Construction of 2D and 3D Models of the Kutubu Oilfield, Papua New Guinea Fold Belt*

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Abstract

The Kutubu Field in the jungle-covered mountains of PNG, comprises the Hedinia Anticline containing mainly gas and the oil-bearing Iagifu Anticline. Together they hold reserves of >1 tcf gas and >350 MMBL oil in a basal Cretaceous Toro Sandstone reservoir overlain by 1 km of Cretaceous shale and 1 km of karstic Miocene limestone. Over 70 wells and sidetracks have been drilled but there are only 7 2D seismic lines which are of poor quality. In 2D, sequential balanced cross-sections along seismic lines were constructed and revealed that the structure formed as a large detachment fold cored by the Jurassic syn-rift facies of a pre-existing half-graben. This was then cut by forethrusts and backthrusts making a pop-up structure with hydrocarbon reserves both in the gently folded hangingwall and the separate 1 km vertical forelimb. A 3D model was constructed of the hangingwall revealing the many small faults that compartmentalise the structure. The model relied on detailed correlation of all base Cretaceous and Upper Jurassic horizons, determination of their TSTs and rigorous analysis of the well dipmeter data tied to surface geological maps and dips. As most wells are highly deviated each stratigraphic horizon could be projected in 3D to make a construction panel at reservoir level, resulting in several hundred panels representing top Toro. The panels could be trimmed and joined where appropriate but also connected by faults as necessary. It is important to note that this was done directly in 3D without sections and that the 3D orientation of the faults was revealed by the panels, not by pre-conceived ideas. In areas away from dense well data, the model was infilled by projection along plunge tied to the seismic data and regional sections. The model revealed a transverse fault through a saddle in the centre of the structure that separated an area with gas on water to the west from gas on a 250 m oil column on water to the east. Furthermore, the oil-filled syncline in the east is cut by several axial faults creating many compartments with different pressures and perched water. The model has allowed optimal depletion of the reservoir and together with detailed production simulation, has defined areas of untapped potential. It has also increased our understanding of the timing and nature of deformation in the Fold Belt of Papua New Guinea.

Introduction

Exploration in fold and thrust belts, usually in mountains, has both advantages and drawbacks in comparison to typical offshore terrains. On the positive side the rocks crop out and it is possible to analyse their morphology, structure, facies, reservoir, seal, and source potential and to construct geological maps and cross-sections. On the negative side, 2D seismic data are very expensive to acquire and are usually of poor quality and 3D seismic is normally out of the question due to cost and logistics. This is particularly true in the jungle-covered, highly karstified mountains of Papua New Guinea (PNG). However, it remains incumbent on us to construct detailed 3D models of the oil and gas fields. Here we outline a method for constructing a reservoir model directly in 3D in areas where there are many wells, tied to cross-sections in areas of lower well density.

The Kutubu oil and gas field comprises the Iagifu and Hedinia Anticlines which lie in the frontal ranges of the Papuan Fold Belt (Figure 1) and are responsible for most of the oil production from PNG to date. The field has produced well over 300 MMBBLs of oil mainly from the Iagifu Anticline (Figure 1), whilst drawdown of the large gas cap in the Hedinia Anticline has recently commenced as part of the PNGLNG project. The Iagifu-2 discovery well was drilled in 1986 encountering oil in the Neocomian Toro Sandstone reservoir and in underlying Upper Jurassic sandstones and the field went on production in 1992.

Early drilling was based entirely on field mapping and cross sections (Lamerson, 1990). The first seismic line was acquired in 1988 and seven further lines have been acquired giving a total of four dip-lines at 2-2.5 km spacing, one strike-line, the ends of two other strike lines and one oblique line. All lines are of poor to moderate quality as shown in Hill et al., 2015 and Bradey et al., 2008. The geometry of the Iagifu Anticline can be discerned on the seismic data, but data across the Hedinia Anticline are very poor and misleading, in part due to the gas cap and the overturned, decapitated forelimb proven by drilling (Hill et al., 2015). On the plus side, over 70 wells and sidetracks have been drilled on the field, many of them strongly deviated and >52 of them have moderate to good quality dip data. The tops for all formations are well known and the True Stratigraphic Thicknesses (TSTs) above and below the reservoirs are well-defined and generally consistent across the field. At surface, Miocene carbonates crop out, the Darai Limestone, in which over 2000 dips have been recorded along geologic traverses, each with xyz co-ordinates and an assigned formation age. The ages are based on micropaleontological dating and over 1000 Sr^{87}/Sr^{86} ratios (Hornafius et al., 1993). This has allowed construction of the geological map shown in Figure 1.

3D Methodology – Panel Beating

The structure of the Kutubu Anticline is shown schematically on three sections in Figure 3, illustrating the 3D complexity with different fluid contacts across the field. Of note, in the Toro Formation, there is a 217 m oil column in the SE part of the field and none in the NW. The double-humped structure has been popped up on the SW-vergent Hedinia Thrust and the NE-vergent Iagifu Thrust creating the Hedinia and Iagifu anticlines respectively. To fully understand the structure and maximise remaining potential a 3D model is required that honours and explains the fluid contacts and is consistent with all geologic and seismic data.

Areas of dense highly-deviated well control such as the syncline between the Hedinia and Iagifu anticlines and the Iagifu Anticline crest provide the ideal situation from which to build directly in 3D. This process involves a rigorous QC programme of over 70 wells and sidetracks

that includes re-surveyed well positions and deviation surveys. Each stratigraphic top was re-picked with particular focus paid to the reservoir units and all the dipmeter data was QC'd and subsequently re-interpreted. With a solid database established and the stratigraphy understood (Figure 2), the TSTs could be calculated to be used as an essential aspect of 3D model building.

The process of model building directly in 3D is illustrated in Figure 4. It begins with building panels at all drilled formation tops within 500 m above and below the reservoir, using the correct dip and azimuth interpreted for that depth (Figure 4A). On their own these panels provide a limited amount of information concerning the structure of the Toro reservoir. However when combined with structural information obtained throughout the wellbore a more complete picture of the reservoir structure can be built and the higher the deviation of the well-bore the more valuable the information represented by these panels becomes.

The second stage is to use the known stratigraphy and TST information to project each panel up from beneath the Toro or downwards from the overburden to reservoir level, thereby creating a web of Toro panels around the well (Figure 4B). Thus a highly deviated well that drilled beyond the reservoir unit can produce several panels that represent the Toro reservoir despite only intersecting it once. This process was repeated for all of the key horizons in upwards of 70 wells and sidetracks in the Kutubu Field, focusing on producing as many panels that represent the reservoir unit as the data would allow.

In the third stage of this process, the panels are widened until they intersect other panels and they are cut at the intersection. Where the panels do not intersect they are left unjoined, allowing for discontinuities and offsets in the model, which are later interpreted as faults. This method reveals structural geometries away from the wellbore and discontinuities or offsets in horizons (Figure 4C). Faults are introduced to the model after offsets are observed in the horizon data (Figure 4D). The fourth and final stage of model building is to join and smooth each of the panels, tidy to faults and to combine with the 2D section interpretation discussed in the next section (Figure 4D and Figure 6).

3D Methodology – Cross-sections

In areas of less dense well data, the 3D panel method is not applicable and we resorted to the traditional construction of cross-sections. Firstly, three key sections were constructed along the regional seismic lines and were balanced and restored and also forward-modelled to check their validity (see Kutubu section in Hill et al., 2015). A further 18 local and detailed sections dip-cross-sections were constructed well within 25° (<10% geometrical error) of the inferred tectonic transport direction, NE to SW, using MoveTM software. For each section, 3D structural domains were established within which the plunge was consistent based on the available surface and well data. These plunges were used to project dips and formation tops onto the section. Typically data were projected less than 1 km and usually <500 m. In areas where the 3D panel model overlapped the section it was 'sliced' along the section and given priority. The key sections were used as a guide to interpret the remaining 18 sections, by projecting the interpretation down-plunge onto the section and adjusting it to fit the constraining data.

In the Hedinia Anticline, the seismic data are of very poor quality and there are few wells as it hosts the gas-cap which remained untouched whilst the oil was being produced, reinjecting the gas. Here different structural interpretations were possible and it became important to use the observed structural style along strike in PNG to choose between them. Using inferred TSTs, the base of the Miocene Darai Limestone was projected from surface data and tied to the available wells. However, the surface geology map shows lower Darai TMD4 juxtaposed against

upper Darai TMD3/2 across a fault (Figure 1). Lamerson (1990) interpreted this to be a backthrust, which thickens the Darai Limestone and pushes down the crest at Toro reservoir level. However, along strike in the Mananda Anticline a similar structure was defined by four wells and drilled by two sidetracks (Keenan and Hill, 2015) and found to be an old normal fault that had been decapitated by the main thrust. Furthermore, the Cretaceous section at Mananda was ~20% thinner in the footwall of the normal fault, which further elevated the Toro reservoir. This interpretation for Hedinia is shown on Figure 5 and is consistent with thin Cretaceous section encountered in wells along strike in the Hedinia Anticline.

Once the three key sections and 18 local sections were drawn, the faults were constructed in 3D by triangular interpolation followed by smoothing. Then the horizons were similarly constructed, but were cut-off at the faults. For the whole model, the initial hydrocarbon contacts were drawn on for each horizon to check that the positions of saddles and sealing faults made sense geologically. In general, few alterations were needed, but structure and faults were adjusted between wells which were known to have different contacts. A view of the final 3D model with translucent cross-cutting faults is shown in Figure 6.

Conclusions

- Given the 3D complexity of the structure and the paucity of good quality seismic data, the only way to constrain the interpretation was by building a detailed 3D geologic model.
- Building the model directly in 3D from structural panels was both efficient and reliable in areas of dense well data
- In areas of low well density, many serial sections were constructed in the tectonic transport direction, with the interpretation guided by key regional balanced and restored sections
- Where multiple interpretations were possible, the structural style observed along strike in the Papuan Fold Belt was used to select the most likely solution
- Overall the Kutubu oil and gas fields comprise a double-humped 'pop-up' structure with the Hedinia Anticline above the SW-verging Hedinia Thrust and the Iagifu Anticline above the NE-verging Iagifu Backthrust.
- The syncline between the Hedinia and Iagifu anticlines is interpreted to lie along a minor normal fault active in the Cretaceous and reactivated more recently. The fault system accounts for oil-water contacts in the Digimu and for thinner Ieru Formation on the Hedinia Anticline.
- The Iagifu Anticline is very well constrained by abundant borehole data and moderate quality seismic data. It is offset by a down-to-the-NW cross-cutting fault that separates the SE-nose which has a 217 m oil column from the NW-nose that has no oil column.
- The Hedinia Anticline is less well constrained due to a paucity of boreholes and very poor seismic data so the 3D model was largely built from closely-spaced geologic cross-sections. Based on analogies with the Mananda Anticline, the Crestal Fault in the Darai Limestone was interpreted to be a normal fault with thin Cretaceous section in the footwall, producing the interpreted Toro reservoir crest. The alternate Lamerson (1990) backthrust interpretation may also be considered.
- The final 3D model was consistent with all initial hydrocarbon contacts and explained them in a geologically reasonable way.

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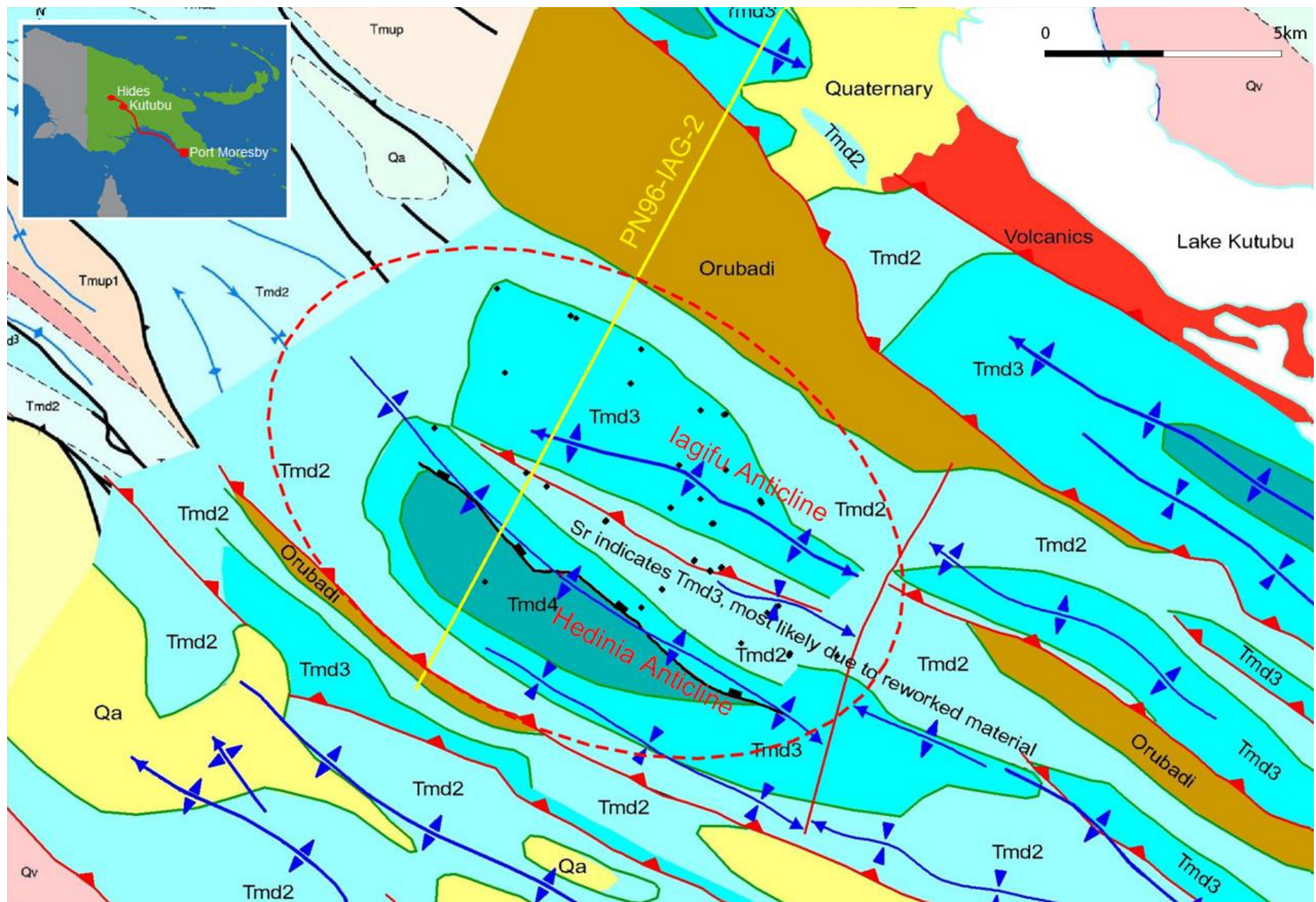
Figure 1. Surface geology map of the Kutubu anticline (within red dashed line) showing line of cross section in Figure 5 (in yellow); inset is a location map showing the Kutubu field. Units as in Figure 2.
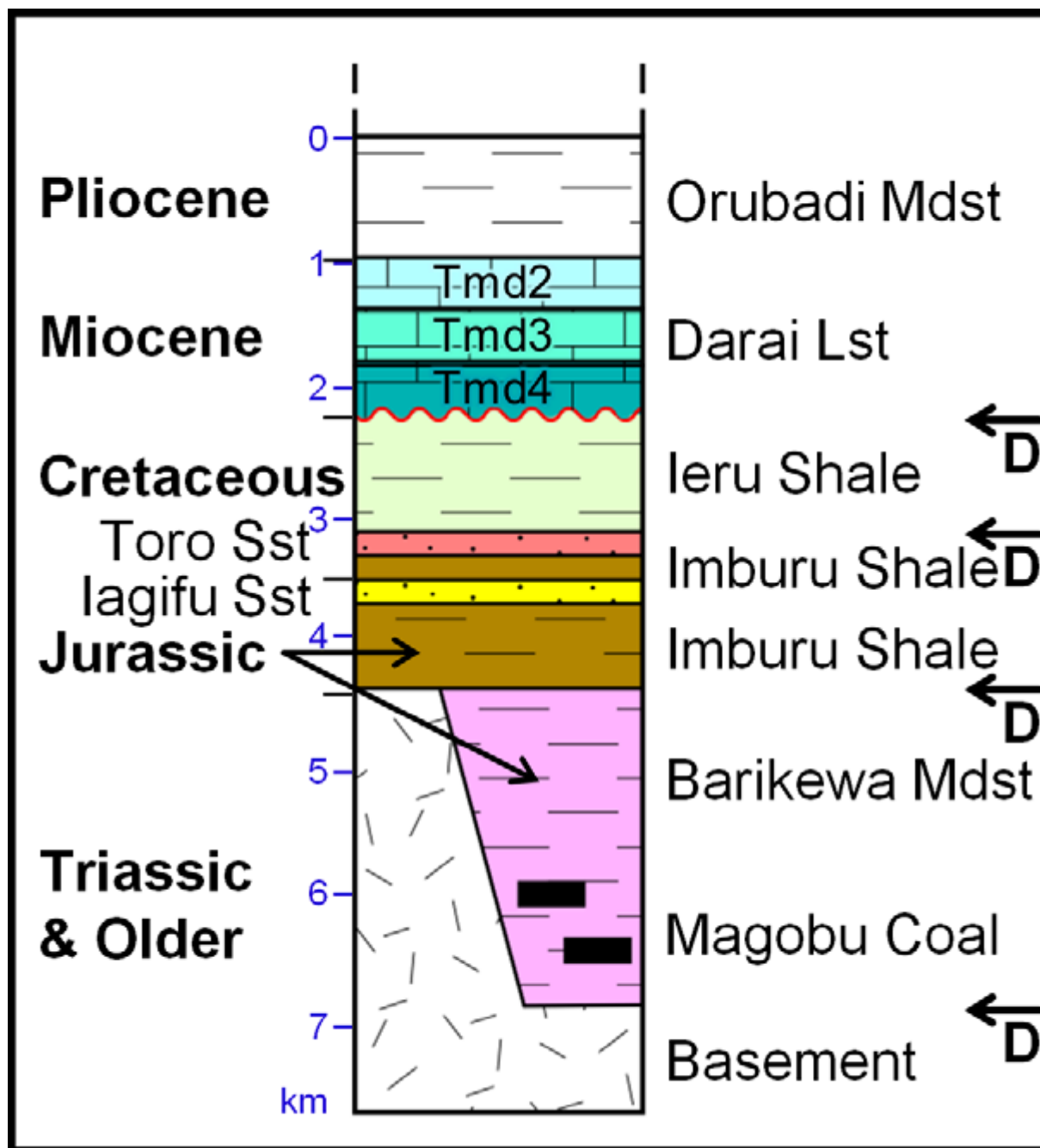
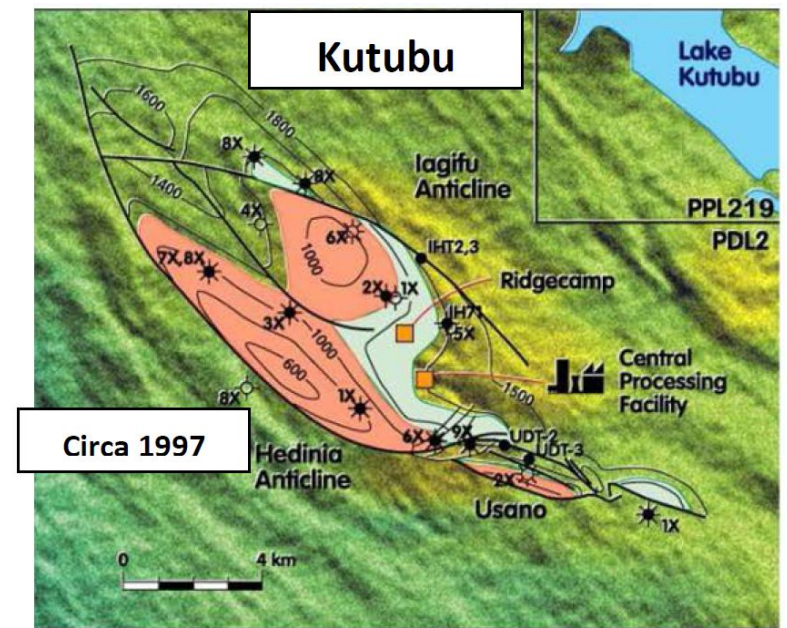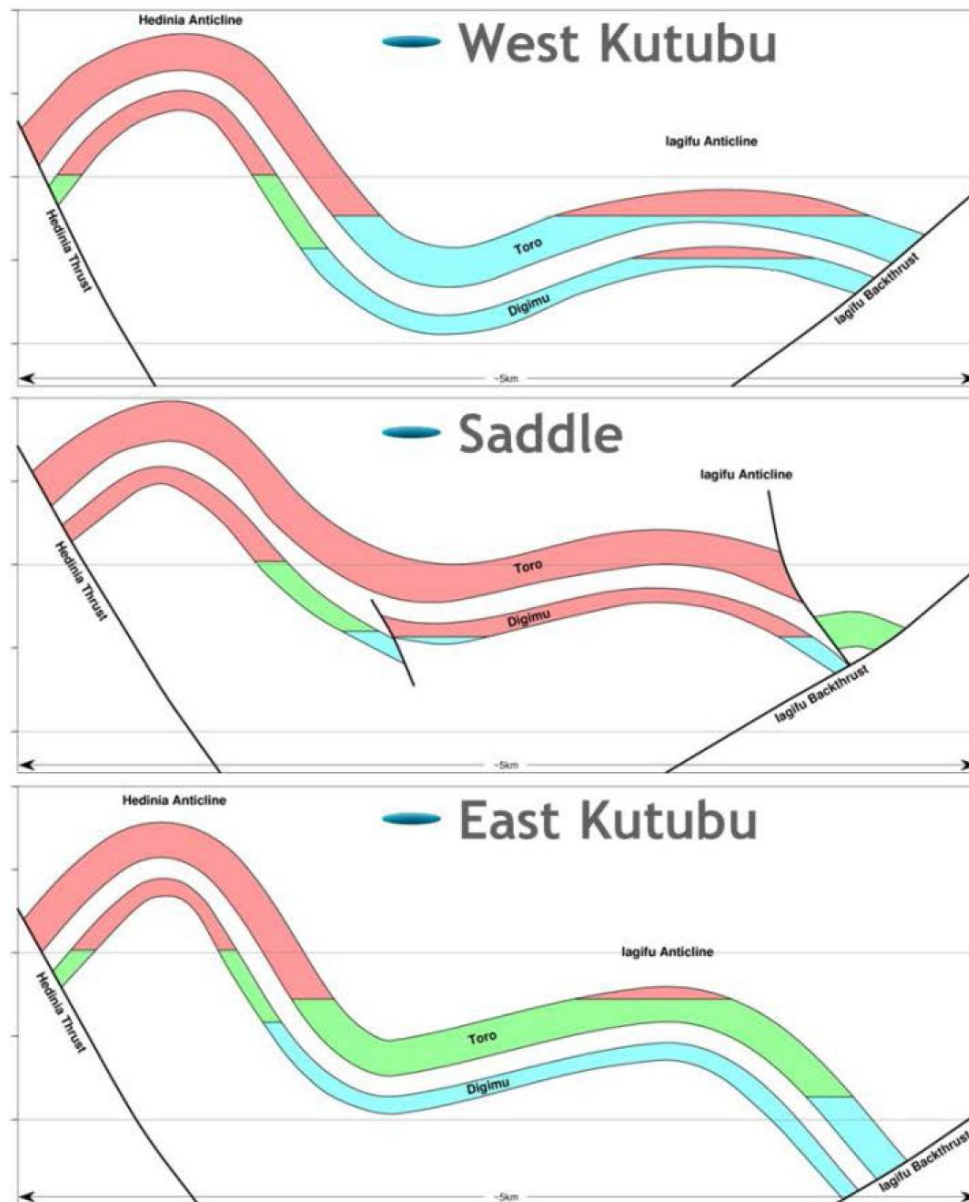Figure 2. The stratigraphic column at the Kutubu anticline.

Figure 3. Schematic cross sections of the Kutubu anticline with different fluid contacts across the field; a map of the Kutubu anticline with fluid contacts.
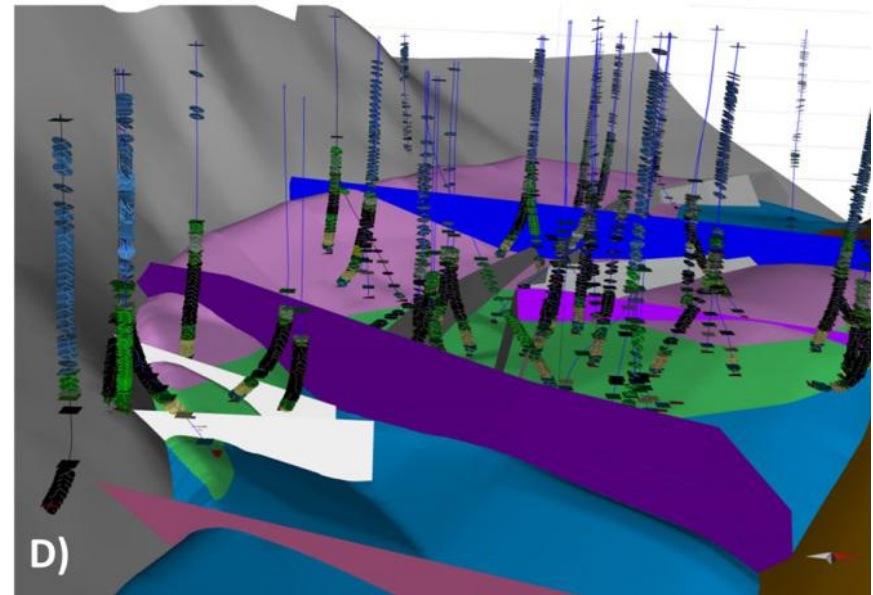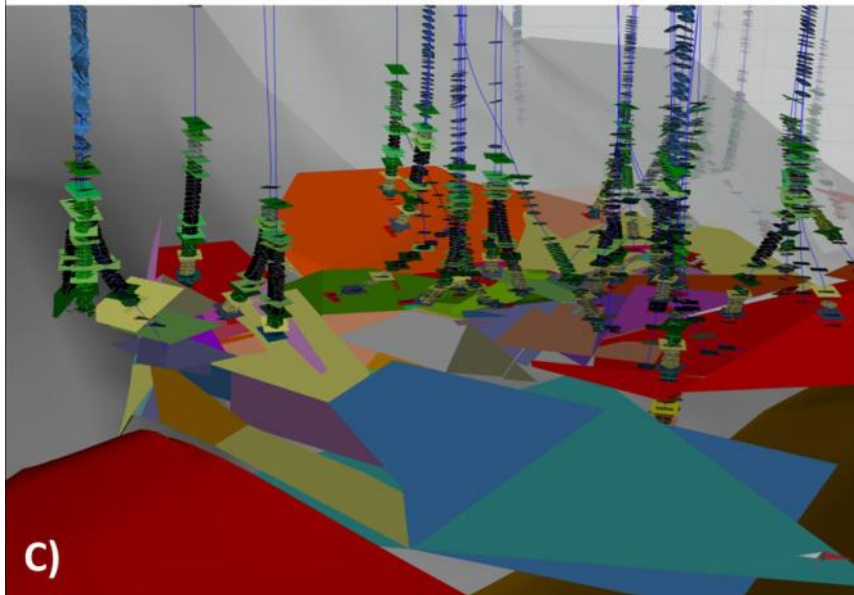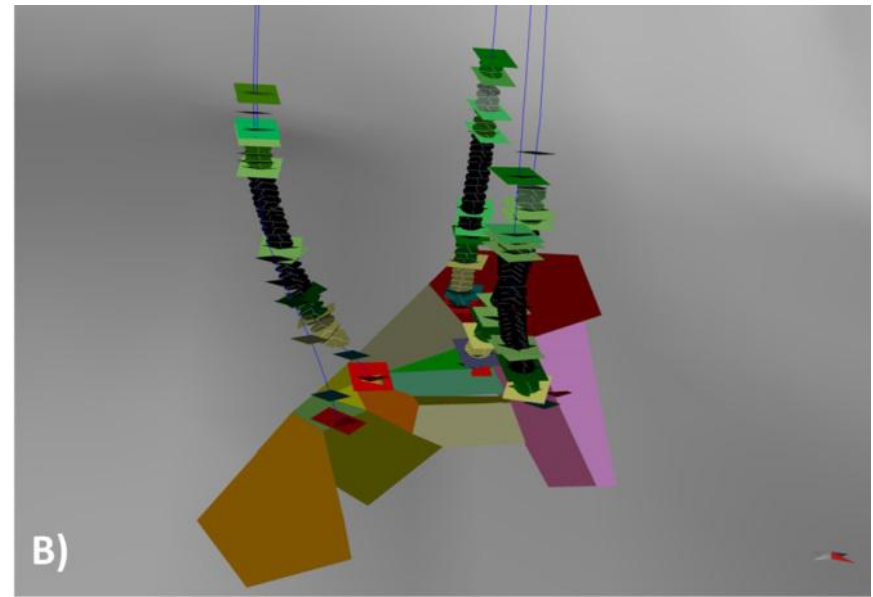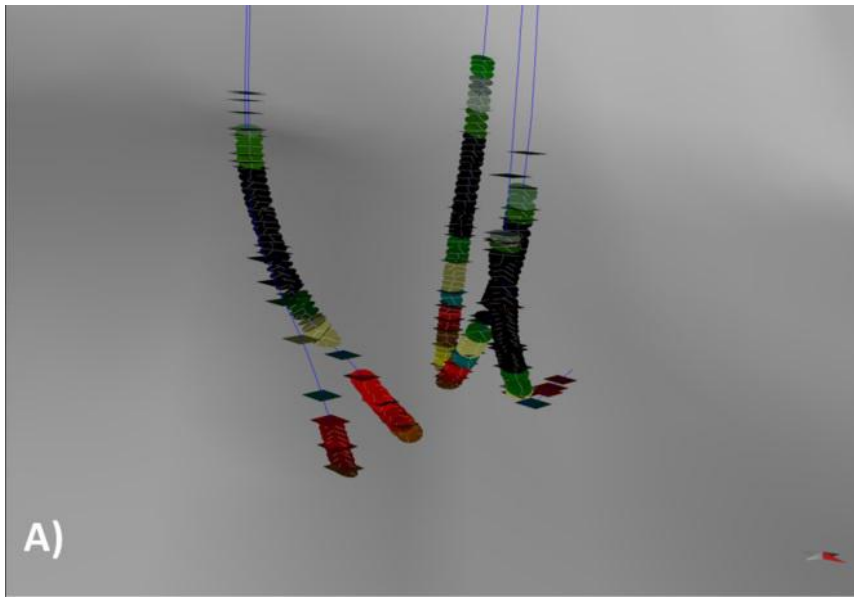
Figure 4. A) Five deviated wells with tops (square) and dips (round) coloured by formation, B) Top Toro panels projected from adjacent formations on a selection of wells, C) Top Toro panels for all wells and sidetracks, D) Top Toro panels joined, smoothed and tidied to faults and coloured by fluid content, pink=gas, green = oil and blue = water.
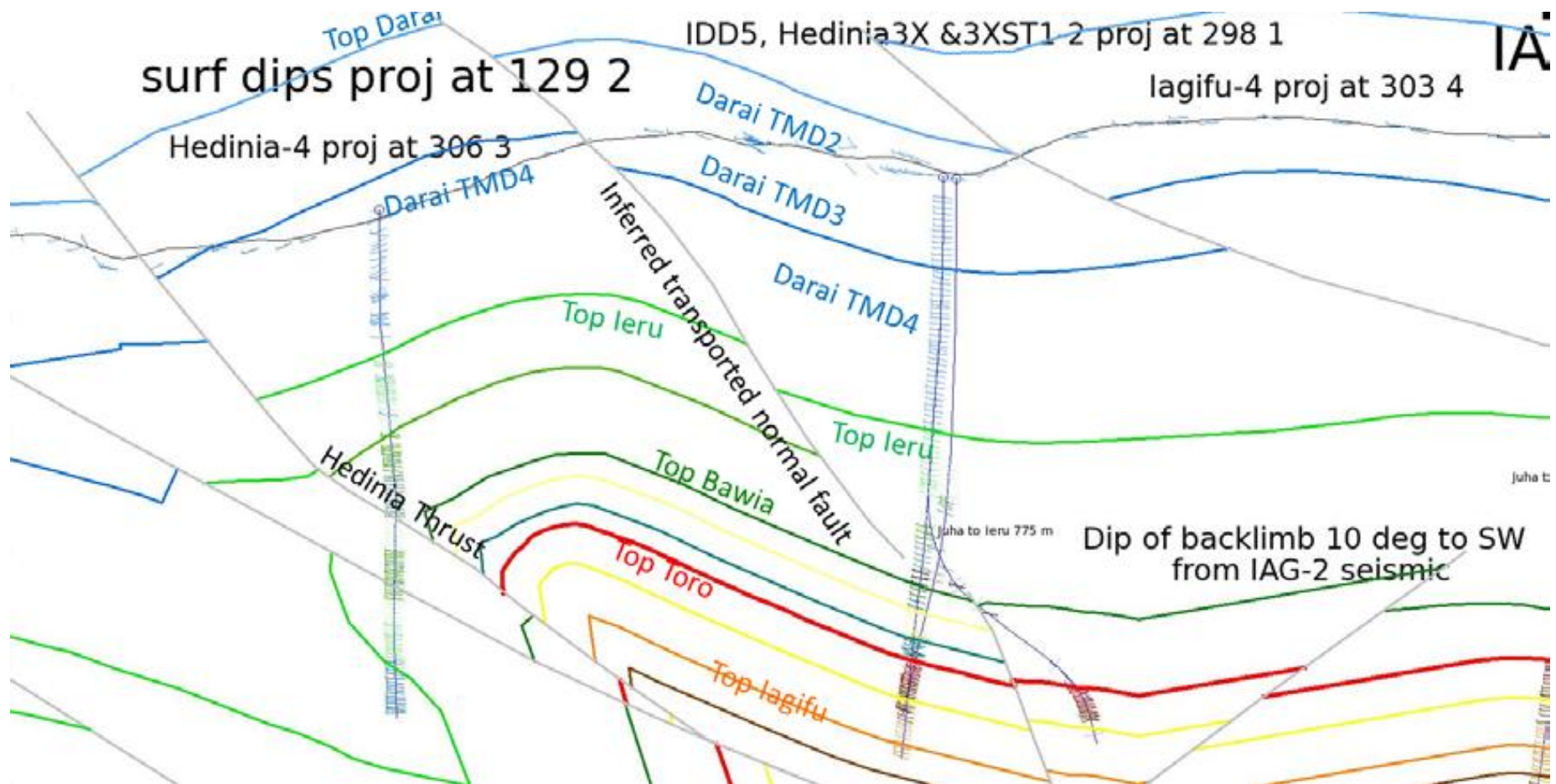
Figure 5. Interpretation of the Crestal Fault on the Hedinia Anticline assuming a normal fault as in the crest of the Mananda anticline (Keenan et al, this volume).
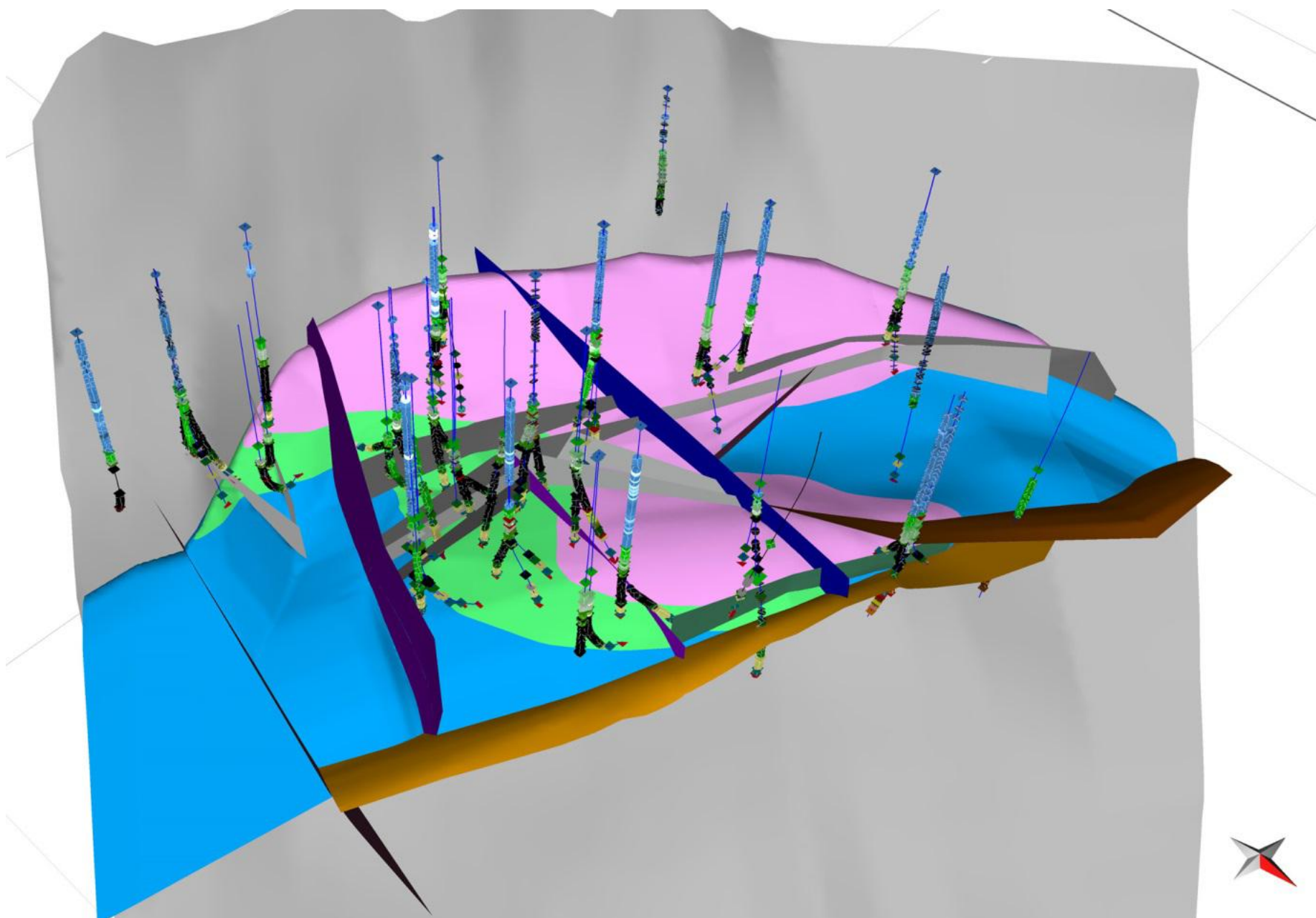
Figure 6. 3D perspective view of the final top Toro surface and main faults in the 3D model, looking towards the SW. Pink is gas, green is oil and blue is water.