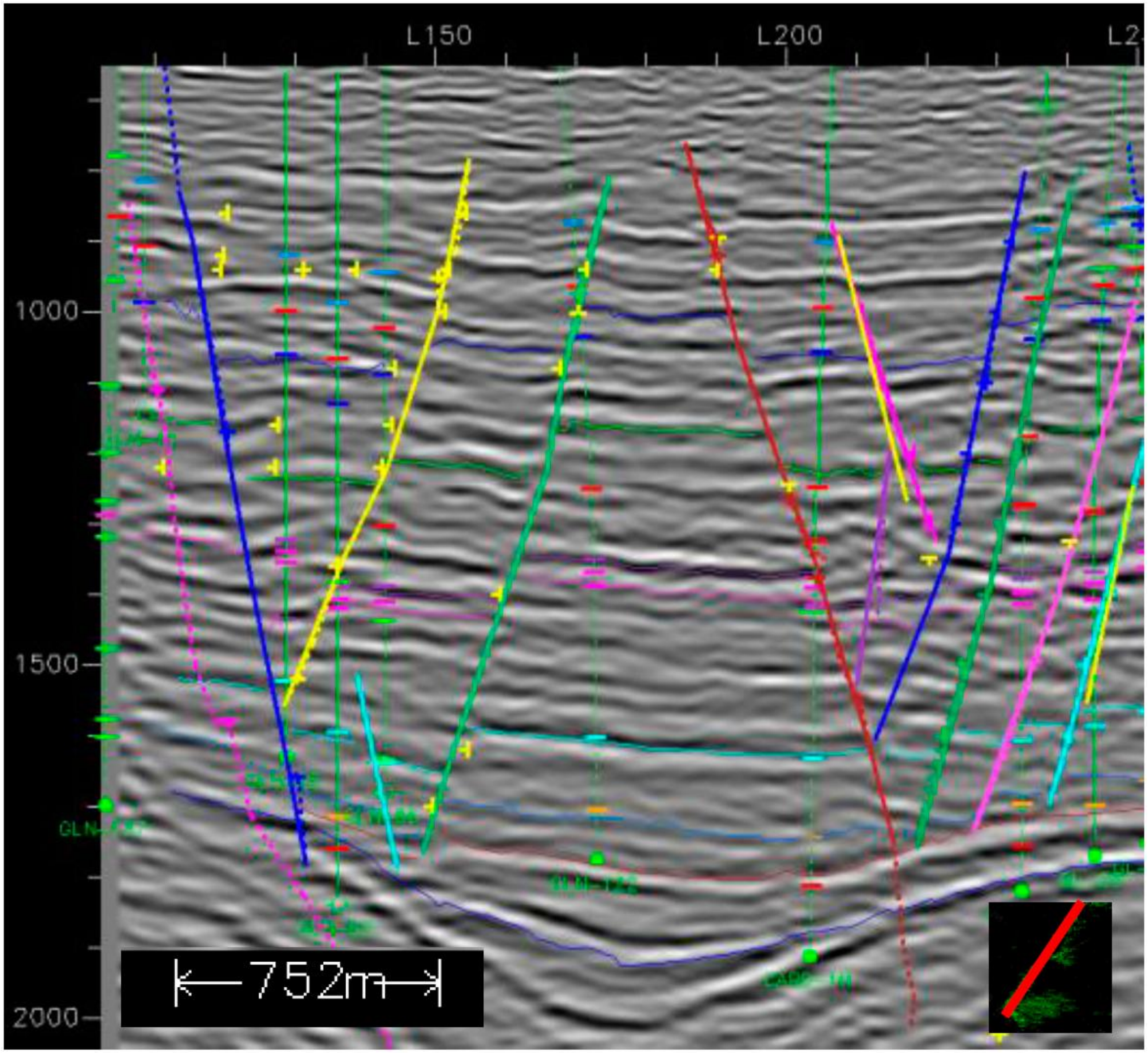


Figure 21. Structural Block in Northern Galan and Cardales Sector (Between Green and Brown faults).

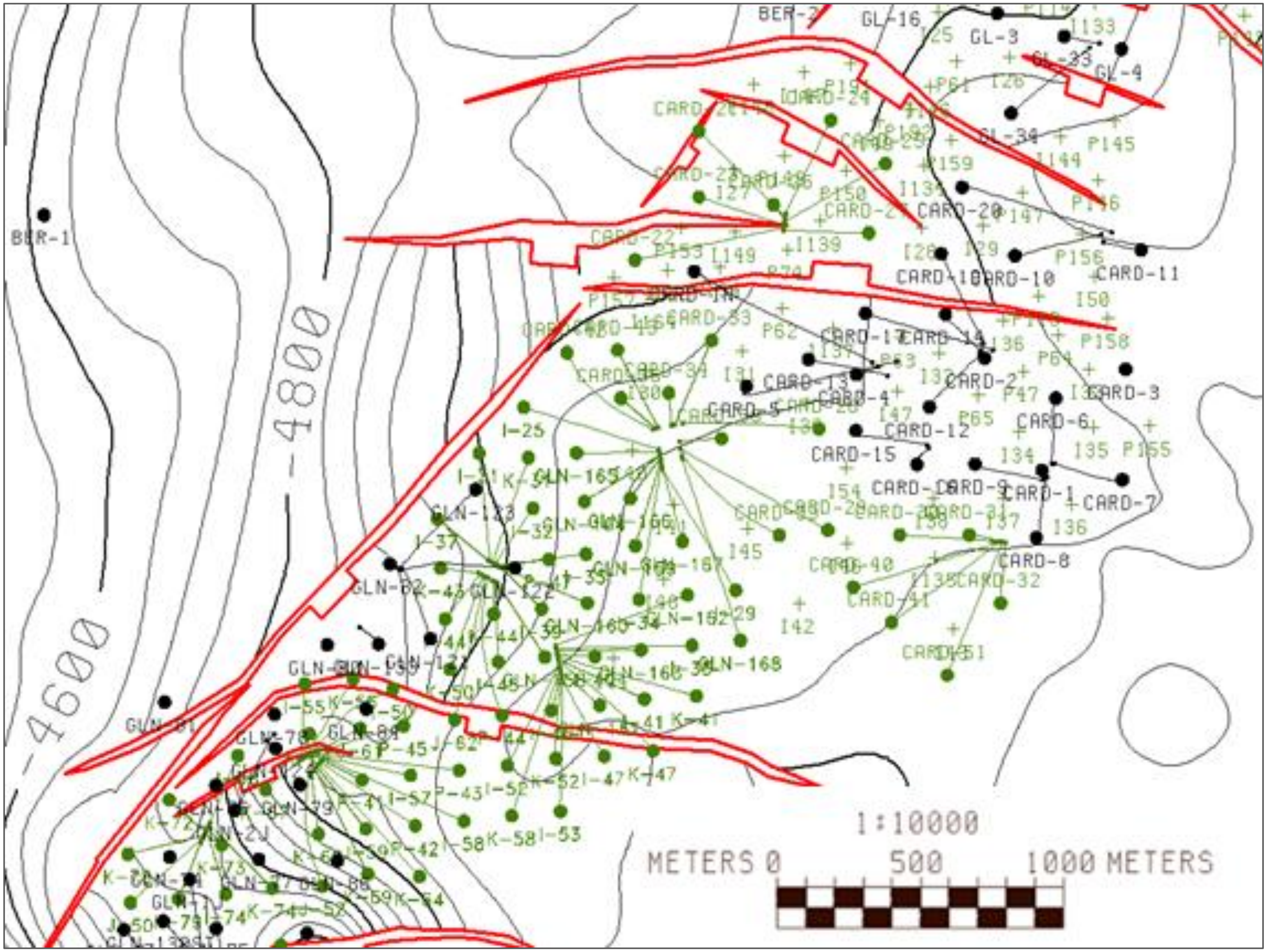


Figure 22. Proposed Wells as part of the development plan between Northern Galan – Cardales Sector (Green wells).

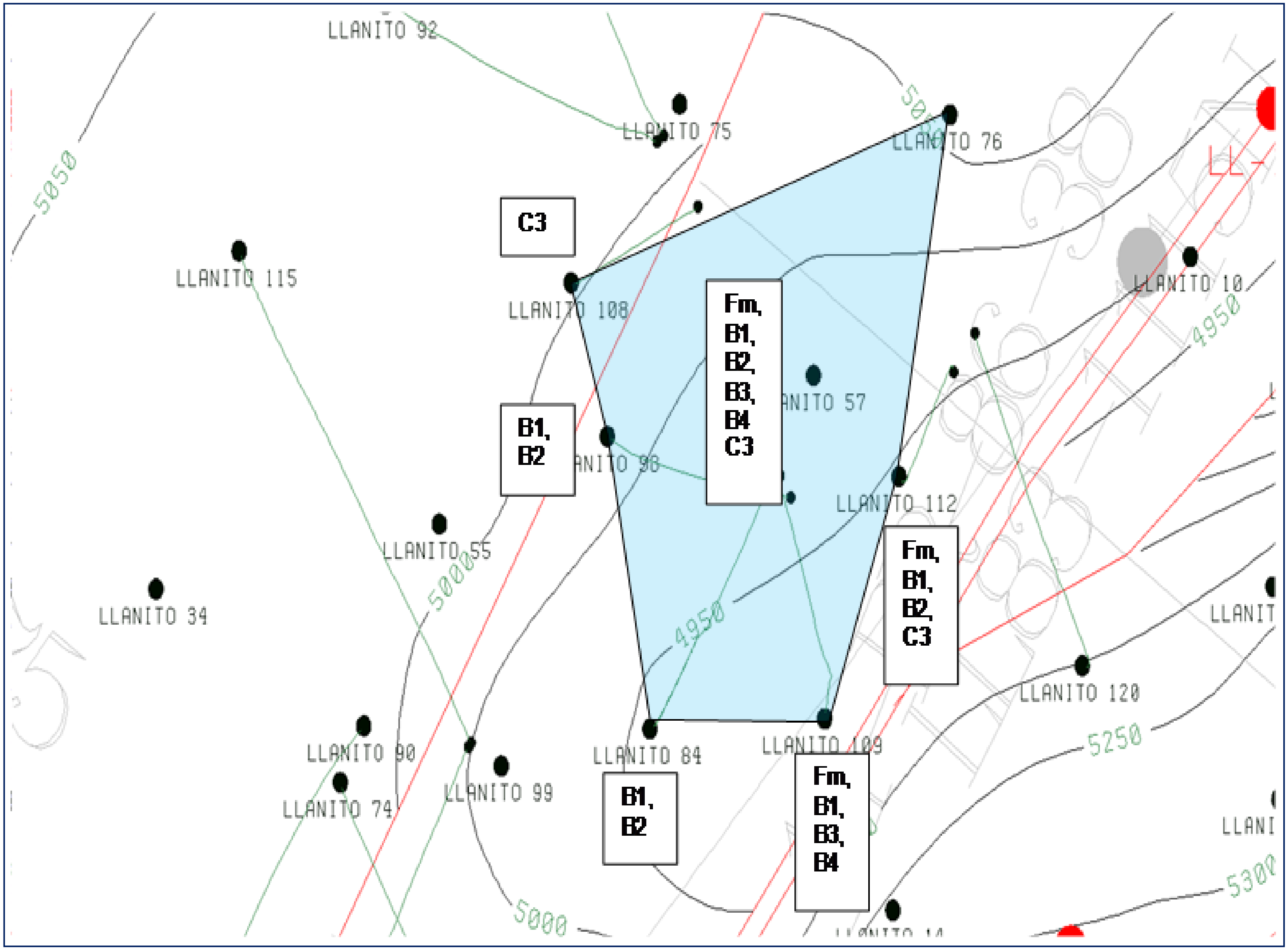


Figure 23. Waterflooding pilot in Llanito Field.

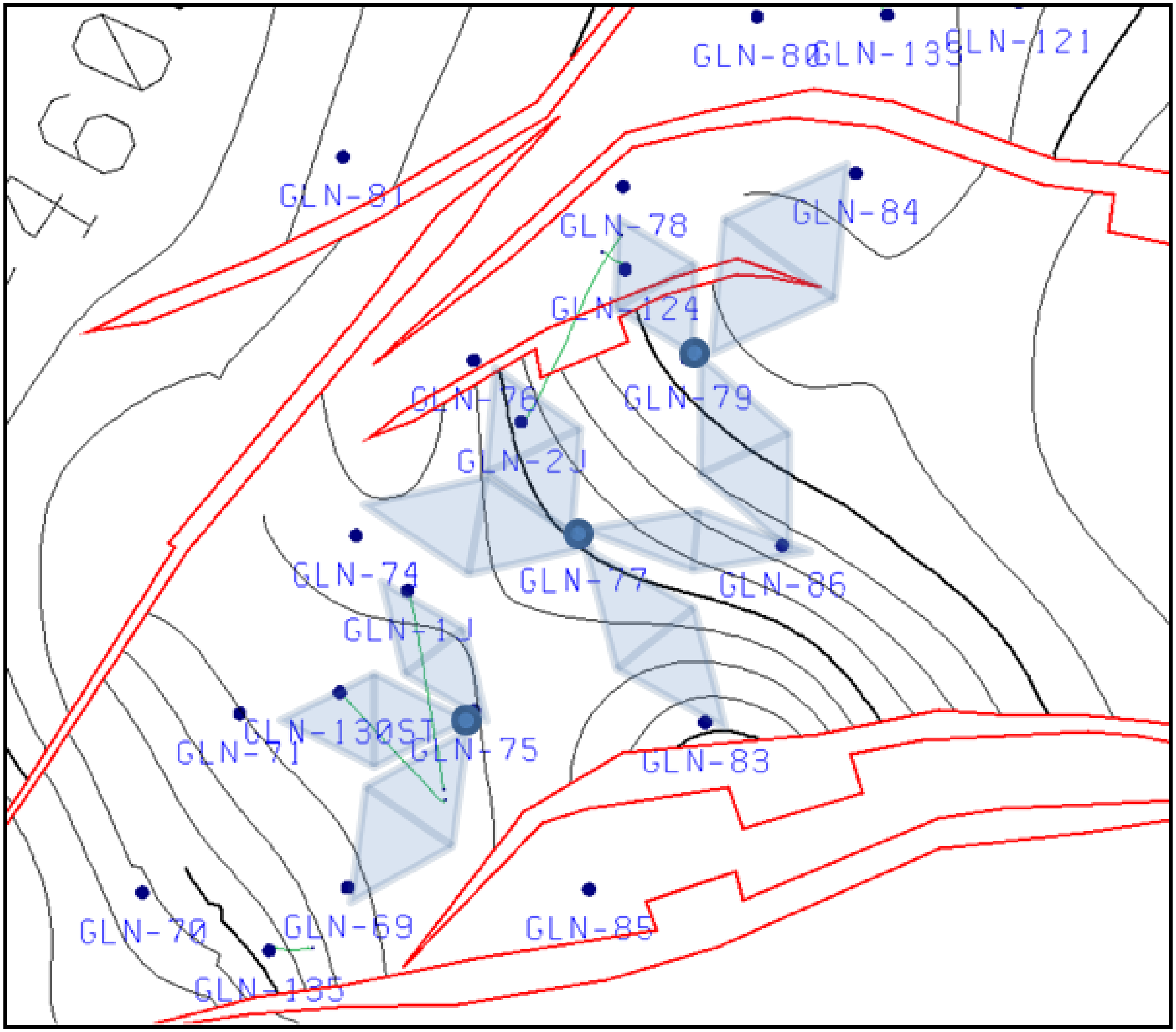


Figure 24. Waterflooding pilot in Galan Field.

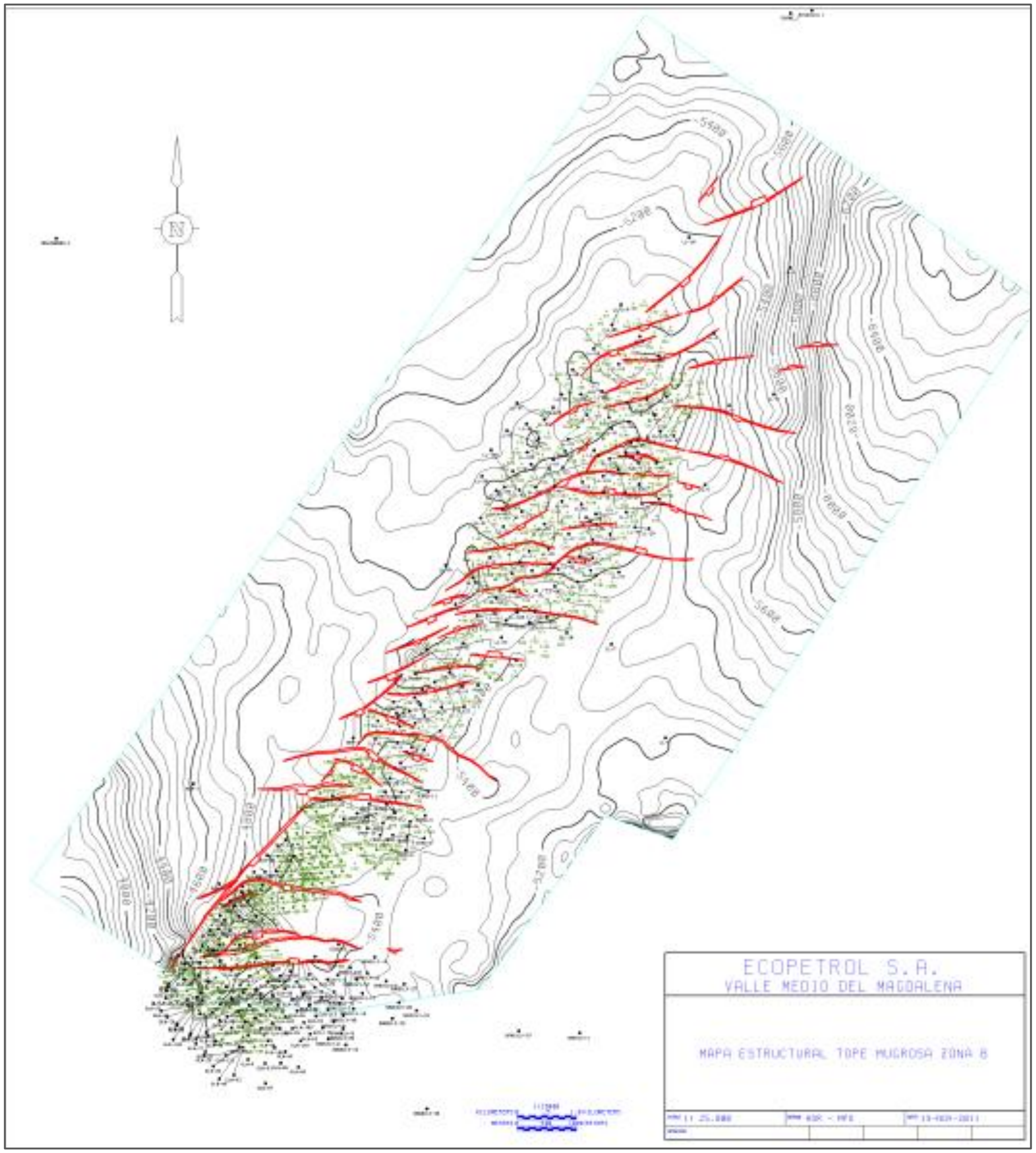


Figure 25. Expansion of water injection in Llanito Area.

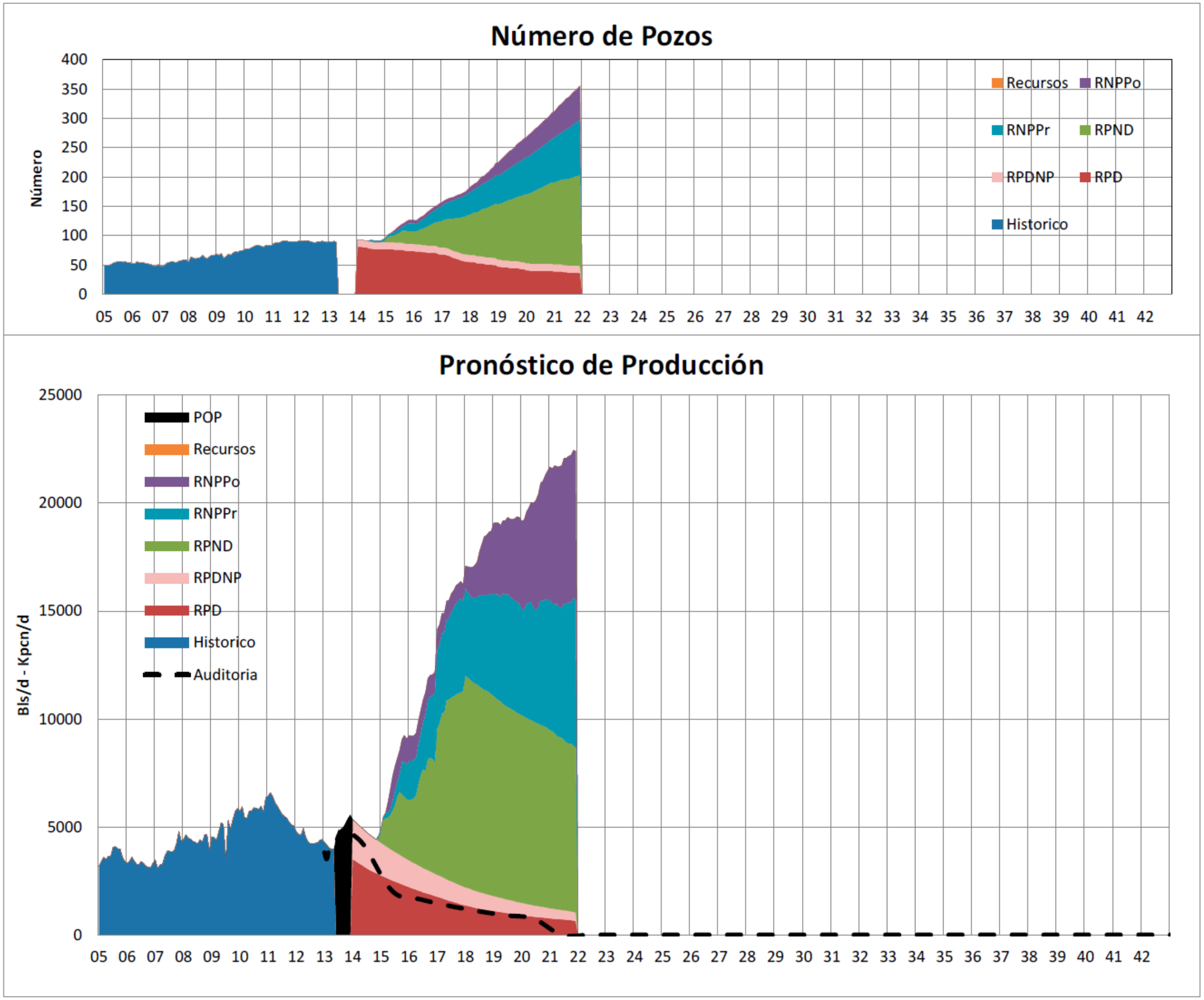


Figure 26. Oil Production profiles and Well entries in Llanito – Gala Field.

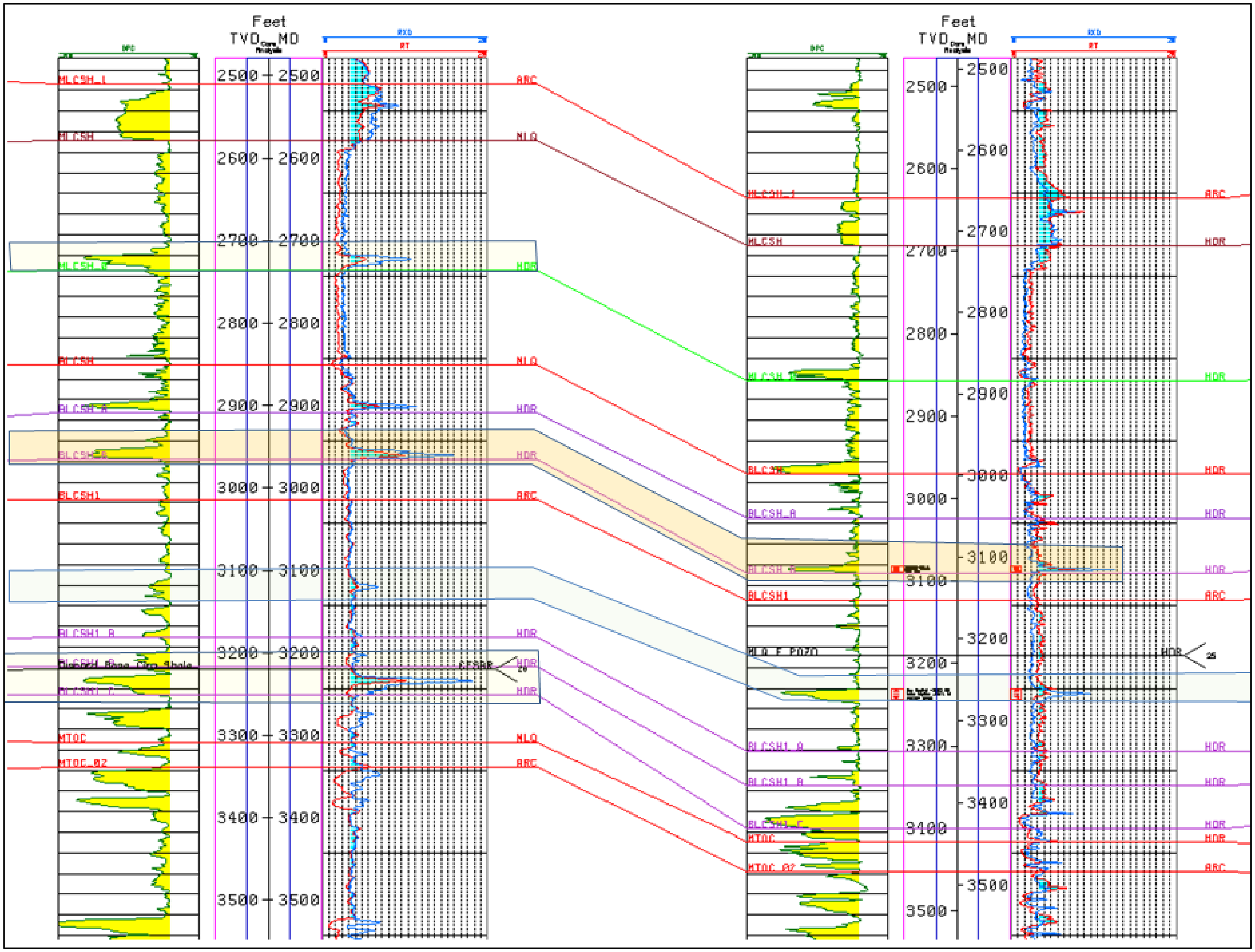


Figure 27. Gas producing zones in Colorado Formation – Llanito Field.

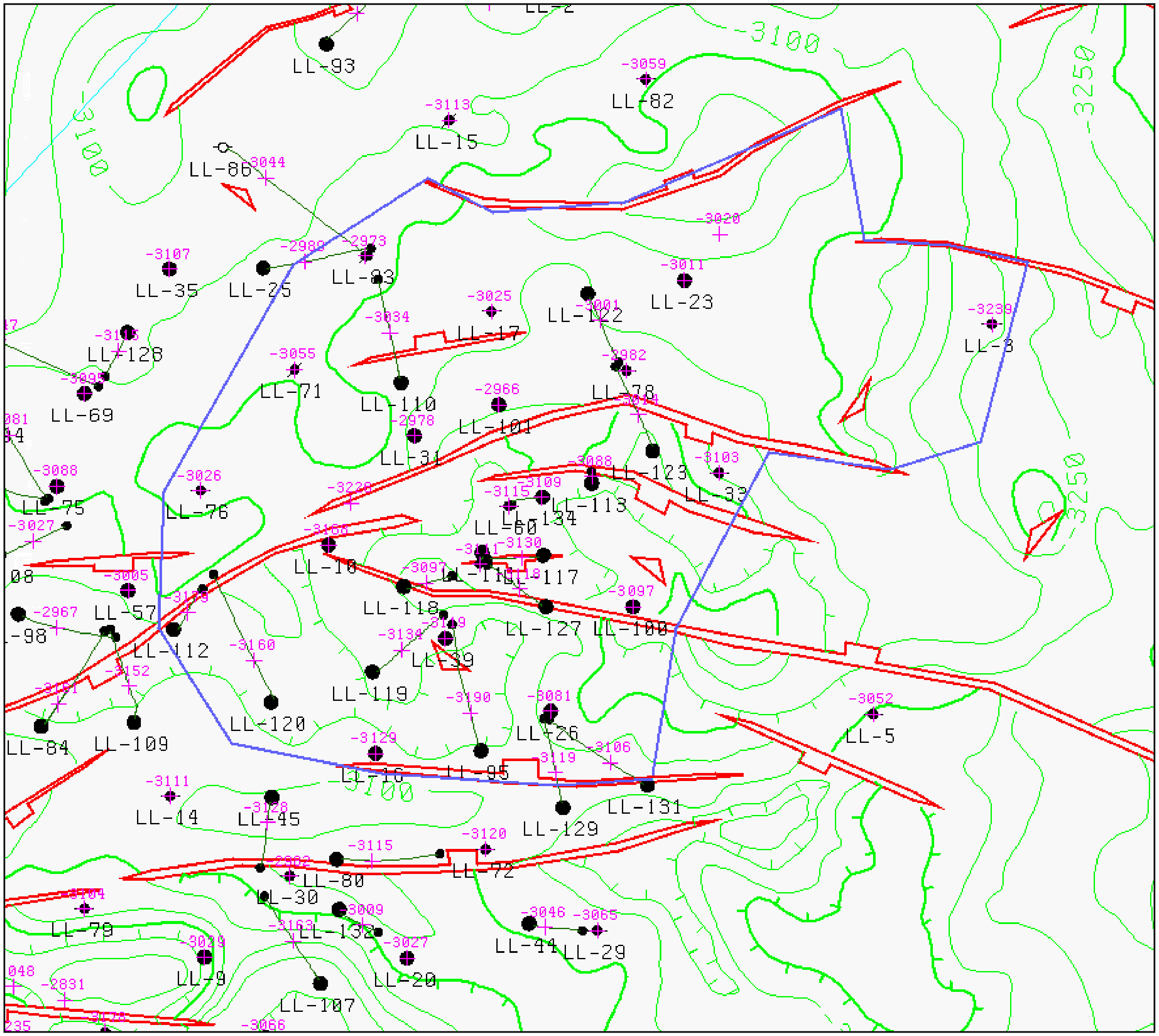
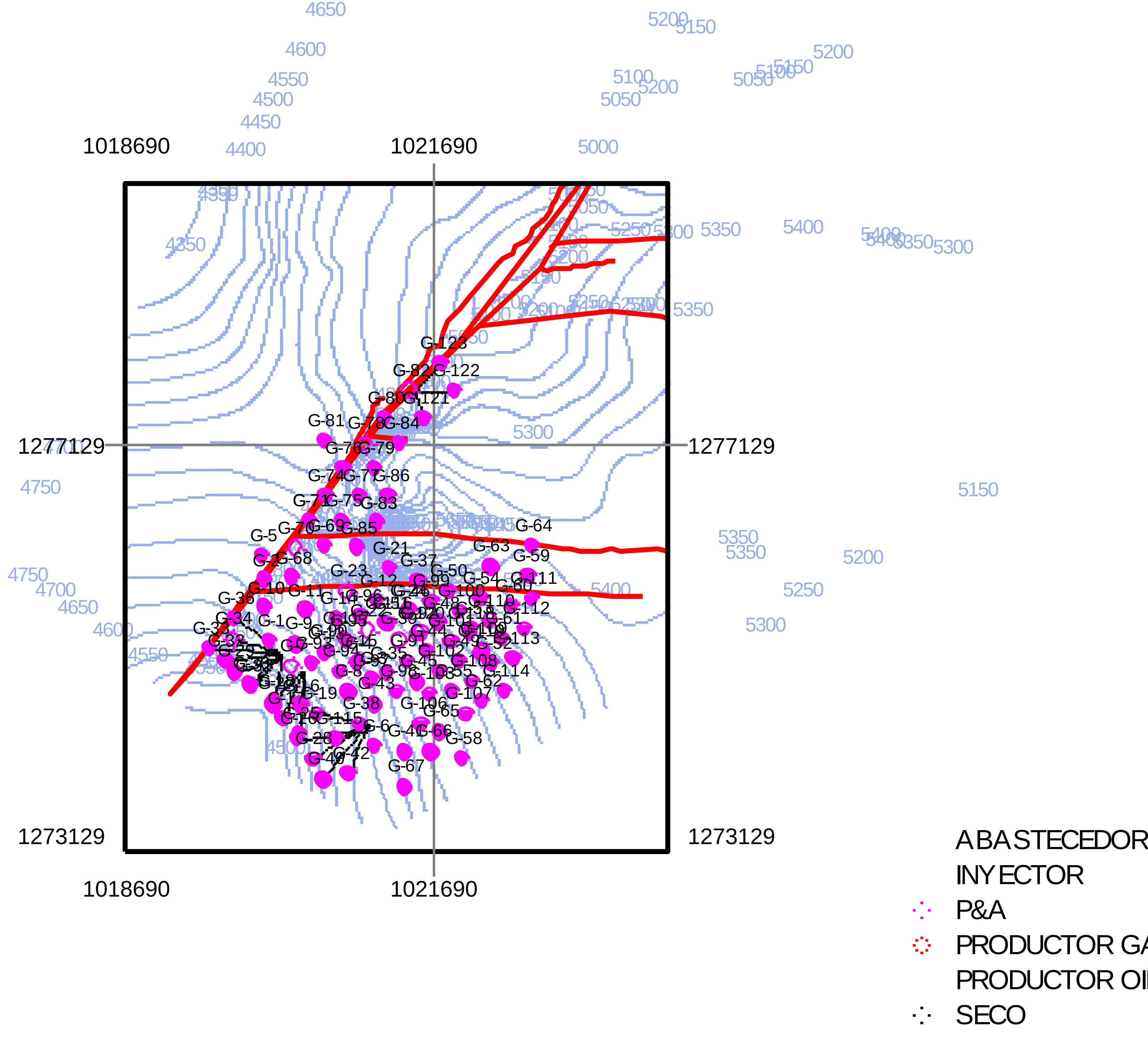


Figure 28. Areal distribution of gas producing wells. Colorado Formation, Llanito Field.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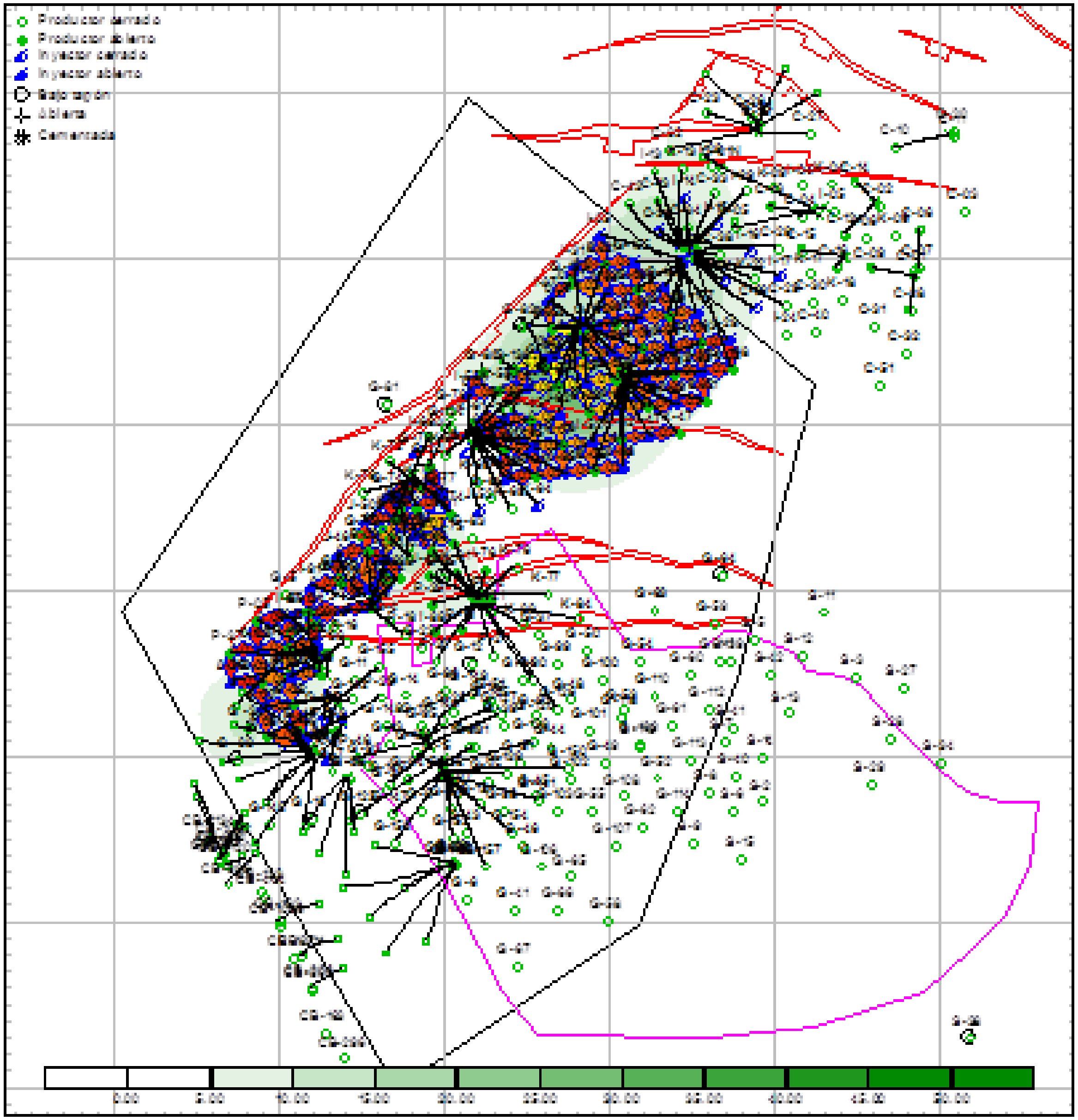

Figure 30. Extended secondary recovery project in Galan Field and delimiting polygon (black color) with variable royalties.

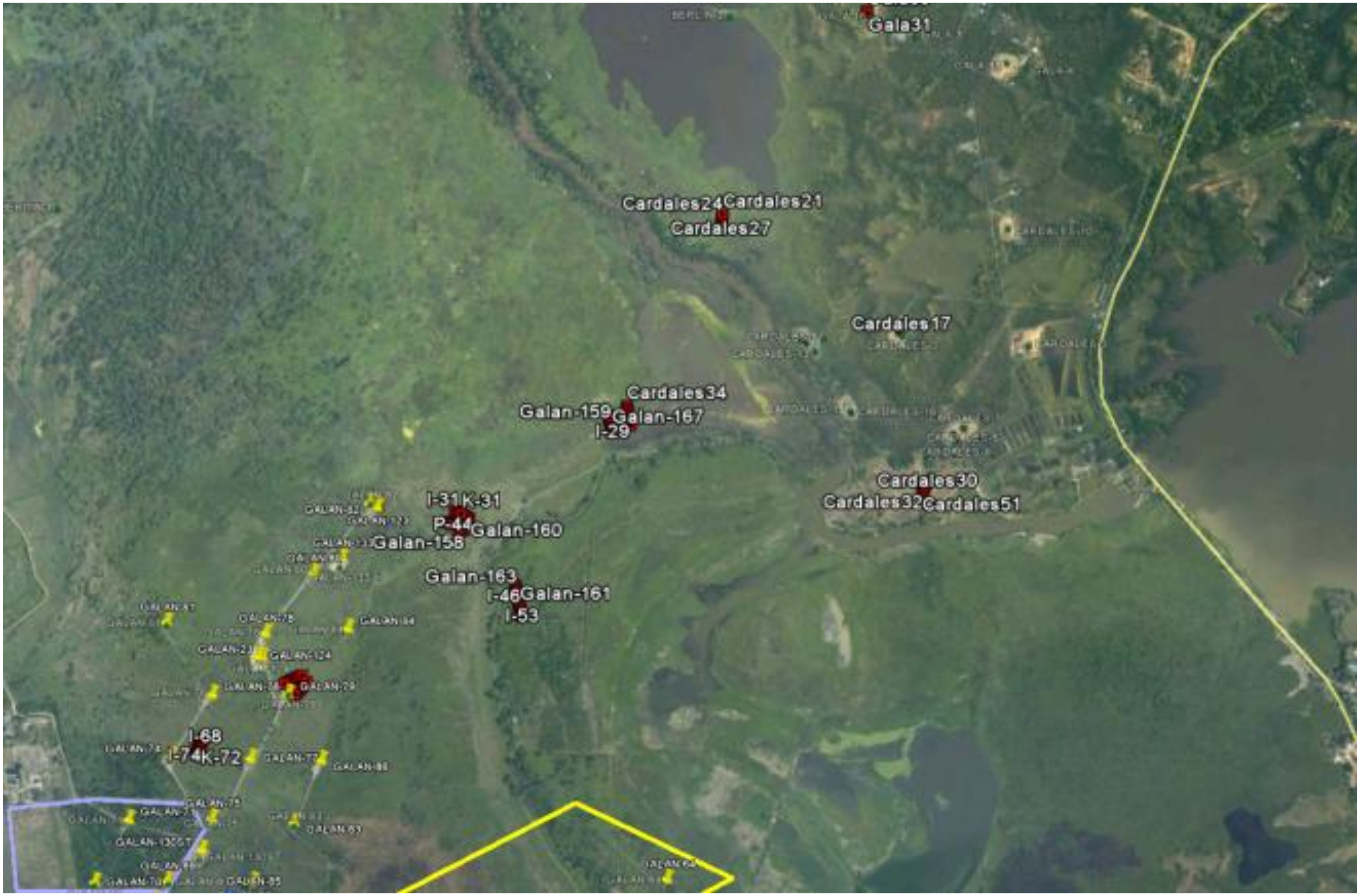

Figure 31. Proposed Galan and Cardales Cluster zones (red color) near the swamp of San Silvestre.

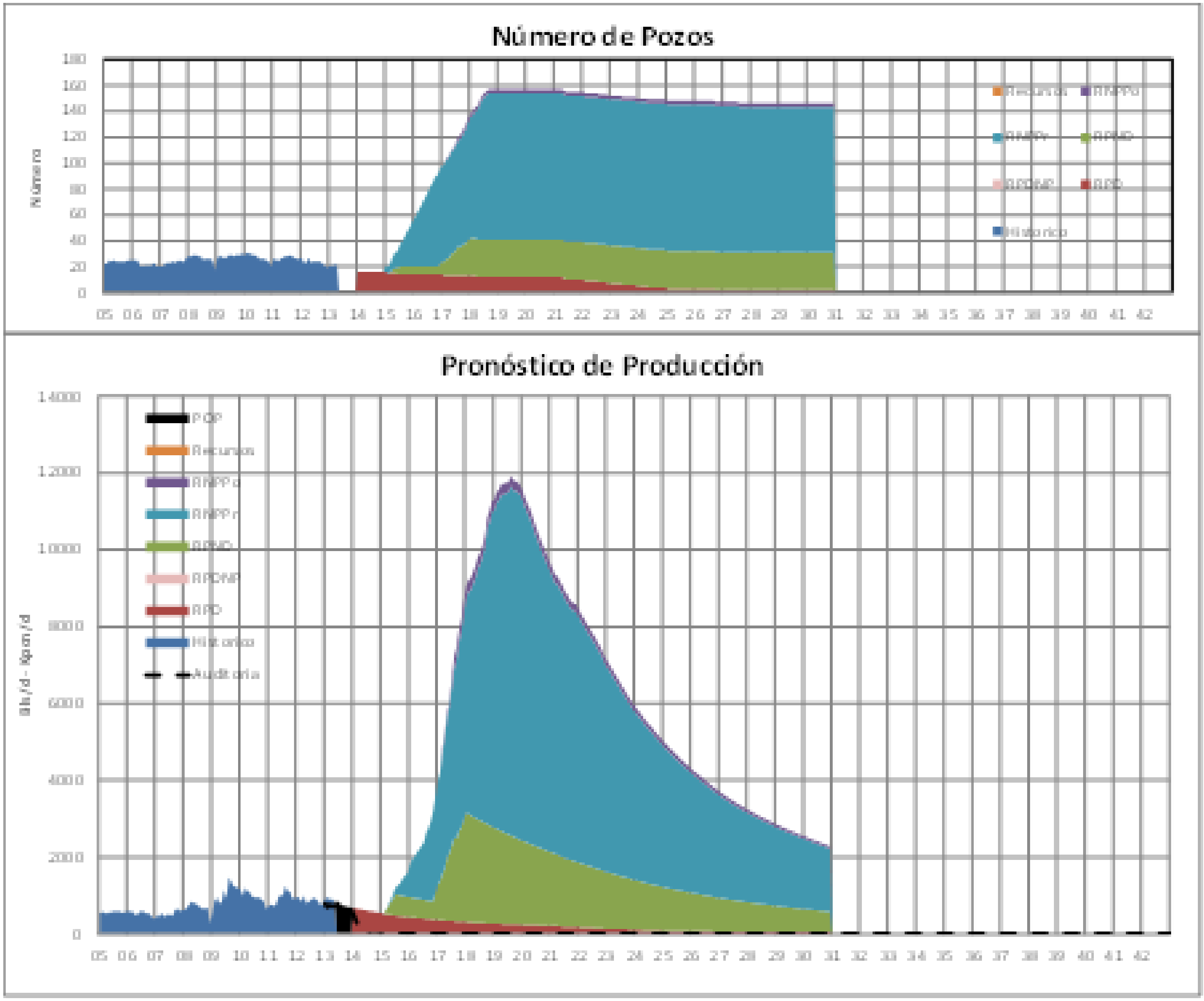

Figure 32. Oil Production profiles and Well entries in Galan Field.

PROGRAMA DE REGISTROS ELECTRICOS PARA LOS POZOS GALA-29 Y GALA-32

Sección	DETALLE PARA LA TOMA DE REGISTROS ELECTRICOS
1 Hueco de 8 1/2	Gamma Ray (GR)
2 De: Zapato 9 5/8" Hasta:Profundidad	Resistivo Induccion - Potencial Espontaneo y Caliper
3 Zona Interes: desde 1500 " Hasta: Profundidad Final	Densidad Neutron, Microlog o Microesferical, Sonico , Registro de Imágenes, MDT
4 Microesferico enfocado	USIT- VDL-CBL

Observaciones	Tomar mínimo 20 puntos de presión. Utilizar multiprobador de formaciones con sensor de cuarzo.
	Entregar 3 CD's con formatos LAS, LIS,PDF(TVD,MD), 6 copias en Papel y 1 en Cepia a escalas 1/200 y 1/500

PROGRAMA DE REVESTIMIENTO PARA LOS POZOS GALA-29 Y GALA-32

	Intervalo (ft)		Tamaño	Grado	Peso
1	De	Superficie	9 5/8 "	P-110	29
	Hasta	1000"			
2	De	Superficie	7 "	P-110	
	Hasta	TD			

Observaciones	El diseño definitivo de revestimientos de los pozos será definido por la Superintendencia de Perforación

PROGRAMA DE MUESTRAS DE ZANJA PARA LOS POZOS GALA-29 Y GALA-32

Intervalo (ft)		Describir cada	Preservar humedas cada	Preservar secas cada
De:	Superficie	30'		100'
Hasta:	Tope Zona B - Fm Mugrosa			

Intervalo (ft)		Describir cada	Preservar humedas cada	Preservar cada
De:	Tope Zona B - Fm Mugrosa	10'	10'	10'
Hasta:	Profundidad Final			

Observaciones	

PROGRAMA DE TERMINACION Y PRUEBAS DE PRODUCCION PARA LOS POZOS GALA-29 Y GALA-32

Unidad a Cañonear	Profundidad a cañonear
Zona B y C Según evaluacion de registros	Recomendado herramienta de Maxima Penetración
Esmeraldas Según evaluacion de registros	Recomendado herramienta de Maxima Penetración

Observaciones	• Cañonear con cable en presencia de aceite muerto de produccion
	• La sarta de producción y el equipo de extracción serán diseñados por la Superintendencia de Operaciones.

Figure 33. Model of information required for the drilling of a type well in Llanito Field.

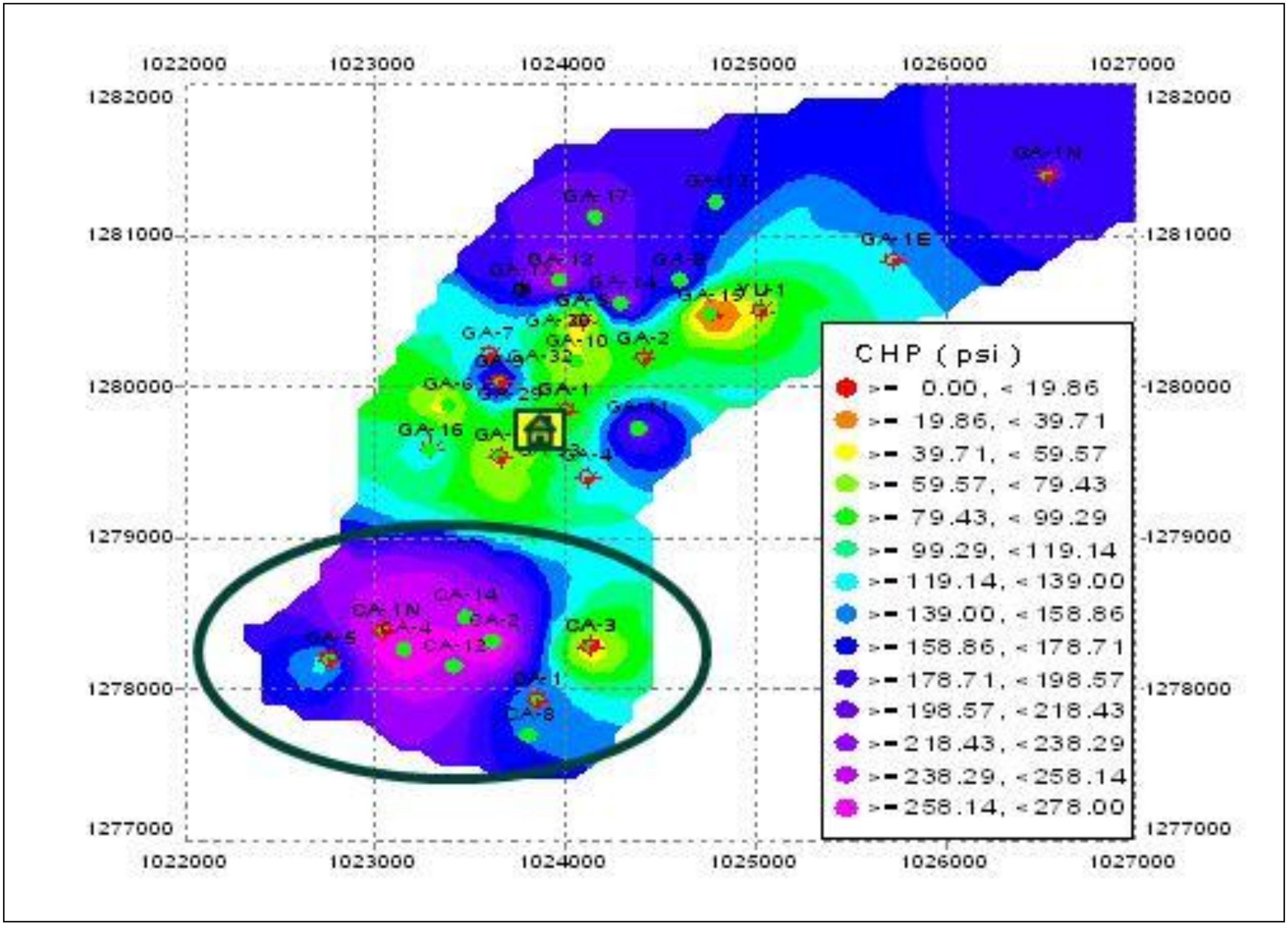

Figure 34. Productivity analysis to prevent high pressure at surface.

Figure 35. Stimulations performed in Llanito Field.

Parámetros	Zona A	Zona B	Zona C	Zona D
Gravedad API	18.4	20	22	24
Viscosidad (cp)	50	19.4	12.1	5
Tipo de crudo	Nafténico	Nafténico	Nafténico	Nafténico
Factor volumétrico	1.058	1.094	1.105	1.2
Factor volumétrico a Pb	1.061	1.096	1.109	1.206
GOR Inicial (SCF/STB)	150	500	400	600

Table 1. Main Characteristics of Oil from the Galan Field.