Fracture Modeling in a Dual Porosity Volcaniclastic Reservoir: A Case Study of the Precuyo Group in Cupen Mahuida field, Neuquén, Argentina*

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Abstract

The synrift deposits of the Precuyo Group in the Cupén Mahuida gas field consist of a large succession of massive and fragmented volcanic rocks and volcaniclastic sediments of Late Triassic to Early Jurassic age. Structurally the field consists of an E-W-trending anticline, vergent to the south, developed during Upper Jurassic and Lower Cretaceous times by oblique inversion of prior half-grabens.

Build-up tests define a dual porosity system reservoir, where the pore space is divided into two distinct media: the matrix, with high storability and low permeability, and the fractures with high permeability and low storability. Interpretation of image logs closely relates best productive zones with open fractures.

Open fractures tend to be organized in clusters as they show lithology dependency. Three sub-vertical systematic sets were defined. The most dominant appear to be aligned with the present day tectonic stress in a NW-SE direction. The other two sets (NE-SW and E-W) seem to respond to local fracture swarms. From seismic interpretation, three sets of faults were recognized: E-W, N20, and N120. The fractal dimension of each set was used to model sub-seismic faults and the associated damage zones.

A discrete fracture network was generated, where realistic simulation is constrained to match well and seismic data. Fracture distribution allowed the definition of new deviated wells with an azimuth of 205° and a dip of 45° to optimize fracture frequency.
Fracture assessment opened a new insight to well planning. As a result new structural plays are depicted, and new well locations pointed out. Fracture density and interception probability is estimated to optimize best production results.

Introduction

For the past half-decade the deep gas discoveries in synrift deposits of the Neuquén basin have initiated a series of studies regarding reservoir characterization of volcanic and volcaniclastic rocks. To date no geological model has been able to characterize reservoir quality or predict the presence of hydrocarbons. From nearby locations (800 m), wells show anomalous productions. Initial rates may vary between 500,000 and 100,000 m^3/d, or show no production at all. With reservoir thickness beneath seismic resolution, trace inversion contribution has been misleading. Although the matrix plays a decisive role in reservoir response, core information, borehole image logs interpretation, and well completion show that fractures often define reservoir productivity. Furthermore, build-up tests show a dual porosity system, in which poor matrix permeability relay on natural fractures to carry out hydrocarbons.

Fracture assessment becomes, therefore, important to recreate a valid geological model that can help us achieve better development and exploration results.

A workflow is proposed using FRACA, a Beicip-Franlab software, to generate a discrete fracture network, constrained by seismic, well, and field data. It also includes the understanding of the petroleum system, structural mapping, and stratigraphic interpretation of volcaniclastic rocks. The model is tested with the drilling of a new deviated well and results shown as a function of fracture frequency and well production.

Placing a discrete fracture network in a structural context allows this workflow to be applied in other potential areas of interest.

Geological Framework

The Cupén Mahuida field is located in the Loma La Lata - Sierra Barrosa area, 100 km west of Neuquén city, in the western portion of central Argentina (Figure 1). It produces gas from the Precuyo Group (Figure 2), a succession of volcanic and volcaniclastic rocks of variable thickness, covering an area of 70 km^2 (Pángaro et al., 2002).

During Late Triassic to Early Jurassic times, the Neuquén basin went through an extensional regime that resulted in a series of half grabens of NW-SE orientation, which acted as isolated troughs for the Precuyo synrift deposits (Gulisano, 1981).

A following sag stage is represented by the Los Molles Formation. The lower section of this unit, a 400 m succession of black shales, records the first marine ingression to the basin. The shales from Los Molles constitute the regional seal as well as the source rock of the petroleum system (Veiga et al., 2001). The overlying sedimentary units are beyond the scope of this paper. Regional studies can be found in Uliana and Legarreta (1993), Legarreta et al. (1999), Vergani et al. (1995).

A period of compressive deformation took place along with this sag stage, giving birth to a series of structural trends related to the formation of the Huincul High, where wrench-dominated tectonics, oblique inversion of half-grabens, and basement-related lineaments without influence of previous extensional features, were developed.

Under this tectonic regime, from Late Jurassic to Valanginian age, Cupén Mahuida anticline was formed by oblique inversion of a half-graben, generating an E-W oriented anticline verging to the south (Figure 1).

Main Reservoir Features

The Precuyo group in the study area can be divided into two sections. Although they both show very similar composition and lithology variations, the upper one has proven to host the best reservoir rocks and gas production. It consists of a 300-m succession of stratified and massive tuffs. In space, these tuffs defined as pyroclastic flows, form overlapping lenses with strong lateral variations, often restricted to an area not larger than 1 km^2.

Rocks from the upper section are defined as acid volcanic rocks (fenodacites) of Late Triassic to Early Jurassic age. The geochemical composition of these rocks (> 63% SiO_2) defines them as subalkaline acid rocks from the calco-alkaline series. The strong alteration makes it difficult to distinguish between lava or pyroclastic flows due to the host of textural features.

Hydrothermal alteration was caused by the circulation of hot fluids (150°C – 300°C) with neutral pH, and controlled by permeable zones, generating secondary matrix porosities on the order of 12 to 15%. The presence of micro-fractures and micro-breccias (hydraulic fractures) in porous levels inside the tuffs is associated with both hydrothermal alteration processes and low-temperature sea-water-contact deposition.

Productive intervals show a corrected gas permeability of 10 mD, corrected effective porosities of 9 to 12% and gas saturations (Sxo) of 30 to 40 %. The rest of the column shows poor permeability and porosity values (0.0001 mD – 0.5%). A well core, image log and thin section can be seen in Figure 3.

Facies Modeling

Theoretically, fracture density is dependent on lithology and bed thickness (Cacas et al., 2001; Peacock and Mann, 2005). Therefore, if it is possible to establish a relation between these variables, a facies model can gain importance to control fracture appearance and distribution.

Seismic data constrains (amplitude and acoustic impedance) combined with well logs interpretation and correlation, in addition to a detailed cutting analysis for each of the present wells, were used to define eight volcanic and clastic facies for the Upper Precuyo Group. These are*: massive pyroclastic flows (tuffs)* - *stratified pyroclastic flows (tuffs and chonites)* - *breccias of pyroclastic flows* - *lava flows* – *sandstones* - *shales* - *volcanic sandstones* - *upper chonites.*

Lateral correlation of the mentioned facies resulted in a complex stratigraphy and a 2D facies modeling between wells (Figure 4). 3D modeling could not be done due to the poor seismic data quality and strong lateral variations. For practical purposes, a three-layered model consisting of three units and facies was built to constrain lithology distribution, mainly bed thickness.

Despite the lack of a solid facies model, there are a few considerations to be made here.

The continuity of fractured reservoirs cannot be defined by means of lithology distribution. This means that it is not possible to trace the reservoir (or fractured layers) outside the perimeter of the well. Neither can its position be defined in the stratigraphic column. Fracture distribution along the wells is not uniform but rather random and organized in clusters. This implies that in our model, we will not be able to vertically place in space our fractures; they will be forced to appear in clusters, but distributed in a random way.

In contradiction to what we are used to expect, thinner and stratified beds concentrate less fractures than thicker and massive ones. Therefore reservoirs rocks are dominated by massive tuffs, breccias, and volcanic flows.

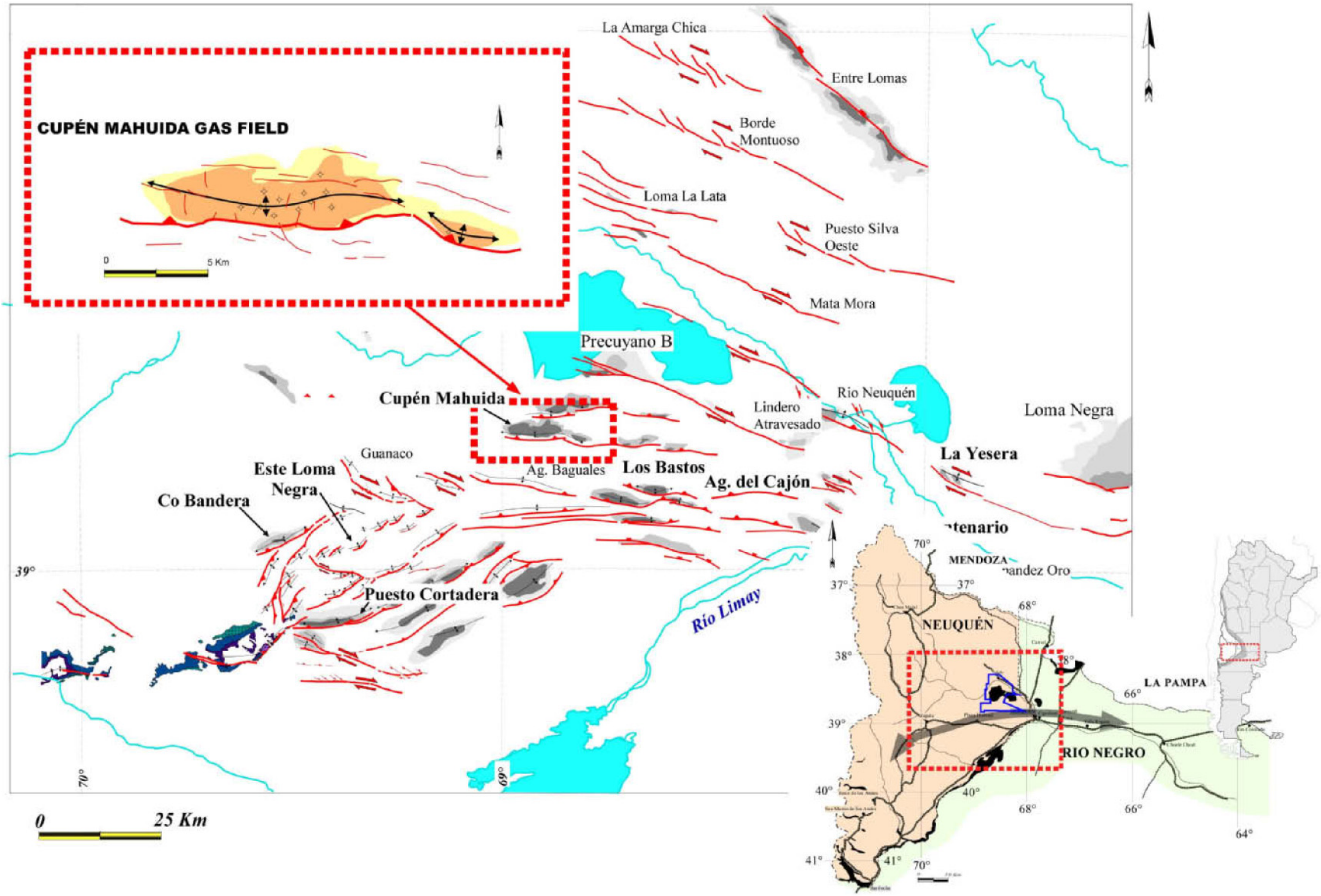

Figure 1. Location map of Cupen Mahuida Field.

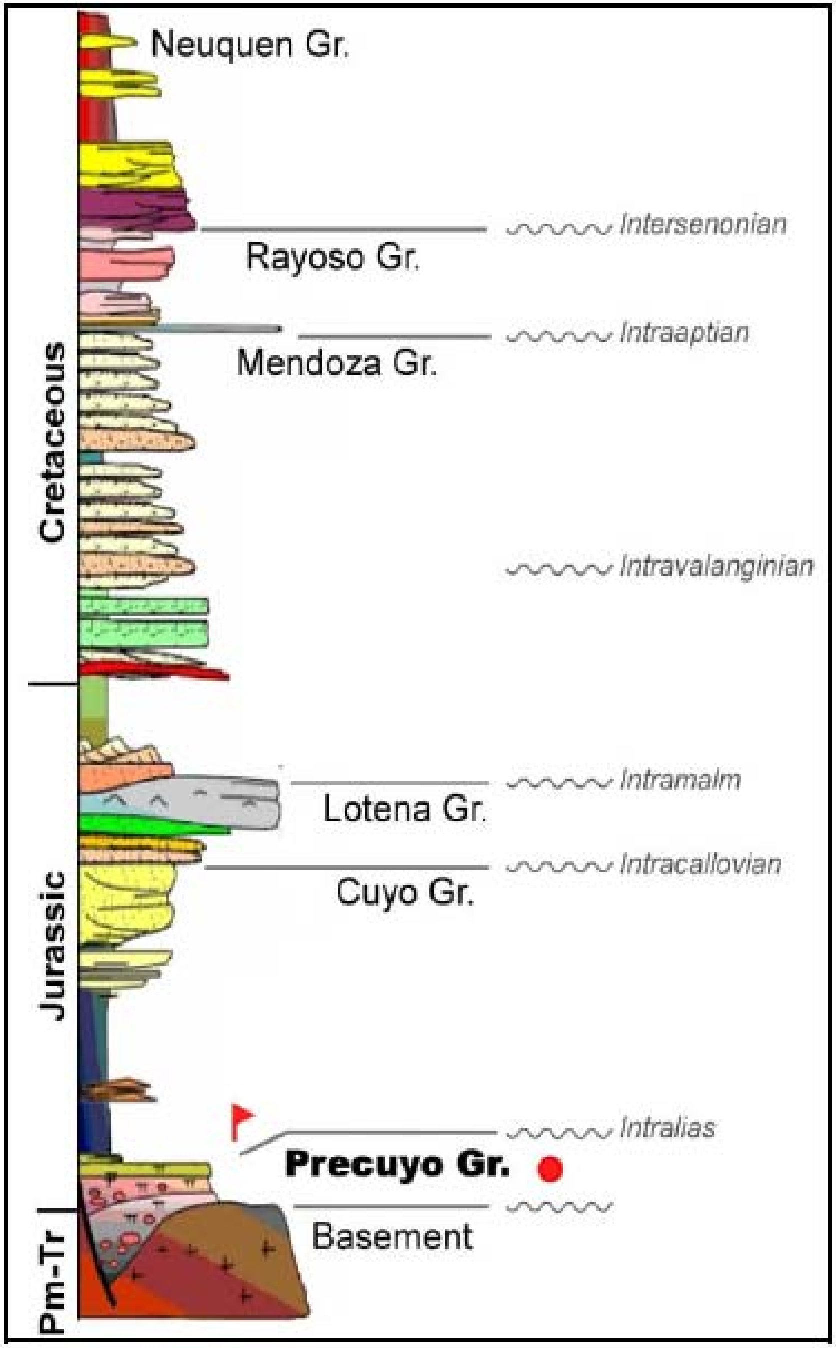

Figure 2. Generalized stratigraphic column.

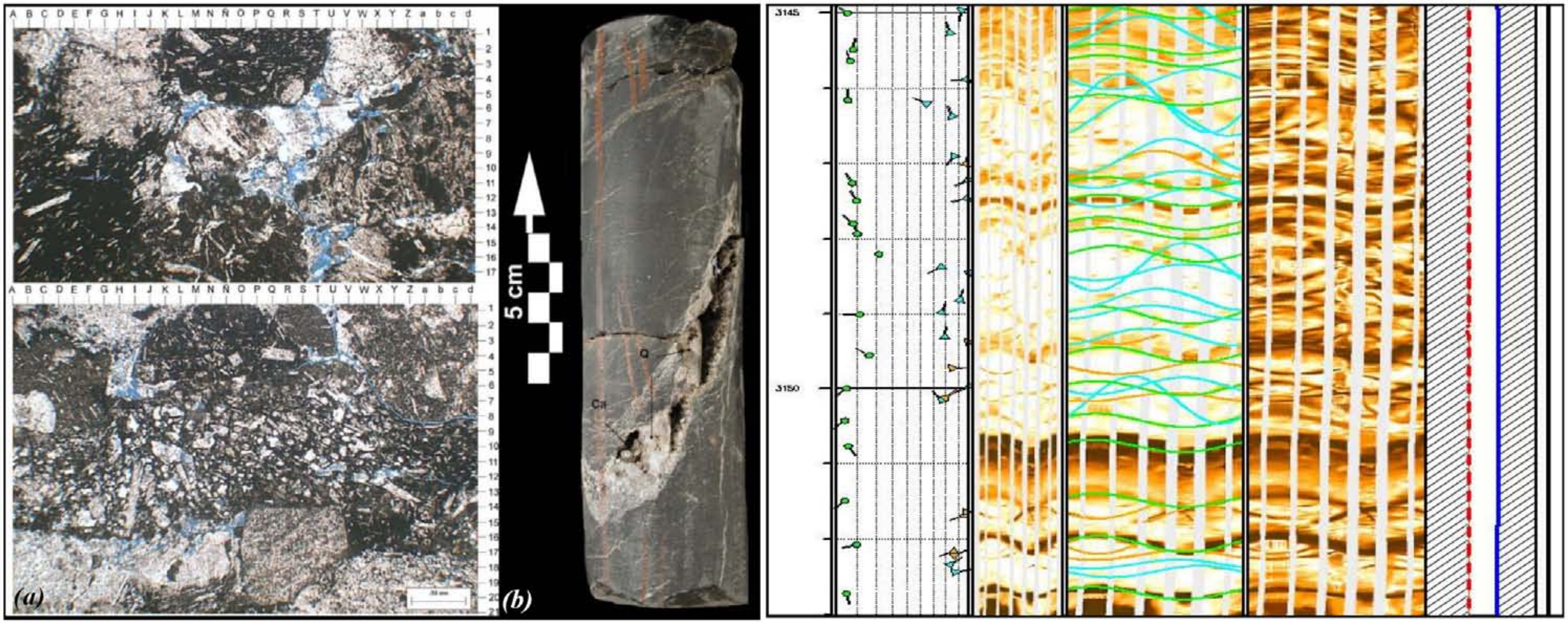

Figure 3. (a) Thin-sections of a tuff showing perlitic structures, micro-fractures, alteration and dissolution of minerals. The porosity is 9.11 %, and the permeability is 42.66 mD. (b) Open fracture in core, partially filled with calcite and silica. (c) Interpreted image log showing open (orange) and closed (blue) fractures and bed boundaries (green).

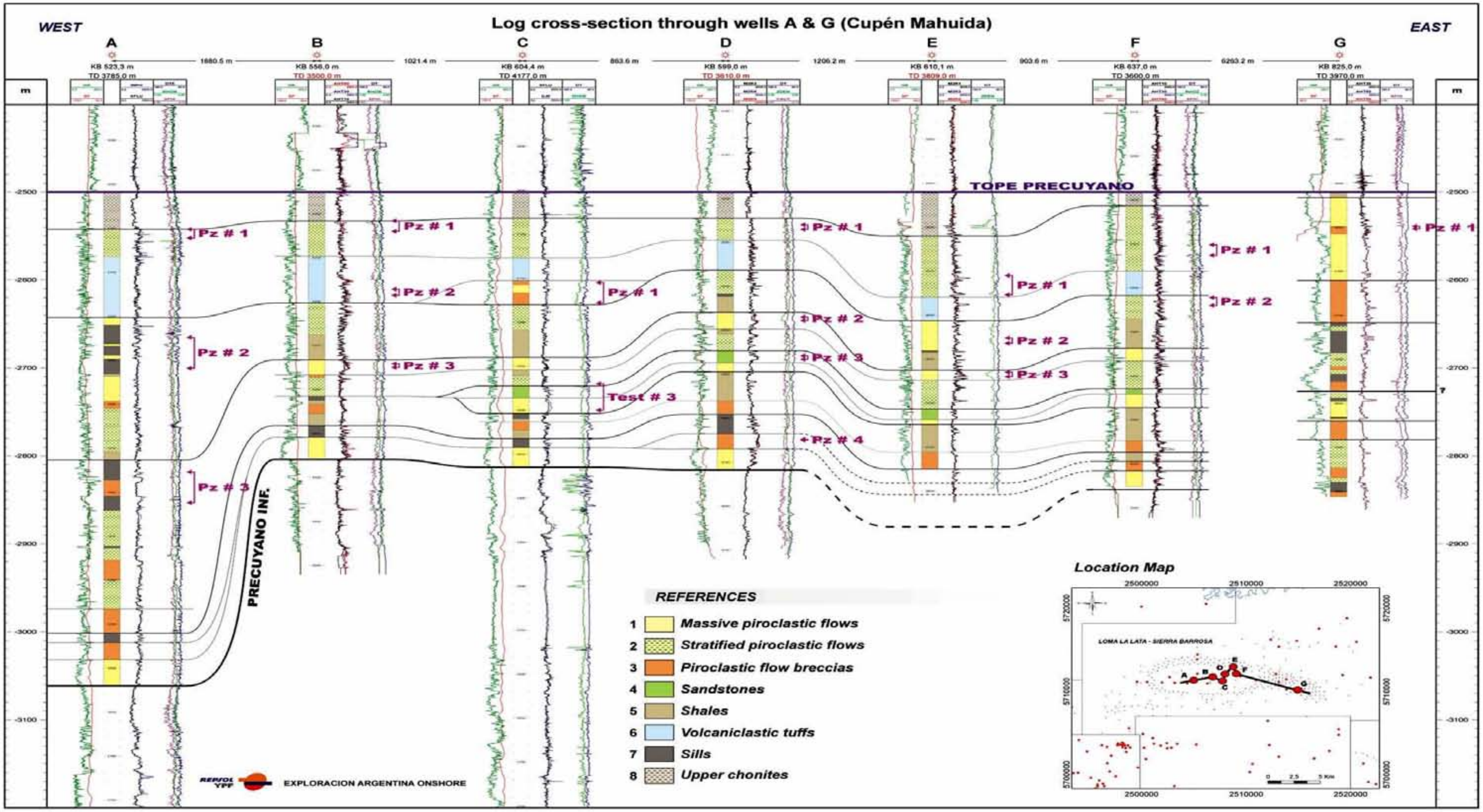

Figure 4. Log cross-section between wells showing facies and productive zones.

Fracture Modeling

Seismic Fault Analysis

Major fault geometries and distribution can be interpreted directly from seismic data. However, smaller faults beneath seismic resolution need to be modeled in a different way. If seismic faults show fractal behaviour, synthetic sub-seismic faults can be reproduced via stochastic modeling, constrained with fracture density maps.

Three sets of seismic faults were defined from seismic data: E-W, N20, and N120. The fractal dimension of each set, together with maps with similarity with reference to distance to faults, curvature, and acoustic impedance, were used to model sub-seismic faults.

A fracture zone (Figure 5) is associated with every seismic and sub-seismic fault. This zone consists of a swarm of systematic joints of similar attitude, here named fracture swarm. Fracture density decreases as we move away from the fault; choosing the correct shape factor and swarm width ensures us a proper model.

Systematic Fracture Analysis

A multi-well analysis was made for five wells. Open and semi-open fractures interpreted in image logs are characterized in this section. All fractures are defined as systematic joints and sorted out in four sets according to their dip and azimuth: E-W, N20, N120, and sub-horizontal. Mean dip, dip-azimuth, and average true spacing values are obtained from a statistical analysis. Closed fractures should be analyzed as well. In the present case we could not find a clear relation between wells and closed fractures, and therefore they were discarded for the analysis.

Well analysis allows us to quickly visualize and correlate fractured zones with productive zones and/or lithology. For most of our wells, we observed a close correlation between fracture density, bedding, lithology, and productive zones. Even though the frequency of fractures is less than expected in classic fractured reservoirs, they often play an excluding role in production. Best production is obtained in the presence of fractures. Figure 6 illustrates this correlation.

Discrete Fracture Network

Geomodel

For the input model we defined three units that represent three different structural facies of the upper Precuyo Group, based on fracture distribution and facies analysis (Figure 7). A structural facies is independent of the lithology and strictly related to fracture response. With just one layer we would have a more uniform distribution of fractures, while we are trying to reproduce clusters, as seen in Figure 4. Each of these facies is characterized by different parameters to allow fracture-density variations. Top and base of our model is obtained from seismic interpretation.

Static Model

Once we define all systematic and sub-seismic sets, we can start modeling the fracture network. The network is meant to reproduce throughout the model the geometric patterns of fractures seen in wells. This includes the dip, azimuth, average spacing, length, and aperture of each set of fractures defined above. Field studies in closely related areas have been consistent with well data, and were especially useful for defining the length and aperture of fractures.

Seismic attribute maps are used to constrain fracture density; in particular, normalized coherence maps are used to enhance fractured zones. Other maps may include distance to faults, impedance, or curvature analysis.

Network simulations are first done in cells that contain the wells. A cell represents the minimum unit of volume defined by the user. For this work each cell covers an area of 120 x 120 meters. In this way we can assure that non-conditioned simulations are comparable to real well data. This is measured by comparing the number of fractures intercepted in each well for a conditioned and non-conditioned simulation. When this number is similar, we assume we have obtained a correct fracture distribution, and therefore the simulation is propagated to the rest of the cells. Figure 8 shows a fracture network simulation for one cell.

From well analysis we have established a preferential direction for open and semi-open fractures and break outs. This direction has an azimuth of 130° and corresponds to the present-day maximum tectonic stress. From this perspective we simulate vertical and deviated wells with an azimuth of 220° to estimate a comparative percentage of intercepted fractures. The number of fractures increases as we move towards a horizontal well (Figure 9). With a deviation of 30° the number of fractures intercepted is increased by 63% with respect to a vertical well; with 45° it rises to 130%, and with 60° up to 300%. Since we are not able to define where fractures will appear, the angle of deviation must take this into account. A horizontal well is therefore not recommended--but a well with an angle of 45° which increases the chances of finding the fracture clusters.

Results Obtained from Deviated Well

From the multi-well analysis we can see that sub-vertical fractures are practically missing on vertical wells. Even though we might be able to estimate their frequency (Terzaghi), this is not very precise. The proposed and drilled deviated well on the other hand, has its mean fracture frequency in 88.9 degrees, meaning most of the open fractures are vertical or sub-vertical (Figure 10). The number of fractures was therefore increased by 500%.

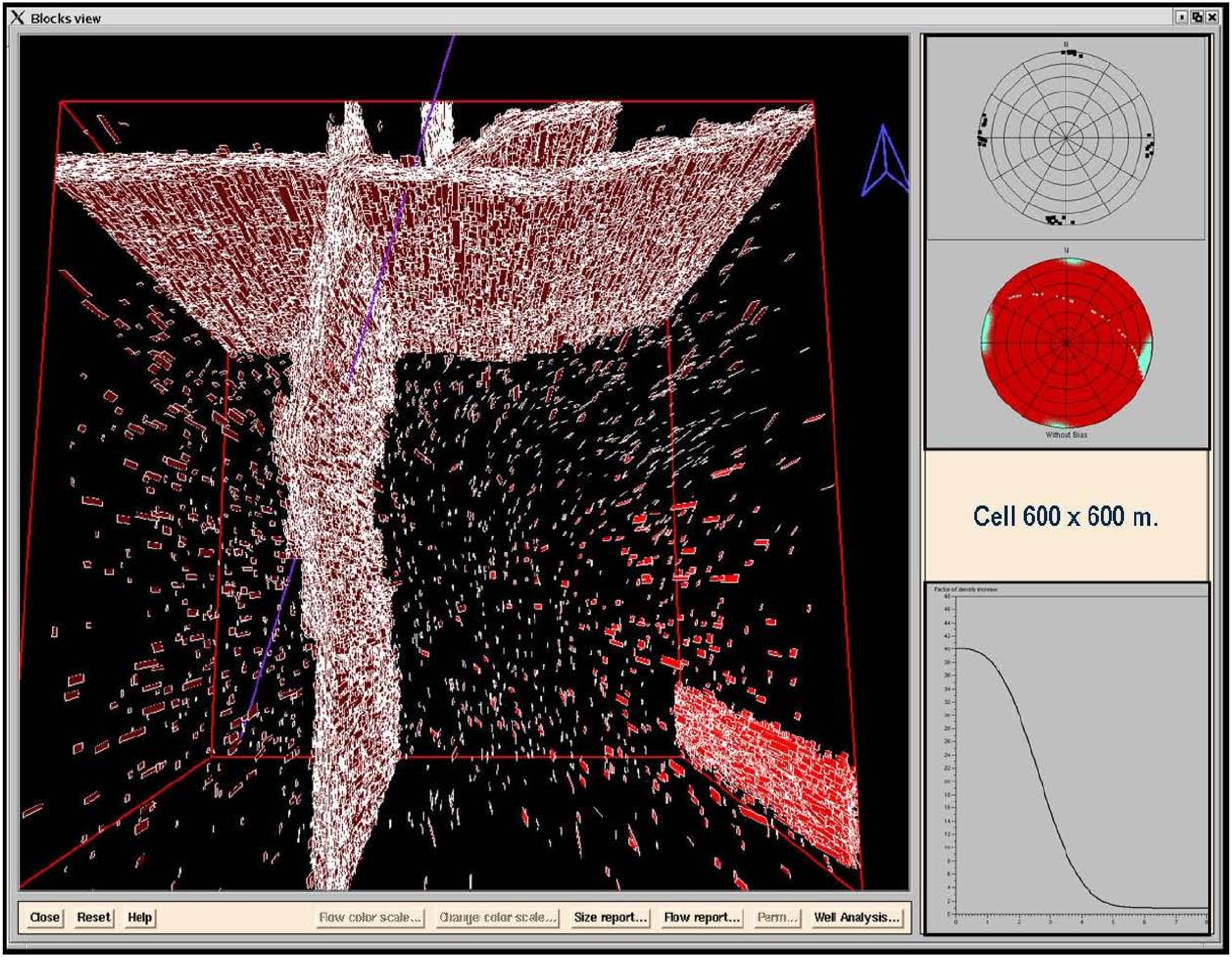

Figure 5. Fracture swarms and damage zones. Systematic joints are concentrated close to faults and tend to disappear a few meters away.

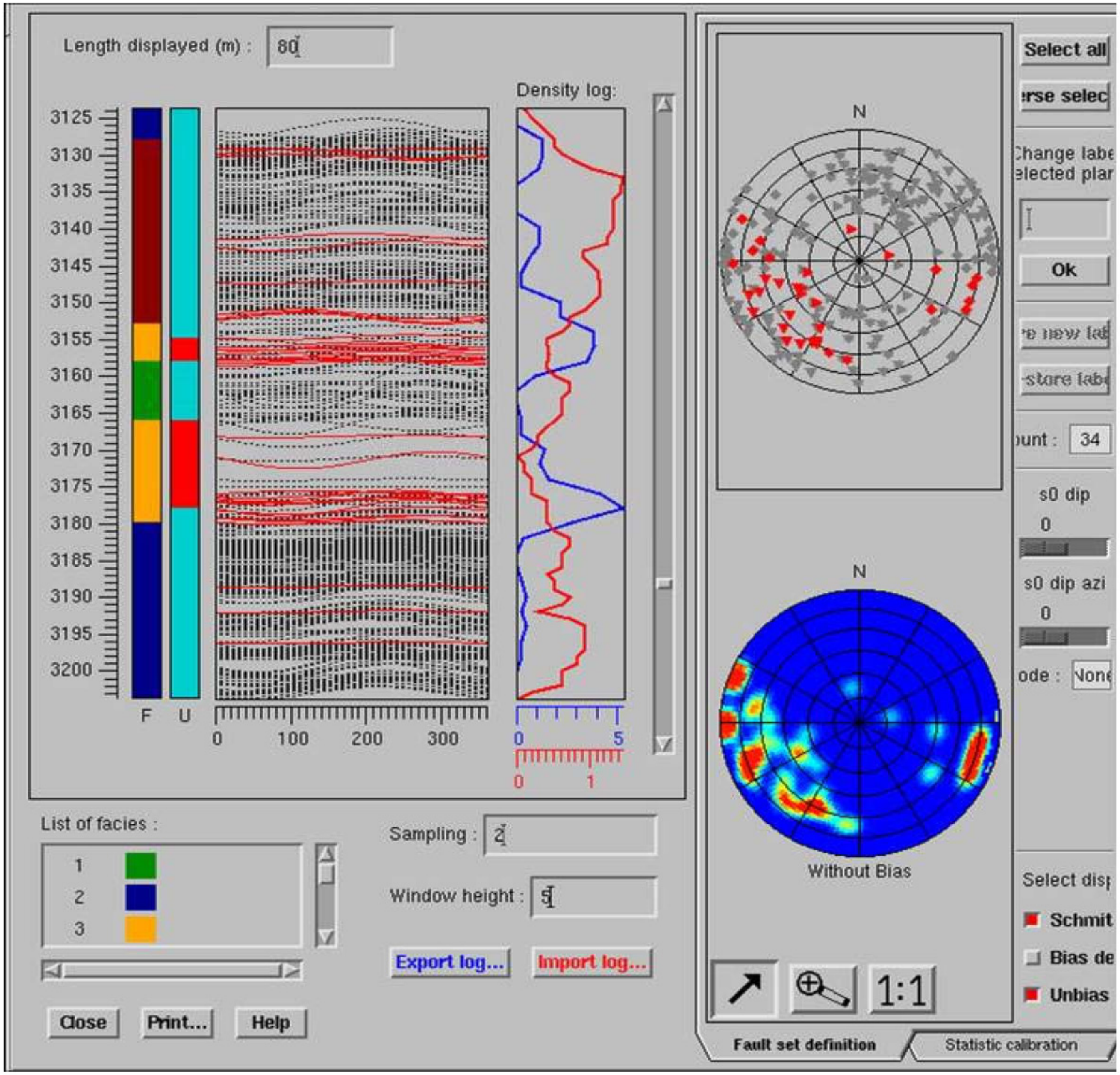

Figure 6. Correlation between open-fracture density (blue log), bedding (red log), productive zones (red) and reservoir facies (yellow). Open fractures appear on massive beds.

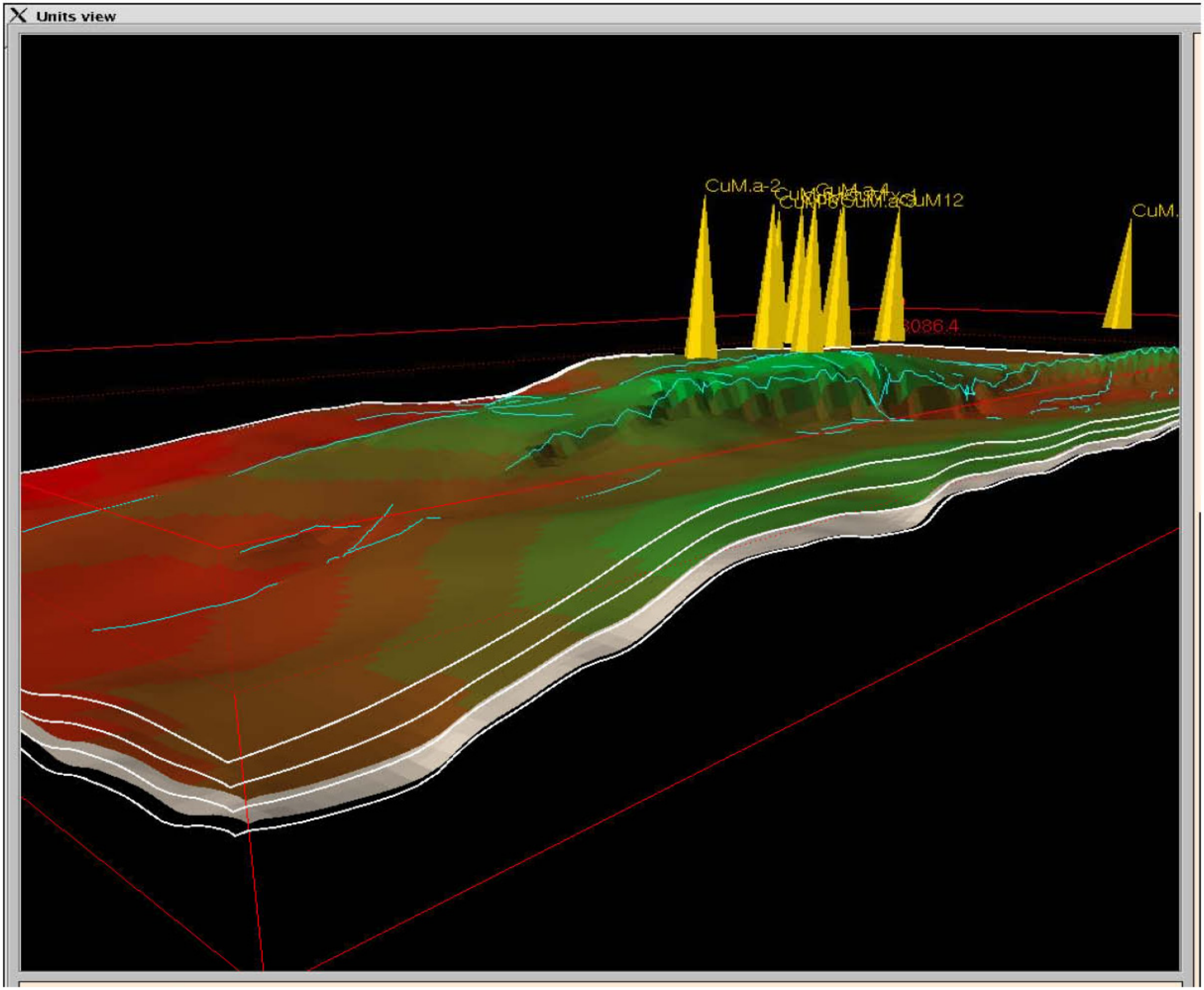

Figure 7. Three layered block geomodel.

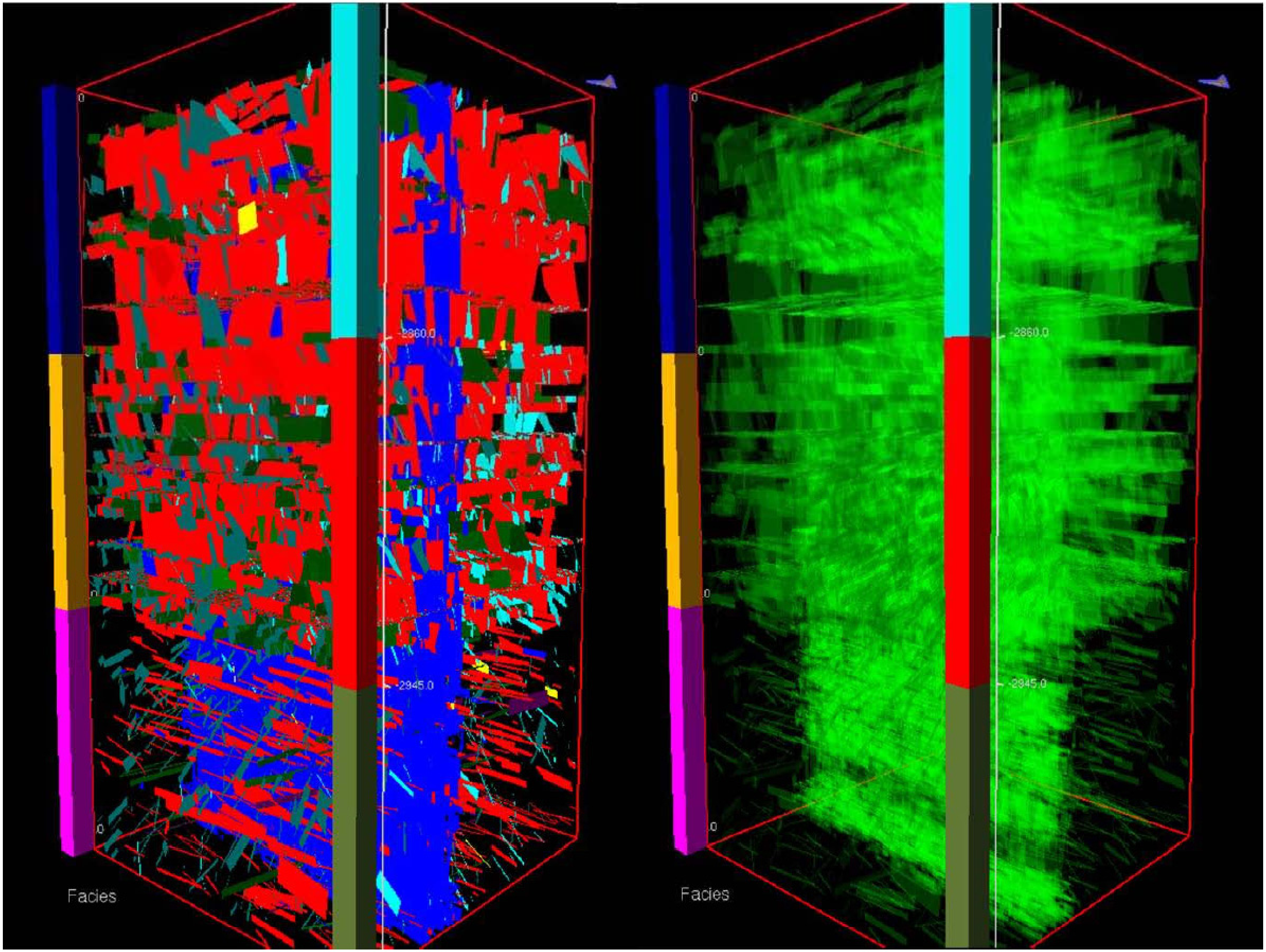

Figure 8. Local discrete model in a box-cell (120 m), where fracture spacing and distribution is constrained by bed thickness and faults. All sets of systematic joints and sub-seismic faults are displayed.

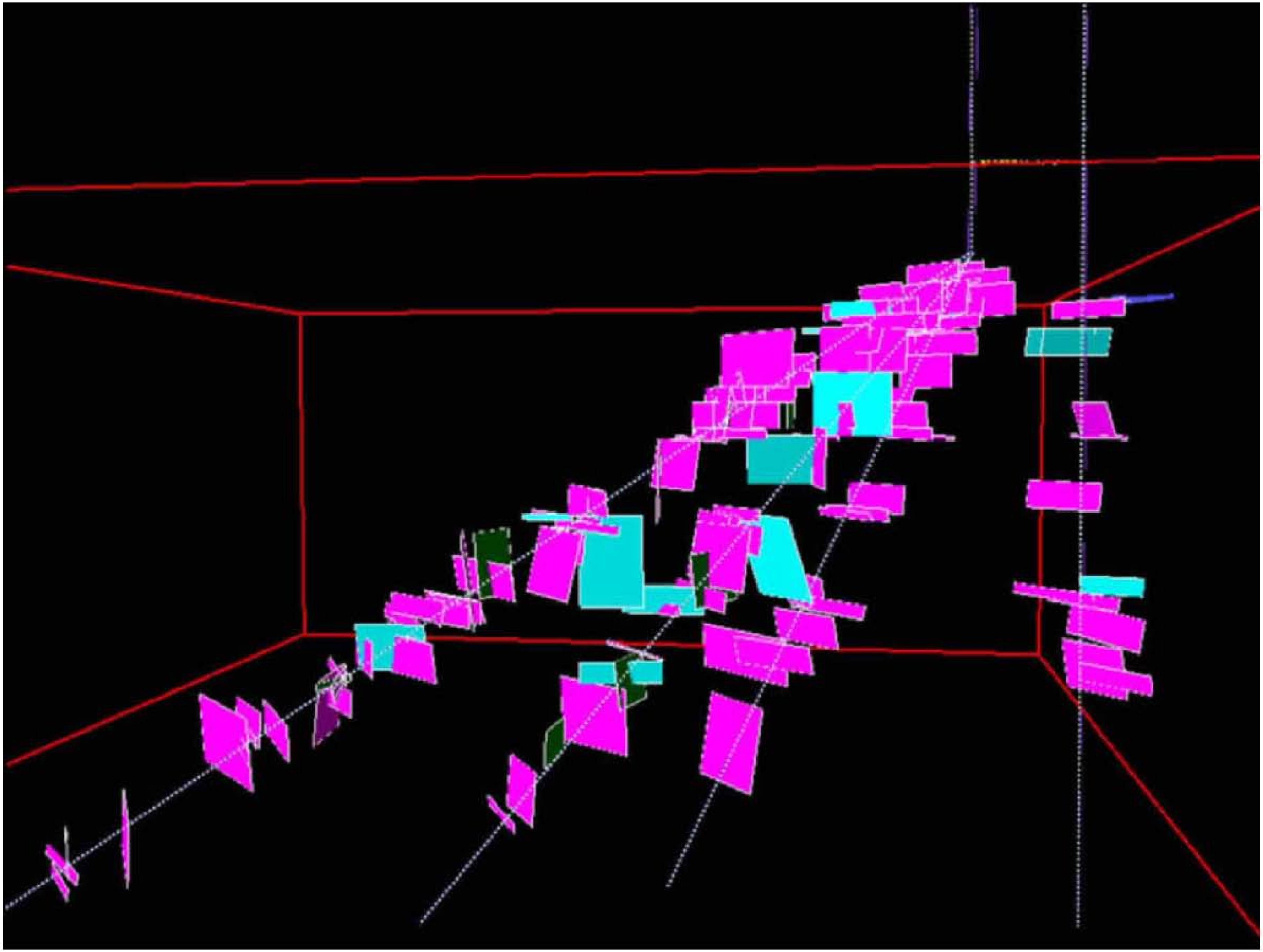

Figure 9. Fracture density in vertical and deviated wells (30°, 45°, and 60°). Fracture density increases up to 400 % in a 60° deviated well.

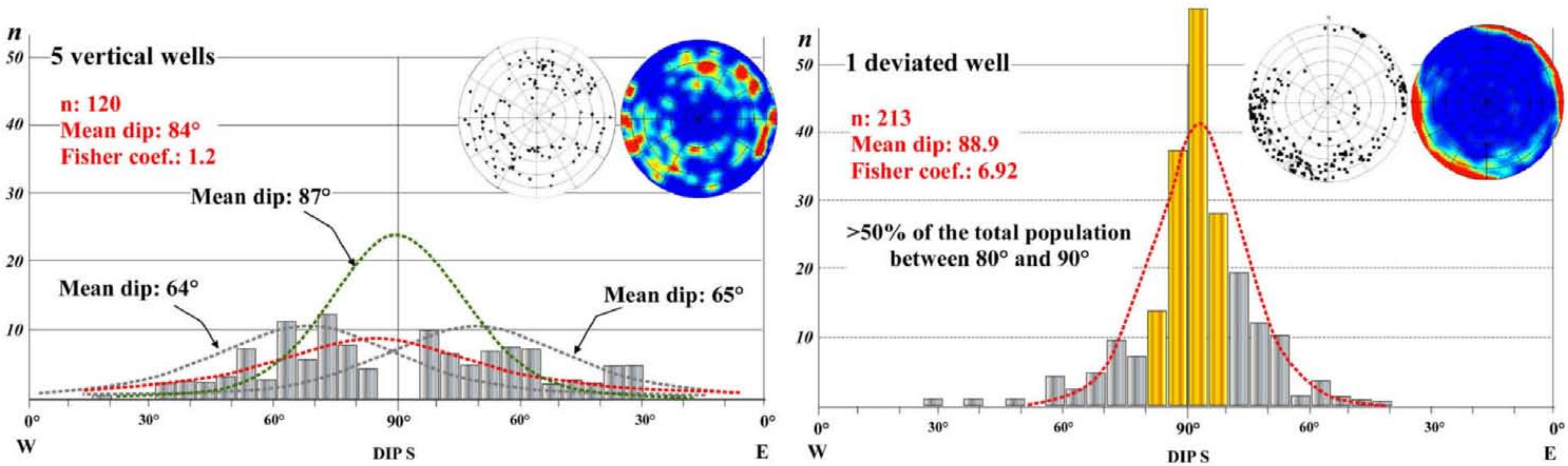

Figure 10. Dip distribution of fractures in vertical and deviated wells.

Conclusions

A dual porosity system is proposed for the Precuyo reservoirs, in which the presence of open fractures substantially increases productivity and reservoir quality.

Sub-seismic faults patterns were obtained via stochastic modeling of major fault fractal dimensions, helping the definition of new structural plays and well locations.

Three sets of systematic fractures were defined from well image logs. The most dominant (N120) appears aligned with the present day maximum tectonic stress. The other two (N20 and N90) are associated with major fault geometries.

Fractures appear organized in clusters and constrained to massive lithologies: tuffs, breccias, and lava flows.

A Discrete Fracture Network was generated, which allowed us to simulate fracture density in different wells along the structure. A preferential azimuth of 220° and dip azimuth of 45° was defined.

The model was tested with an infill well which is actually being tested. Fracture density was increased by 500 %.

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