The Gobe Field, PNG: Influence of Basement Architecture on Fold and Thrust Belt Structural Style*

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Please see closely related article, Structural Style in the Eastern Papuan Fold Belt, From Wells, Seismic, Maps and Modelling, Search and Discovery Article #30433 (2015). http://www.searchanddiscovery.com/documents/2015/30433hill/ndx_hill.pdf

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Abstract

The 25 km long Gobe Anticline in the SE Papuan Fold Belt is sinuous in map view, being divided into at least three structural compartments along strike, believed to be in part controlled by Early Jurassic rift architecture in the Permo-Triassic basement. The main hydrocarbon-bearing reservoir is Upper Jurassic Iagifu Sandstone. The overlying 1 km thick Cretaceous mudstone is relatively weak, and has detached the reservoir sequence from the overlying 1 km thick more competent Miocene limestone that formed the Pliocene to recent thin-skinned structures seen at the surface. In contrast to the thin-skinned deformation, a few km to the south is the basement-cored Iehi Anticline that appears to converge with and intersect the Gobe Anticline to the NW. Data at Gobe are spatially limited relative to this structural complexity. Hence, the geological model has uncertainty concerning reservoir presence, geometry, and compartmentalisation. To minimise risk for ongoing field development it is key to understand the relative role and timing of thick and thin-skinned tectonics at the reservoir level. A new 3D structural model was constructed honouring regional trends and incorporating all data including surface maps, well tops, true stratigraphic thicknesses (TSTs) and dips in ~40 wells, and twelve 2D seismic lines of poor to moderate quality acquired under challenging surface conditions. 3D data integration and sequential structural restoration allowed testing of concepts and scenarios and led to balanced, valid and internally consistent sections, and an improved understanding of the structural style and history. The Gobe Anticline resulted from a progressive interplay of two conjugate contractional fault sets, both spatially related to the sides of an inverted basement horst. The fault set on the NE side comprises the NE-dipping Gobe Thrust, displacement on which resulted in development of the majority of the Gobe Anticline by fault-bend folding. Inversion of faults on the SW side of the horst created the Iehi-trend. Inversion occurred both before and after the Gobe Anticline was formed. The present-day first order geometry of the reservoir as well as compartmentalisation has resulted from the interplay of the two fault sets, with the relative importance of each dictated by the width and extent of the underlying basement horst. A 3D model of the basement horsts, grabens, and transfer faults has guided interpolation at reservoir level.

Introduction

The Gobe oil- and gas-field is part of the 25 km long Gobe Anticline in the hanging wall of the Gobe Thrust, located at the SE end of the Papuan Fold Belt, Papua New Guinea (Figure 1). This area was subjected to rifting in the Jurassic with large offsets across basement faults (Figure 2) that continue to influence the structural evolution (e.g. Hill et al., 2010). The main hydrocarbon-bearing reservoir is Upper Jurassic Iagifu Sandstone (Powis, 1993) encased in an Imburu Mudstone seal and source rock (Figure 2) with the overlying Toro Sandstone testing water. The succeeding 1 km thick Cretaceous Ieru Mudstone is relatively weak, and has detached the reservoir sequence from the overlying 1 km thick Miocene Darai Limestone (Figure 2) during Pliocene thrusting.

The Gobe structure occurs at the convergence of two regional structural trends, the thin-skinned fold belt trend, which is E-W east of Gobe, and the thick-skinned Darai Plateau trend which is NW-SE (Figure 1). More locally, the convergence is between the thin-skinned SSW-verging Gobe Thrust and the NE-verging, thick-skinned Iehi counter-regional thrust with a triangle zone in between, as pointed out by Hobson (1986). Importantly, the Gobe and Iehi anticlines are separate structures in the east, but overlap and interfere towards the west (Figure 3). This causes the Gobe Anticline to be sinuous in map view, being divided into at least three structural segments along strike. Despite the apparent continuity of the Gobe Anticline at the surface, the production history from ca 40 wells and sidetracks points to compartmentalisation of the field. It was hypothesised that the compartments are controlled by the Early Jurassic rift architecture in the Permo-Triassic basement, comprising extensional horsts, half-grabens, and transfer structures. Thus, the aim of this project was to construct a detailed 3D model of the main reservoir and compartmentalising structures tied into basement architecture, and overlapping thin-skinned and inversion deformation.

Methodology and the Most Significant Results

A new, refined, geological map was compiled (Figure 3) by draping existing maps on a high resolution SRTM elevation model, and by including dip data and strontium isotope data (Hornafius and Denison, 1993). The Darai Formation was subdivided into three units (Tmd-2, 3, and 4) based on strontium isotope ages as shown in Figure 2. Structures were amended from existing maps, and further interpreted after integration with the high resolution topography and the seismic sections.

Apart from the thrust-faults that are parallel to the fold-belt trend, effort was made to map high-angle lineaments representing cross-faults and fractures. Most of the lineaments are bound by the anticlinal structure and are possibly caused by the folding, but some lineaments cut across and extend beyond the Gobe Anticline, some of which even offset the stratigraphy. These high-angle faults and fractures may be significant faults that have affected the reservoir levels (Figure 4). They are postulated to be located above reactivated transfer structures that would have controlled the orientation of any newly formed faults and fractures during reactivation. Hence, the cross-faults at Gobe are thought to be related to the same set of regional structures (although smaller scale) that controlled the location of the nearby volcanic centres, such as the Bosavi Transfer Zone (e.g. Smith 1990).

The cross faults observed at the surface were expressed on seismic as discrete breaks in reflectors or as damage zones, most clearly on the strike lines. These breaks, where they tied to surface lineaments, would constrain the geometry of the fault and allow construction in 3D

(Figure 4). Locally, damage *zones* were mapped - rather than discrete fault lines – represented by a collection of fault sticks. Some 3D fault surfaces still have a swarm of associated fault sticks around them to represent this.

Geological sections were constructed along the seismic lines (e.g. Figure 5) and the strontium ages combined with surfaces dips were used to construct the base of the Darai Formation assuming constant true stratigraphic thickness (Hornafius and Denison, 1993). Where needed additional sections were constructed in between the seismic lines using projected well data and map data only. For each section, wells were projected generally from within a distance of 500 m. Projection angles were either along the structural axis (as determined from dipmeter analysis), or at right angles to the section if no dip data was available. The seismic was depth converted in Move2014 using stratigraphic polygons of a first-pass interpretation and corresponding interval velocities.

For each section a stratigraphic database was set up with names and local TSTs as determined from image log interpretation and palynological constraints. The TSTs allowed consistent horizon interpretation and construction of horizons that were not intersected by wells. Thickness variations occur across the Gobe Field and within sections. In particular, the Ieru Formation shows thickness variation, thought to be the result of the structural development and its role as a relatively soft detachment. Sections were balanced and sequentially restored to test validity and deformation style.

Thrust faults were interpreted on seismic and tied to surface fault traces. The Gobe Thrust was constructed using the geological map, the seismic sections, and observed stratigraphic duplication in wells from image logs and from palynological constraints. This, combined with readings of dipmeter data, such as steeper to even overturned dips towards a suspect fault plane, and fracture density increase, has pointed to a Gobe Thrust that is at least 30 km long and relatively straight at the level of the reservoir. Thrust splays shoot off the Gobe Thrust in its hanging wall and have a NNW-trend. Smaller, less deep en-echelon thrusts with similar trend are found to detach on the Ieru Formation and are limited to the Darai Formation.

Construction of 3D horizons, in particular the Iagifu Formation (e.g. Figure 4 and Figure 6), was done directly in 3D from tops and dips on wells. Orientated tops allowed construction of local horizon panels that were connected between wells to form bigger horizon patches when well density and top orientation permitted (see a detailed description of this method in Munro et al., 2015). The 3D panel method prevents the loss of orientation data that occurs during projection of dip data onto sections. A continuous 3D model is then constructed by extrapolation and linkage of the horizon panels and patches, incorporating horizon lines on sections and traces on the geological map. To optimise accuracy, all wells were QC'ed, including their well positions, trajectories, and dipmeter data. Dipmeter data from 35 wells were reinterpreted, with special attention to the dips of tops and the attitude of any structural disturbance of the bedding dip, such as drag caused by faulting or folding, and fracture density.

3D Interpretation of the Interaction of the Different Thrust Systems

The main structures identified and constructed for Gobe comprise the fold-parallel SW-vergent thrusts including the 30 km long Gobe Thrust and anastomosing sets that splay off the main thrusts to trend NNW. The Iehi Thrust verges to the NE and thrusting is related to the inversion of an extensional fault block, the Iehi block. A family of NE-trending faults extend beyond the Gobe Anticline and these faults are suspect to be linked to deeper transfer structures and cause compartmentalisation of the Gobe Field at reservoir level (Figure 4, Figure 5, and Figure 6).

Our current interpretation is that the Gobe Anticline resulted from a progressive interplay of two conjugate contractional fault sets, both spatially related to the sides of an inverted basement horst (Figure 5). The NE side is defined by the NE-dipping Gobe Thrust, displacement on which resulted in development of the majority of the Gobe Anticline by fault-bend folding. The second set of structures is related to inversion of faults on the SW side of the horst creating the Iehi-trend. This inversion occurred both before and after the Gobe Anticline was formed. In the far NW of the Gobe Anticline, the interference of the two horst-bounding faults formed a pop-up block (see NW seismic section of Figure 5). The final 3D model of the Iagifu Formation reservoir throughout the Gobe-Iehi area is shown in Figure 6. This model will form the basis of future development planning and possibly exploration wells in the area.

Main Conclusions

- The Iagifu reservoir in the Gobe Structure is not a simple anticline above a thin-skinned thrust. Rather complexity is caused by lateral variation in the location of basement extensional fault blocks and the amount of inversion, which dictates the final hanging wall geometry and dominant fault vergence as a result of the relative importance of inversion with respect to the SW-verging Gobe Thrust.

- Further complexity is caused by an oblique compression angle to the basement blocks. This angle results in a complex thrust pattern at surface, with thrust-splays trending NNW. Some detach at Ieru levels and form an en-echelon pattern at surface. These do not affect reservoir levels. All faults should be taken into account when constructing beds using TSTs from the surface to depth.

- The present-day first-order geometry of the Iagifu reservoir and its compartmentalisation has resulted from the interplay of a number of families of faults. The first-order, NE and SW-vergent faults are dictated by the width and extent of the underlying basement horst, extensional grabens and transfer faults. A 3D model of the basement horsts, grabens, and transfer faults has guided interpolation at reservoir level.

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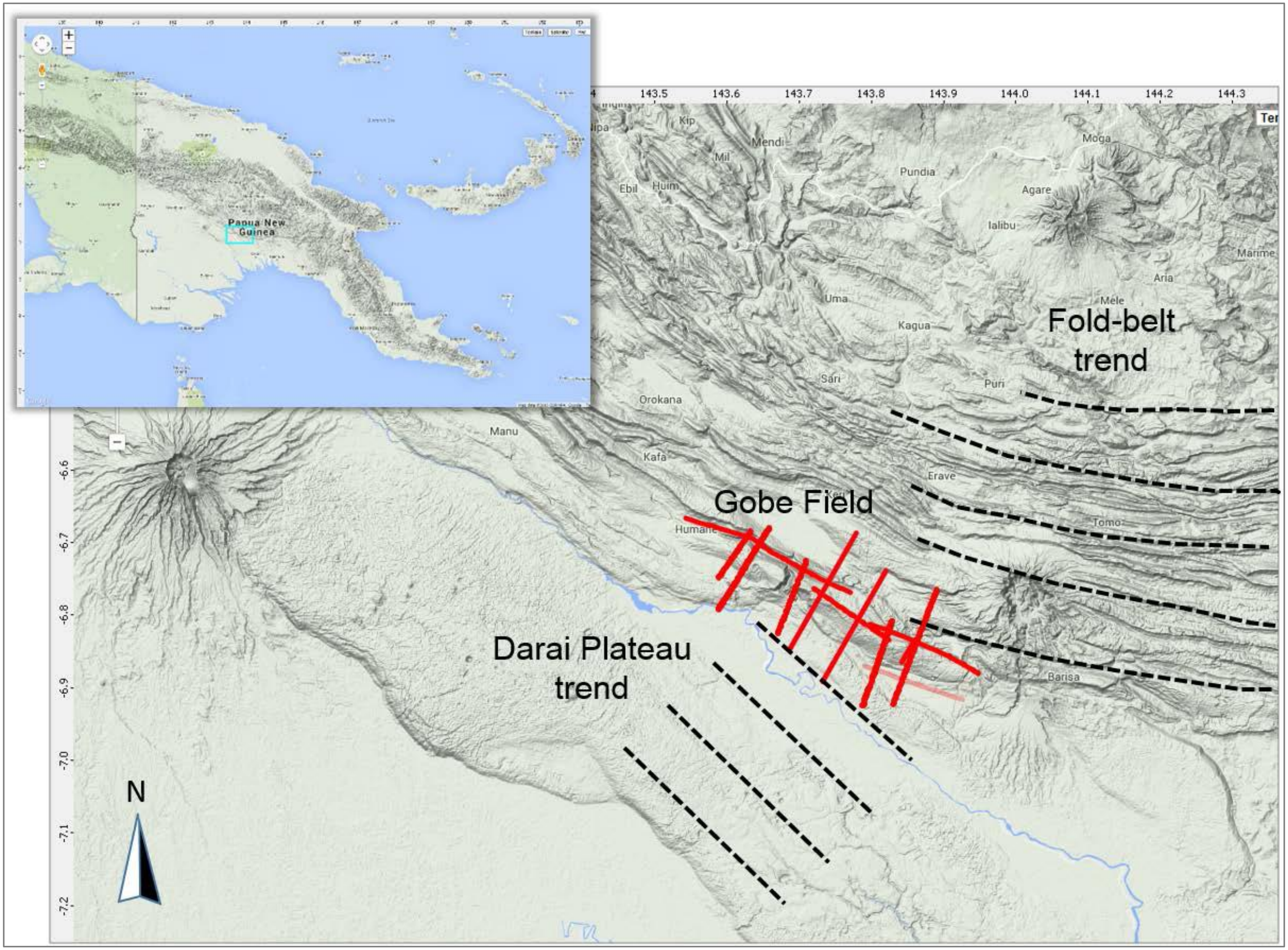

Figure 1. The Gobe Field in the SE Papuan Fold Belt, at the intersection of the E-W fold-belt trend and the NW-SE Darai Plateau trend. Red lines are the key 2D seismic lines used in this study.

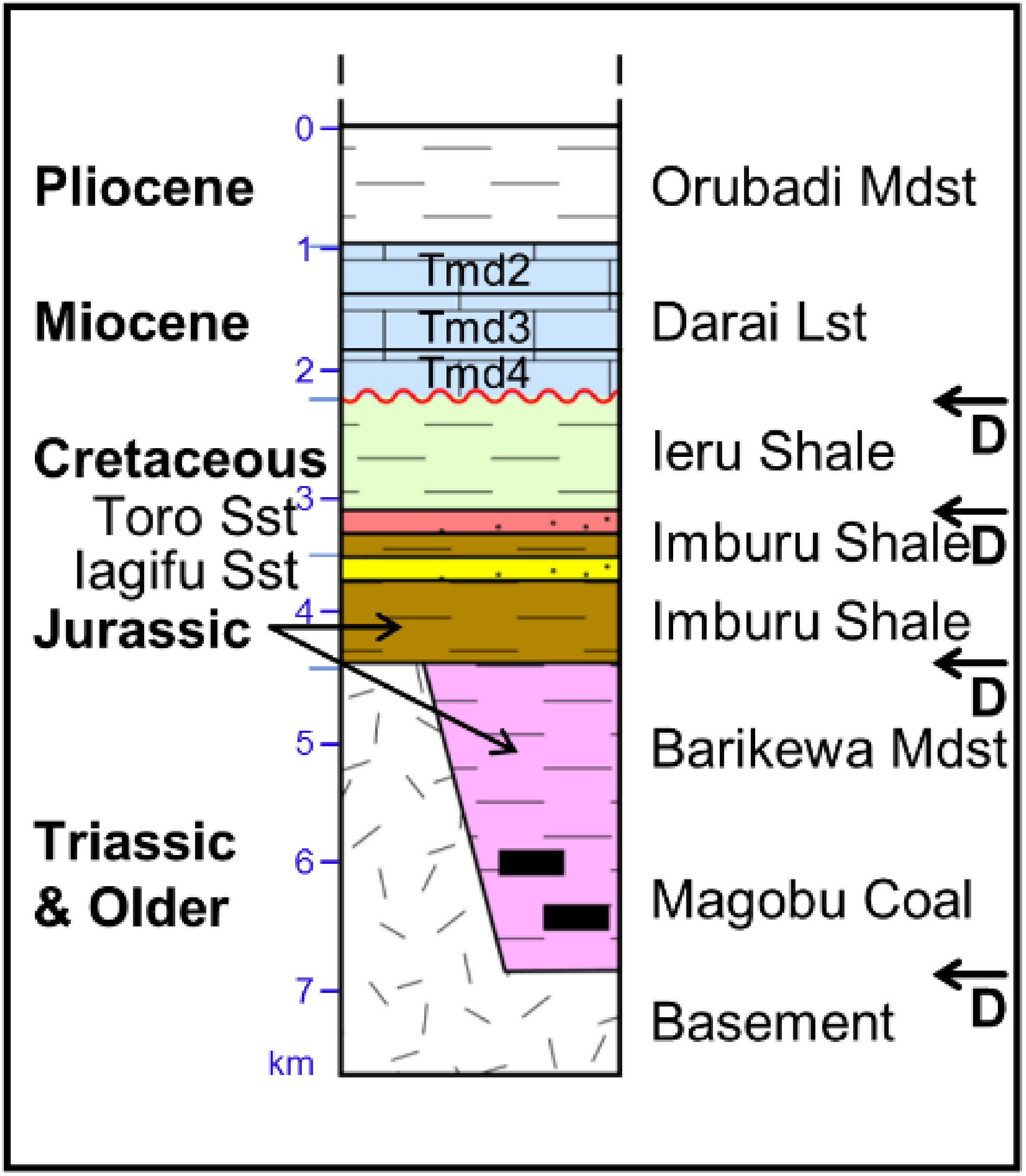

Figure 2. Stratigraphy, ages and thicknesses of the sediments in the Gobe area. The sediments reflect Jurassic rifting, Upper Jurassic and Cretaceous post-rift subsidence, Miocene subsidence and Pliocene compression. The Miocene Darai Limestone is divided into three sub-units as shown, which were used in geological mapping and section interpretation.

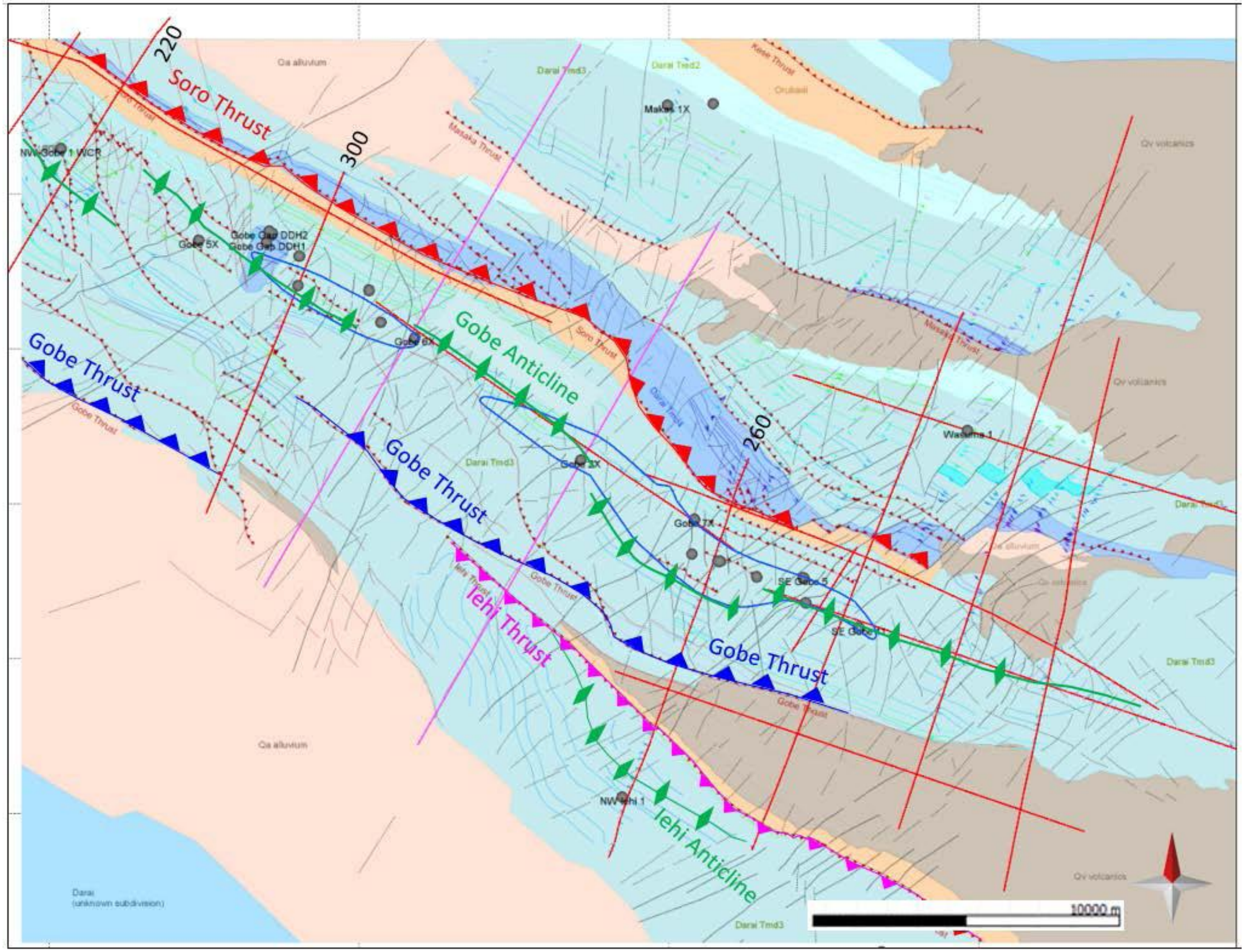

Figure 3. Geological map of the Gobe Anticline. The Darai Fm. of Miocene carbonates shows three mapped units (Tmd2, 3 and 4) based on strontium isotope ages in Figure 2. Note that pink is alluvium and light brown is recent volcanics. The Gobe Field outline is marked in dark blue. The main structures include the SW-verging Gobe Thrust and Soro Thrust, marked in blue and red, respectively. The Iehi Thrust to the south of the Gobe Anticline verges to the NE and is an inversion fault believed to offset basement (Hobson, 1986). The map also shows prominent cross-cutting lineaments and conjugate fractures. 2D seismic lines are marked in red. Section lines in pink have no seismic.

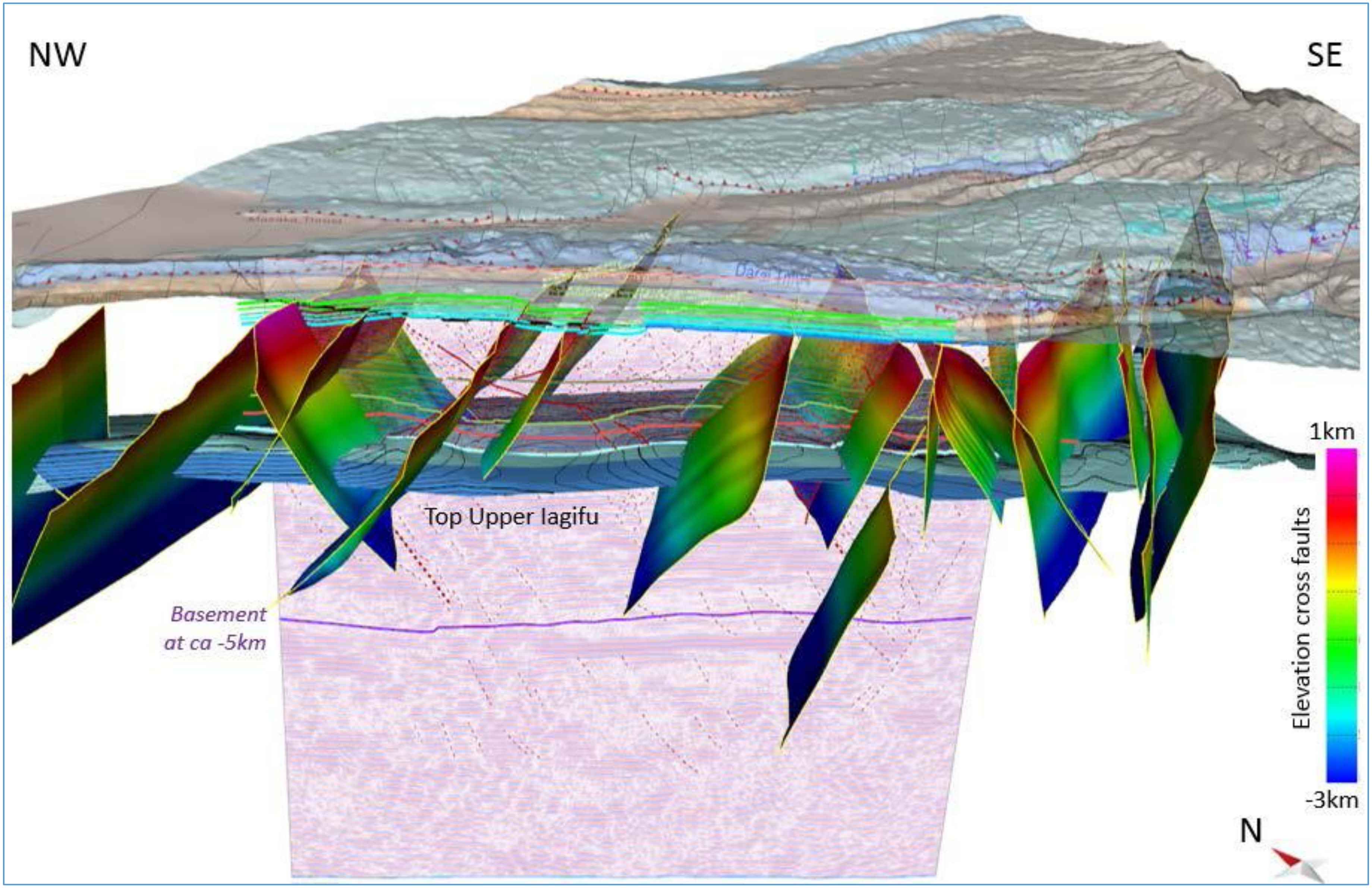

Figure 4. Oblique view to the NE showing the modelled 3D cross faults based on surface fault and lineament traces (Figure 3) and strike-line seismic fault stick interpretation. Most faults trend to the NE. The Iagifu Formation is in light blue and contoured for depth and the geology map is shown draped on the Digital Elevation Model.

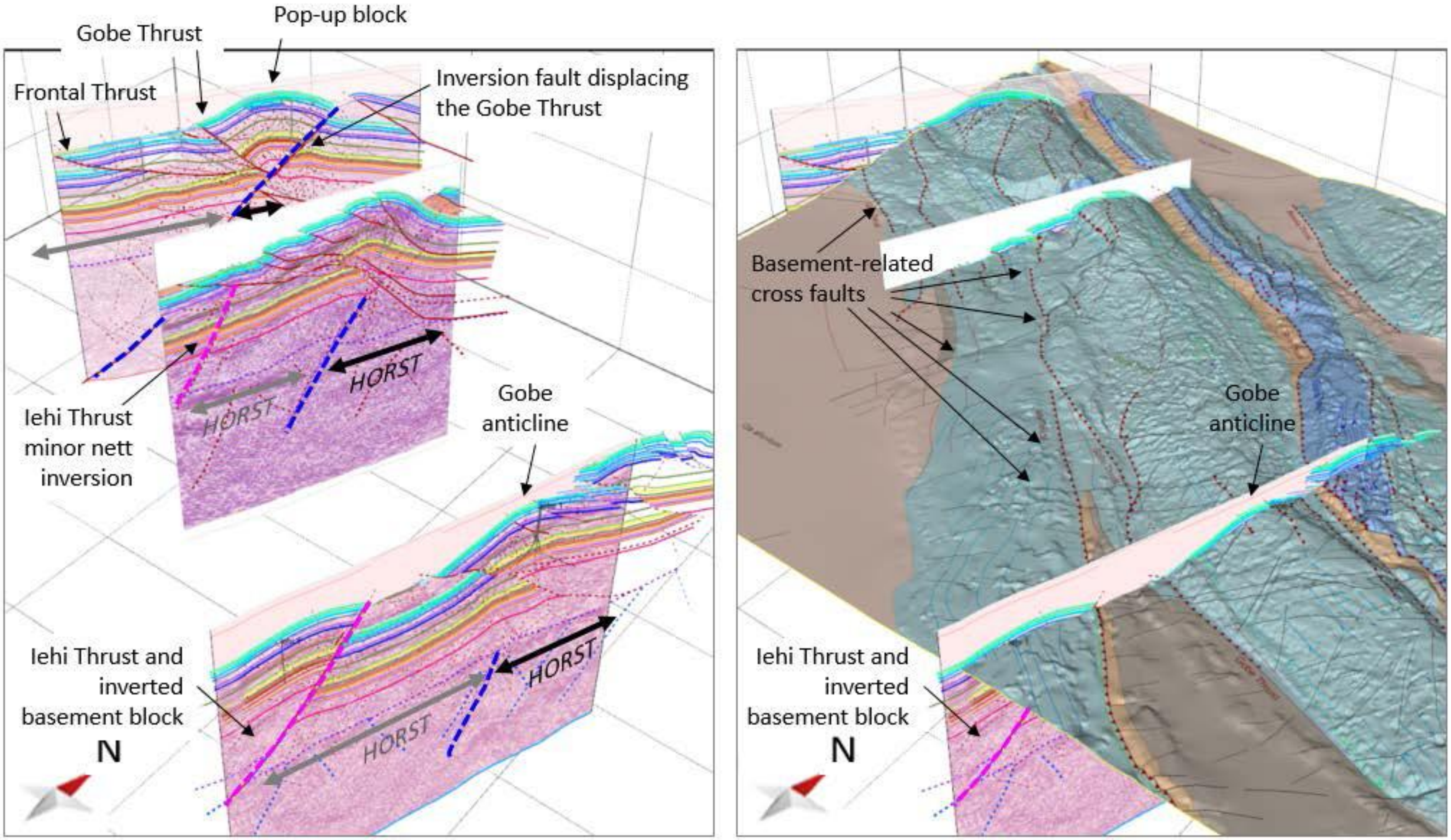

Figure 5. (Left) Oblique view looking NW at the three key seismic sections illustrating the lateral change in the relative role of SW-verging thrusting and NE-verging basement inversion. The SE section shows the inverted Iehi basement block and the Gobe anticline sitting separately to the east of it. The Iehi surface expression shows that the effect of inversion diminishes towards the NW, such that when it reaches the middle section, there is no evident inversion. However, a basement-related cross fault with minor offset that stepped to the SW, may have accommodated differential inversion. The NW section is interpreted to show a basement fault, the initially extensional NW-Gobe fault, which was subsequently inverted and cut through the SW-vergent Gobe anticline. This basement counter-regional thrust is not directly along strike of the Iehi fault, but is a separate fault segment linked by transfer faults that were probably formed during rifting. The NE-trending cross faults in the rocks at surface may reflect the location of the extensional transfer zones in the basement.

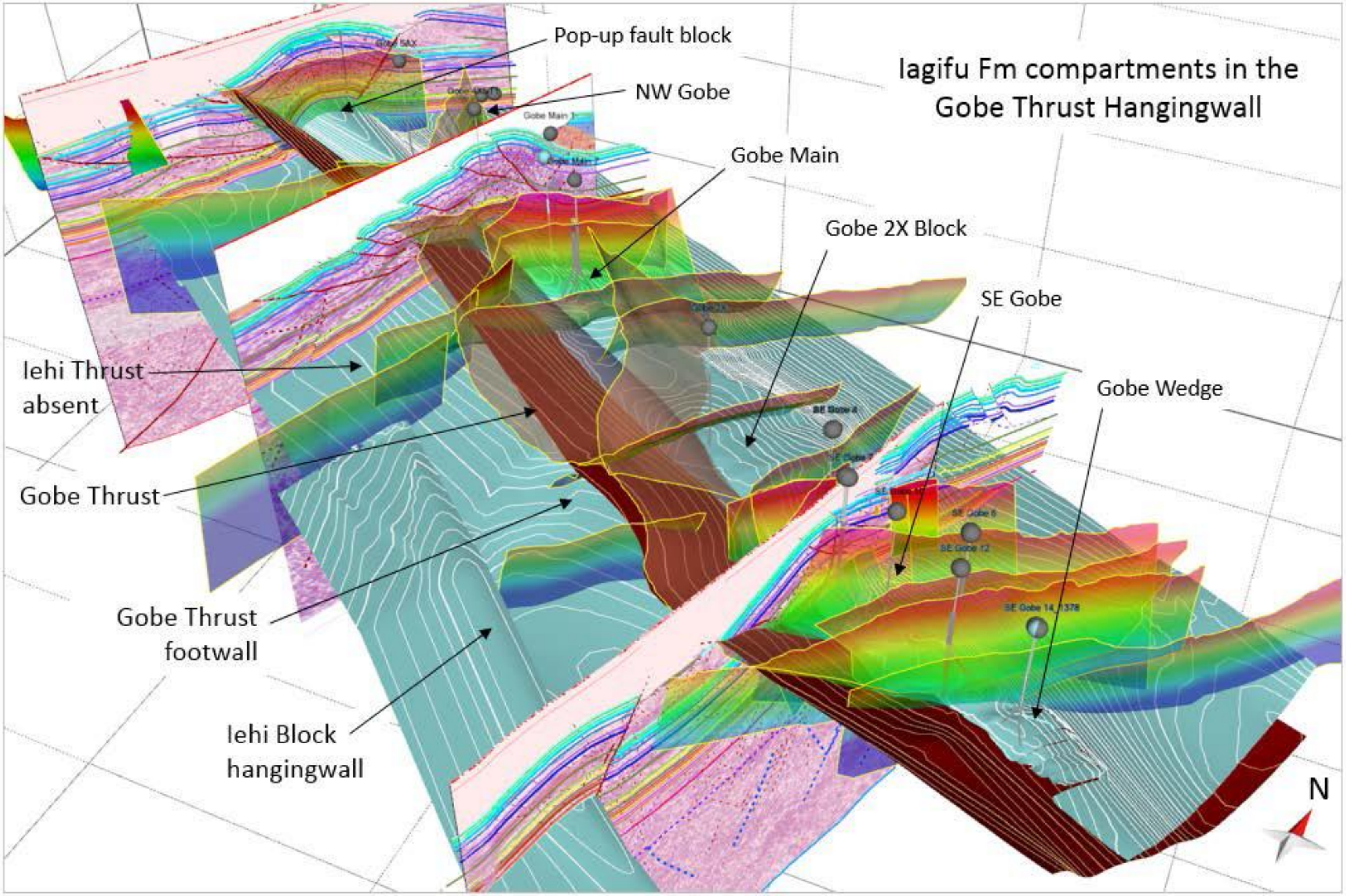

Figure 6. Oblique view looking NW showing the final 3D model for the Gobe Field, with the Iagifu reservoir contoured for depth, and the Gobe Thrust in dark red. The Gobe Thrust hangingwall is in the NE and the footwall in the SW. The footwall contains the inverted Iehi Fault Block (bottom left). From SE to NW, the seismic sections show a change in structural style from a SW-vergent Gobe Thrust with an opposing Iehi inverted basement fault, to absence of a Iehi Thrust, to a pop-up hangingwall fault block where a NE-vergent inverted basement fault has cut across and displaced the Gobe Thrust. The compartmentalising cross faults are colour-coded for depth.