KINEMATIC STRUCTURAL RESTORATIONS AND DISCRETE FRACTURE MODELLING OF A THRUST TRAP, A CASE STUDY FROM THE TARIJA BASIN, ARGENTINA

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Abstract: High gas production rates from the Santa Rosa Fm. in the Tarija basin, Argentina, indicate the presence of naturally fractured reservoirs whose reservoir's production potential is dominated by the secondary porosity and permeability. A consistent structural model and a good knowledge of the fracture systems is therefore of key importance in reducing risk in the exploration and development strategies of these settings. The structural evolution of the Santa Rosa reservoir through time forms the basis for understanding the development of the 3D fracture system. A total of nine 2D balanced cross sections were used to build a 3D geological model of the San Pedrito and Tuyunti structures. The fault blocks that compose the Santa Rosa Fm. reservoir were subsequently restored to their pre-deformation states using 3D structural modeling software. From here, the structures were kinematically forward modeled in 10 time steps to simulate the structural evolution of the reservoirs. At each time step the dilatational strain was calculated and cumulatively added throughout the modeling history. The resulting total strain maps record the total spatial variation in strain in the reservoir due to its structural history. The benefit of this technique over for example traditional curvature analysis is that the structural evolution of the trap is taken in account, a factor that likely dominates fracture formation. Together with well data, the resulting accumulative strain maps were used to simulate geologically realistic discrete fracture networks.

INTRODUCTION

Several fields in the Acambuco area in Northern Argentina (Fig. 1) are host to fractured hydrocarbon reservoirs. They consist of strongly lithified sandstone/quartzitic traps in for example the paleozoic Huamampampa and Santa Rosa formations (Fig. 2). Some of these fields are successful gas producers (like San Pedrito and Macueta, Girardi et al., 2002) while exploration and development of other fields is actively pursued. The fracture networks form a large part of the overall porosity (as secondary porosity), and therefore responsible for the potential reservoir volume (Nelson, 2001). More importantly, the fracture system facilitates permeability and flow through its “plumbing system” (McKeown et al., 2002; Smallshire et al., 2002). The understanding of the in-situ natural fracture network is of key importance in the development of this petroleum play and similar plays all along the American Cordillera. The key is to find the geological process controls the fracturing observed in these settings, or in a modelling language, what parameters are the dominant factors that are able to describe the observed fracture pattern. These insights allow for reliable regional extrapolation of the fracture network from the existing data points (wells), and facilitate reservoir flow simulation based on a thoroughly understood reservoir architecture and properties. The fundament is laid with a valid geological model, as there is no use in sophisticated analysis when all the risk is carried by a poorly constrained and poorly understood geological framework.
The aim of this paper is to describe the workflow and techniques for fracture assessment as was applied to the Tuyunti and San Pedrito structures, as they form a case study for these petroleum plays. Both structures form narrow elongated anticlinal thrust stacks in the Subandean region (e.g. Hernández et al., 2002) in the North of Argentina. Other fields like Aguaragüe and Macueta are present in a series of isolated structures with very similar deformation style (e.g. Hernández et al., 2002). The workflow for fracture assessment that is described in this paper can be summarised as follows:

1) Geological model building: based on individual geological profiles
2) Balancing sections
3) 3D geological model building from balanced sections
4) Kinematic restoration of the reservoir horizon in 3D
5) Forward kinematic modelling with integrated strain analysis
6) Discrete Fracture Network (DFN) simulation

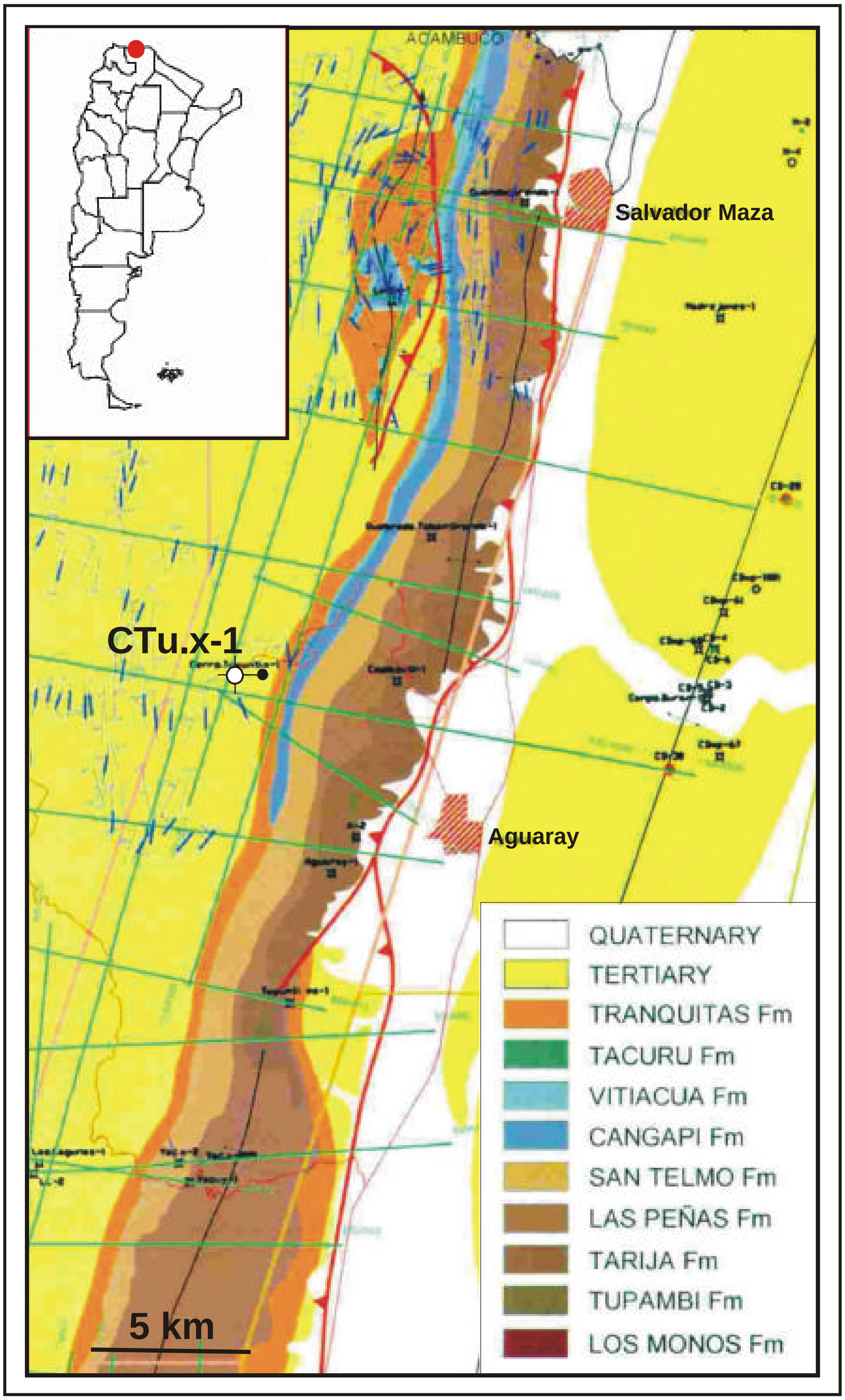

Figure 1. Location and geologic maps of the Tuyunti area, Acambuco block, Northwestern Argentina.

GEOLOGICAL MODEL BUILDING

The data used to build the geological model in this case consists of a number of 2D seismic lines, outcrop measurements, and well data. Neither data set is complete, i.e. the 2D data shows good controls on the flanks of the structure, but little on the core where steep tilting of the strata has been observed in wells and outcrop. In order to build a valid geological model all data was integrated and projected to four selected section lines. These profiles were constructed and subsequently balanced in 2D restoration software to check for their geological validation. In addition, kinematic restorations were carried out in order to constrain the shape of the basal thrust and it’s hanging wall as seismic imaging showed incomplete reflections here. The same technique was applied to the other profiles. A single structural concept was used to explain the observations in all profiles. As such, consistency of structural style is thought to reduce risk in geological interpretation.

The four balanced profiles were subsequently imported in 3D structural restoration software. Here the horizons of the individual profiles were connected to make a 3D geological model. Apart from the useful visualisation, this also serves to test whether the lateral variations in interpretation are valid in the 3D space, as the individual profiles show some variety in fault pattern, and to what extend the profiles are part of a continuous lateral structure. Geological maps were used to track lateral trends. Finally, 3D seismics, where available, was imported to validate the constructed model.

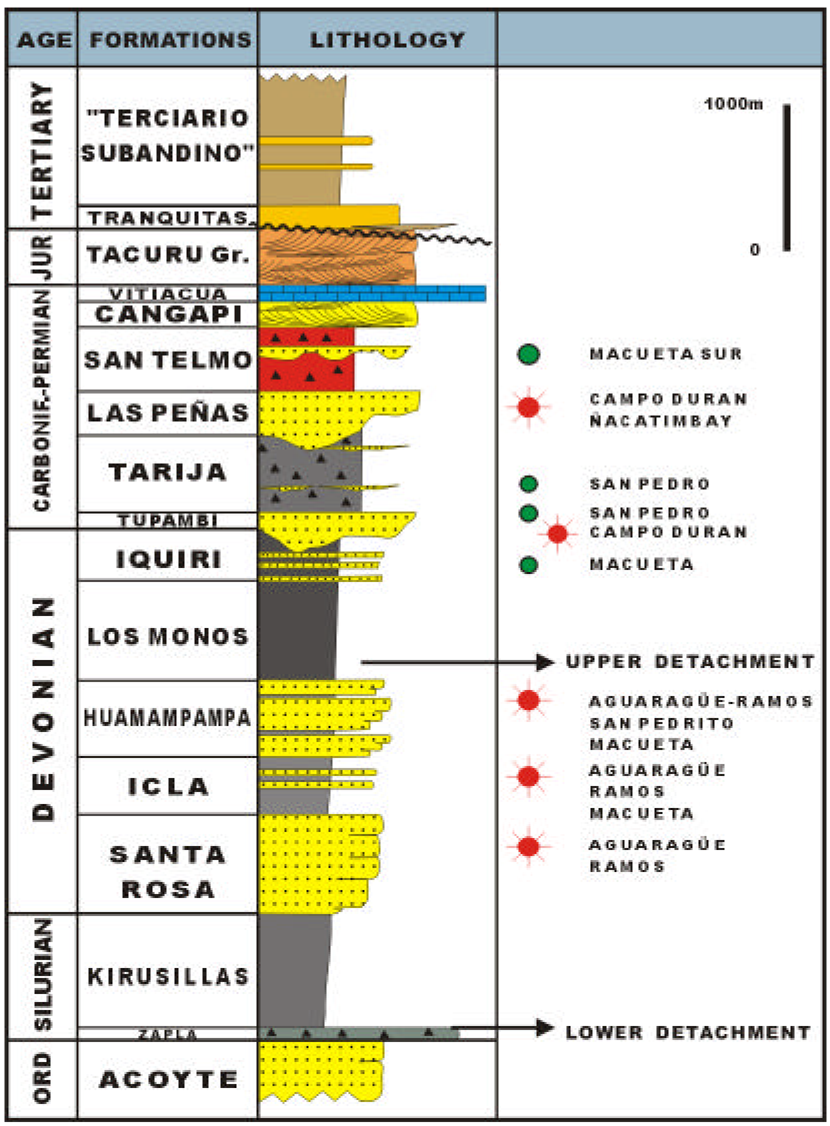

Figure 2. Simplified stratigraphic column for the Southern sector of the Tarija Basin.

The Tuyunti and San Pedrito structures are both characterised by a basal thrust with a classic flat-ramp-flat fault geometry. The overlying thrust block consisting of the Santa Rosa reservoir wedges progressively into the Los Monos Shale formation. In the Tuyunti structure (Fig. 3) an overlying out-of-sequence thrust is thought to develop in a later stage. It explains all the observations of the individual profiles and shows very consistent total shortening along the model, although fault patterns vary laterally. (Note that since the presentation of this paper PanAmerican Energy has modified the interpretations of both structures, but this is not critical for the scope of this paper).

STRUCTURAL ANALYSIS

In order to predict regional fracture patterns it is necessary to identify the main process(es) responsible for fracturing. No straightforward answer exists as different processes may be dominant in various geological settings (Sanders et al., 2002; Price and Cosgrove, 1990), and is highly dependent on the various phases and characteristics of the local geological history. As such fracture simulation requires workflows tailored to the case. In this case we focus on thrust tectonics.

From our experience, and as a rule of thumb, we know that in areas of intense deformation, fracturing tends to be concentrated in the high strained zones. In the brittle upper crust of the earth (where all petroleum plays are situated), fracturing is the dominant process that accommodates deformation. Note that fracturing also takes place in essentially undeformed regions (e.g. Price and Cosgrove, 1990) but this has a much more regional character and is potentially strongly lithology related.

With a 3D geological model in place we can analyse the geological history of the structure in an analytical way and identify the highly deformed regions. Traditional curvature analysis has often been used for fracture assessment. Though useful, curvature analysis (Lisle, 1994) on the present day geological model give limited insights for fracture purposes as it only analyses the geometry on the static present day model. In other words, the geological history is not considered, and therefore prone to underestimation of the total deformation endured during the geological history. This is particular the case for thrust faults with substantial shortening, as the hangingwall moves over a non-planar flat-ramp-flat fault surface. Some parts of the hangingwall will show no curvature in the present day model, although they have been deformed intensely at some stage during the displacement. The same problem occurs for strain analysis, when restorations are done in a single time step. To incorporate the factor time we used 3D kinematic restorations to simulate the deformation history due to faulting. As such we get a understanding of the change in geometry of the hangingwall during movement over the fault at any time step. In combination we use cumulative strain calculations instead of curvature, to record the local variations in strain at every time step. Strain is in this case study calculated as dilational strain. Every cell of the hangingwall reservoir surface is tracked for its change in surface area during the deformation. Strain is then calculated as the difference in surface area of a cell between the last and the actual time step. For cumulative strain, the individual dilational strain values are added to the existing values at every time step, for every cell, and so forth. As such, the structural evolution does have a profound impact on the identification of highly deformed zones. Note that with one present day model, but using different deformation history scenarios, it is possible to get different cumulative strain patterns.

The workflow is as follow: In the 3D model, the fault blocks are kinematically restored by moving them over the fault surface, until footwall cut-off matches hanging wall cut-off along the fault (i.e. displacement is zero all along the fault). The way the hangingwall deforms during the restoration depends on the restoration algorithm (fault parallel flow in this case) in relation with the shape of the fault and the displacement profile along the fault plane. The algorithm aims to mimic the bulk deformation behaviour of the rocks during its movement over the fault plane. Rock volume is preserved during the restoration. If the restoration results in an acceptable pre-deformation geometry, we have a valid geological history, and a valid geological model.

The restored model is now ready for forward modelling by reversing the faultblock restoration in a number of time steps (i.e. simulating the true deformation evolution). We used 10 time steps for the forward modelling of every individual fault. At each time step the geometry of the last step is compared to the actual geometry, and the difference defines the local strain values. These strain values are added up at every time step in order to arrive at a cumulative strain value at the end of the forward modelling routine, i.e. the present day geometry. For visualisation they are colour coded on the reservoir surface in the 3D model.

This workflow has been applied to the Santa Rosa formation in the Tuyunti structure. The two faults have been forward modelled in 10 steps each and the total cumulative strain calculated. First the lower fault, as this is believed to be the older fault, followed by the out-of-sequence fault movement. (some minor second order faults have been ignored for simplification. Their offset is sufficiently small to justify this). The resulting final cumulative strain patterns show a typical pattern of high strain values in the front limb of the lower fault block, intermediate strains in the crest, and very low strains in the back limb. For comparison, a curvature analysis indicates high values only in the crest of the structure and is remarkably different from the cumulative strain pattern. The upper fault block shows similar strain patterns but lower values, even though it formed the hangingwall of two active underlying faults (It formed most of the back limb of the lower fault, and the upper fault is fairly planar and therefore does not create a lot of local deformation). Now that the structural history is constrained and we have several deformation indicators (strain-curvature maps), we can start building an example of a fracture network.

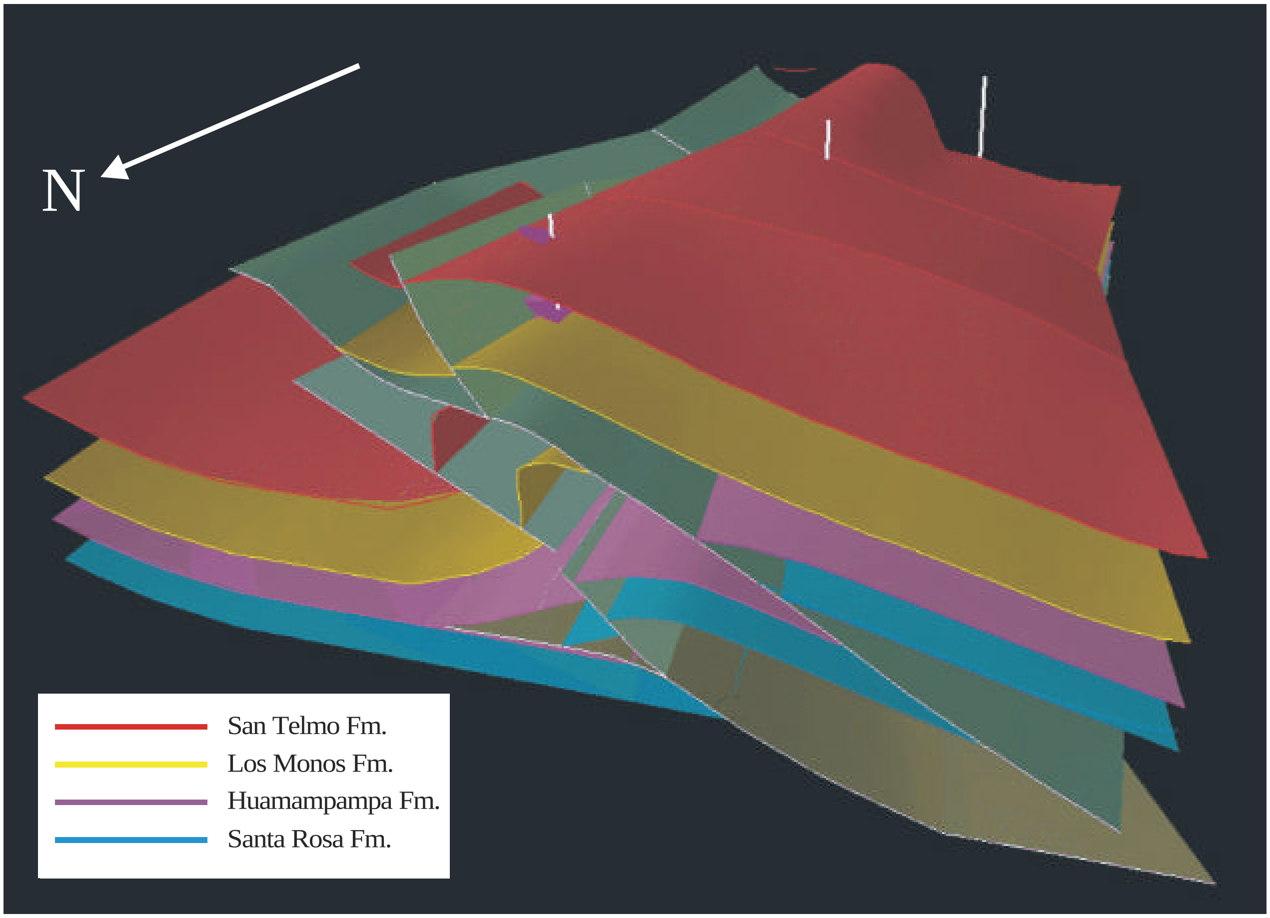

Figure 3. Perspective view of the 3D geological model of the Tuyunti structure.

DISCRETE FRACTURE NETWORK SIMULATION

It is important to simulate fracture networks as they allow to visualize and analyse the temporary and spatial variation in fracture intensity, fracture type and fracture orientation. As such they can help understand the fracture observations we have from wells and outcrop (Hennings et al., 2000), and extrapolate fracture networks for areas where we have no data. In order to do so the simulated fracture network needs to be geologically realistic, and its realisations controlled by geological rules, and not just a stochastic representation of a natural fracture network (Swabey and Rawnsley, 1996). We used a Fracture Generator module in the 3D restoration software to interactively control fracture density, length, orientation and fracture type of multiple simultaneous fracture sets in 3D space. Controls can either be manually, or through numerical attribute maps, such as strain maps. Time for fracture growth is simulated in different steps (usually ten).

For the Tuyunti structure we assume that the modelled cumulative strain values are a proper assessment of local deformation intensity, and therefore form a valid proxy for fracture density. As there was no well data available for Tuyunti at the time of this paper, we assumed a theoretical fracture network, as is often observed in classical field examples of similar structures (Price and Cosgrove, 1990), that seemed justified from well data in nearby fields (Girardi et al., 2002; Cohen, personal communication, 2001). We can expect 3 fracture sets, one parallel to the main fold axis, one orthogonal to it, and a conjugate set around the latter one. The first two were simulated equally for fracture density and length, while the conjugate set was thought to be less profound. The fracture density and growth is the controlled by the strain map. Higher strain means higher fracture density, proportionally to the strain values. Fractures were modelled as joint sets, i.e. a growing fracture will generally not cross an already existing fracture. Lithology influence on fracture growth is constant as we assumed spatial lithology variations to be of minor importance.
The resulting fracture network shows that most fractures occur in the front limb, and the fracture density decreases over the crest towards the backlimb, according to the strain map (Fig. 4). The only way to validate this pattern is through well observations and production data. Wells drilled in several parts of nearby similar structures in the Acambuco area seem to confirm the simulated fracture pattern, i.e. high fracture density in the fore limb, decreasing to the crest and virtually absent from the back limb (non published data). Well data form San Pedrito (M. Cohen, personal communication, 2001) and Macueta (Girardi et al., 2002), shows a similar pattern with the fold axes parallel and orthogonal fractures being dominant. With more available data, more detailed and sophisticated fracture models can be simulated and fitted to the well observations.

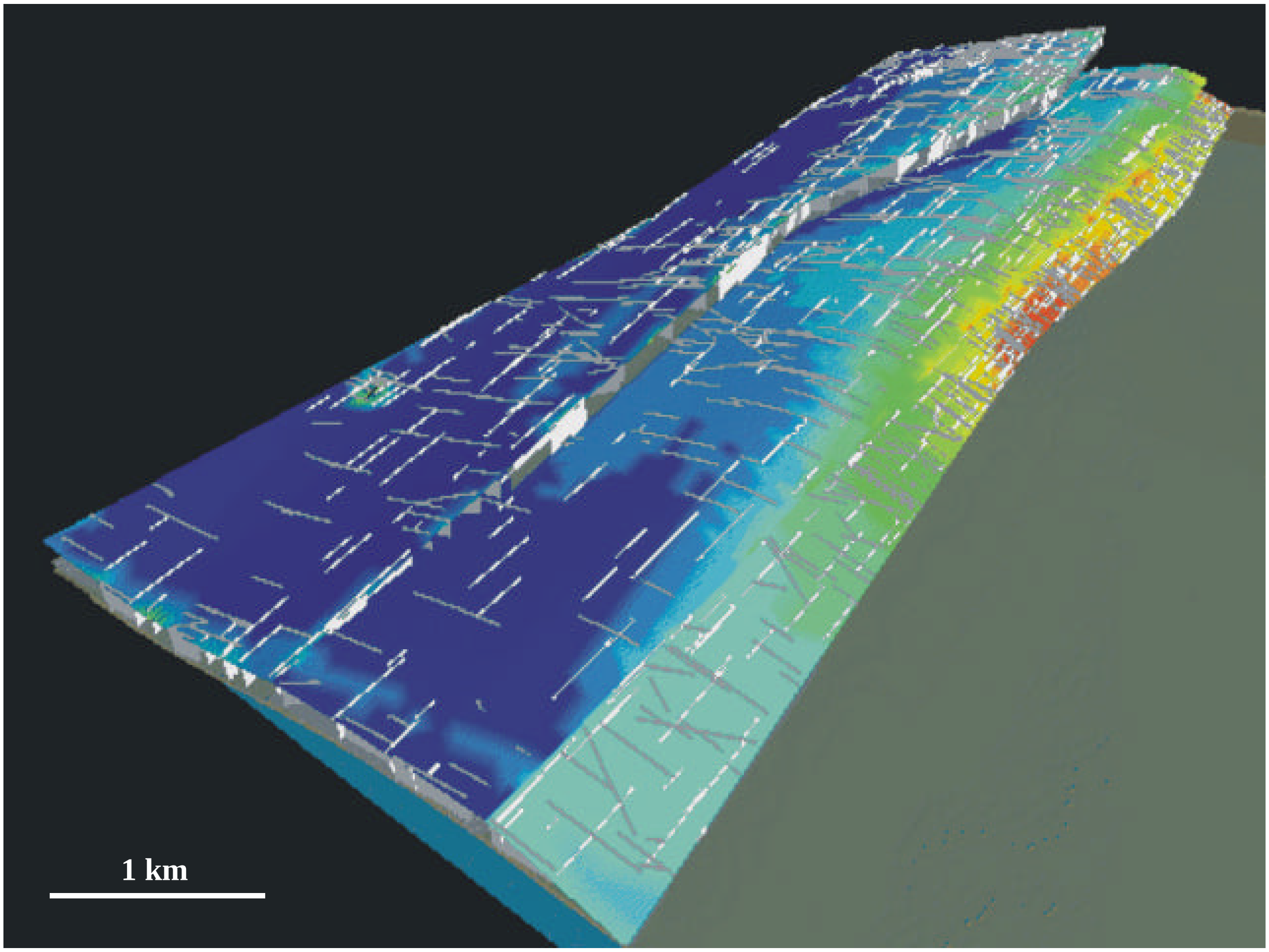

Figure 4. Discrete fracture network in Santa Rosa Fm. of the Tuyunti structure.

The above described workflow was carried out on the San Pedrito structure, a structure where more data is available. Using the same workflow and similar strain measures, the San Pedrito structure showed strain at least 5 times higher than Tuyunti. The modelled fracture orientations are in accordance with observations from wells in San Pedrito. San Pedrito is a successful gas producer due to its high fracture density, but based on the modelling results, this should not be expected to the same degree for the Tuyunti structure. Especially as when fracture density decreases, the connectivity of the fracture "plumbing" system gets interrupted (Smallshire et al., 2002). As such this prospect carries a lot more risk for a successful fractured reservoir.

DISCUSSION

A simulated discrete fracture network helps to understand how a fractured reservoir looks like, but we also need to understand how the existing fracture network behaves. A realisation of a discrete fracture network allows further analysis into insights of this system. As is often observed in fractured systems, a number of fracture sets tend to be closed while others tend to be open. This is commonly attributed to the present day stress regime where the maximum horizontal stress orientation closes fracture planes oriented orthogonal to it, while it opens fracture oriented parallel to it. In a similar way, it is explained why some fractured reservoirs have good flow in the initial stages of production, but than rapidly and unexpectedly "shuts down". Initially all fractures are kept open by the fluid pressure, but as this declines during production, some fracture sets (those orthogonal to Shmax), close, and disrupt the connectivity of the network (Nelson, 2001, personal communication). This process is irreversible and production is lost. It is therefore of utmost importance to have a good understanding of the fracture network in an early stage of the development of a field. The complete fracture network can be analysed for its tendency to be open or closed with software that applies a regional stress field to the fracture network. Closed fractures can subsequently be eliminated from the simulated network as they do not contribute to the plumbing system, or can be given low permeability values in reservoir flow simulations.

Several scenarios of fracture networks can subsequently be exported to reservoir simulation software (LaPointe et al. 2001) for flow simulations. The integration of the above described analyses then helps to define new well trajectories or development strategies (e.g. Girardi et al., 2002)

The presented workflow is not the ultimate answer to fracture assessment. Every geological setting has its own peculiarities and needs a tailored approach. In any case, you need to understand and constrain the geological history in 3D space and in time in order to assess the fracture network. Second, in order to understand the fracture observations it is essential that the simulated fracture network is geologically realistic. Alternative insights in the geology may result in a number of possible scenarios with final fracture pattern which may look remarkably different. Well and production data will help distinguish between the various scenarios. Once a good fit is found, the technical risk for the fractured reservoir is highly reduced and future well observations and performance more predictable.

CONCLUSIONS

This study showed that, even with very limited data sets, the use of structural validation tools and interactive fracture simulations allow risk analyses and production prognoses to be carried out on fractured reservoirs in an early stage of the development of a field. The fracture potential is highly controlled by the structural history of the area and structural and fracture analyses are therefore inseparable. The use of rule based geologically realistic fracture network simulations helps the understanding of the in-situ natural fracture network. It makes the geologically realistic extrapolations of the fracture network possible from wells to areas of no data. Export to reservoir models and comparison with production data forms the final stage of validation of the simulated fracture networks.

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