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3D reconstruction of the Oak Ridge fault and related structures in the Ventura Basin, southern California, USA

By

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Master Thesis

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Abstract

The Oak Ridge fault is located in the Ventura Basin, southern California, USA. It is a south-dipping reverse fault formed under the effect of Miocene extension, followed by Pliocene to middle Pleistocene compression, late Quaternary uplift and associated clockwise rotation of the western Transverse Ranges. In this thesis, the integration of well data, well image, subsurface maps, fault interpretation and public well correlations were used to interpret cross sections and build a 3D structural model of the Oak Ridge fault in an area of about 500 km^2. The 3D model contains 36 cross sections, 2 fault planes and 6 horizons. Based on the strike variation of the Oak Ridge fault, the model was subdivided into four segments: (1) NE-SW striking coastal segment with an eastwards increased dip angle up to 80 degrees, (2) NE-SW striking segment dipping 85 degrees, (3) ENE-WSW striking segment with an eastwards decreasing dip angle from 80 degrees to 60 degrees, and (4) N-E striking segment with an eastward increasing dip angle from 60 to 80 degrees. With the well tops and dip meter data control, in the region from coastal area to the Santa Paula city, horizon modeling was performed on both hanging wall and footwall block. However, in the area from Santa Paula city to the eastern end, the top Santa Barbara and top Pico surfaces were made in the footwall block, while only the top Sespe surface was made in the hanging wall. Unfaulted horizons show a monoclinal structure in the western area. To the east, the Oak Ridge fault offset all horizons. The hanging wall Sespe horizon expresses an anticlinal structure due to late Quaternary uplift deformation, while the footwall Pico and Santa Barbara horizons show a synclinal structure. Cross sections interpretation and final model show that the thickness of the Pliocene Pico and Pleistocene Santa Barbara strata decreases eastwards on the hanging wall but increases eastwards on the footwall from the coastal area to the Santa Paula city. Fault displacement analysis shows the displacement of Oak Ridge fault decreases westwards. The 3D structural model built in this study can be used to improve the understanding of the large number of fields in the Ventura Basin, which its developments are linked to the Oak Ridge fault.

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1. Introduction

The study area is located in the Ventura Basin, which is a late Cenozoic east-west trough embedded in the western Transverse Ranges of southern California. The area of this study region is around 50 km long by 10 km wide. The NE-SW striking, south-dipping Oak Ridge reverse fault formed under the effect of Miocene extension, followed by Pliocene to middle Pleistocene compression, late Quaternary uplift and associated clockwise rotation of the western Transverse Range blocks. This fault caused relative folding in the adjacent region which mainly includes the north Santa Clara syncline and the South Mountain-Oak Ridge anticline (Figure 1). This area is rich in oil and gas reservoirs (e.g. Saticoy oil field) due to a well-developed petroleum system. In 2015, the amount of oil production from this area was around 4.7 millions of barrels (Rotzien et al., 2015).

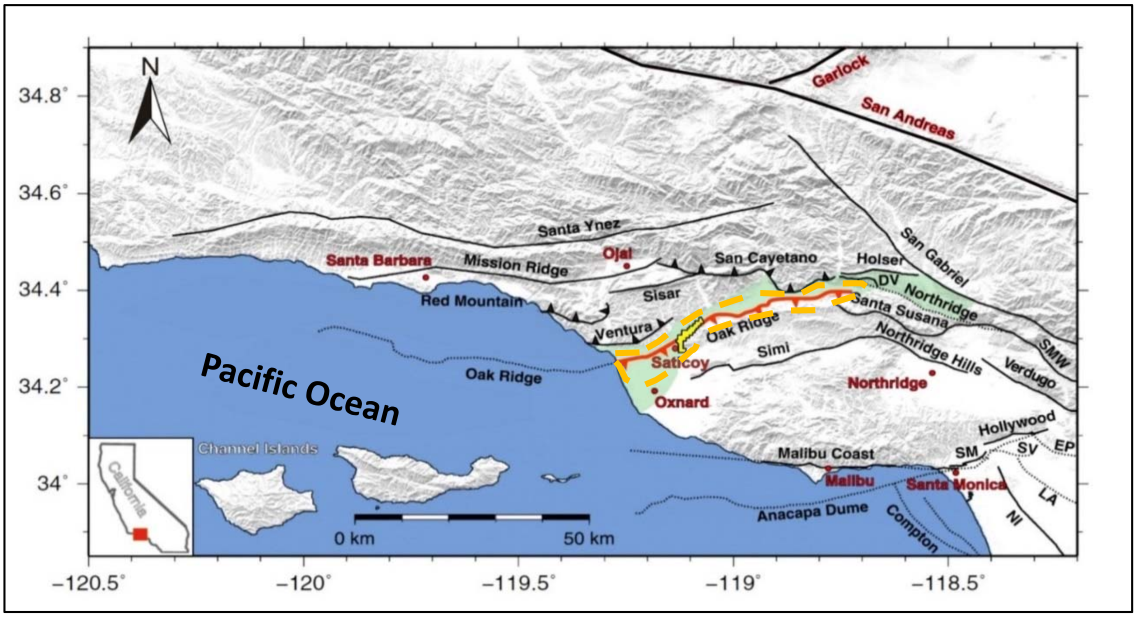


Figure 1. Geologic map of the study area in the onshore Ventura Basin, southern California. Modified from Marshall et al. (2013). The orange dash line shows the study area. The red solid line is the surface trace of the Oak Ridge Fault. The yellow area is the Saticoy oil field. Black lines are faults. Green area shows the Ventura Basin.

The steeply south-dipping Oak Ridge fault (60-85 degrees) and the late Pleistocene uplift structures together with stratigraphic traps in the growth strata are the main traps in this area. The Saticoy oil field is a good example. In this field, the major trap is the up-dip stratigraphic pinch-out (Figure 2a). Yeats and Taylor (1990) indicate that the Saticoy field produces oil trapped in Pliocene and early Pleistocene turbidites on the steeply dipping south limb of the Santa Clara syncline. However, Harding and Tuminas (1988) interpret another oil trap which is a combined structural-stratigraphic trap produced on the eastern part of the field, especially in the lower footwall blocks where oil is trapped against the Oak Ridge fault and sealed by this fault (Figure 2a). Laterally, the Oak Ridge fault bounds the south of the Saticoy field, broad positive warp provides longitudinal closure (Figure 2b). Although the conditions affording closure in the field are not completely understood, oil is found immediately adjacent to the fault and considerable shows are often encountered in the fault zone properly (Higgins, 1958). Therefore, good understanding of the Oak Ridge fault and its related folding plays a vital role in evaluating the hydrocarbon prospect in the area.

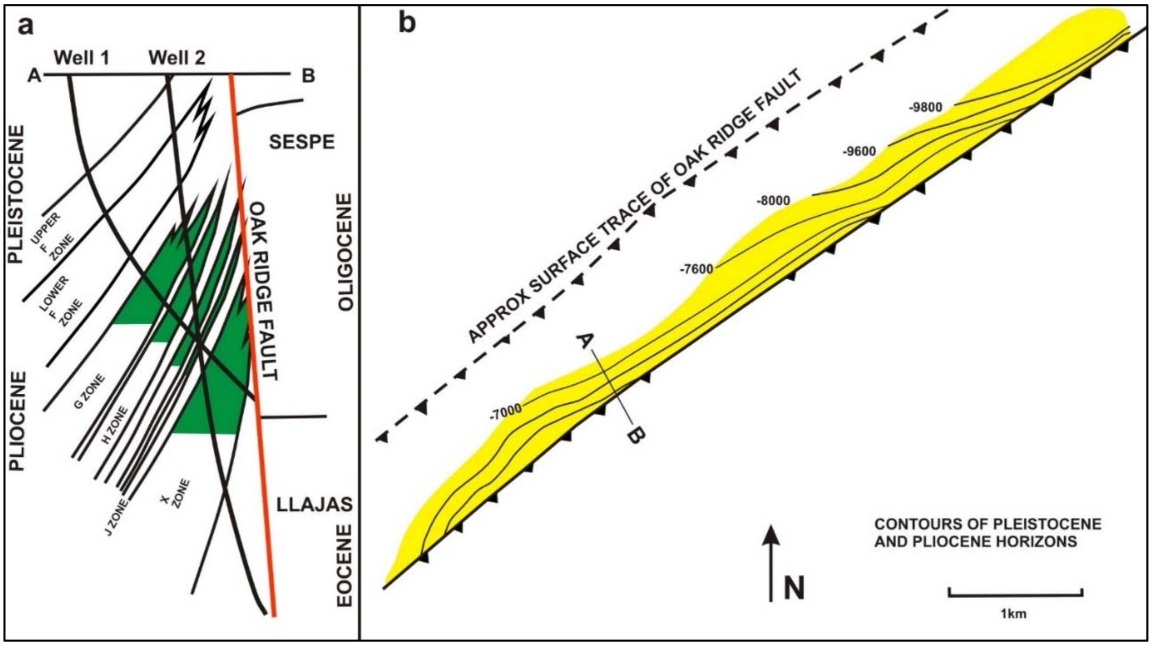


Figure 2. a) Cross section AB of the Saticoy oil field, transverse (up-dip) closure is partially accomplished by reservoir pinch-outs. b) Structure contour map of the Ventura Basin, broad footwall warp provides longitudinal closure (yellow area) parallel to the Oak Ridge fault. Adapted from Harding and Tuminas (1988).

In this thesis, 3D structural modeling was used as a methodology to integrate scattered 2D and 3D data. The dataset contains: 1) one regional geologic map, 2) 108 wells with well tops and dip-meter data, 3) four structural maps, 4) preliminary fault interpretation, and 5) a high-resolution digital elevation model. These data complement each other and bring about an internally consistent 3D structural model, they delineate the geometry of the Oak Ridge fault and related anticline and syncline structures in 3D. In addition, this dataset offers an unique opportunity to understand faulting and folding in this complex area involving shortening, and associated clockwise rotation of the western Transverse Ranges (Sorlien et al., 2000).

This study is a continuation of previous work that incorporated the data in a Petrel (Schlumberger) project. The results were not good in Petrel since the Oak Ridge fault related folds have steeply overturned limbs. Additionally, horizon models were not completed in the study region, they are only located in the coastal area. Therefore, this work was carried out in Move software instead of Petrel. Move has better algorithms for structural modeling, the use of triangulated grids in Move also facilitates modeling the folds in 3D, and allows constructing a better 3D structural model that follows the well data and honors the geological setting of the study area. The resultant 3D structural model gives insight into the structural geometry, fault displacement and layer juxtapositions along the Oak Ridge fault.

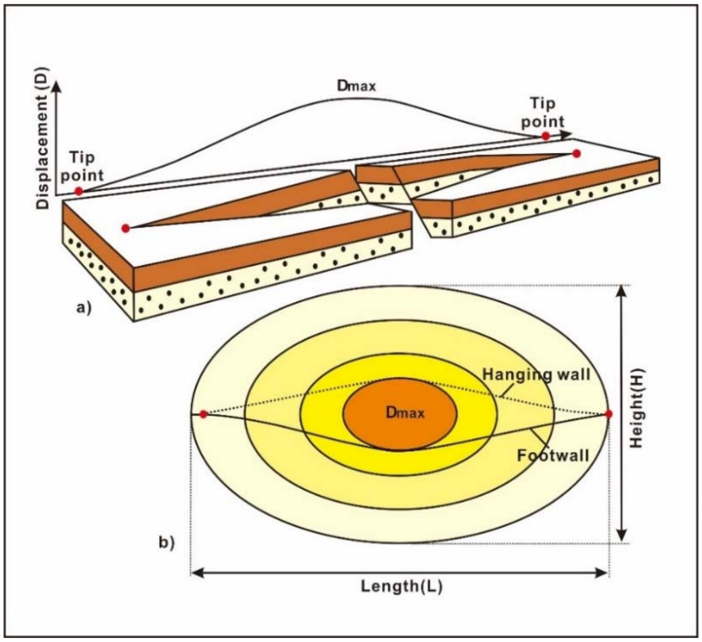


Figure 3. a) Schematic description of an ideal, isolated fault. Displacement is maximum at the center of the fault and decreases outwards to be zero at the fault tip-line. b) The fault plane with displacement contours. The distance between hanging wall and footwall cutoffs indicates the fault separation. Modified from Fossen (2010).

This thesis is subdivided into two main topics: reconstruction of a 3D structural model and validation of the model based on fault displacement analysis. The 3D structural modeling consists of the Oak Ridge fault, Montalvo fault and six reconstructed stratigraphic horizons. Before structural modeling, the data was transferred from Petrel to Move. Well tops and dip meter data were checked with the well image and the original Petrel project to make sure the input data were correct and respected the original data set. After this preparation work, I selected a series of cross sections that cross the Oak Ridge fault perpendicularly with well control first, projecting adjacent wells with well tops and dip meters to the cross sections, and then interpreting the faults and horizons. After the interpretation, I collected the Oak Ridge fault traces that appear consistent in all cross sections to create the fault surface in 3D. Likewise, the traces of the horizons in the serial cross sections were used to reconstruct the 3D geometry of the beds. The surfaces produced were split into the hanging wall and footwall areas to avoid inconsistencies produced for example by overturned forelimbs. An important concept as shown in Figure 3 is that the faults should show a reasonable variation of displacement, with zero displacement at the fault tip-line and maximum displacement at the center of the fault surface (Fossen, 2010). In this study, the displacement on the Oak Ridge fault decreases from northeast to southwest (Yeats et al., 1988). To check the consistency of the 3D structural model, fault displacement analysis was conducted. This method can calculate the hanging wall and footwall fault cutoffs allowing estimation of the fault throw. The final 3D structural model of the Oak Ridge fault and related structures in the Ventura Basin give insight into the structural geometry, fault displacement and layer juxtapositions, as well as the vertical and lateral variation of the structure in the research area.

2. Geological Setting

2.1 Regional tectonic setting

The study area lies within the Ventura Basin, which is a late Cenozoic east-west trough embedded in the western Transverse Ranges of southern California. This area is crossed by the Oak Ridge fault and has experienced a complex tectonic evolution related to the Pacific and North America plate tectonics, including: 1) Cretaceous-Paleogene subduction, 2) Miocene transtension with accompanying 80-110° clockwise rotation, and 3) Pliocene-Quaternary transpressional deformation with Transverse Ranges continuous rotation accompanied by compression, uplift and faulting (Kamerling and Luyendyk, 1985).

2.1.1 Subduction

In the Mesozoic, as Atwater (1998) pointed out ‘‘the western coast of North America was a subduction zone, where the Farallon plate was subducting obliquely under the North America plate’’. Then in the middle Cenozoic, around 28 Ma, Luyendyk (1991) indicated ‘‘the spreading center between the Farallon and the Pacific plates approached the North America plate boundary, and made the Farallon plate break up into the Arguello, Guadalupe, Magdalena, Monterey and microplates’’ (Figure 4).

2.1.2 Transtension

Figure 4 shows the regional tectonic evolution during the early Miocene. With the spreading center having entered the subduction zone, these microplates were captured by the Pacific plate and started to move northwest with the Pacific plate. As Luyendyk (1991) pointed out ‘‘this change made the continental margin from an east-northeast oblique Farallon-North American plate subduction zone, to a northwest Pacific-North American plate transtentional boundary’’.

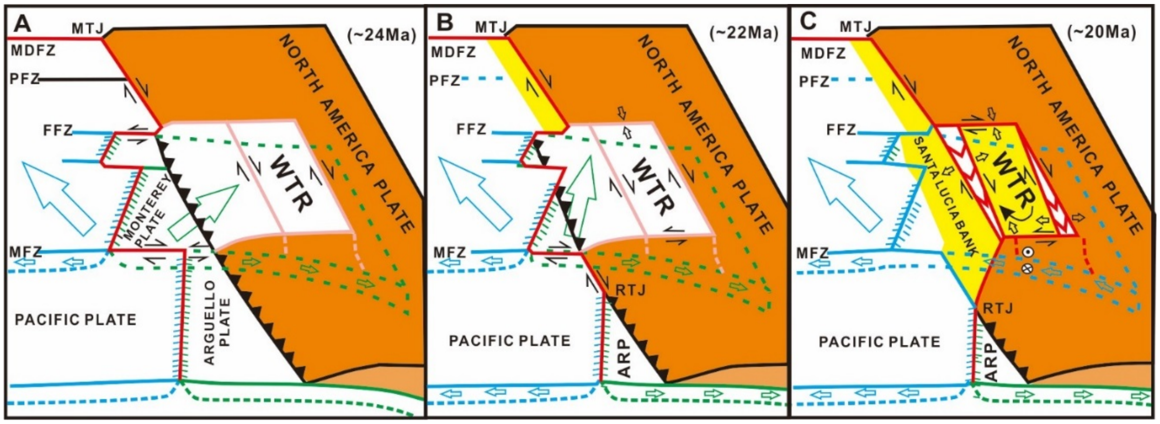


Figure 4. Schematic illustration of the Monterey plate by the Pacific plate showing directions and magnitudes of relative plate movements. A) Arguello (ARP) and Monterey plates subducted under the North America plate. B) Spreading between the Monterey and the Pacific plates became slowly, and the direction of relative plate movement starts to rotate. C) Full capture of the Monterey plate by the Pacific plate, detachment of the Santa Lucia Bank (SLBF) and Transverse Ranges (WTR) from North America by basal shear, and a slab window opened as the Transverse Ranges starts rotation (Nicholson et al., 1994).

This new Pacific-North America plate boundary is the 3,000 km long San Andreas fault, which is a complex, interlocking broad system of active faults. This fault system is a right-lateral fault associated with transpressional stage in this region (Share, 2015)

As the plate motion happened, the basal shear generated by the captured Monterey microplate split three north-south oriented blocks of continental crust from the North America plate. The Santa Lucia Bank and the Outer Continental Borderlands were captured by the Pacific plate and moved obliquely up the coast and slightly seaward (Atwater and Stock, 1998). However, the Transverse Ranges block was trapped against the North America plate in the plate boundary and started to rotate clockwise, ultimately 80-110° (Nicholson et al., 1994).

During the Transverse Ranges block clockwise rotation, a slab window opened as the Santa Lucia Bank, the outer Continental Borderlands and the southern end of the Transverse Ranges approached to the Pacific plate. This large rotation and extension caused extensive normal faulting and a number of basins opened, which contributed to the early stage of the Oak Ridge fault and Ventura Basin, and provided the mechanism for the eruption of extensive Miocene volcanics (Atwater and Stock, 1998; Jackson and Molnar, 1990).

2.1.3 Transpression

Figure 5 shows the last stage in the evolution of the Transverse Ranges block in this region. As the captured microplates shifted to the northwest with the Pacific plate, Baja California rifted away from mainland Mexico and was captured by the Pacific plate. It was transported northwest and formed the southern portion of the San Andreas system. The compression of Baja pushing northwest against southern California changed the previous transtensional regime and created two transpressional bends in the San Andreas fault that trapped the Transverse Ranges block at the east against the larger of the two bends, extruding it westward and compressing it north-south. Compression caused uplift in this region and result in reverse faulting and folding in adjacent crustal blocks. The pre-Miocene Oak Ridge normal fault was inverted to a reverse fault, a few mountains formed on the south block of the Oak Ridge fault due to late Quaternary uplift (Bohannon and Geist, 1998; Bohannon and Parsons, 1995; Crouch, 1979).

In conclusion, the structural history of the Oak Ridge fault consists of three stages based on the regional tectonic evolution: 1) Miocene normal faulting coinciding with extension and volcanism. 2) Pliocene to middle Pleistocene reverse faulting related to the transpressional regime, and 3) late Quaternary uplift.

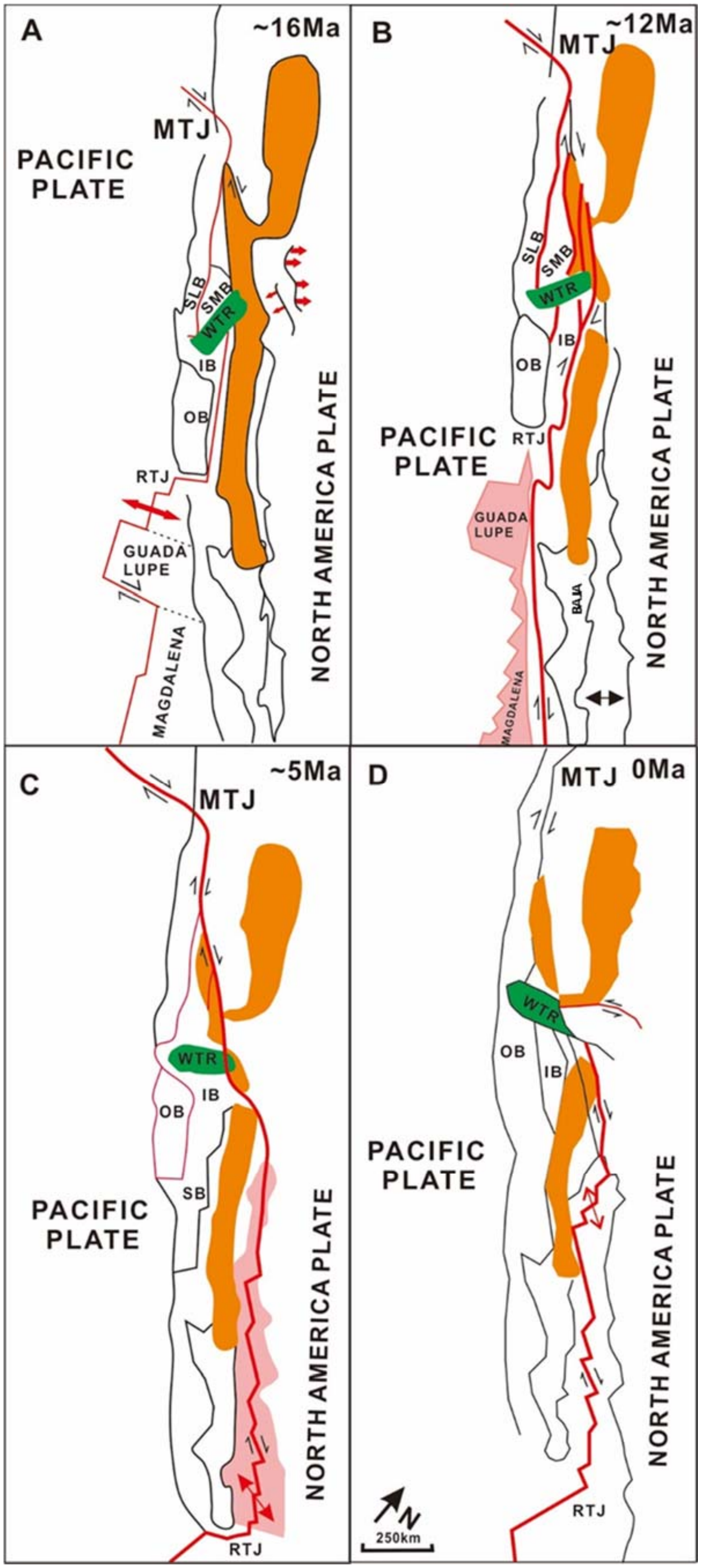


Figure 5. A) Ongoing rotation of the Transverse Ranges caused a slab window open, and the Inner continental Borderlands (IB) intrusion. The Farallon plate continued to fragment into the Magdalena and Guadalupe microplates. B) Spreading began in the Gulf of California. A transform boundary was well formed on the Pacific side of Baja. C) Capture of the Magdalena and Guadalupe microplates and Baja California by the Pacific plate. Plate boundary realigned through southern California. D) Baja started to move to northwest, pressing its northern end against southern California and changing to a transpressional tectonic regime with the Transverse Ranges being extruded around the larger transpressional bend of the San Andreas fault (Red line) and shortened north-south (Nicholson et al., 1994).

2.2 Tectono-stratigraphic setting

As the study area lies within the Ventura Basin and the Oak Ridge fault bounds the south boundary of the Ventura Basin, the stratigraphy of the Ventura Basin can be used to study the tectono-stratigraphic setting of the study region (Figure 6). In this case, Pliocene-Pleistocene and Quaternary deformation can be understood by analyzing the thickness of these sequences in the hanging wall and footwall blocks.

2.2.1 Pre-Miocene strata

Cretaceous and Paleogene strata

This unit primarily is a thick sandstone sequence, including unnamed Cretaceous strata and the Eocene Juncal, Matilija, Coay dell and Coldwater Formations. However, on the south of the Oak Ridge fault, the Eocene strata of the central Ventura Basin are missing (Yeats, 1988).

Llajas Formation

This unit is a lower to middle Eocene marine strata with a thickness of 750-1280 m, overlying unnamed Paleocene and Cretaceous strata with a low-angle unconformity. These strata contain sandstone and gray siltstone, Bathyal foraminiferal faunas and neritic faunas are found in the middle and late Eocene respectively, reflecting the transgressive-regressive cycle of this sequence (Rotzien et al., 2014; Yeats, 1988).

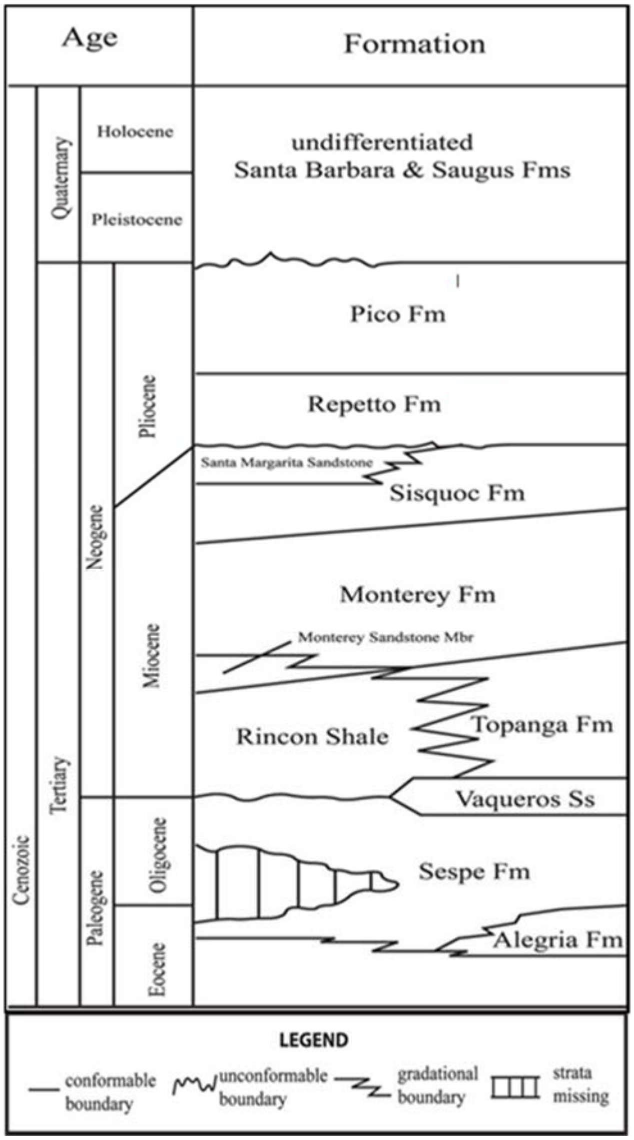


Figure 6. Chronostratigraphic chart of the Santa Barbara-Ventura Basin province with stratigraphic units. Adapted from Rotzien et al. (2014).

Sespe Formation

This unit is a non-marine Eocene and Oligocene strata. It is a red bed sequence including sandstone, mudstone and local conglomerate with a thickness of 1770 to 2120 m (Huftile and Yeats, 1995). This unit was cut by Miocene normal faulting before the deposition of the Vaqueros Formation (Yeats, 1988).

2.2.2 Miocene strata

The Miocene south of the Oak Ridge fault consists of three sequences: 1) the lower Miocene Vaqueros Formation, 2) the middle Miocene Topanga Formation, and 3) the middle and upper Miocene Monterey Formation (Yeats, 1988).

Vaqueros Formation

This unit is a shallow marine sandstone formation. It lies with angular unconformity over the normal-faulted Sespe Formation with a thickness of 100 to 200 m (Yeats et al., 1988).

Topanga Formation

The Topanga Formation is a marine sandstone intruded by a sill of hornblende andesite (Yeats, 1988).

Monterey Formation

Kew (1924) subdivided the Monterey Formation into a lower, more siliceous member and an upper, more clay-rich member. The lower member consists of thin-bedded organic shale with interbedded sandstone, limestone, and chert, and the upper member includes chocolate-brown to white diatomaceous shale, siltstone, and chert. The uppermost Monterey Formation contains a siliceous fauna that is not age-diagnostic. The thickness of the Monterey Formation generally increases eastward from 150 m to 730 m approximately.

However, wells on the north of the Oak Ridge fault are not deep enough to penetrate the Miocene. Information on the Miocene is based on exposures on the north side of the Ventura trough where the Sespe Formation is overlain by the Vaqueros Formation (primarily shallow-marine sandstone), Rincon Shale, and Monterey Formations. Miocene thicknesses on the north side of the Ventura Basin are thick due to the transtensional regime at this time. They are 450-600 m for the lower Miocene Rincon Shale Formation and 600-

780 m for the middle and upper Miocene Monterey Shale Formation (Crouch, 1979; Huftile, 1988; Jackson and Yeats, 1982; Nagle and Parker, 1971; Schlueter, 1976). The Monterey Formation is the source rock in this area (Yeats and Taylor, 1990).

2.2.3 Pliocene and Pleistocene strata

Sisquoc Formation

This unit is predominantly fine-grained deep-water marine shales and sandstones. The thickness of the Sisquoc Formation is 640 m in the Carpinteria area (Jackson and Yeats, 1982) and 460 m in the upper Ojai valley (Schlueter, 1976).

Fernando Formation

This Formation consists of two units: The Repetto Formation and Pico Formation. The Repetto-Pico succession is an abyssal-plain turbidite sandstone with interbeds of marine siltstone and mudstone. This succession is from 5.3 to 2.6 Ma. The Repetto Formation lies unconformable over the Sisquoc Formation and underlies the Pico Formation. The thickness of this succession is around 5 km near the coast, and 7.7 km thick in the deepest part of the Basin east of Santa Paula. During the deposition of these units, both sides of the Oak Ridge fault subsided, but the north side received greater sediments than the south block due to larger subsidence (Yeats, 1988).

Santa Barbara and Saugus Formations

The Santa Barbara-Saugus succession is a shallow-marine and nonmarine sandstone, claystone and conglomeratic braided-channel unit of Pleistocene age. This sequence is regressive, changing up-section from bathyal hemipelagic and submarine fan turbidite deposits to granular shallow marine, local transitional, and granular continental deposits. The Pleistocene sequence is nearly 5 km thick in the deepest part of the basin. This succession is the main reservoir rock in the study area (Yeats, 1988).

2.2.4 Late Quaternary sediments

During late Quaternary, the shift from deposition to erosion accompanying major folding and faulting from 0.2 Ma to the present lead to the poor preservation of the late Quaternary geological record. During this time, the Oak Ridge, South Mountain, and the Ventura Hills north of the lower Santa Clara River were uplifted, and the shoreline migrated westward and eastward in response to Pleistocene eustatic sea-level changes. The late Quaternary uplift caused by intense compression affected the Ventura Basin except the coastal area, therefore coastal area kept good preservation of the late Quaternary sediments (Yeats, 1988).

3. Data

The data set included in this research consists of wells, subsurface maps, faults interpretation and cultural data (Figure 7). These raw data were included in a Petrel project.

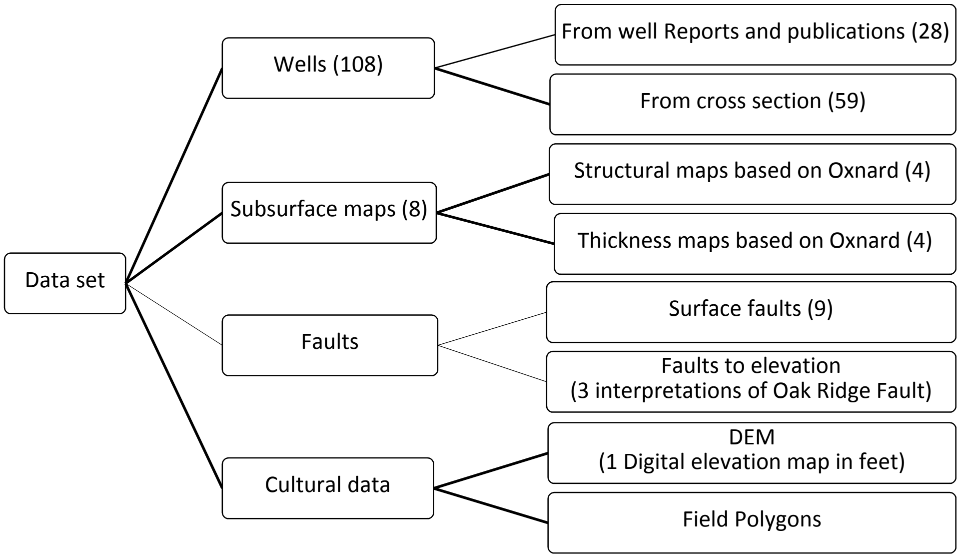


Figure 7. Raw data set in Petrel for this research.

3.1 Well data

This research includes 108 wells from well reports and publications. This information consists of the trajectory, dip/azimuth data, well tops, total depth, ground elevation and well image. Table 1 shows the number of wells related with the type of input information and the source data. As 17 wells do not have dip-meter, well tops or well image except trajectory, 91 wells were used in this research to generate the 3D structural model.

Table 1. Well raw data information in Petrel of this research.

Sub-folder	*No. of wells*	*Information*							
		Dipmeter		*Welltops*		*Trajectory*		*Image*	
		Yes	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*
Original	21	5	16	13	8	21	0	6	15
Reports	28	18	10	4	24	28	0	0	28
Cross-section	59	41	18	57	2	59	0	38	21
Total	**108**	64	44	74	34	108	0	44	64

Well tops

The well top data was defined based on well reports, well log images, well correlation sections, and publications. The well tops taking into account in this research were Santa Barbara, Pico, Repetto, Santa Margarita, Monterey, and Sespe Formations.

Subsurface maps

This folder contains four structural maps (Pliocene, Base Monterrey, Top Sespe and Miocene) and four thickness maps (Pliocene-Miocene, Lower Pliocene- Repetto, Top Pico-top Repetto, and Top Pliocene-Pico). The contours of these maps were imported as points (XYZ) in Move.

3.2 Fault information

The surface faults were geo-referenced and digitized using ArcGIS. The points were exported as XYZ files and imported into Move software. The fault structural contours information that existed in the original Petrel project was given by Shell. The fault contours were imported as points (XYZ) in Move.

3.3 Cultural data

This information includes a DEM (digital elevation model) and the field polygons. One geological map derived from a publication (Shearer, 1998) allowed identification of faults and folds on the surface.

As most of the well tops derived from the cross sections were identified based on well logs images, there is a considerable measure of uncertainty due to different geologist’s explanation and resolution of the well profile.

4. Methodology

In this research, in order to describe and analyze the geometry of the Oak Ridge fault and related folding, a 3D structural model was built. The 3D model was important as it gave a visualized insight into the structural geometry, fault displacement, growth strata and layer juxtapositions.

When the fault plane and related horizons were reconstructed, and the relationship between these two were checked, it was possible to evaluate the consistency of the model to see whether the model was geologically reasonable or not. The 3D model process consists of two steps: 1) Fault plane reconstruction, and 2) horizons reconstruction.

4.1 Fault plane reconstruction

As all the data needed in this research was originally in the Petrel project, the first step was to transfer the data from Petrel to Move with the tool ‘Move Link for Petrel’. Figures 8 shows the location and well information on map view and 3D view of all wells.

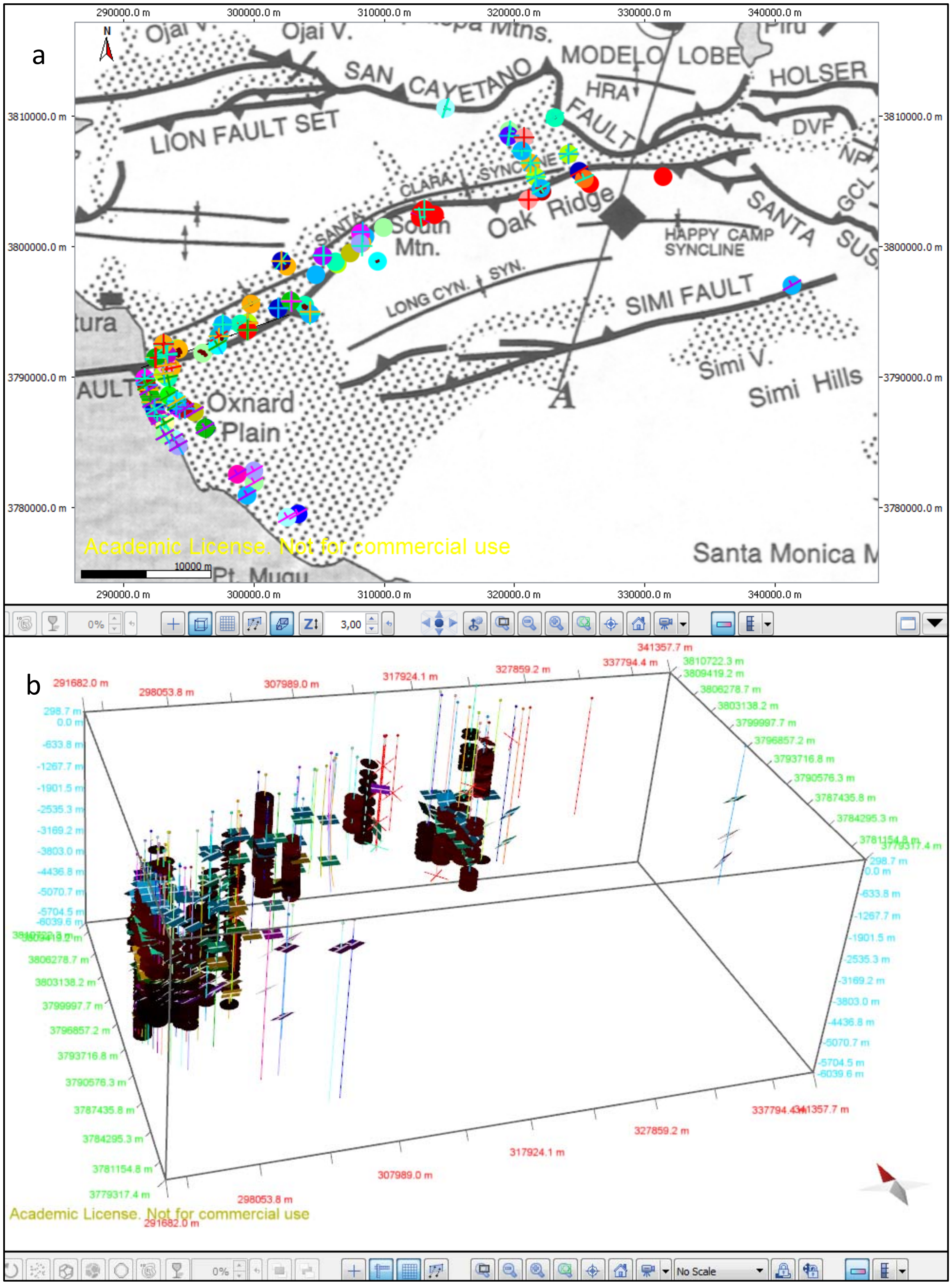


Figure 8. a) 2D view of wells location. b) 3D view of wells with well tops (square), fault markers (red cross) and dip meter data (circle).

The second step is to make serial cross sections along the Oak Ridge fault (Figure 9). Most cross sections were made perpendicular to the Oak Ridge fault, while some were made parallel to it to model the lateral distribution of horizons. Then nearby wells were projected into the sections. Finally, the fault dip data was used to interpret the fault on the cross sections (Figure 10). In this research, I made 36 cross sections (Figure 9) to build the geometry of the Oak Ridge fault, 15 of them were built based on the well images from the original Petrel project and the well correlations in publications. However, the rest of the cross sections were used to control the shape of the fault surface and horizons in the area with less well data. The fault contour lines derived from Petrel were used as a reference to reconstruct the fault surface in the area with less well data control.

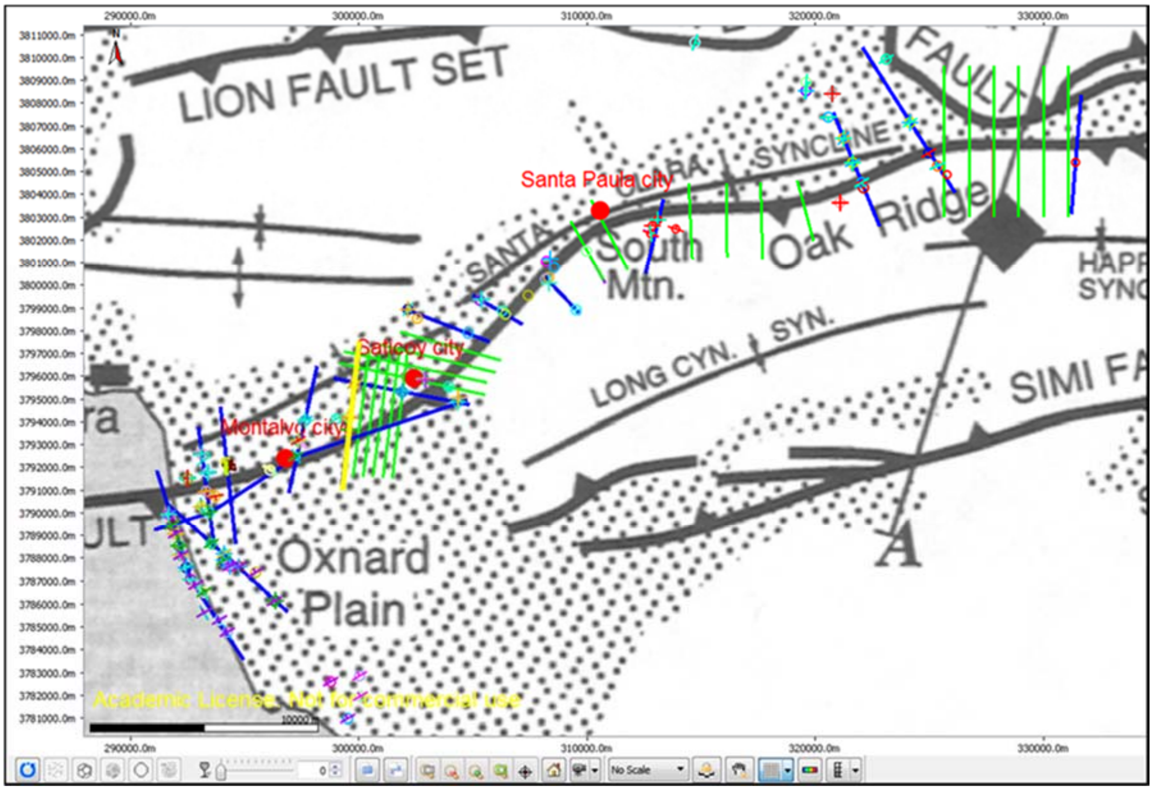


Figure 9. Well location and cross sections in the study area. Blue traces are generated based on the well image from the original Petrel project and well profile in publications, while green traces are "fake" cross sections to control the shape of the fault surface and horizons in the area with less well data control. Yellow line represents the cross section in Figure 10. Red points are Santa Paula city, Saticoy city and Santa Paula city.

After finishing the interpretation of the fault in the serial cross sections (Figure 10 and Figure 11a), I collected the traces that appear consistent in all cross sections to create the fault surface from these traces (Figure 11b). Linear and Delaunay Triangulation methods were used to reconstruct the fault surface (Figure 12). The Linear Method can join the neighboring control points with straight lines and produces a grid of triangles between control points. This method honors all control points and to some extent interpolate the surface between the collected lines. In order to create a smoother fault surface, the ‘Sample Density’ tool was applied when using the linear method. This tool can increase additional control lines parallel to the selected interpreted lines to produce more control points and therefore produce more triangles to create a denser surface mesh. Delaunay Triangulation was used to create fault surface from fault contour points. This method can make the geometry of triangles in a grid more uniform, and also has the advantage of honoring data points without adding or removing data points.

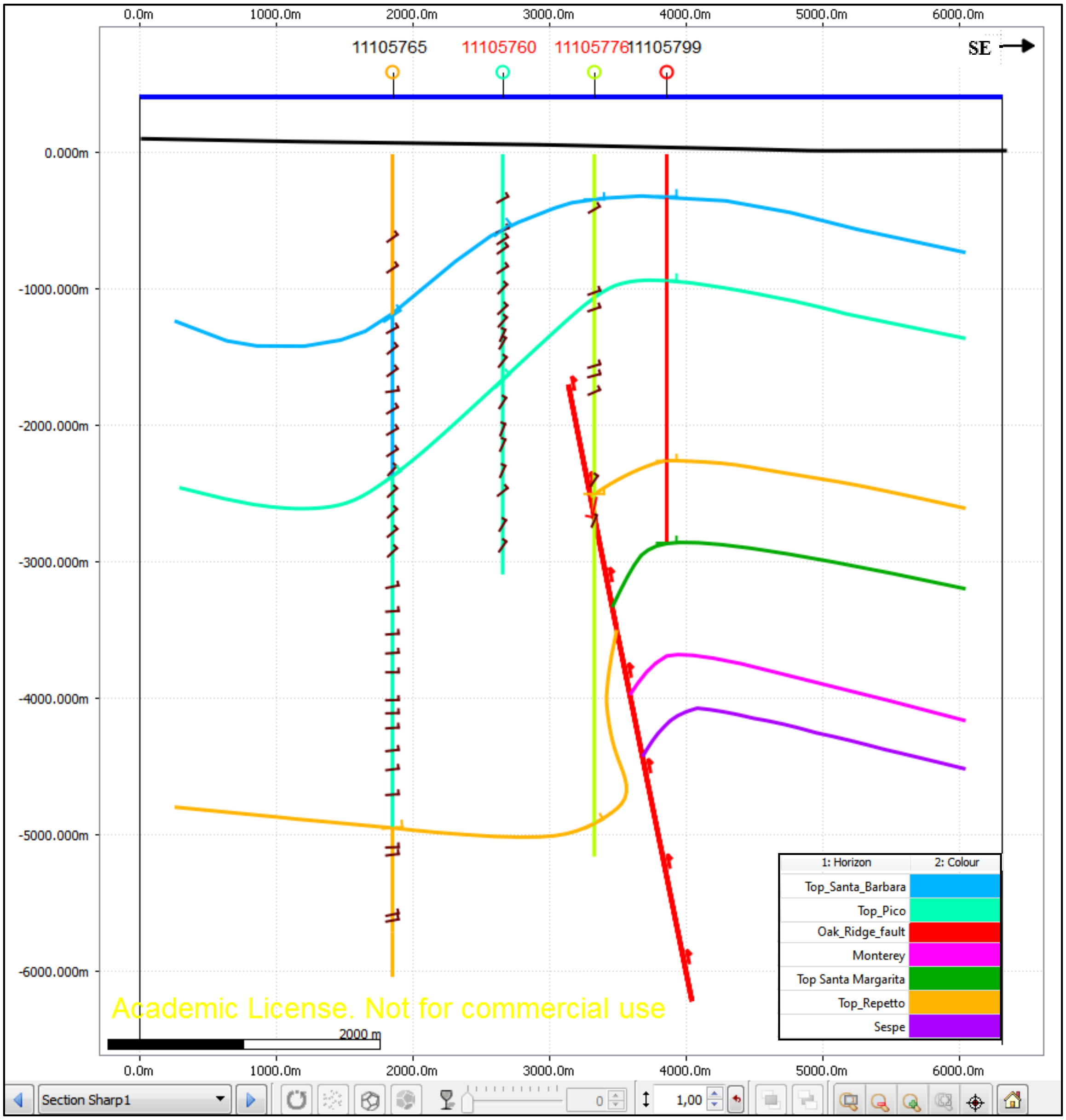


Figure 10. An example (cross section 7) shows the interpretation of the fault and the horizons based on well tops and dip meter data.

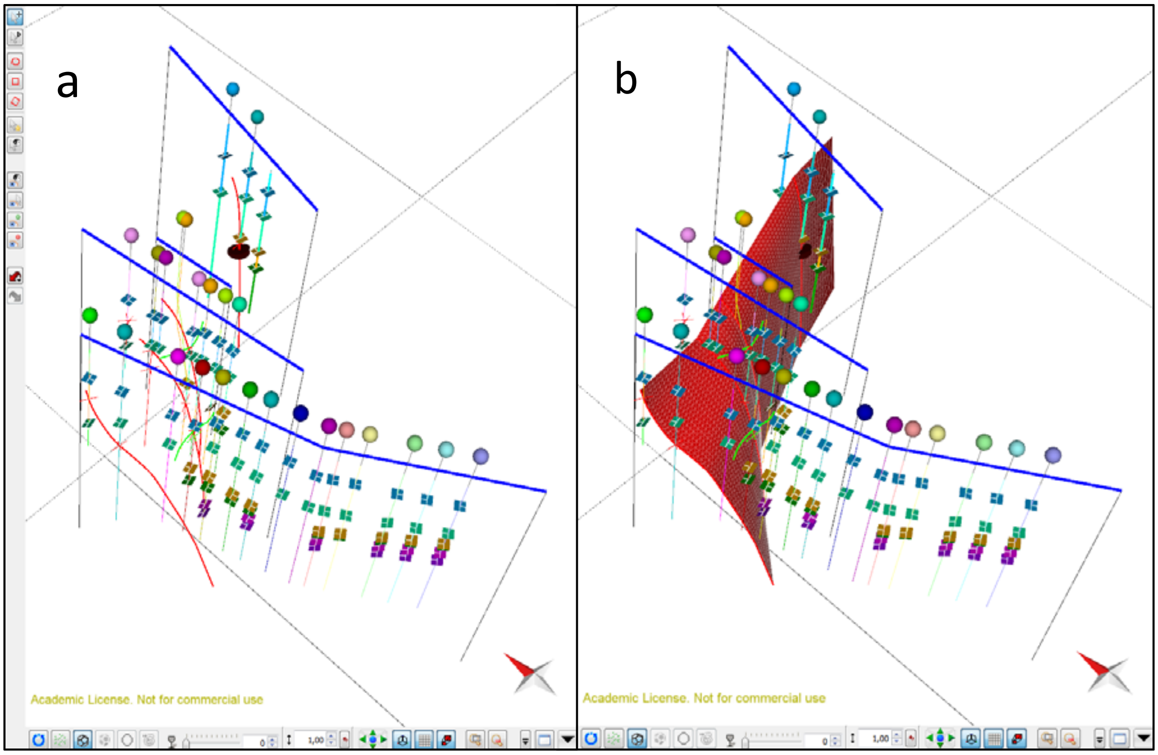


Figure 11. Fault surface construction example in 3D view. a) Three cross sections with fault line interpretation. b) Fault surface creation from fault lines using the linear method.

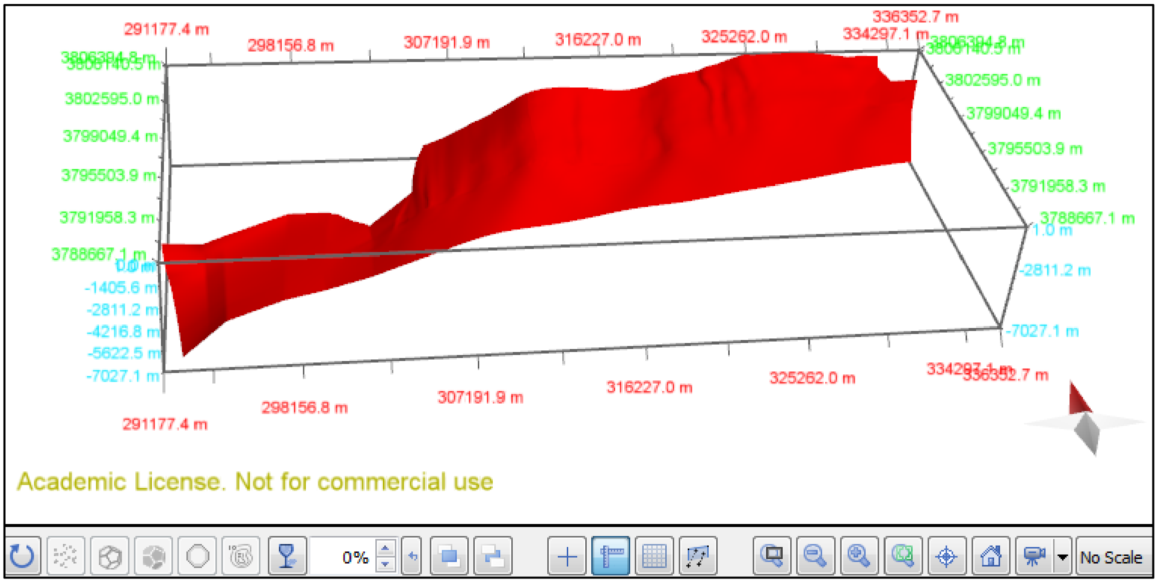


Figure 12. Final Oak Ridge fault surface in 3D window.

4.2 Horizons reconstruction

The horizons reconstruction process is similar to the fault plane creation. At first, I interpreted the geometry of the horizon by integrating well tops, dips and azimuth data on the cross sections (Figure 10). Then I collected the same horizon traces that appear consistent in all cross sections to create the horizon surface.

In this step, the DEM (digital elevation model) was collected as the topography on the cross section, 4 structural contour maps and 4 thickness maps were collected on the cross sections to control and check the depth, distribution and variation of the horizon surface in different areas, especially in areas with less well data control. Here, I also used the linear method to create the horizon surface from the horizon lines. (Figure 13).

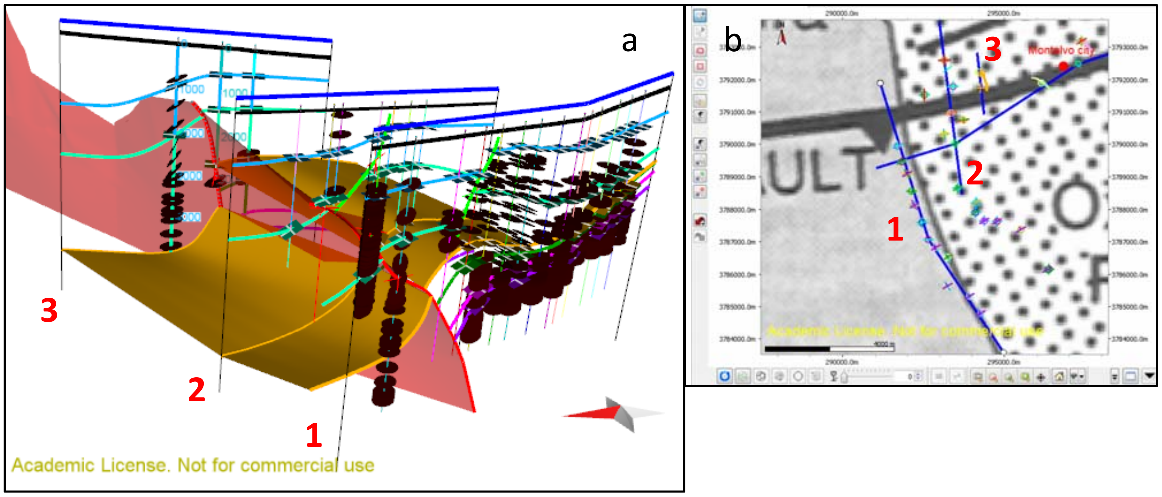


Figure 13. Reconstruction of the Top Repetto surface (coastal segment) with linear method. a) Three cross sections interpretation and Repetto surface (yellow color). The yellow lines are Repetto horizon lines. b) Location of three cross sections.

However, Delaunay Triangulation was also applied to create the horizon surface from points as the throw of the Oak ridge fault is different in different areas. For example, in the middle segment of the model close to the Saticoy oil field, since the Oak Ridge fault does not offset the Repetto Formation, it is difficult to create a consistent surface respecting the well data and the fact that the fault tip-line is below the horizon (Figure 14a). Therefore, I created a series of “fake” cross sections to reconstruct the shape of the Repetto horizon. I collected the traces that appear consistent in the cross sections and created the horizon surface separately on the hanging wall and footwall blocks. Then I merged these separate surfaces and converted them into points (Figure 14b). Finally, I generated the Repetto horizon by using the converted points with the Delaunay triangulation method. Figure 14c shows the result of the Repetto horizon segment.

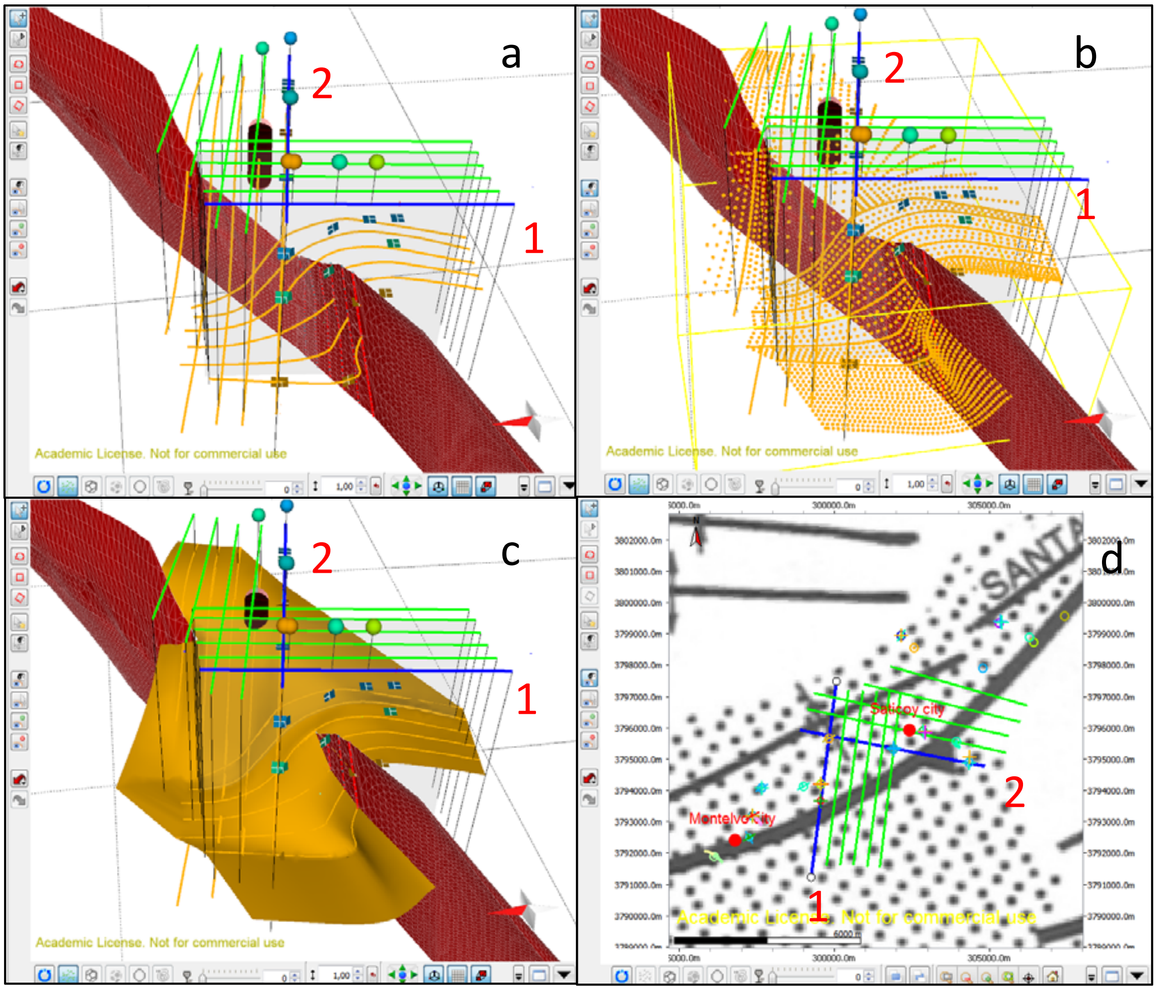


Figure 14. Reconstruction of the Top Repetto surface near Saticoy city. Blue lines are cross sections with well control. Green lines are fake sections. a) Cross section with well top and Top Repetto horizon line interpretation. b) The point data converted from merged separate surfaces. c) Final top Repetto surface created from points using Delaunay triangulation. d) Location of these cross sections in the study area.

The last step is to use advanced model conditioning tools to edit the fault plane and horizon surface based on the relationships between them. Additionally, model building and conditioning tools like Edit, Reshape, Resample, Smooth, Split were also applied to modify the final model and make it more reasonable to reflect the structural framework of the study area. The results of this methodology are presented in the next section.

5. Result

5.1 Fault model geometry

5.1.1 Oak Ridge fault

In this research, well data provide structural control on the Oak Ridge fault to depths as great as 6 km. The fault was subdivided into four segments based on its strike variation, these segments are: (1) coastal segment, (2) oblique-slip segment from Saticoy to Santa Paula city, (3) dip-slip segment from Santa Paula to Balcom Canyon, and (4) dip-slip, lobate segment from Balcom Canyon to Wiley Canyon (Figure 15) (Yeats, 1988). A total of 15 cross sections were made to reconstruct the geometry of the Oak Ridge fault (Figures 16 to 19). All cross sections are at the same scale and have no vertical exaggeration. Rose diagrams (Figure 20) and a dip attribute map (Figure 21) show the strike and dip of the Oak Ridge fault in each segment.

- Coastal segment

The coastal segment is at maximum burial on both the hanging-wall and the footwall. The main orientation of the coastal segment is NE-SW (Figure 20, segment 1). The dip of this segment increases eastwards up to 80 degrees southeast (Figure 21). On the western part of this segment, the Oak Ridge fault cuts the Pico Formation but dies out in the upper Santa Barbara Formation (Figure 16, cross sections 1 to 5). However, at the east end of this segment, the fault does not cut the Pico Formation, which is folded into a steep monocline above the fault (Figure 16, cross section 7).

- The oblique-slip segment

In the oblique-slip segment between Saticoy and Santa Paula city, the Oak Ridge fault dips as steep as 85 degrees southeast with a main orientation NE-SW (Figure 20, segment 2; Figure 21). Unlike the coastal segment, the fault cuts the Santa Barbara and Saugus Formations (Figure 17), and it is probably expressed at the surface by a scarp. However, the Santa Clara river flows down the surface trace of the fault and is in part located in the hanging-wall block, thus the fault does not seem to have a surface expression (Yeats, 1988).

- The dip-slip segment

This segment is located between Santa Paula and Balcom Canyon with a main strike ENE-WSW (Figure 20, segment 3). The dip of the fault decreases eastward from 80 to 60 degrees approximately (Figure 21). Yeats (1988) classified this segment into the dip-slip segment as the strike of the fault curves from NE to E-SE. In this segment, the Oak Ridge fault cuts the Santa Barbara and Saugus Formations (Figure 18).

- The east-striking segment

In this segment, the main orientation of the Oak Ridge fault is NE (Figure 20, segment 4). The dip of the fault slightly increases eastward from 60 to 80 degrees (Figure 21). In this segment, the Oak Ridge fault cuts the Santa Barbara and Saugus Formations (Figure 19, cross section 15).

5.1.2 Montalvo fault

The Montalvo fault is a north- dipping normal fault formed in the coastal segment. This fault diverges southwest from the Oak Ridge Fault (Figure 16, cross sections 1 to 3). The main strike of the Montalvo fault is NE-SW (Figure 22b). The Montalvo fault dips 58 to 84 degree approximately (Figure 22a). This fault cuts the entire Santa Barbara Formation. A greater thickness of the Santa Barbara Formation in the hanging wall block indicates that the Montalvo fault is a growth fault (Figure 16, cross sections 1 to 3). This fault is difficult to explain in a contractional regime. The fault may have a left-lateral strike-slip component with the slip vector trending more easterly than the strike of the fault (Yeats, 1988).

5.1.3 Problems

In this research, since the 3D structural model was reconstructed by using the well tops and dip meter data integrated with the structural maps, fault contours, and well images from publications, the 3D model is more consistent in the area with more data control. The 3D fault surfaces in Figures 21 to 23 show the anomalous areas that do not follow reasonable geometries.

In the coastal segment of the Oak Ridge fault (Figure 23), the well data used for the interpretation of cross section 1 was collected from a well image (Figure 25) in the original

Petrel project, where it is easier to interpret the fault geometry. However, for cross section 3, the fault interpretation is difficult. It should respect the well data and follow the fault geometry on the well profile (Figure 24) derived from publications. The red circle in Figure 23 shows the anomalous area, the fault dip angle decreases rapidly due to an interpretation error.

In segments 2 to 4, I mainly used the fault contours that were included in the original Petrel project to create the fault surface. An anomalous area as shown in Figure 21 is present in the deeper part of the fault model. There are two reasons causing this problem: First, less well data control in this area. Second, the fault contours did not continue as deep as the fault position marked on the well (Figure 26). Therefore the extend fault tool in Move was applied to extend the existing fault surface downwards along the dip. However, since the deeper part has less data control, the dip of the fault surface in the deeper part changes suddenly and does not follow the general geometry of the Oak Ridge fault in each segment (Figure 21). Similar errors are present in the Montalvo fault (red circles in Figure 22a).

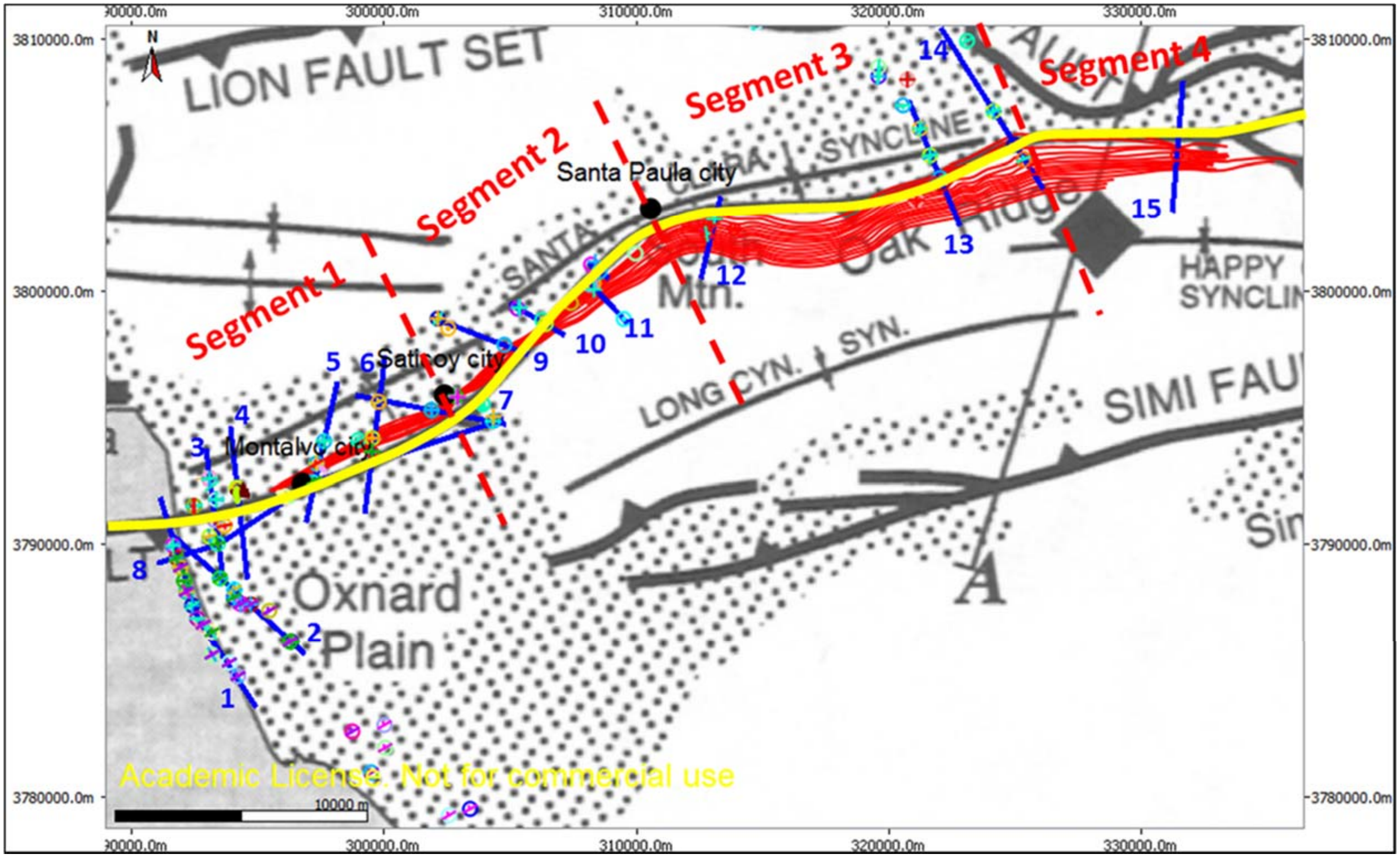
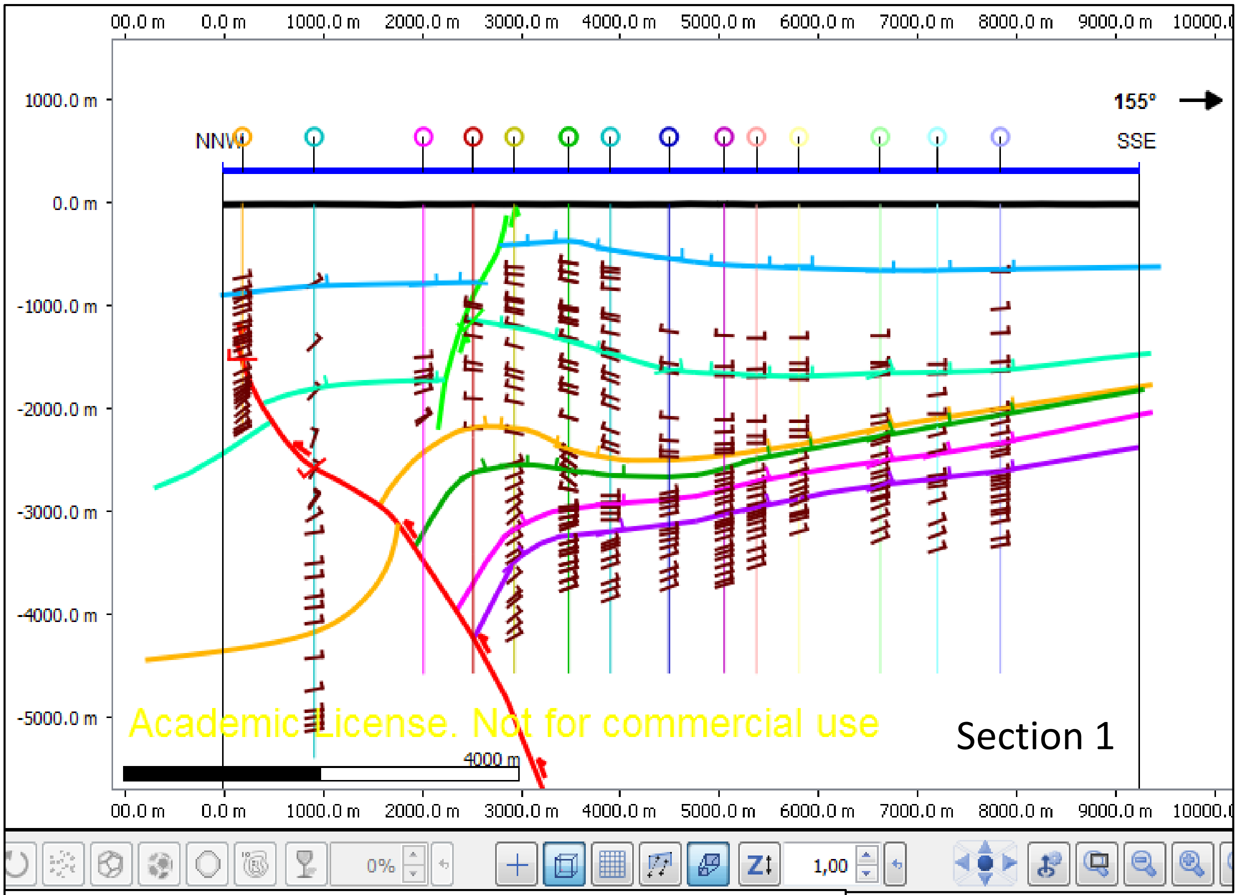


Figure 15. Map view of the Oak Ridge fault segments and cross sections. Yellow line is the surface trace of the Oak Ridge fault. Blue traces are cross sections. Black points are the location of three cities. Color circles show the well locations. Red lines are the original Oak Ridge fault contours used to create the fault surface in the area without well data control.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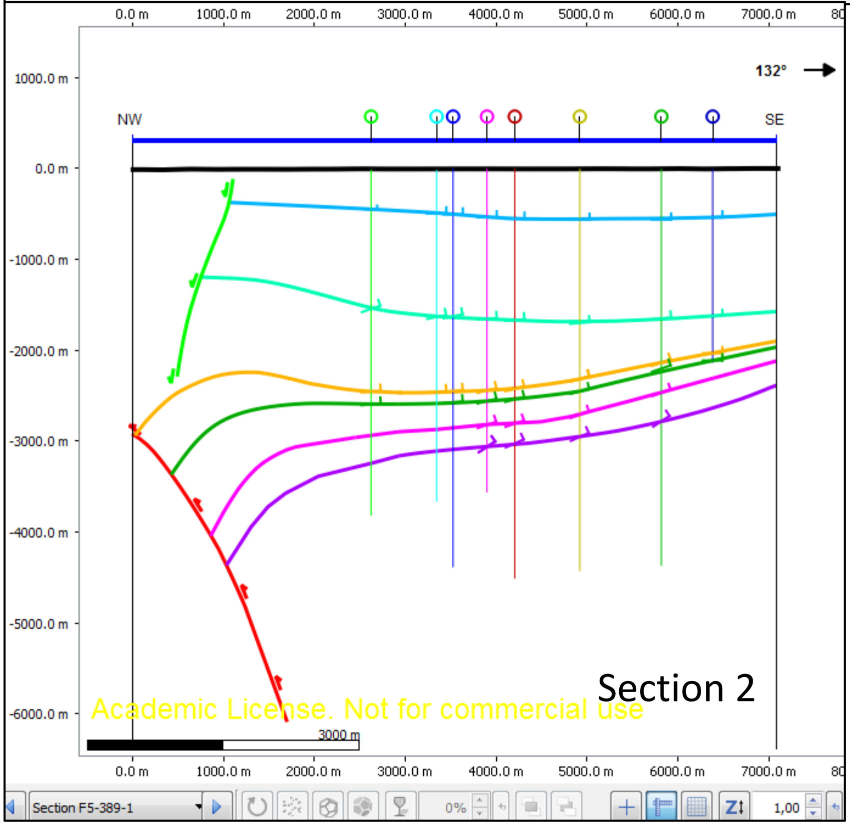
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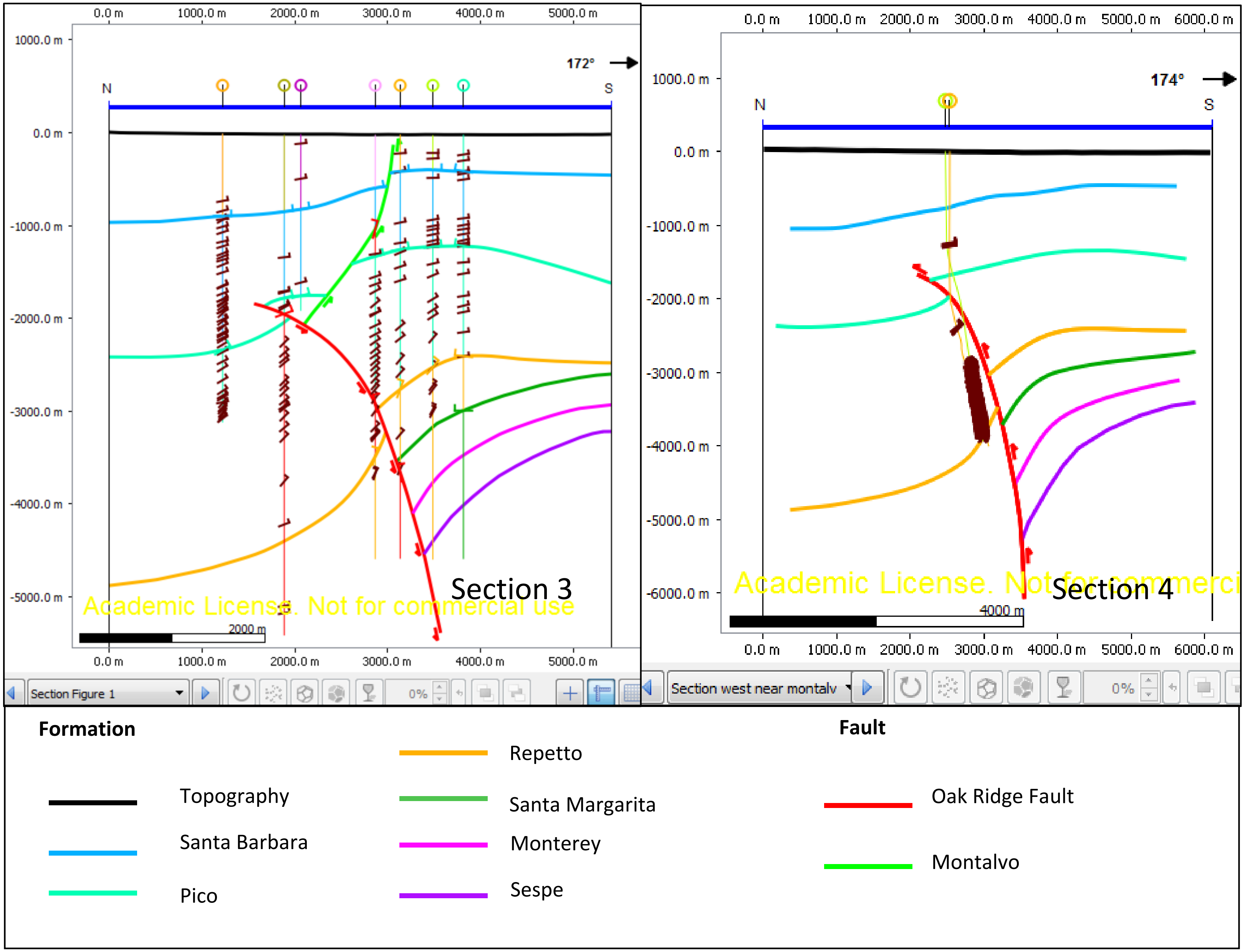
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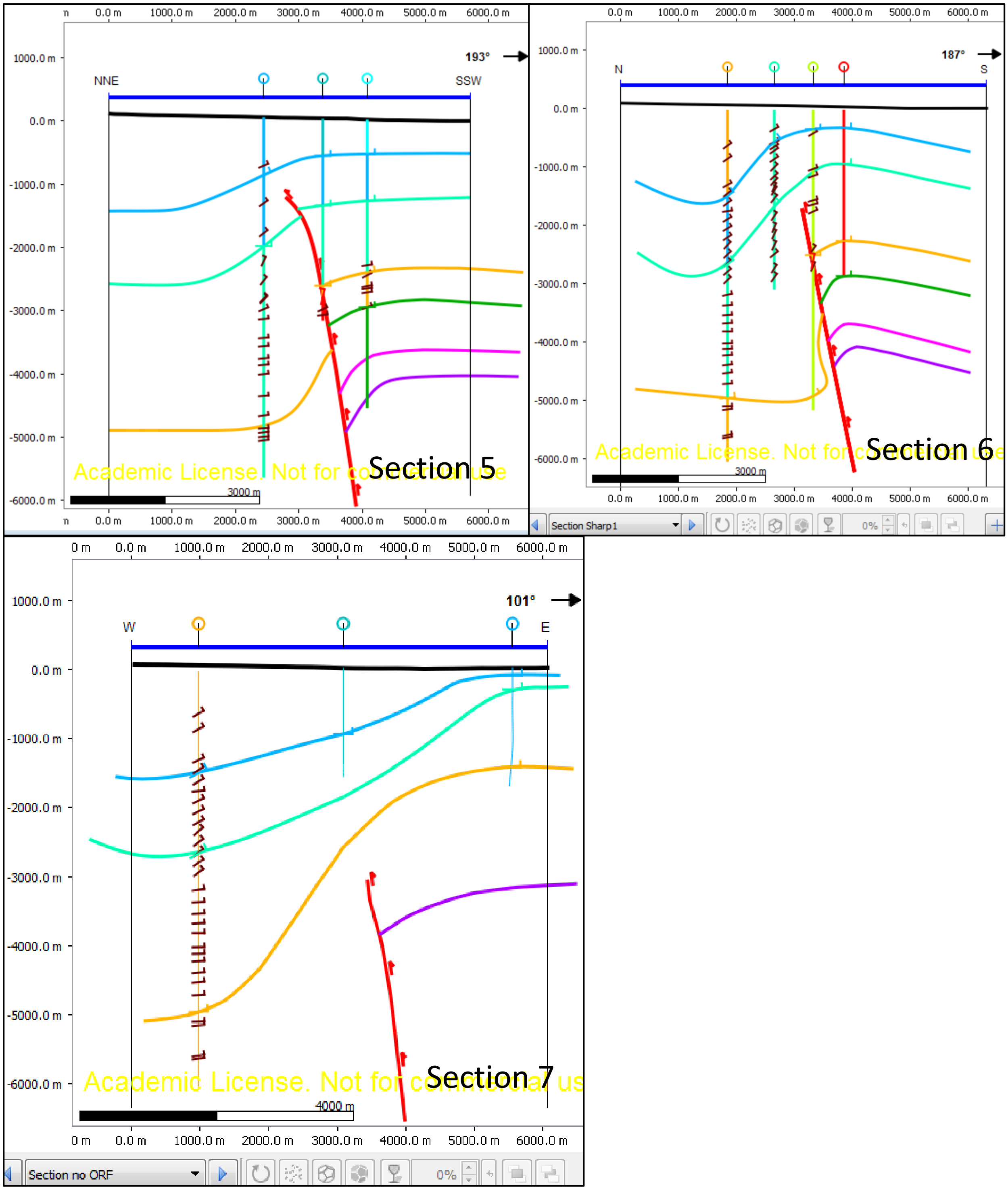

Figure 16. Cross sections 1 to 7 of the Oak Ridge fault coastal segment 1.

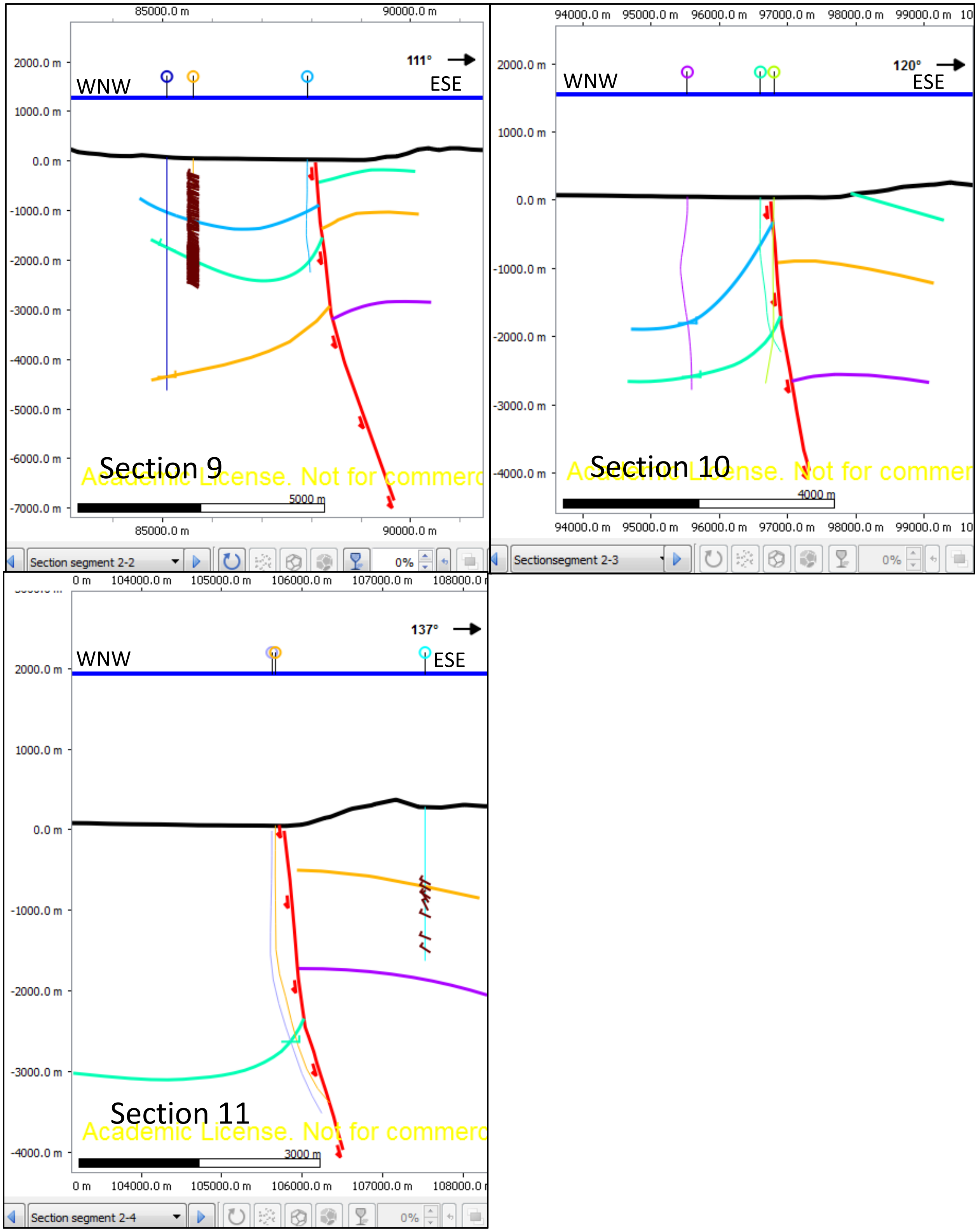

Figure 17. Cross sections of the Oak Ridge fault oblique-slip segment 2. Legend is the same as in Figure 16.

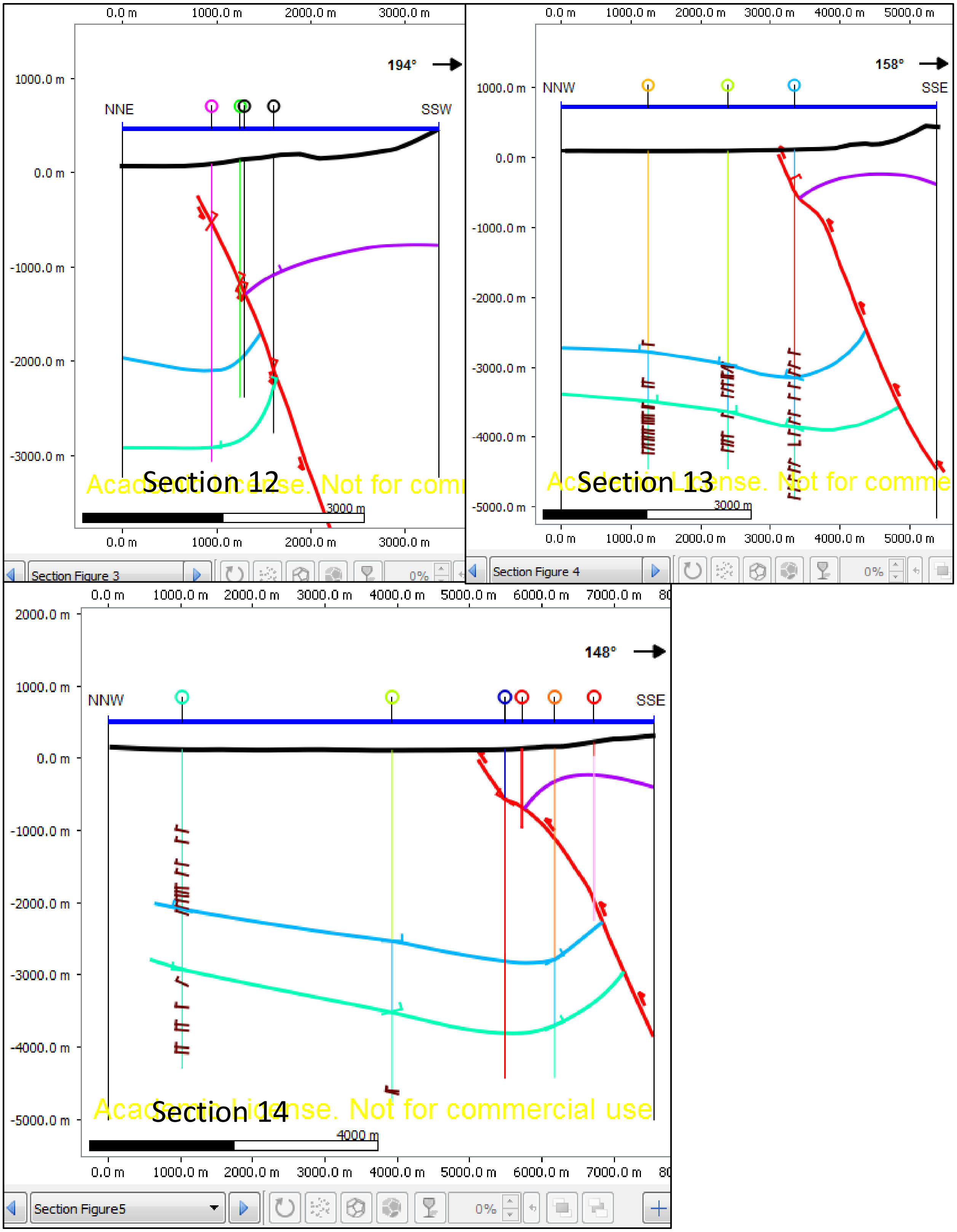

Figure 18. Cross sections of the Oak Ridge fault dip-slip segment 3. Legend is the same as in Figure 16.

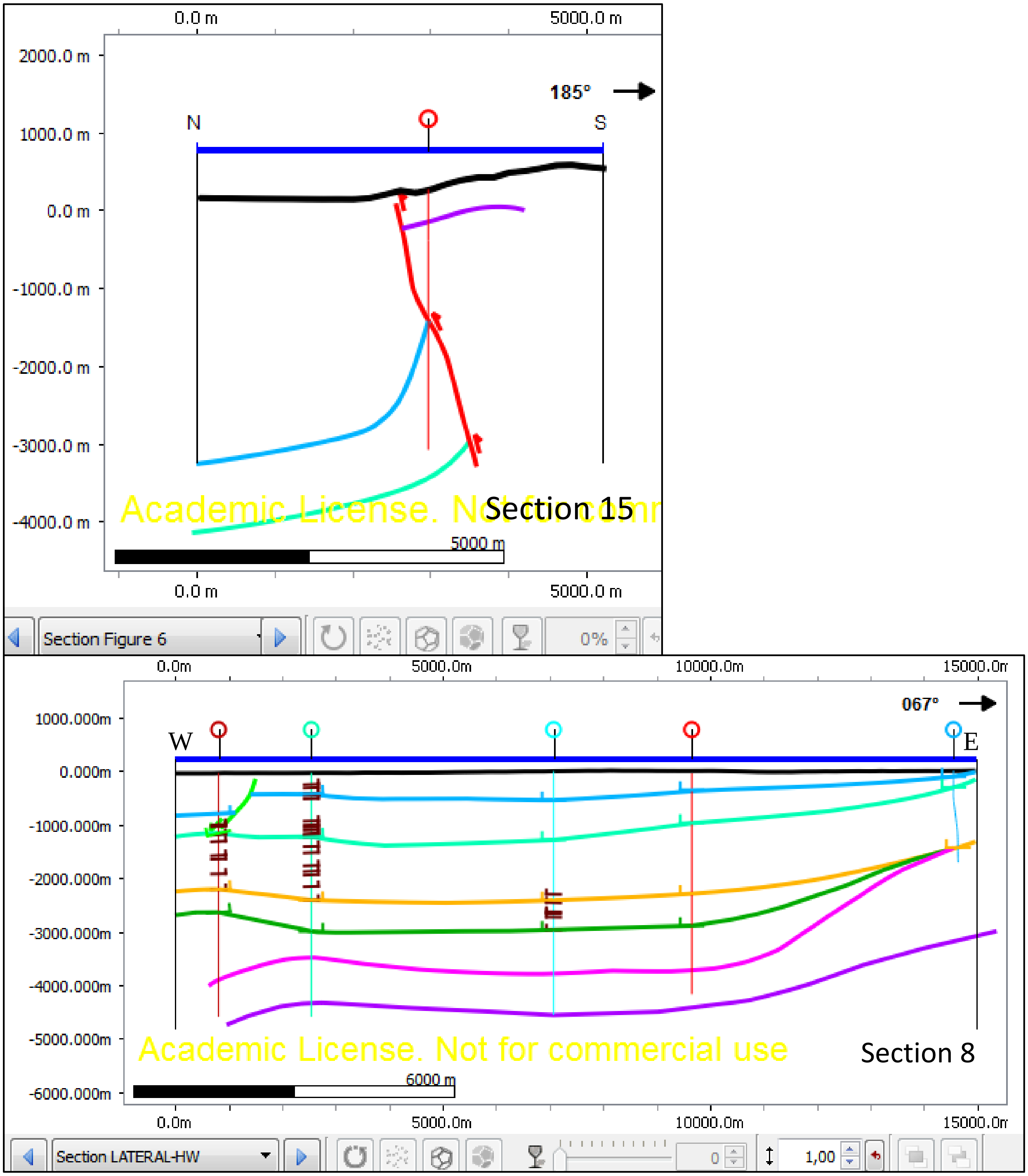

Figure 19. Section 15 shows the Oak Ridge fault geometry of segment 4. Section 8 is parallel to the Oak Ridge fault and shows the Montalvo fault and horizon geometry in the coastal segment area. Legend is the same as in Figure 16.

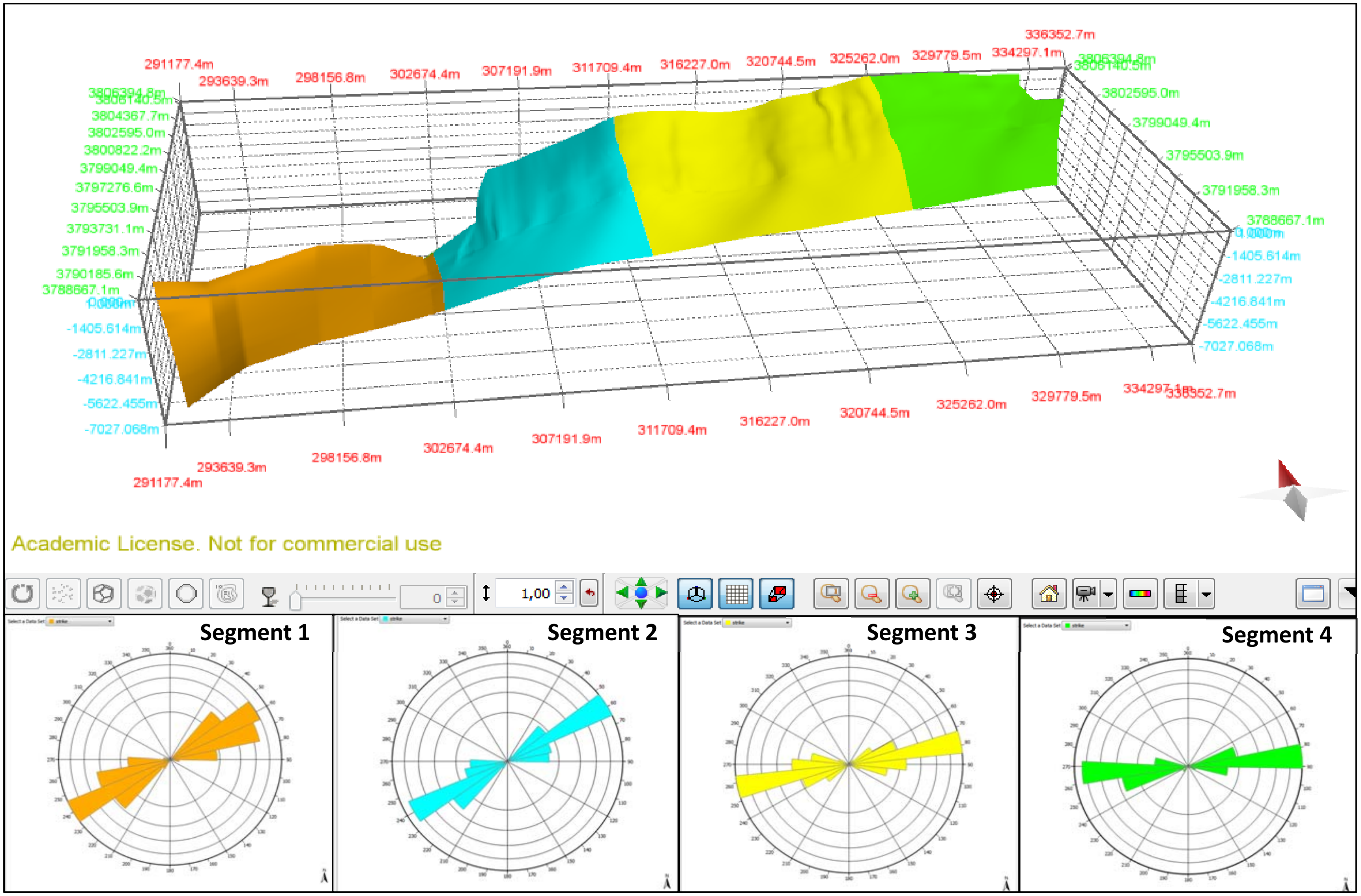

Figure 20. 3D model of the Oak Ridge fault and rose diagrams showing the strike of the Oak Ridge fault in each segment.

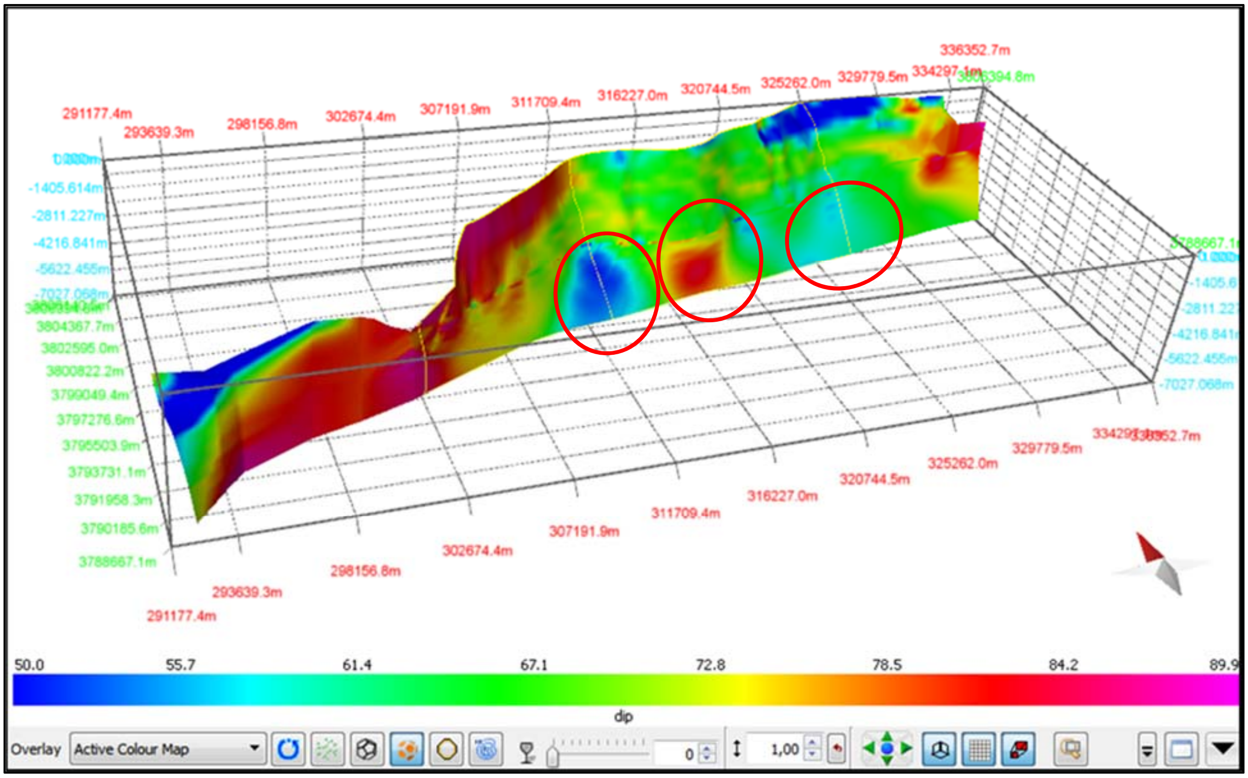

Figure 21. Oak Ridge fault surface colored by dip angle (see color scale bar). Red circles show anomalous areas.

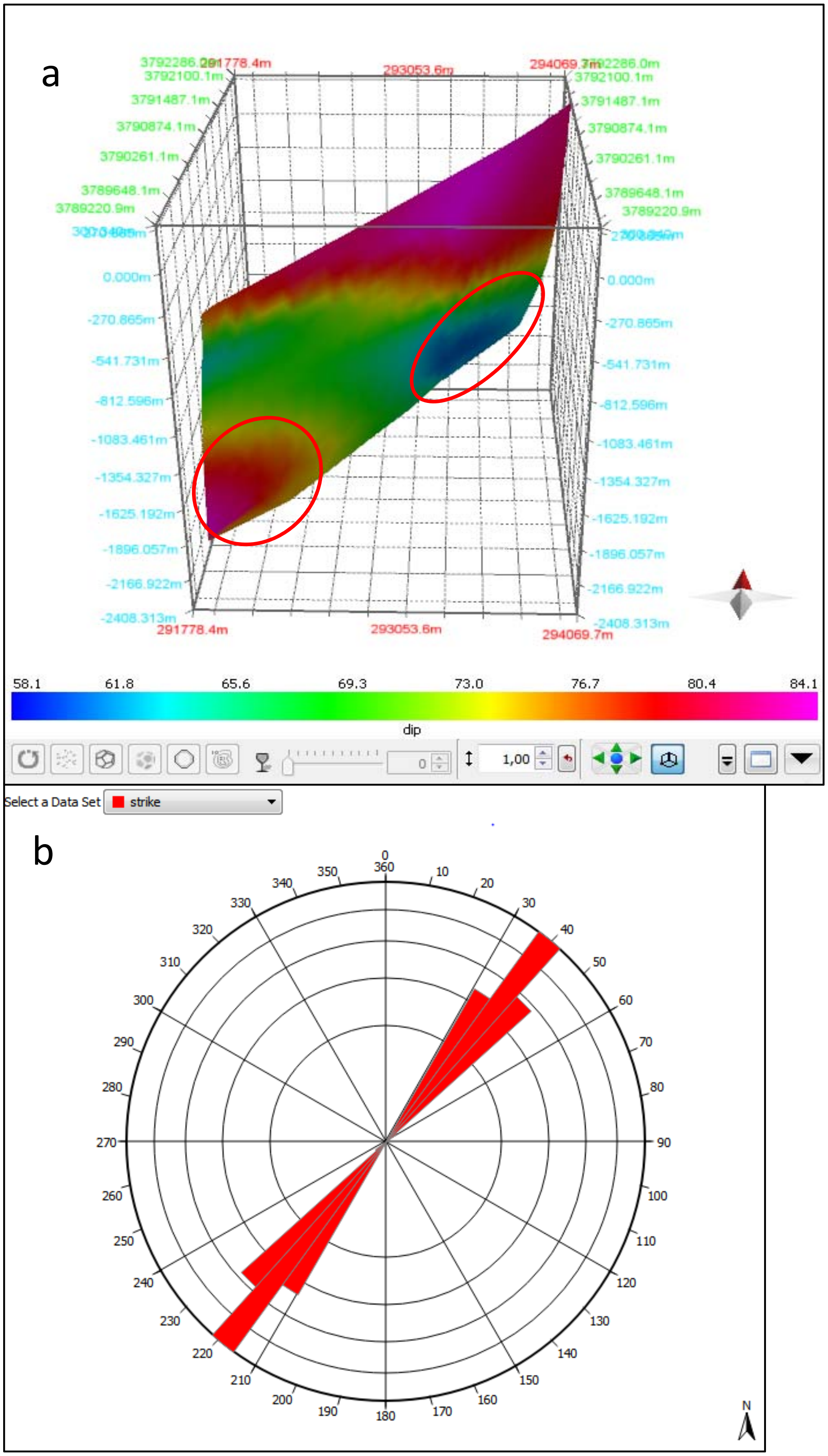

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Figure 22. a) Montalvo fault surface colored by dip angle (see color scale bar). Red circles show anomalous areas. b) Rose diagram showing the strike of the Montalvo fault.

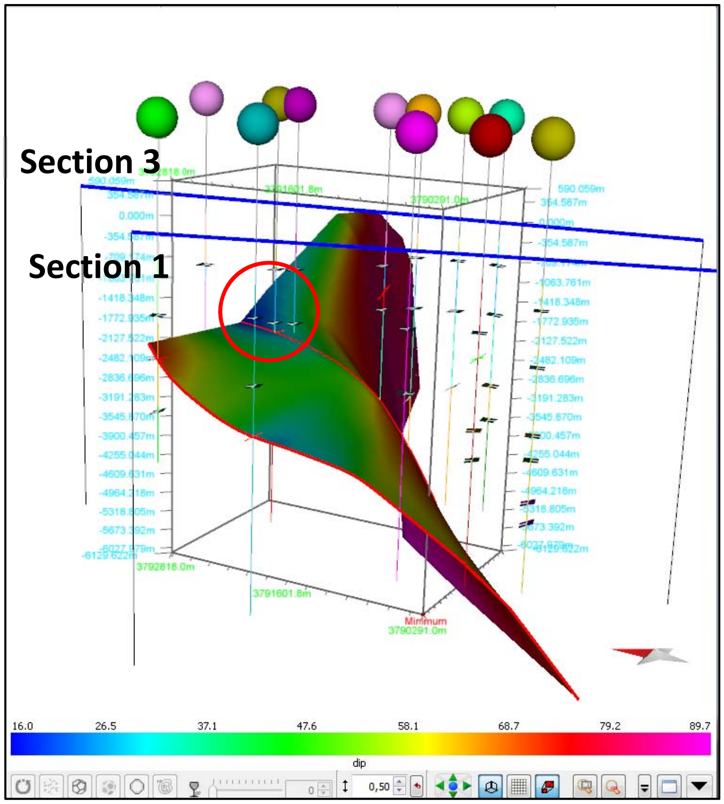


Figure 23. Coastal segment of the Oak Ridge fault surface colored by dip angle (see color scale bar). Red circles show anomalous areas.

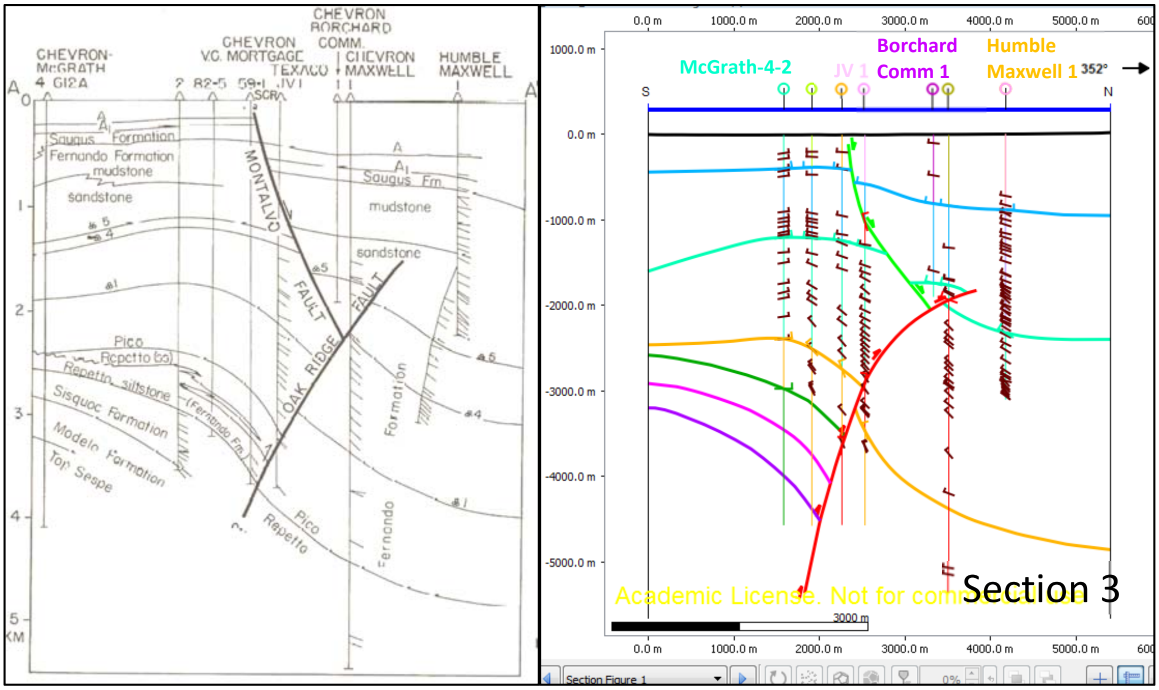


Figure 24. Cross section 3 corresponding to published well correlation image (left) and 2D interpretation (right). Well correlation image is from Yeats (1988).

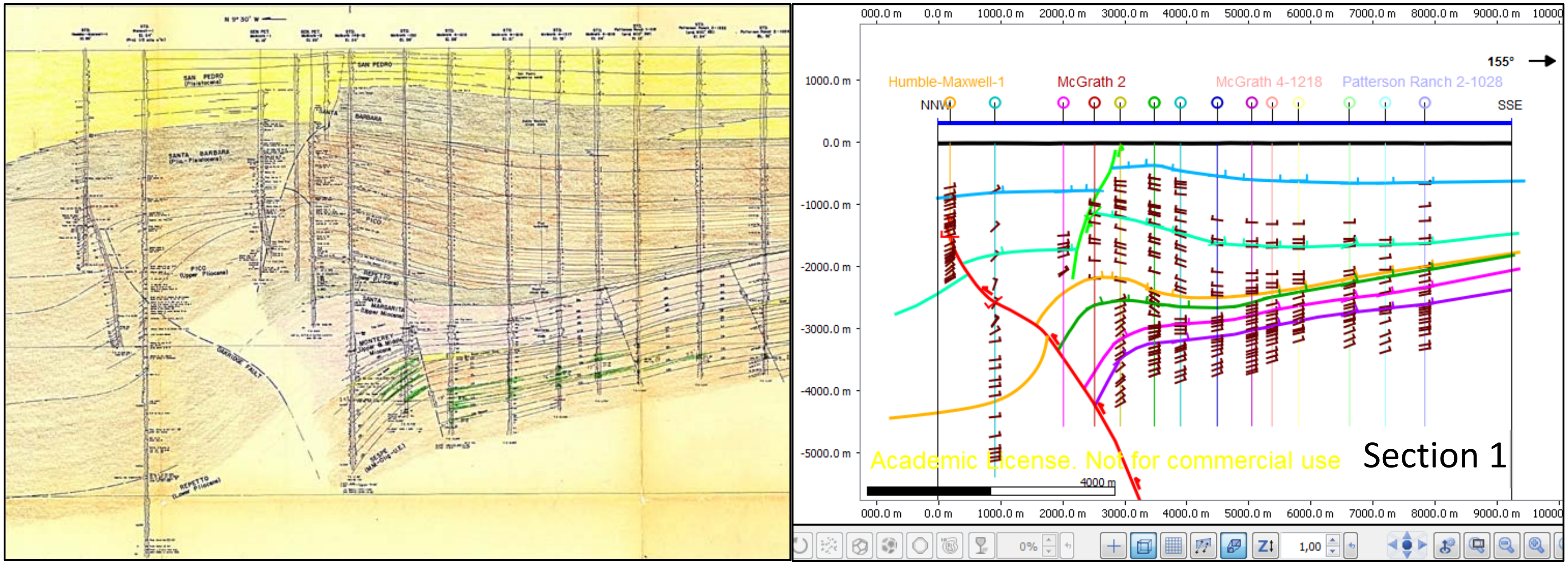


Figure 25. Cross section 1 corresponding to published well correlation image (left) and 2D interpretation (right).

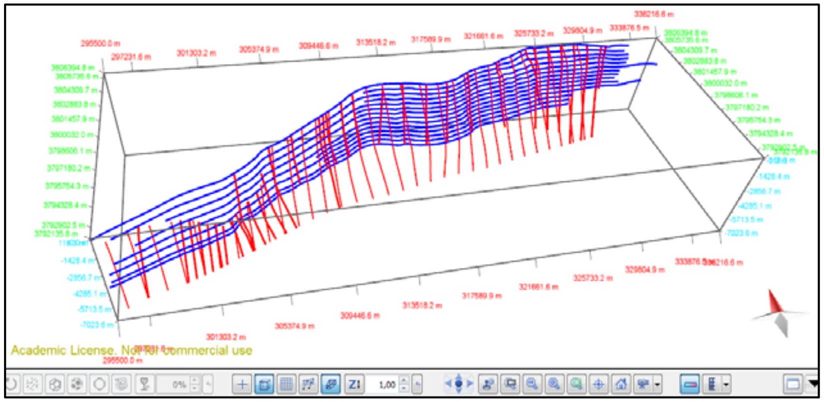


Figure 26. Oak Ridge fault contour lines and interpreted fault lines in 3D view. Blue lines are the Oak Ridge fault contour lines in the original Petrel project. Red lines are cross section interpretation lines.

5.2 Stratigraphic horizons

In the step of horizon modeling, I integrated well data, published well correlation images in the original Petrel project and publications to reconstruct six stratigraphic horizons: Top Santa Barbara, Top Pico, Top Repetto, Top Santa Margarita, Top Monterrey and Top Sespe. Figure 27 shows 36 cross section traces used for horizon surface reconstruction. Figures 16 to 19 are cross sections generated based on the well images in the original Petrel project and well correlation profiles in publications. Figures 28 to 33 are "fake" cross sections to control the shape of the horizons in the area with less well data control. All cross sections are at the same scale and have no vertical exaggeration. Figures 34 and 35 shows the final structural model and the six horizons in 3D view.

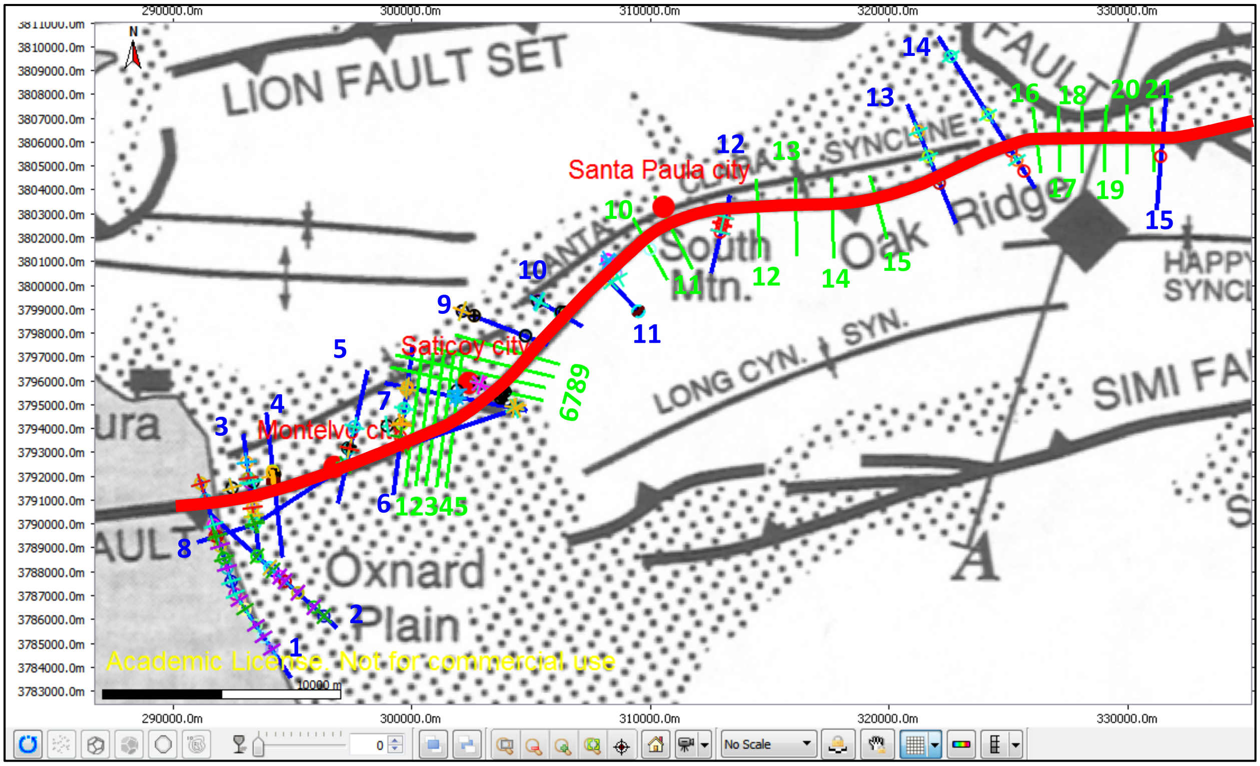


Figure 27. Projected wells and cross sections in the study area. Blue traces are generated based on the well images in the original Petrel project and well correlation profiles in publications, while green traces are "fake" cross sections to control the shape of the fault surface and horizons in the area with less well data control. Red line is the surface trace of the Oak Ridge fault. Red points are Montalvo city, Saticoy city and Santa Paula city. Color circles are projected wells.

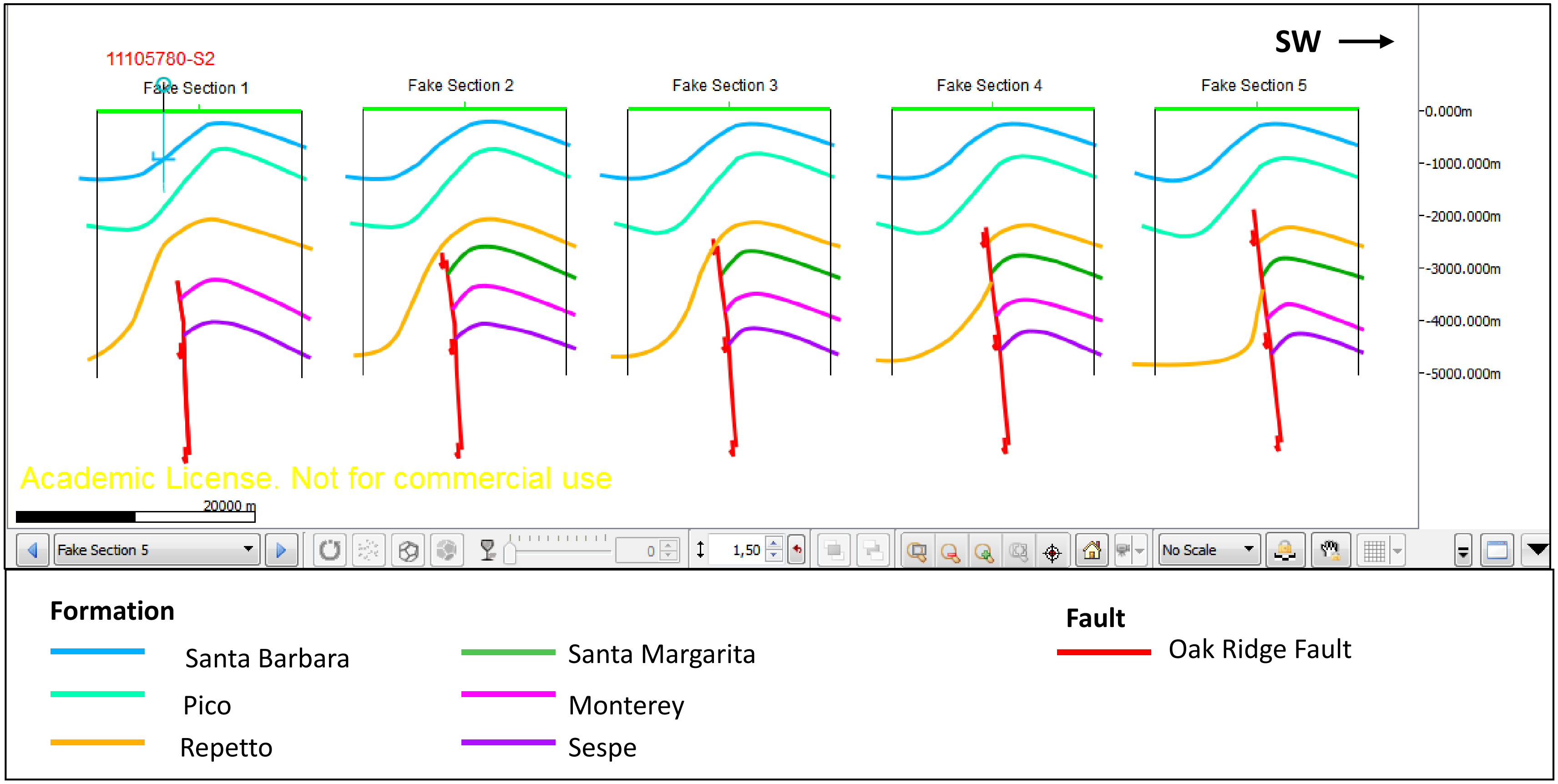


Figure 28. Fake cross sections 1 to 5.

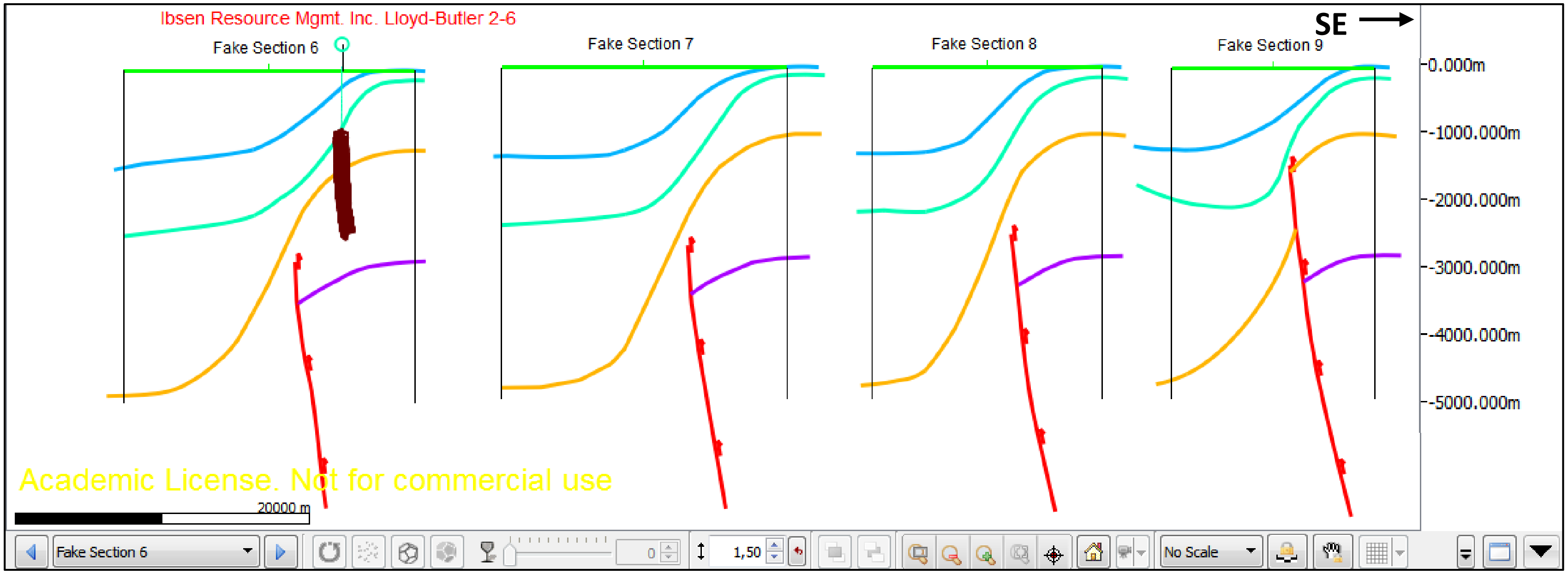


Figure 29. Fake cross sections 6 to 9. Legend is the same as in Figure 28.

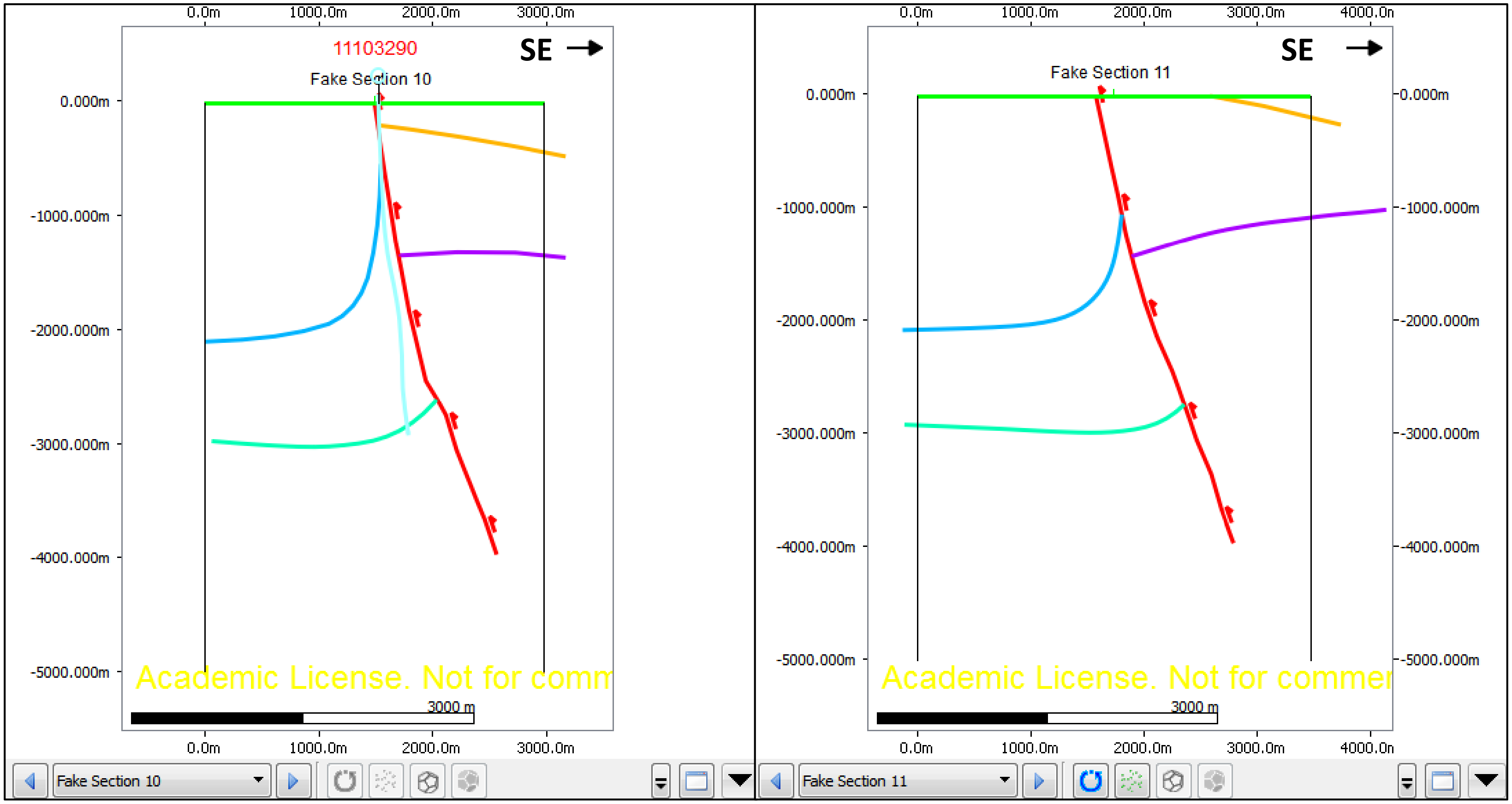


Figure 30. Fake cross sections 10 to 11. Legend is the same as in Figure 28.

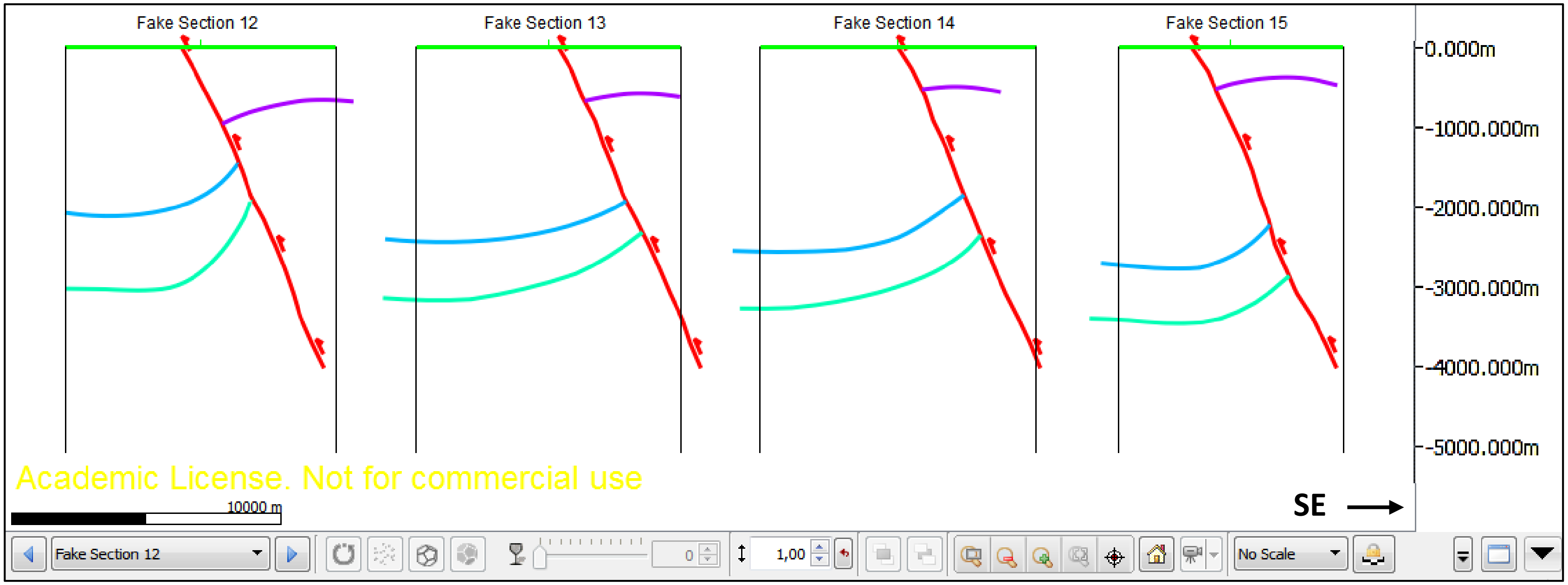


Figure 31. Fake cross sections 12 to 15. Legend is the same as in Figure 28.

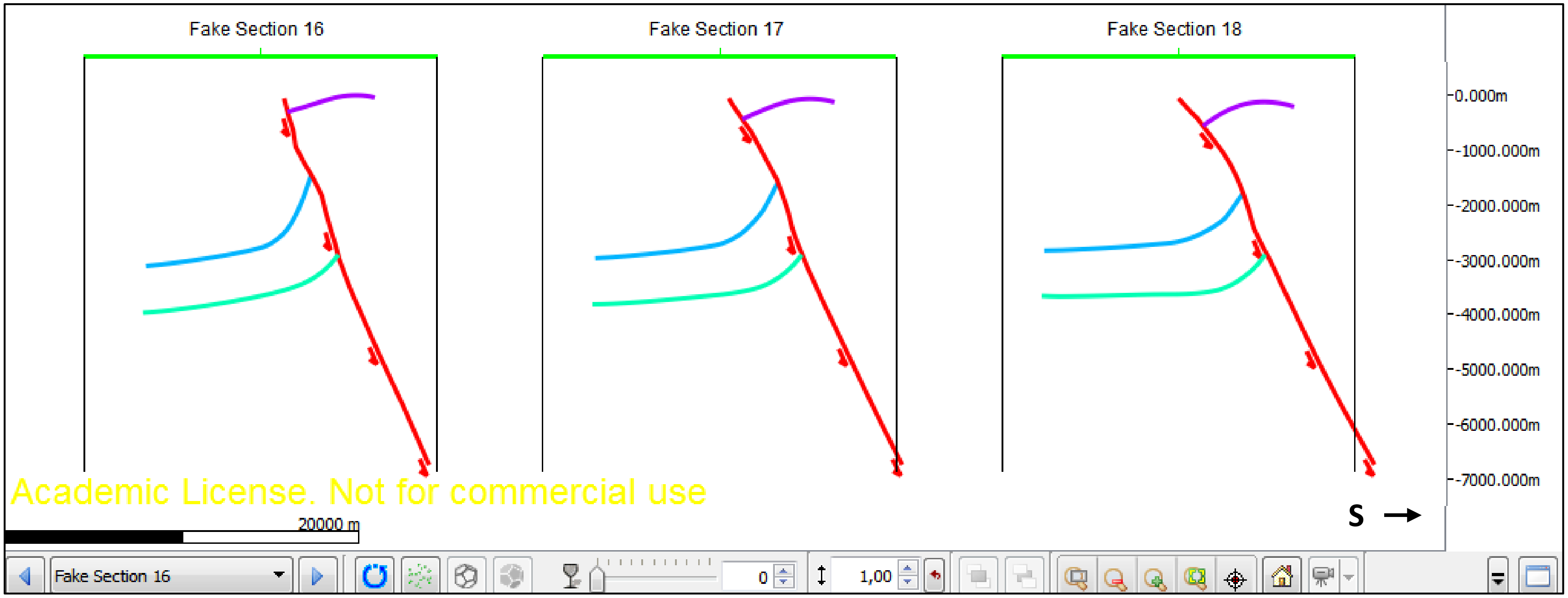


Figure 32. Fake cross sections 16 to 18. Legend is the same as in Figure 28.

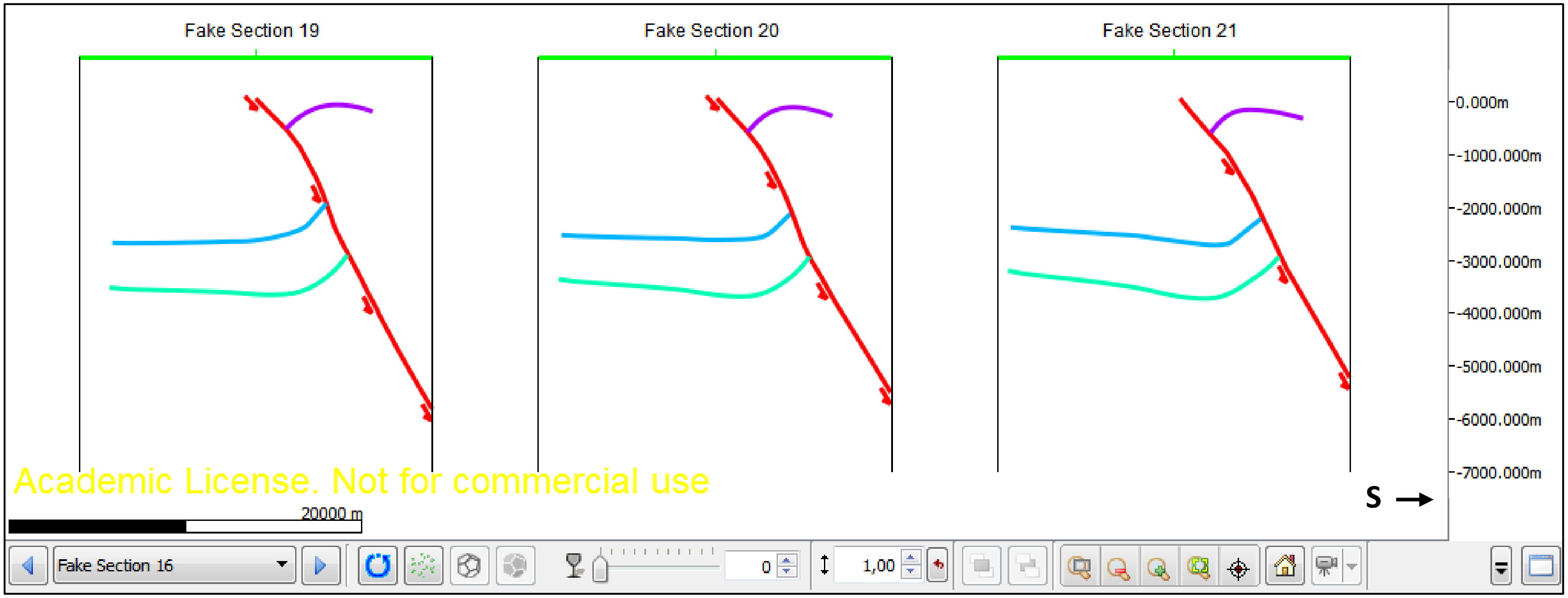
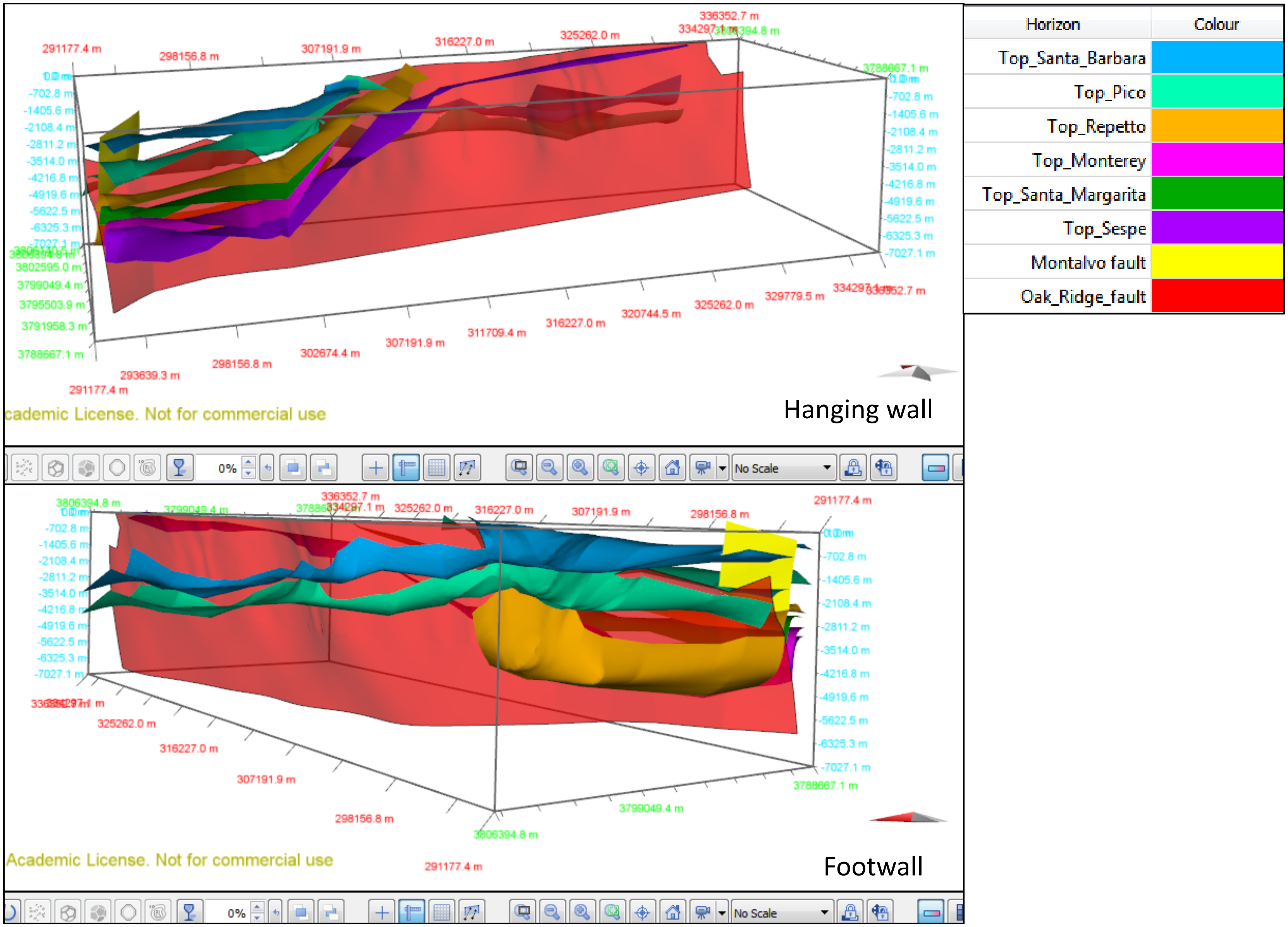


Figure 33. Fake cross sections 19 to 21. Legend is the same as in Figure 28.



Horizon	Colour
Top_Santa_Barbara	🟦
Top_Pico	🟩
Top_Repetto	🟧
Top_Monterey	🟪
Top_Santa_Margarita	🟩
Top_Sespe	🟪
Montalvo fault	🟨
Oak_Ridge_fault	🟥

Figure 34. 3D views of reconstructed horizons on the hanging wall (top) and footwall (bottom) blocks.

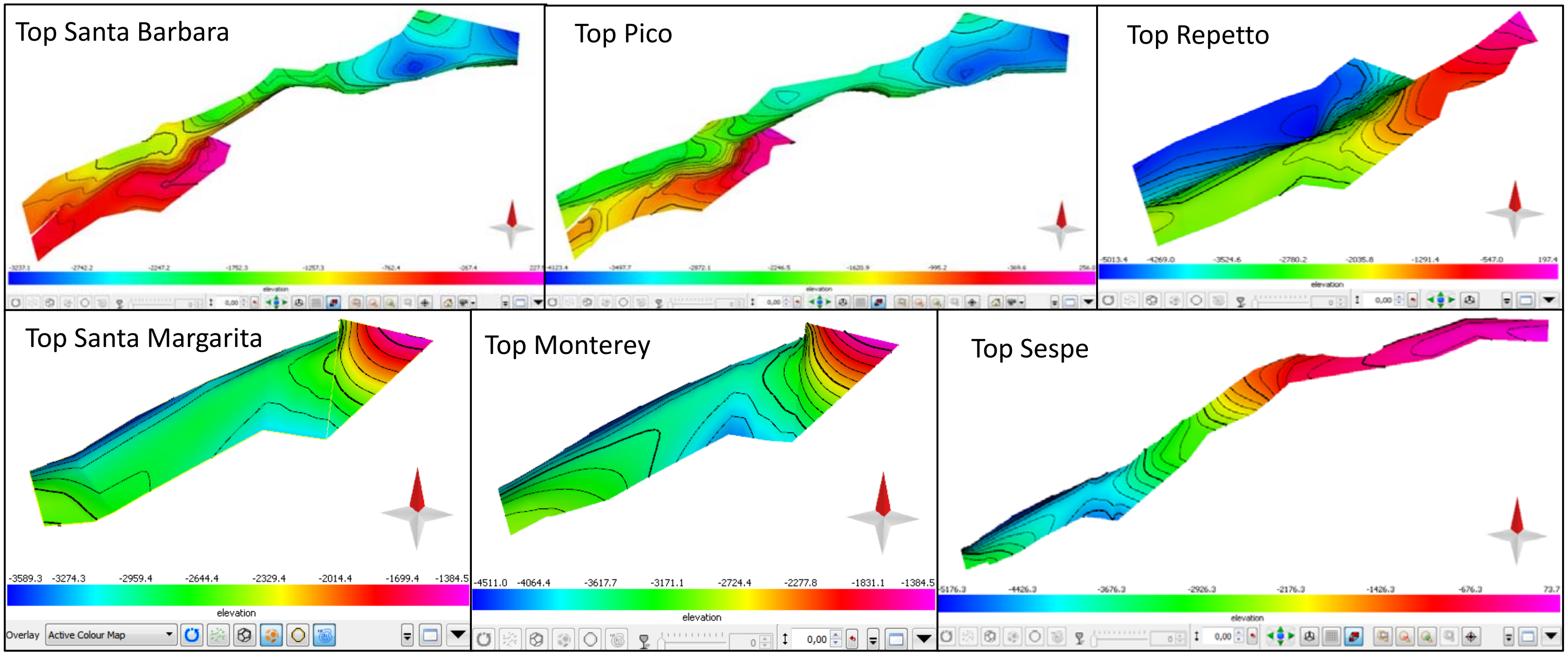


Figure 35. Six reconstructed horizons with depth contours. Contour interval is 200 m in each horizon.

5.2.1 Top Santa Barbara surface

This horizon was built based on a few well tops distributed on the hanging wall and footwall of the Oak Ridge fault and Montalvo fault. In the coastal area where the Oak Ridge fault does not offset the top Santa Barbara surface (Figures 16, 28 and 29), the continuous surface shows a monocline structure (Figure 36). To the east, this surface is cut by the Oak Ridge fault due to late Quaternary uplift in the region. Cross section interpretation shows drag effects of this surface on the footwall block (Figures 17 to 19; Figures 30 to 33). This deformation uplifted the Santa Barbara and brought beds as old as the Oligocene Sespe Formation to the surface. However, the footwall block of this surface shows a synclinal structure in this region (Figure 36).

The Montalvo normal fault cuts the Top Santa Barbara in the Coastal area. Different thicknesses of the Santa Barbara Formation in the hanging wall and footwall blocks of the Montalvo fault indicate the deposition of this unit was controlled by the fault (Figures 16, cross sections 1 to 3).

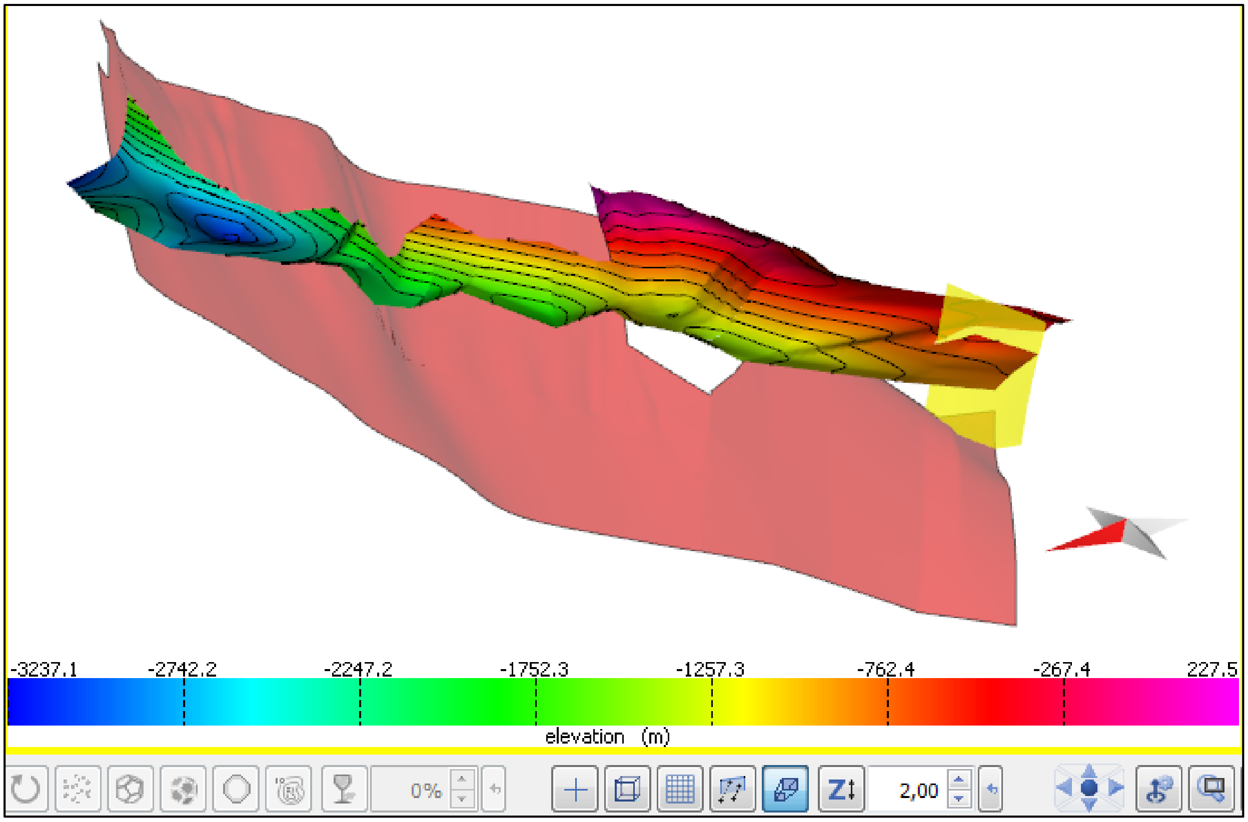


Figure 36. 3D view of the Top Santa Barbara surface. Red surface is the Oak Ridge fault. Yellow surface is the Montalvo fault.

5.2.2 Top Pico surface

This horizon has similar geometry as the Santa Barbara surface (Figure 37). In the coastal area, the Oak Ridge fault cuts the Pico Formation (Figure 16, cross sections 1 to 5), but exists only in pre-Pliocene strata deeper than the well control in the area close to Saticoy city (Figure 16, cross sections 6 to 7) where the entire Pico surface is a monoclinal structure above the fault (Figures 28 to 29; Figure 37). To the eastern side (Figures 17 to 19; Figures 30 to 33), the surface shows slightly drag effects associated to the Oak Ridge fault late Quaternary uplift on the footwall block. The entire surface of the footwall block shows a synclinal structure in the east region (Figure 37). The surface is absent in the hanging wall due to erosion associated with the late Quaternary deformation in the region. The Montalvo normal fault also cuts the Top Pico in the Coastal area. The different thicknesses of the Pico Formation in the hanging wall and footwall blocks of this fault indicate that the deposition of this unit was controlled by the Montalvo fault (Figures 16, cross sections 1 to 3).

Additionally, cross sections interpretation and the 3D structural model show that the thickness of the Pliocene Pico and the Pleistocene Santa Barbara Formations on the hanging wall decrease eastwards from the coastal area to the Santa Paula city (Figure 19, cross section 8).

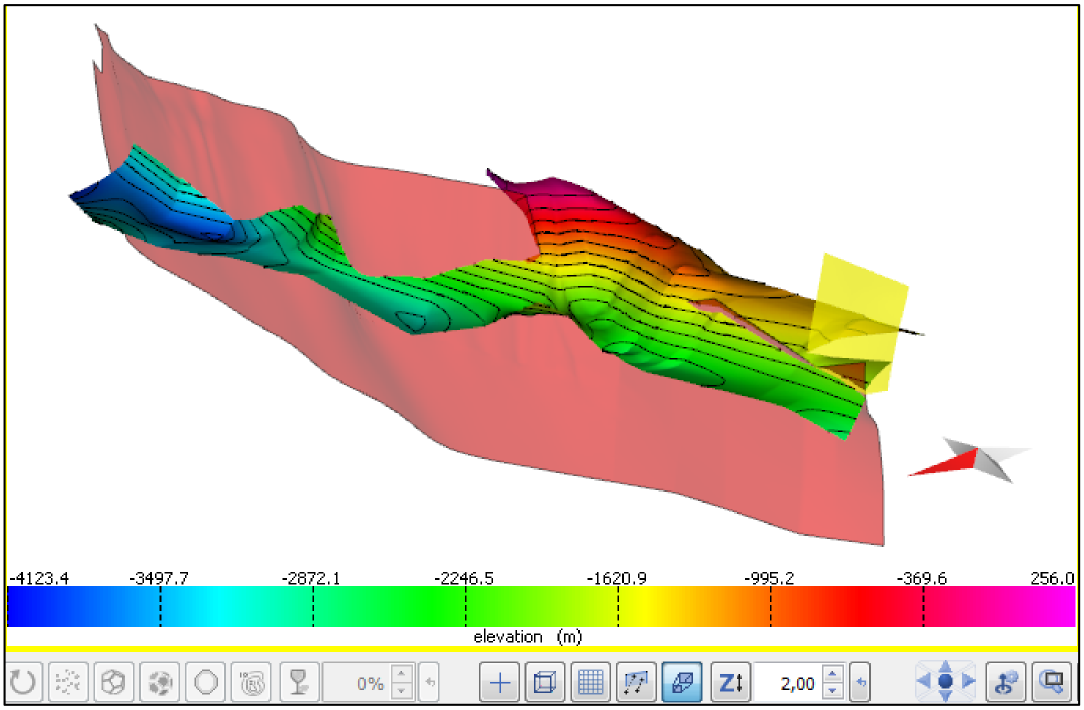


Figure 37. 3D view of the Top Pico surface. Red surface is the Oak Ridge fault. Yellow surface is the Montalvo fault.

5.2.3 Top Repetto surface

This horizon was made based on well data from the coastal area to Santa Paula city (Figure 27). This surface shows an anticline-syncline pair perpendicular to the fault (Figure 38). The Oak Ridge fault cuts the Top Repetto Formation in the coastal area where the hanging wall and footwall block show an incipient anticline and syncline (Figure 38). The dip of the footwall increased steeply eastward and it is overturned in the area near Saticoy city (Figures 27 and 38; Figure 16, cross section 6). To the east between Montalvo and Saticoy city, the Oak Ridge fault exists only in pre-Pliocene strata deeper than the well control (Figure 16, cross section 7; Figure 28, fake cross sections 1 to 3; Figure 29, fake cross sections 6 to 8). The Top Repetto surface is a steep monocline above the fault in this area (Figures 27 and 38). At the eastern end, the Repetto surface is uplifted and exposed due to the Oak Ridge fault late Quaternary uplift on the hanging wall block (Figure 17, cross sections 10 to 11; Figure 30). The Repetto surface in this area shows an anticline on the hanging wall block (Figure 38).

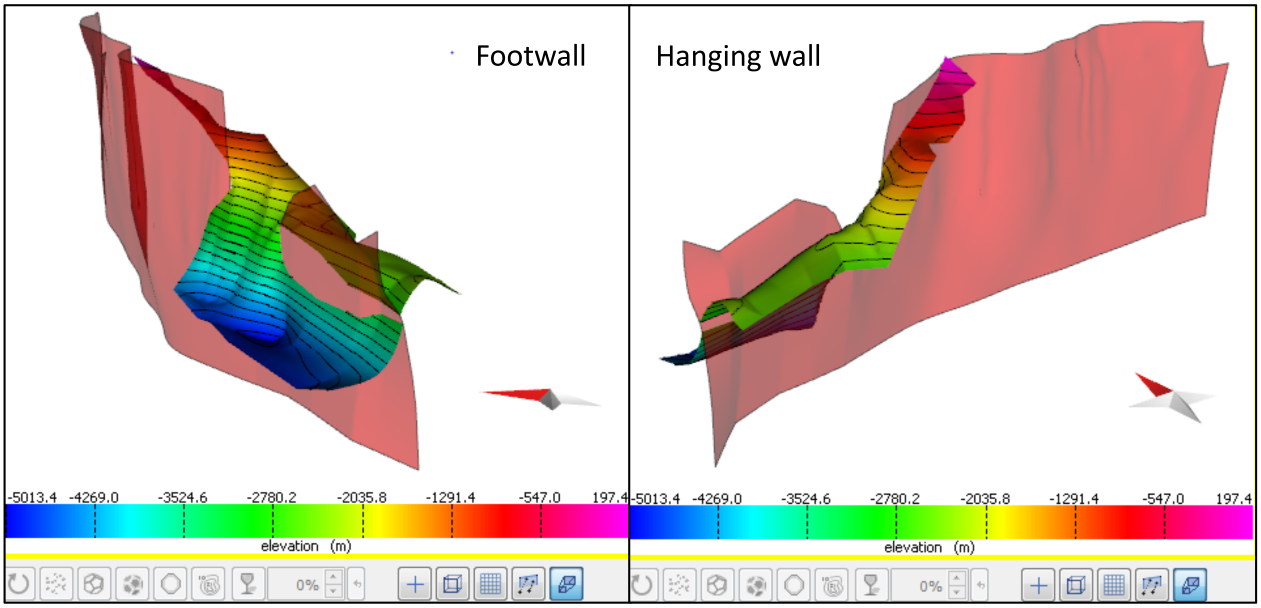


Figure 38. 3D view of the Top Repetto surface on footwall and hanging wall blocks. Red surface is the Oak Ridge fault.

5.2.4 Top Santa Margarita surface

This horizon is localized in a relatively small area as the well tops are only located in the coastal hanging wall block (Figure 16, cross sections 1 to 6; Figure 28, cross sections 2 to 5). The top Santa

Margarita surface shows an anticline in the hanging wall of the Oak Ridge fault (Figure 39) and an unconformable contact with the overlying Repetto Formation (Figure 19, cross section 8).

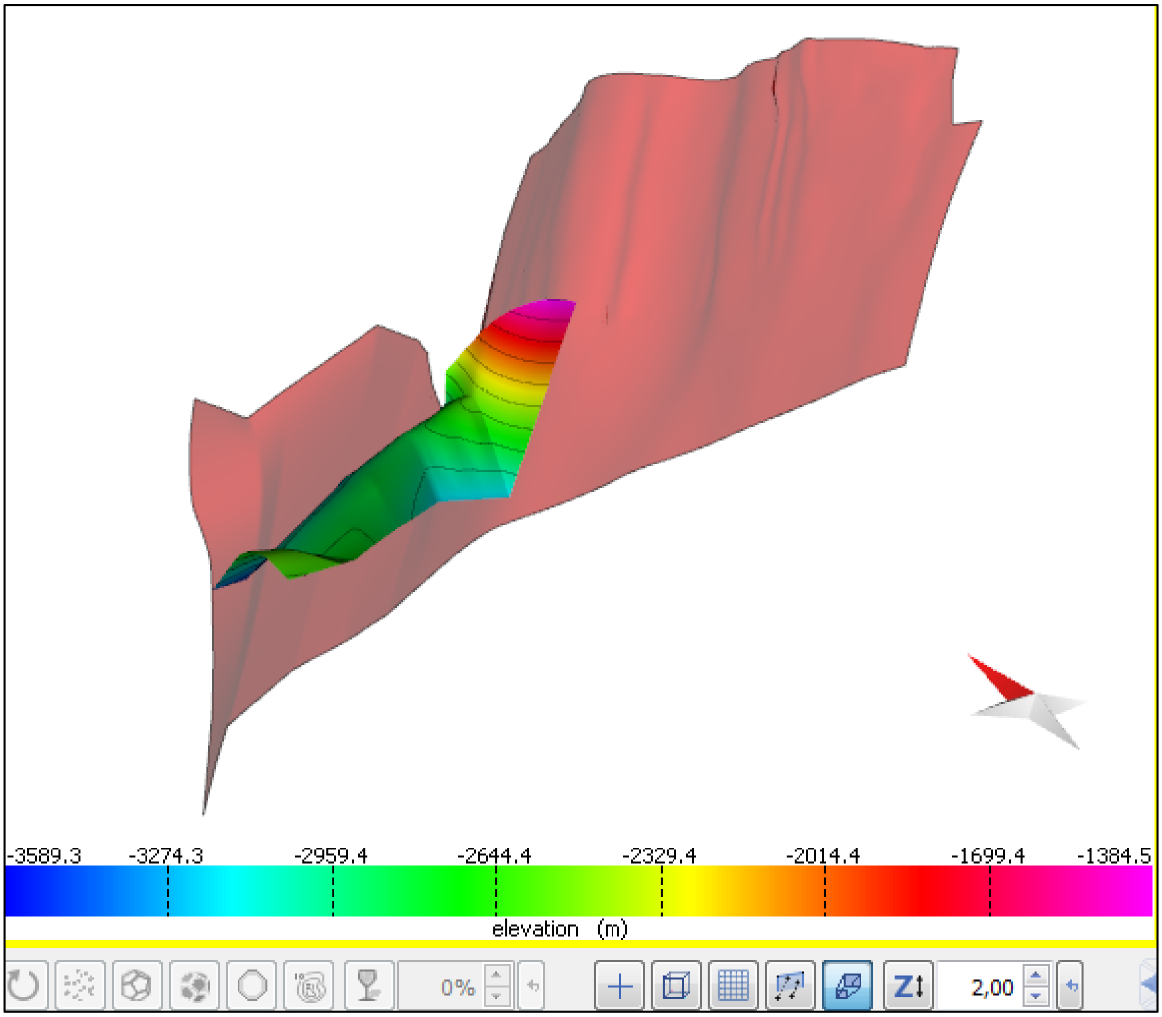


Figure 39. 3D view of the Top Santa Margarita hanging wall surface. Red surface is the Oak Ridge fault.

5.2.5 Top Monterey surface

This horizon is also localized in a relatively small area as well tops are only located in the coastal hanging wall block (Figure 16, cross sections 1 to 6). The surface is a hanging wall anticline with a northern flank dipping around 55 grades towards the northwest (Figure 40). The thickness of the unit is constant along the surface in the coastal area so it can be identified as a pre-tectonic sequence (Figure 16, cross sections 1 to 6). However, this surface shows an unconformable contact with the overlying Santa Margarita Formation close to Saticoy city (Figure 19, cross section 8).

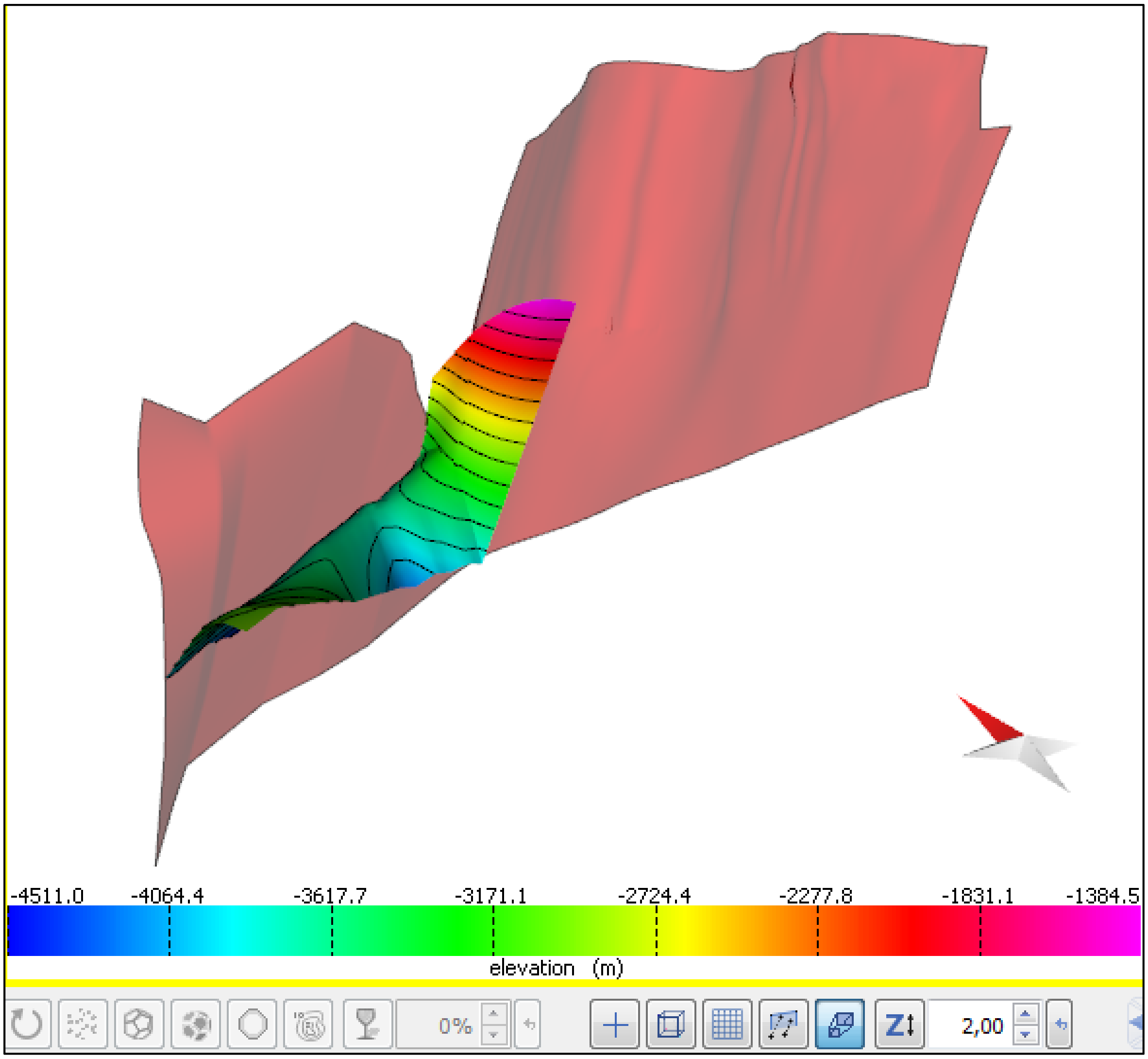


Figure 40. 3D view of the Top Monterey hanging wall surface. Red surface is the Oak Ridge fault.

5.2.6 Top Sespe surface

This horizon only is present in the hanging wall block in the study area as the well tops are only located here (Figures 16 to 19; Figure 41). In general, the Top Sespe is a north-dipping monocline. The dip of this surface decreases along the Oak Ridge fault eastward from 70 to 30 degree approximately. On the eastern region, late Quaternary deformation uplifted the Sespe Formation and brought it to the surface (Figure 19, cross section 15; Figures 31 to 33). The top Sespe shows an anticline parallel to the fault in the eastern area (Figure 41).

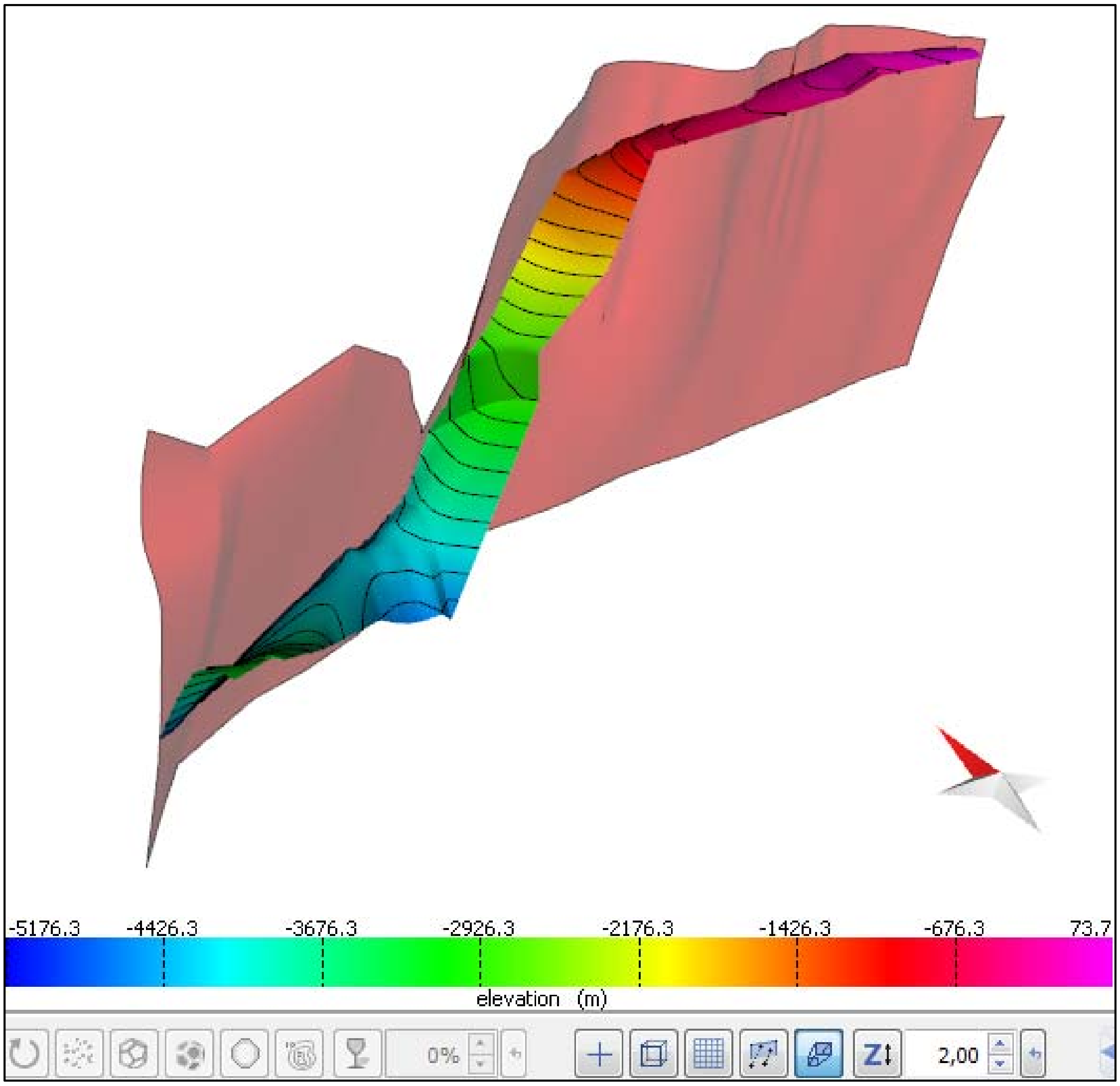


Figure 41. 3D view of the Top Sespe hanging wall surface. Red surface is the Oak Ridge fault.

5.3 Fault displacement analysis

Fault displacement analysis was applied in this research with two objectives: 1) to check the consistency of the final 3D structural model, and 2) to understand the behavior of the fault in terms of its displacement.

As shown in Figure 42, the first step was to create hanging wall and footwall cut-off lines. This process generated a series of polylines that represent the hanging wall and footwall horizons intersections (Figure 42b). The input for this step were the fault planes and horizons of the 3D structural model. After checking the consistency of the modeled fault planes and horizons, the throw on the fault surface is derived from the cutoffs generated by using the displacement analysis tool. With the 3D model and the throw information, fault statistics were calculated, including fault orientation plots, fault displacement profiles, and fault growth diagrams.

In this research, I chose the coastal area where the 3D model has horizons on both the hanging wall and footwall blocks to do the fault displacement analysis. The Top Santa Barbara and Top Pico surfaces were used to analyze fault displacement of the Montalvo fault. The Top Pico and the Top Repetto surface were used to calculate the fault displacement of the Oak Ridge fault.

5.3.1 Montalvo Fault

As shown in Figure 42c and Figure 43, the Montalvo fault throw decreases from southwest to northeast along strike for the Top Santa Barbara and Top Pico surfaces. The cumulative throw of the Montalvo fault shows an increase trend from 2.6 Ma to 1.8 Ma during the deposition of the Pliocene-Pleistocene strata, and this indicates the Montalvo fault is a growth fault (Figure 44).

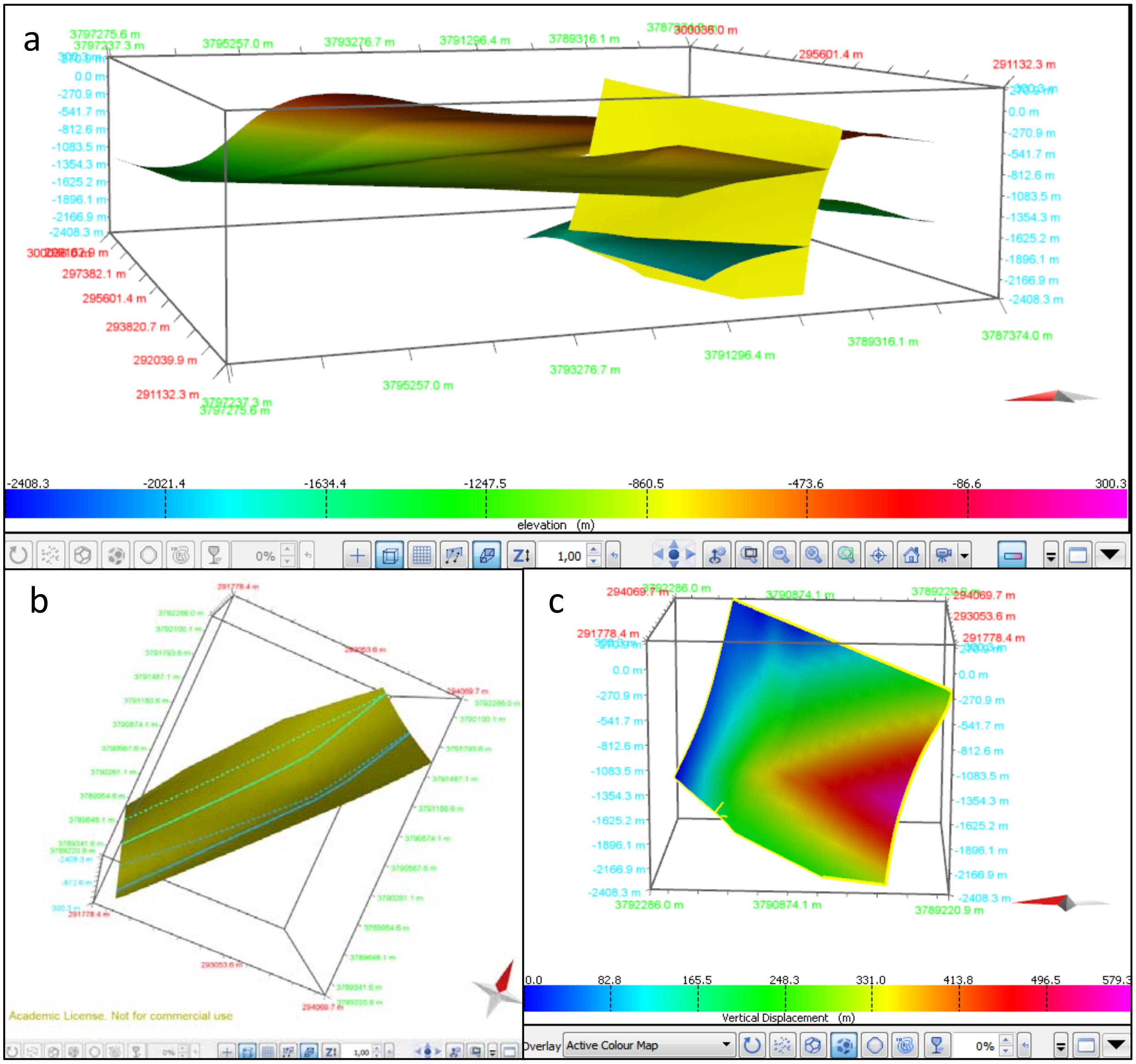


Figure 42. Steps in the fault displacement analysis, using the Montalvo fault as an example. a) Reconstruction of fault plane and horizon model. (Yellow surface is the Montalvo fault. Two color surfaces are Top Santa Barbara and Top Pico surface). b) Computation of fault cut-offs (Solid lines are footwall cut-offs while dashed lines are hanging wall cutoffs. Blue lines represent Top Santa Barbara surface, green lines represent Top Pico surface). c) Estimation of the throw attribute in the fault plane (see color scale bar).

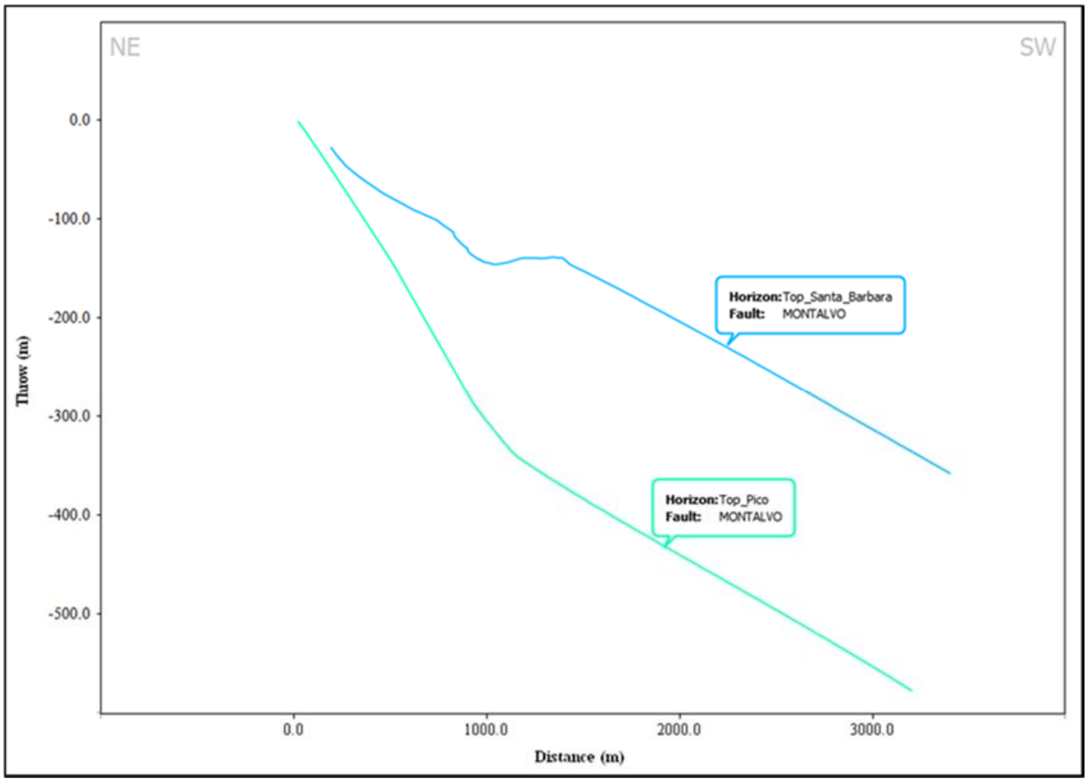


Figure 43. Montalvo fault throw profile. Blue line is the Montalvo fault throw along strike for Top Santa Barbara surface. Green line represents the Montalvo fault throw along strike for Top Pico surface.

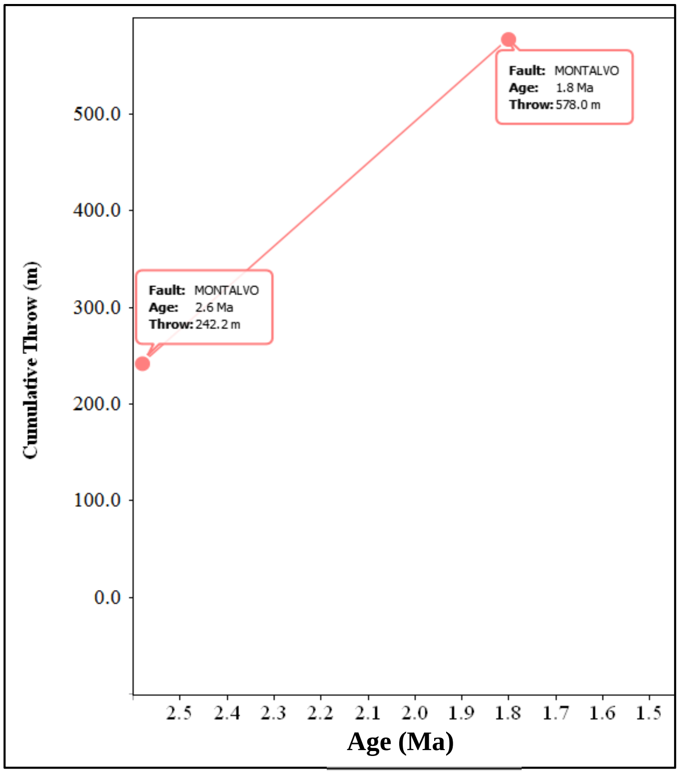


Figure 44. Fault growth plot of the Montalvo fault from 2.6 to 1.8 Ma.

5.3.2 Oak Ridge fault

After inputting the Top Pico and Top Repetto cut-offs (Figure 45a), the vertical displacement is shown in Figure 45b. Two trends are apparent: an increase in throw from 3.0 Ma to 2.6 Ma during the deposition of Pliocene strata (Pico-Repetto succession) (Figure 46b), and a general increase in vertical displacement from west to east along the strike of the Oak Ridge fault. However, as shown in Figure 46a, the fault throw decreases rapidly on the northeast edge of the fault since in this area the Oak Ridge fault does not offset the Top Repetto Formation.

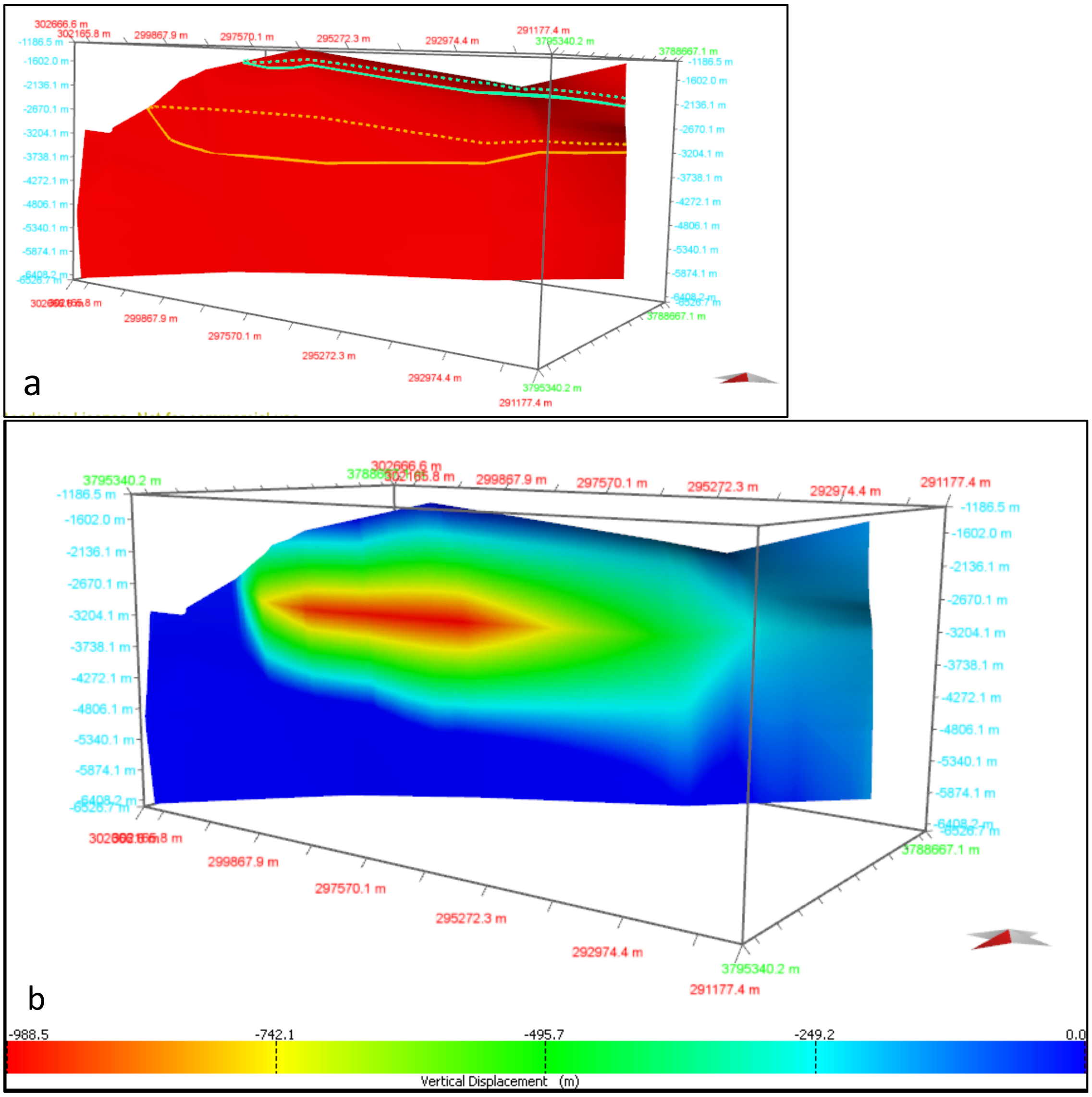


Figure 45. a) The Oak Ridge fault cutoffs of Top Pico surface (green lines) and Top Repetto surface (orange lines). Solid lines are Footwall cutoffs while dashed lines are hanging wall cutoffs. b) Throw attribute color map of the Oak Ridge fault (see color scale bar).

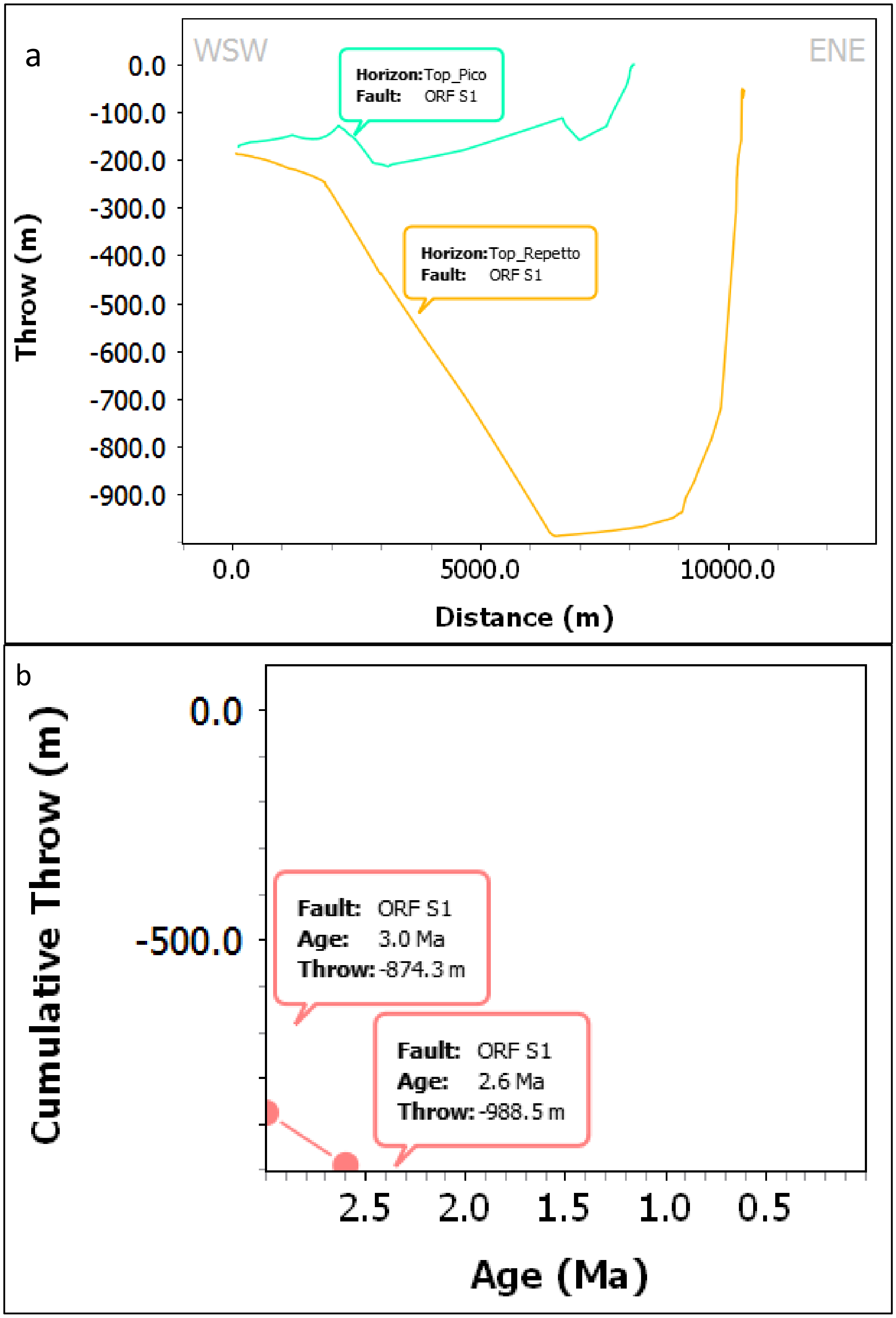


Figure 46. a) Oak Ridge fault throw profile. Green line is the Oak Ridge fault throw along strike for Top Pico surface. Orange line represents the Oak Ridge fault throw along strike for Top Repetto surface. b) Fault growth plot of Oak Ridge fault from 3.0 to 2.6 Ma.

6. Discussion

6.1 3D model evaluation

To verify the interpretation and check the consistency of the modelled fault and horizons, 40 cross sections (36 cross sections perpendicular to the Oak Ridge fault and 4 cross sections parallel to it) were extracted from the model (Figures 48 to 53). Figure 47 shows the location of these generated QC cross sections.

As shown in Figures 47 to 53, the fault and horizons surfaces intersection lines express good consistency on the QC cross sections from west to east. 3D fault geometry and fold variation also follow the structural style in this region. However, fault and horizon model still have some problems, which are highlighted on the cross sections (red circles in Figures 48 to 52). These are discussed below in the 'Issues and surface problems' section.

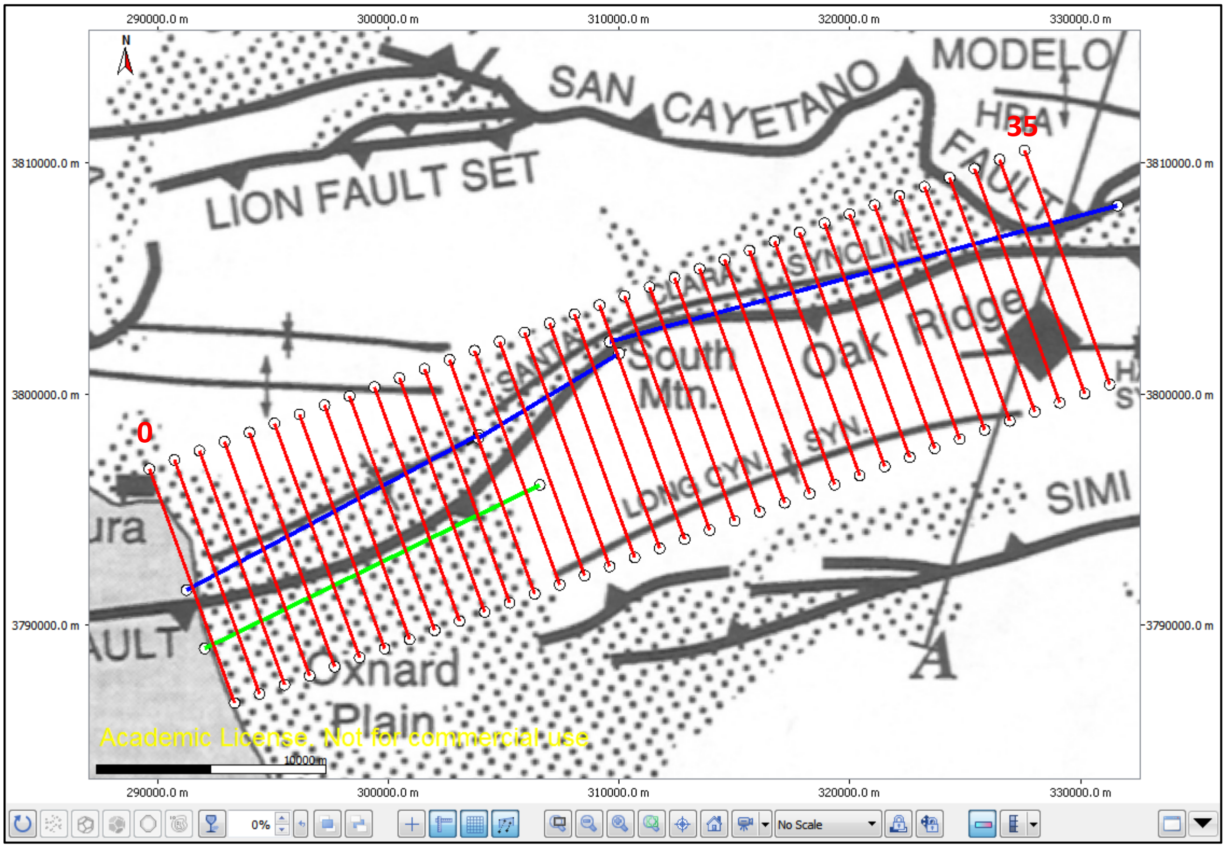


Figure 47. Location of the generated cross sections to check the consistency of the structural model. Red traces are cross sections perpendicular to the Oak Ridge fault. Green trace is the hanging wall cross section parallel to the Oak Ridge fault, while blue lines are footwall cross sections parallel to the Oak Ridge fault.

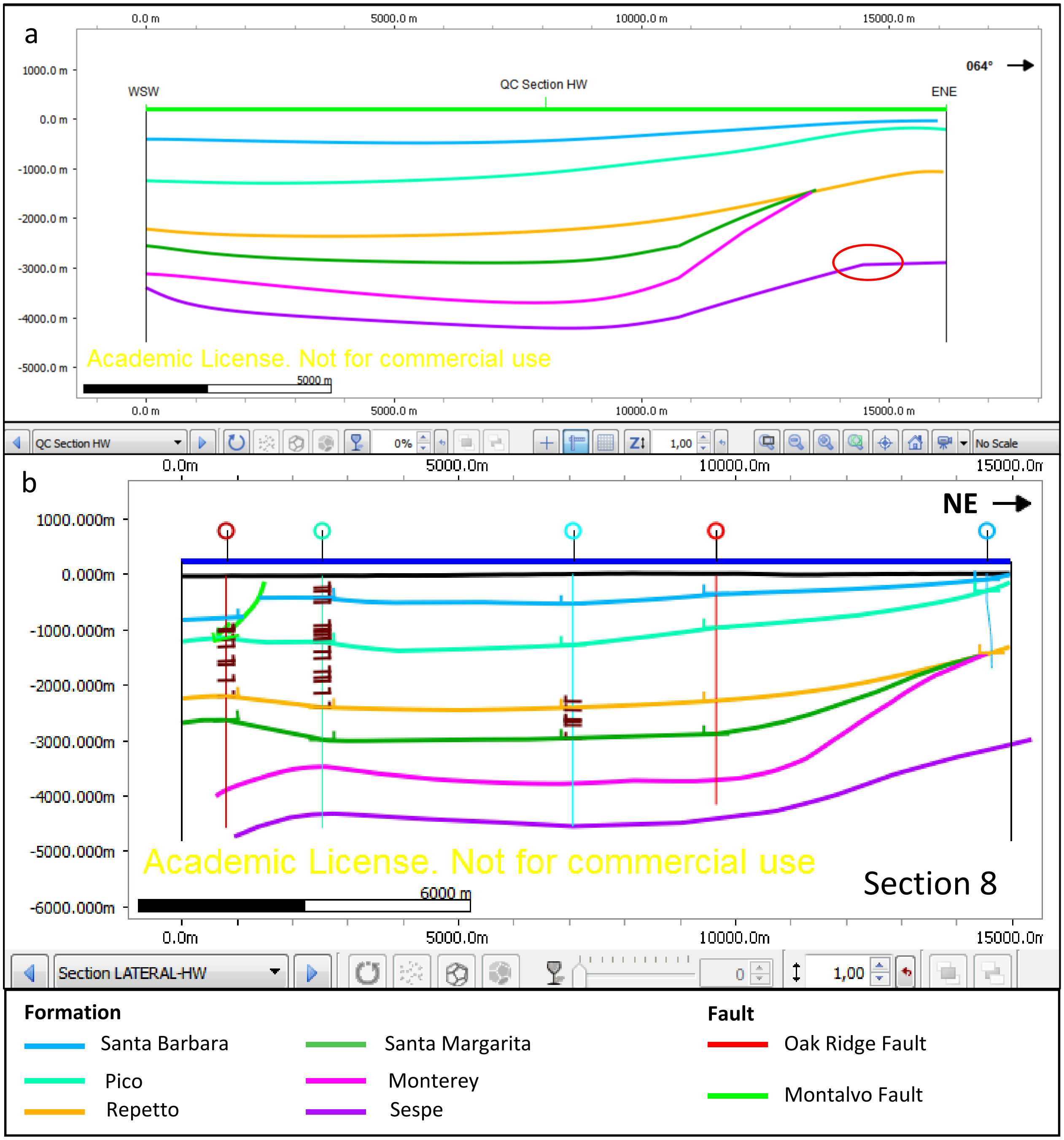


Figure 48. a) QC cross section parallel to the Oak Ridge fault on the hanging wall in the coastal area. b) Interpreted cross section 8 corresponds to the QC cross section. Figure 15 shows the location of interpreted cross section 8.

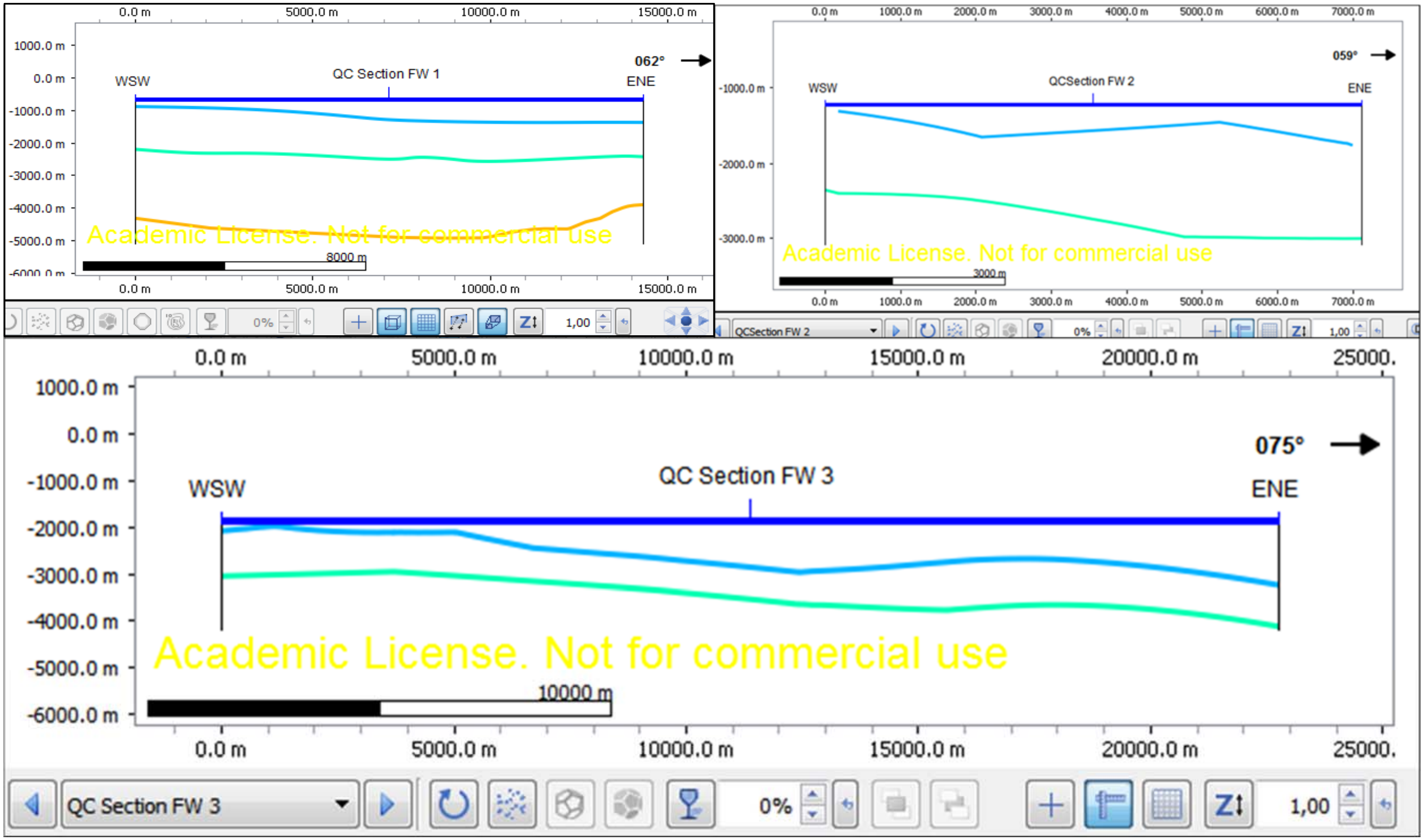


Figure 49. QC cross sections 1 to 3 (WSW-ENE) parallel to the Oak Ridge fault on the footwall. Legend is the same as shown in Figure 48.

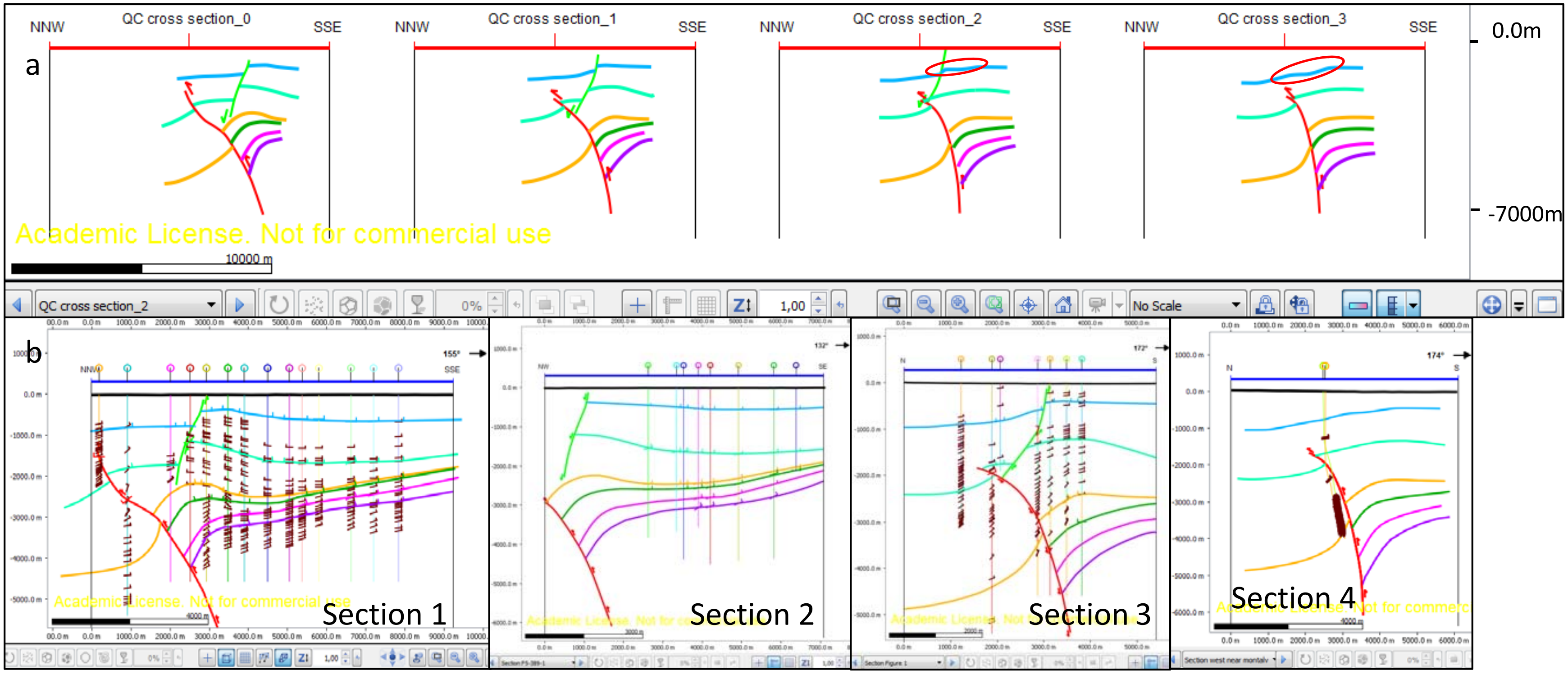
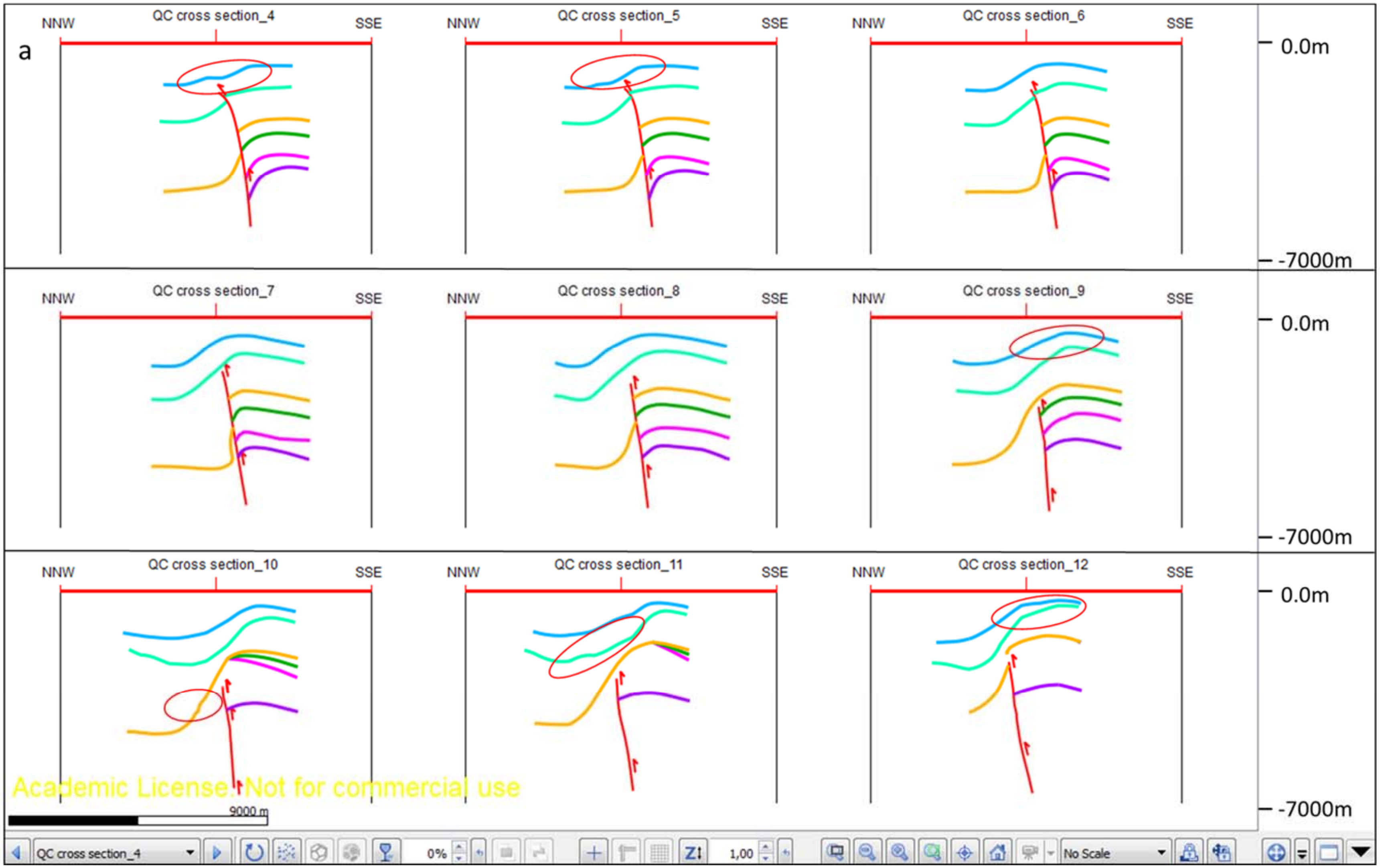


Figure 50. a) QC cross sections 0 to 3 perpendicular to the Oak Ridge fault. b) Interpreted cross sections 1 to 4 correspond to the QC cross sections. Figure 15 shows the location of interpreted cross sections 1 to 4. Legend is the same as shown in Figure 48.


a
QC cross section_4
QC cross section_5
QC cross section_6
QC cross section_7
QC cross section_8
QC cross section_9
QC cross section_10
QC cross section_11
QC cross section_12
NNW
SSE
0.0m
-7000m
Academic License: Not for commercial use
9000 m
QC cross section_4
0%
1,00
No Scale

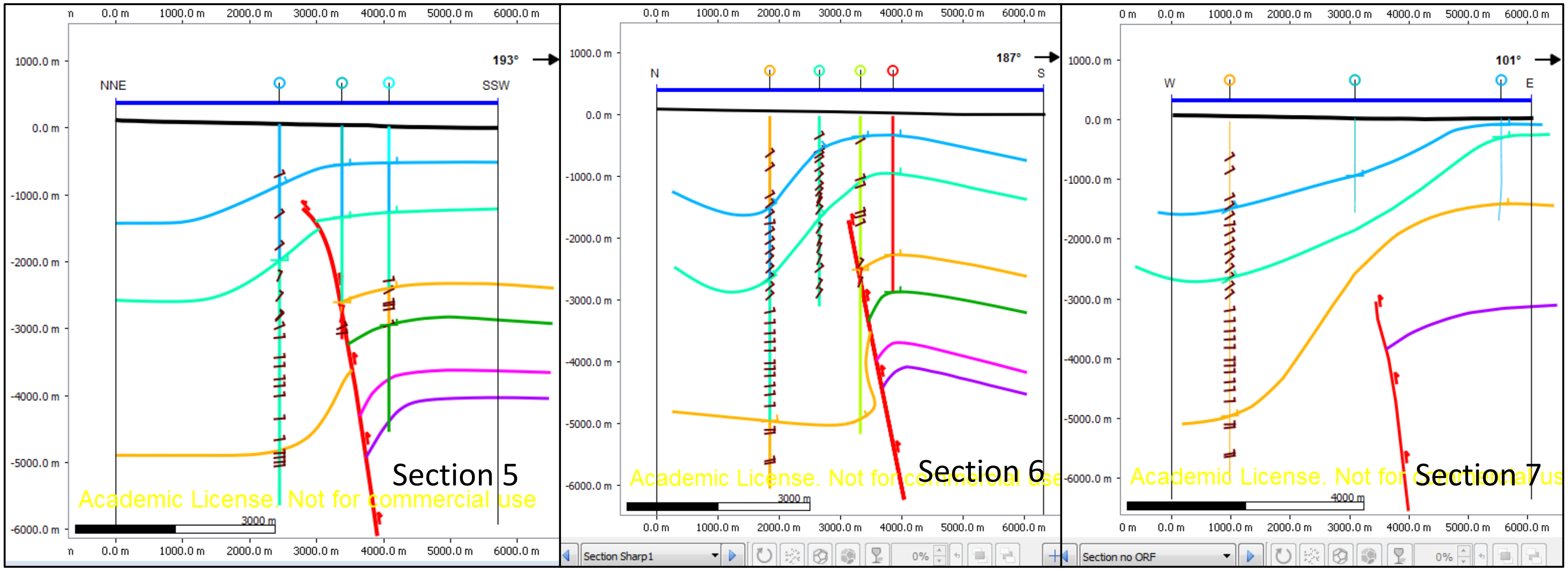
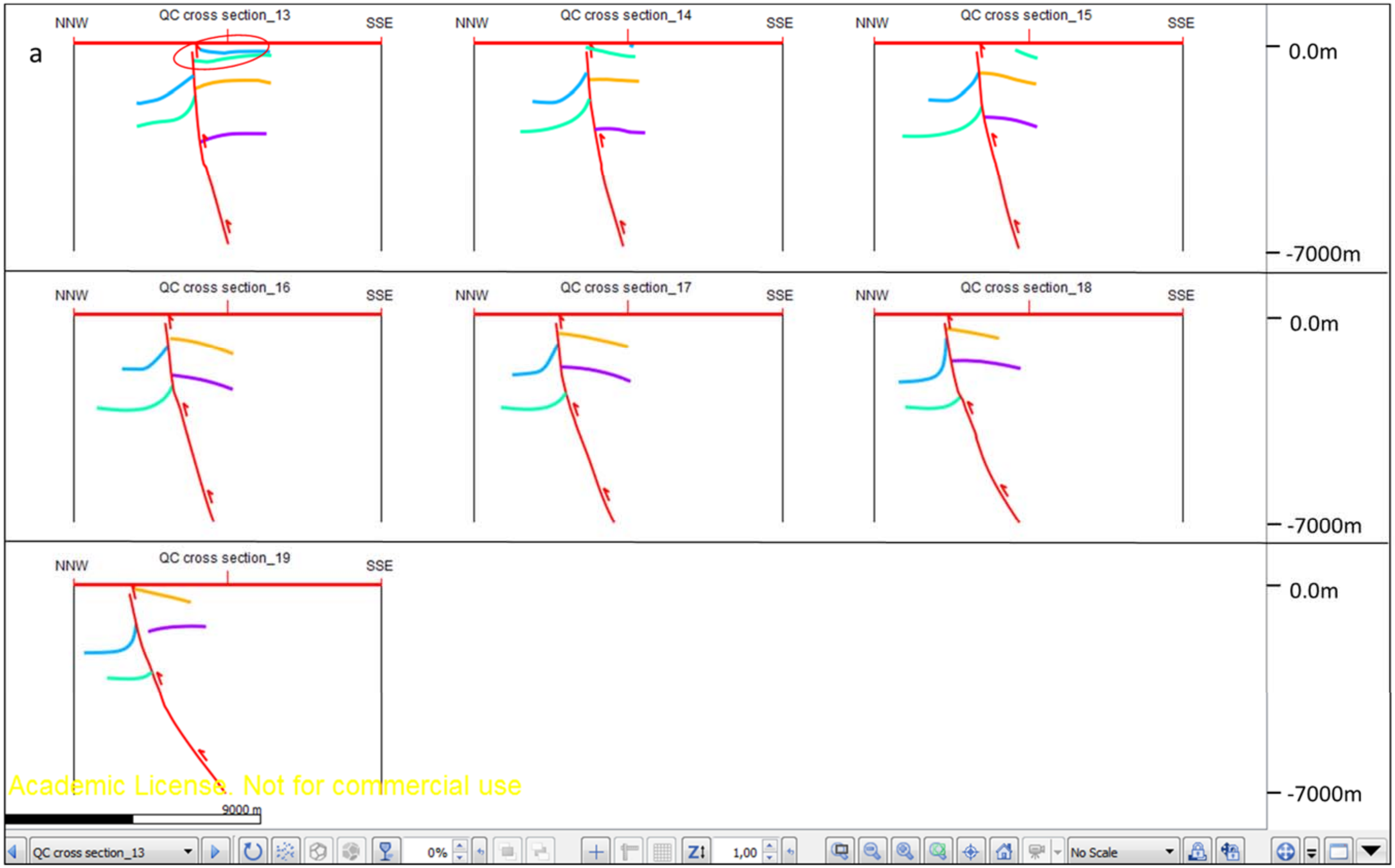


Figure 51. a) QC cross sections 4 to 12 perpendicular to the Oak Ridge fault. b) Interpreted cross sections 5 to 7 correspond to the QC cross sections. Figure 15 shows the location of interpreted cross sections 5 to 7. Legend is the same as shown in Figure 48.


a
NNW
QC cross section_13
SSE
NNW
QC cross section_14
SSE
NNW
QC cross section_15
SSE
0.0m
-7000m
NNW
QC cross section_16
SSE
NNW
QC cross section_17
SSE
NNW
QC cross section_18
SSE
0.0m
-7000m
NNW
QC cross section_19
SSE
0.0m
-7000m
Academic License. Not for commercial use
9000 m
QC cross section_13
0%
1,00
No Scale

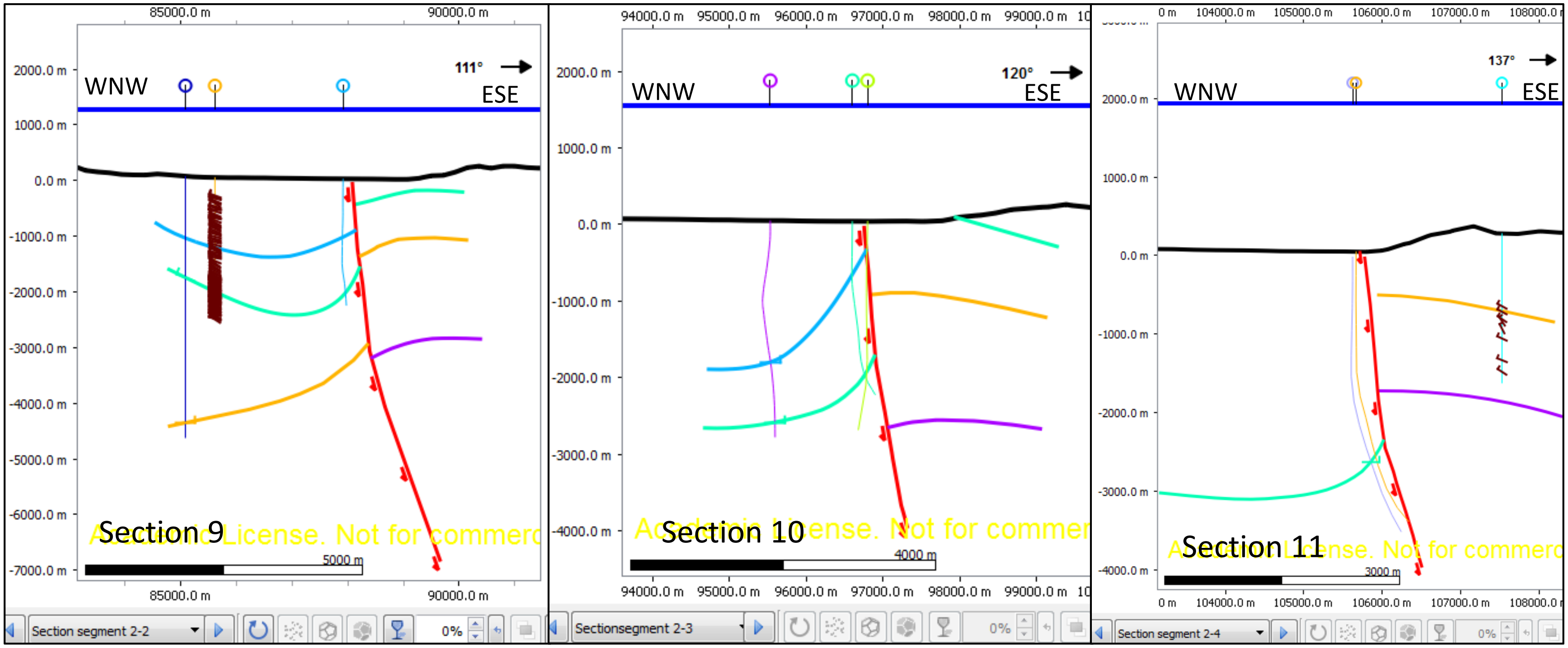
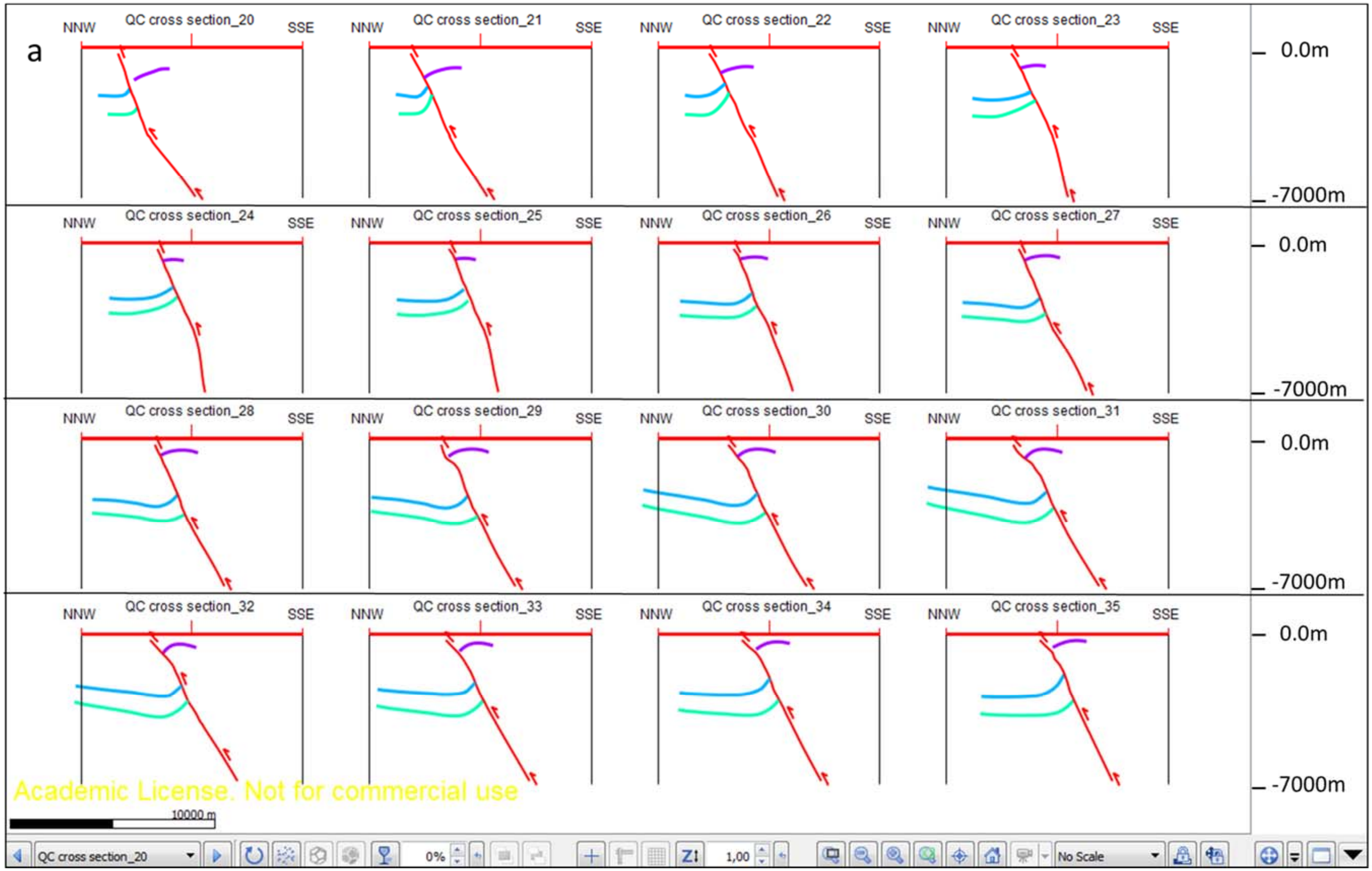


Figure 52. a) QC cross sections 13 to 19 perpendicular to the Oak Ridge fault. b) Interpreted cross sections 9 to 11 correspond to the QC cross sections. Figure 15 shows the location of interpreted cross sections 9 to 11. Legend is the same as shown in Figure 48.


a
NNW
QC cross section_20
SSE
NNW
QC cross section_21
SSE
NNW
QC cross section_22
SSE
NNW
QC cross section_23
SSE
0.0m
-7000m
NNW
QC cross section_24
SSE
NNW
QC cross section_25
SSE
NNW
QC cross section_26
SSE
NNW
QC cross section_27
SSE
0.0m
-7000m
NNW
QC cross section_28
SSE
NNW
QC cross section_29
SSE
NNW
QC cross section_30
SSE
NNW
QC cross section_31
SSE
0.0m
-7000m
NNW
QC cross section_32
SSE
NNW
QC cross section_33
SSE
NNW
QC cross section_34
SSE
NNW
QC cross section_35
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Academic License. Not for commercial use
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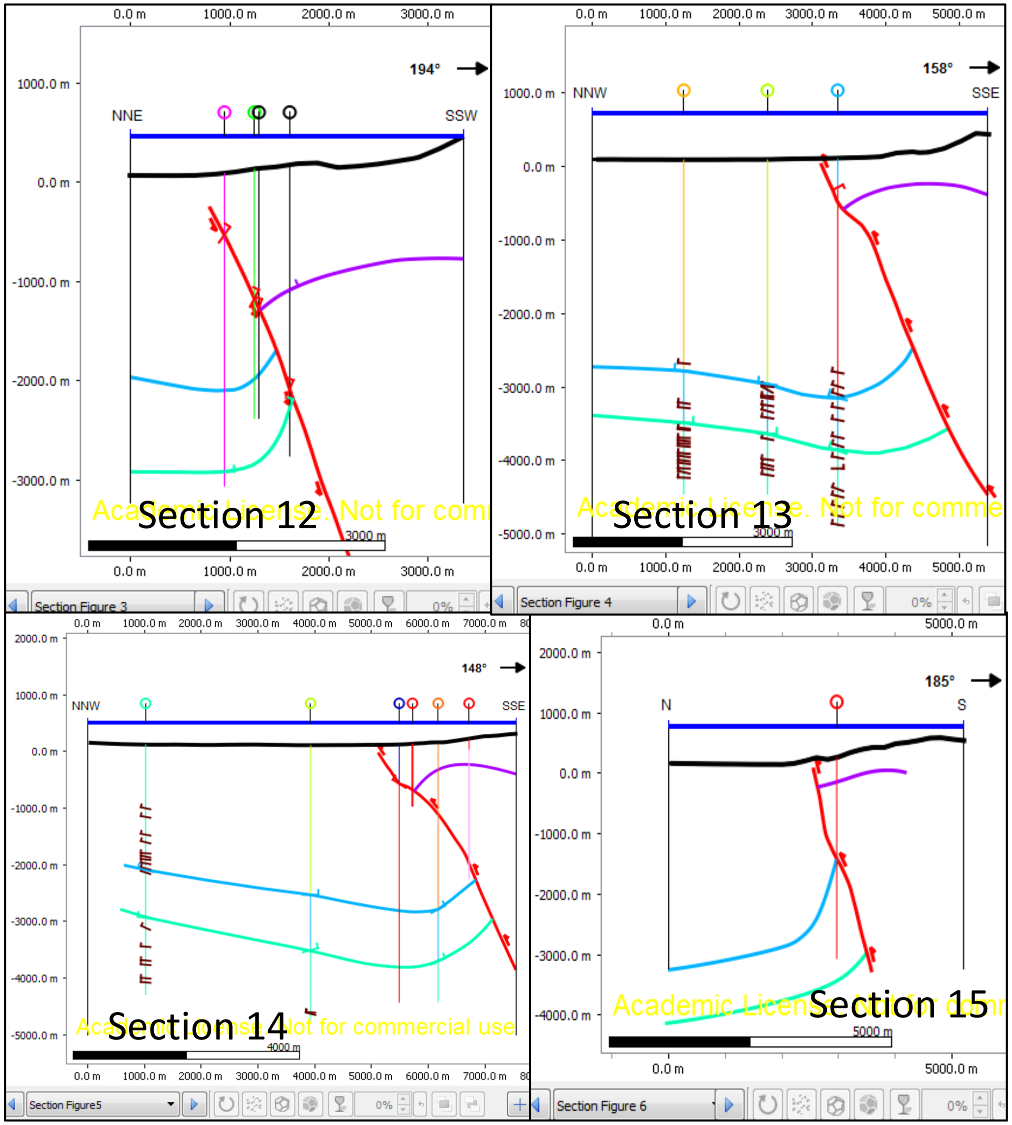

Figure 53. a) QC cross sections 20 to 35 perpendicular to the Oak Ridge fault. b) Interpreted cross sections 12 to 15 correspond to the QC cross sections. Figure 15 shows the location of interpreted cross sections 12 to 15. Legend is the same as shown in Figure 48.

6.2 Issues and Surface problems

There are two main problems for the 3D structural model. Firstly, the horizon modeling is constrained into a local area where there is well data control. In this thesis, although the coastal area has more well data than the eastern part, well drilling in this area did not reach the deeper Miocene strata on the footwall block of the Oak Ridge fault. Therefore, only the Pliocene Pico-Repetto succession can be used to analyze the Oak Ridge fault displacement. In the eastern area, late Quaternary deformation uplifted the hanging wall block of the Oak Ridge fault and brought the Oligocene Sespe Formation to the surface. However, since the Sespe Formation on the footwall block is too deeply buried to be reached by well, fault displacement could not be well studied in this area. Continuity of the model is good only in the areas where the well tops are consistent. Although well correlations from publications were used to mark horizon position and reconstruct the geometry of each horizon, it is very difficult to locate the well tops taken from the reports and interpret horizon shape without dip meter control (Figures 54 to 61). For example, as shown in Figure 59, three wells on the well correlation from report are not included in the original Petrel project. I collected well location data from Division of Oil, Gas and Geothermal Resources Oil of California and imported them into Move. Well tops were marked based on the well correlation from report.

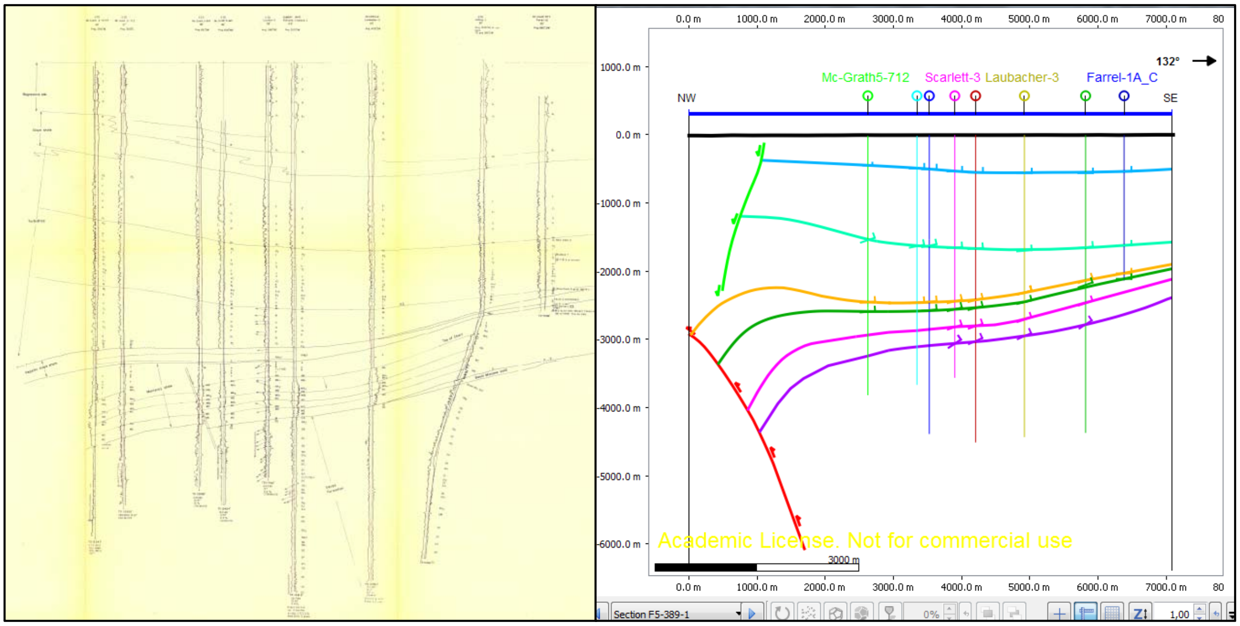

Figure 54. Interpreted cross section 2 (right) and referred well image from original Petrel project (left).

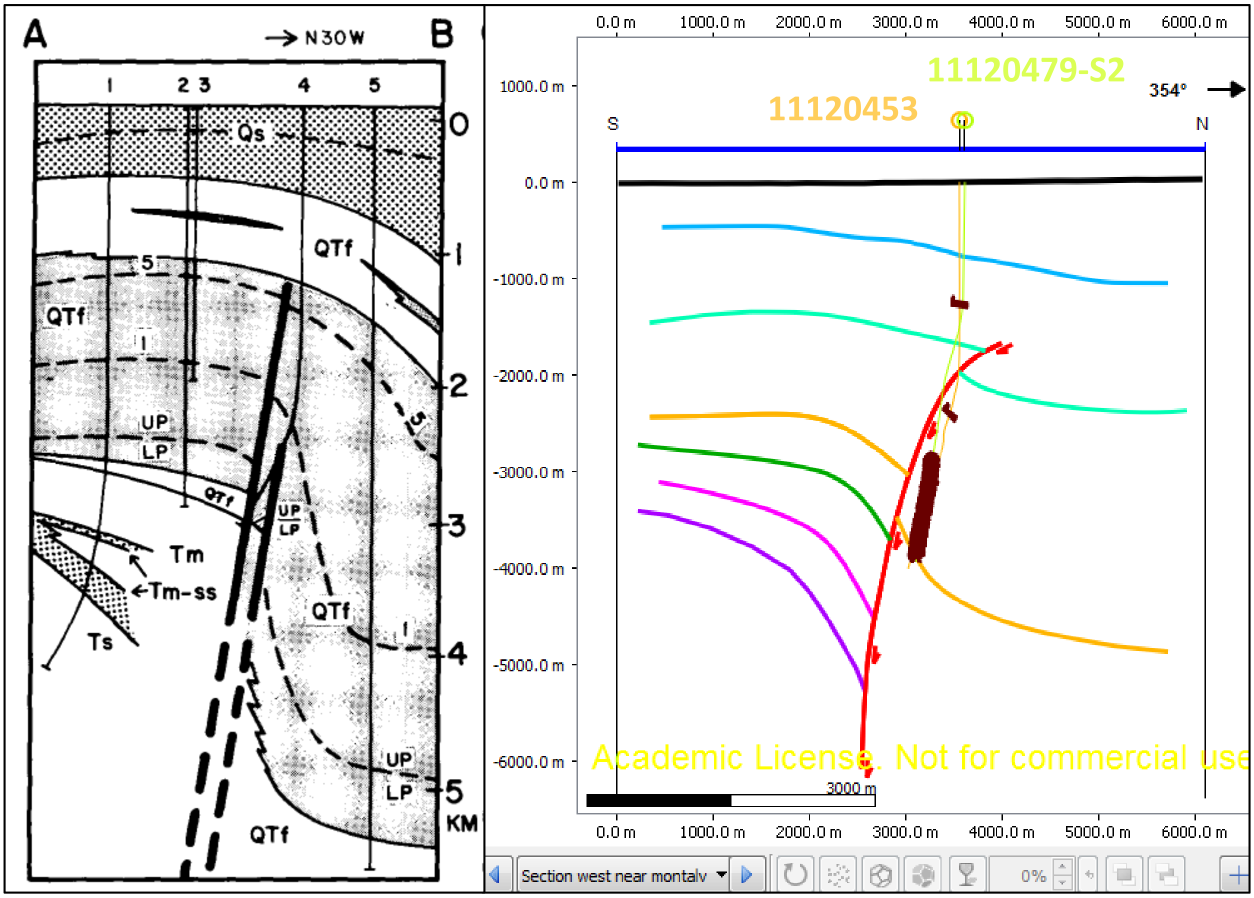

Figure 55. Interpreted cross section 4 and referred well correlation AB from report .Well correlation derived from Yeats et al. (1981).

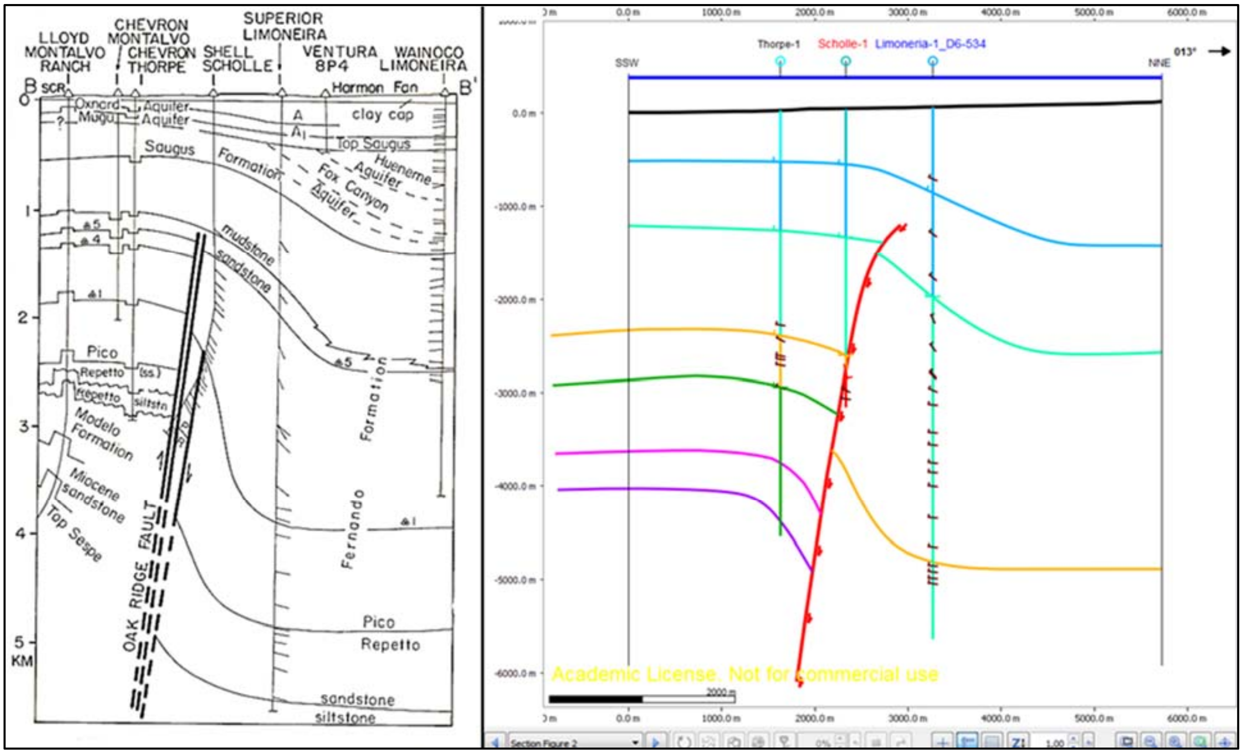

Figure 56. Interpreted cross section 5 and referred well correlation from report .Well correlation derived from Yeats (1988).

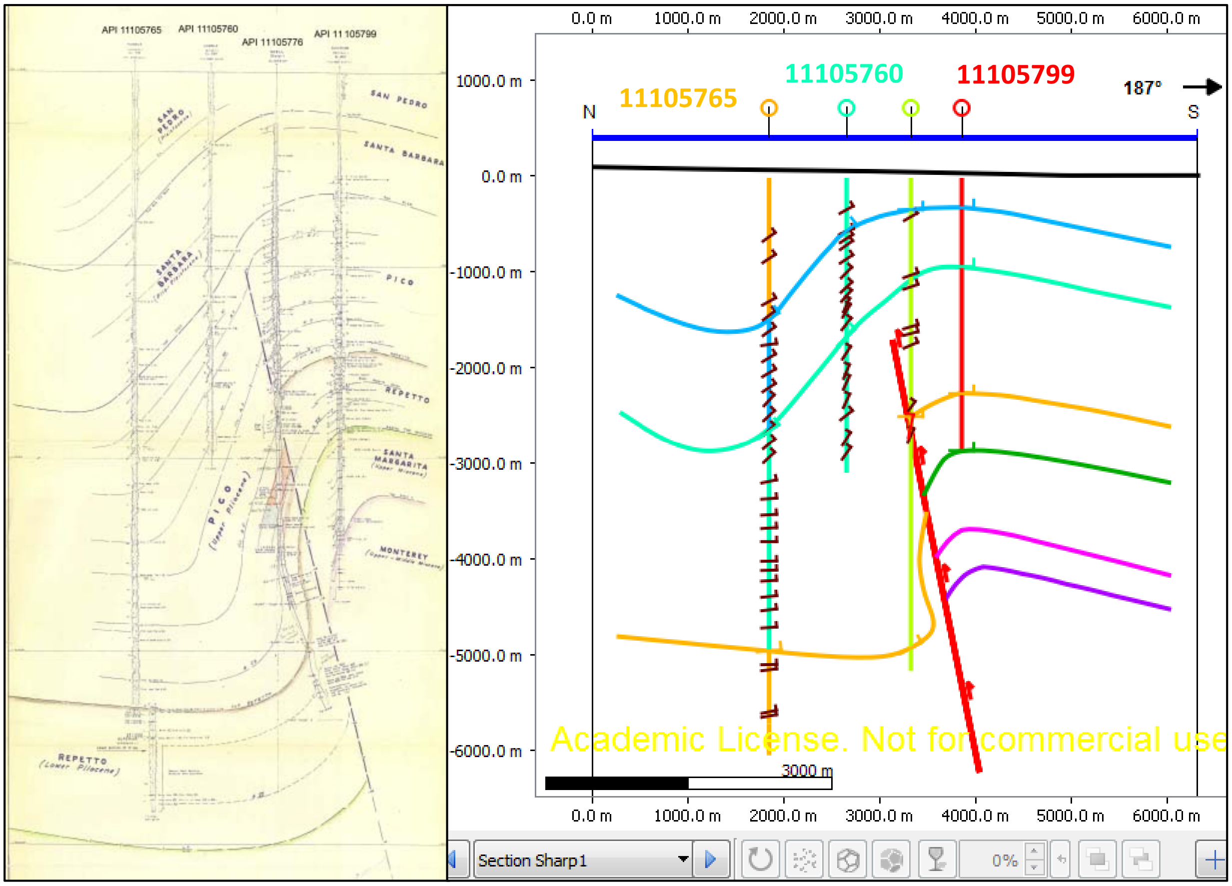

Figure 57. Interpreted cross section 6 (right) and referred well image from original Petrel project (left).

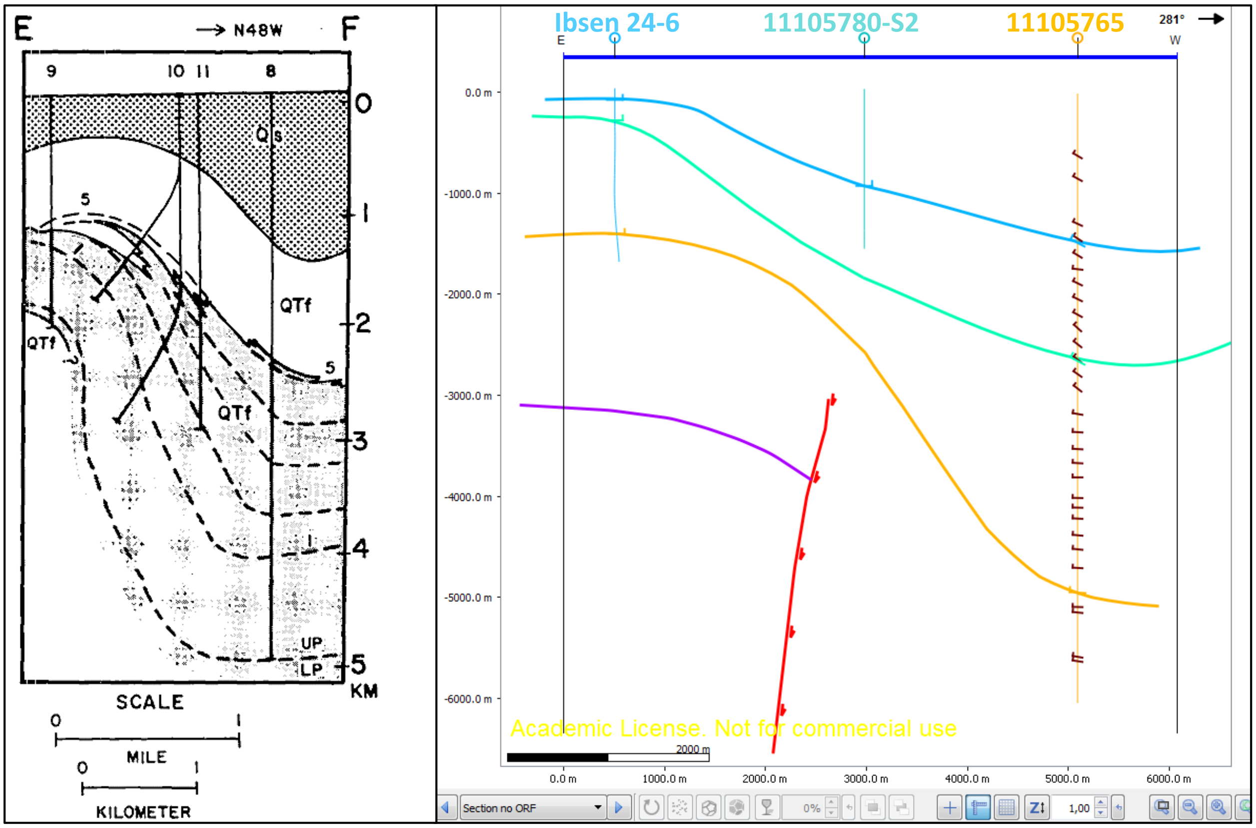

Figure 58. Interpreted cross section 7 and referred well correlation from report .Well correlation derived from Yeats et al. (1981).

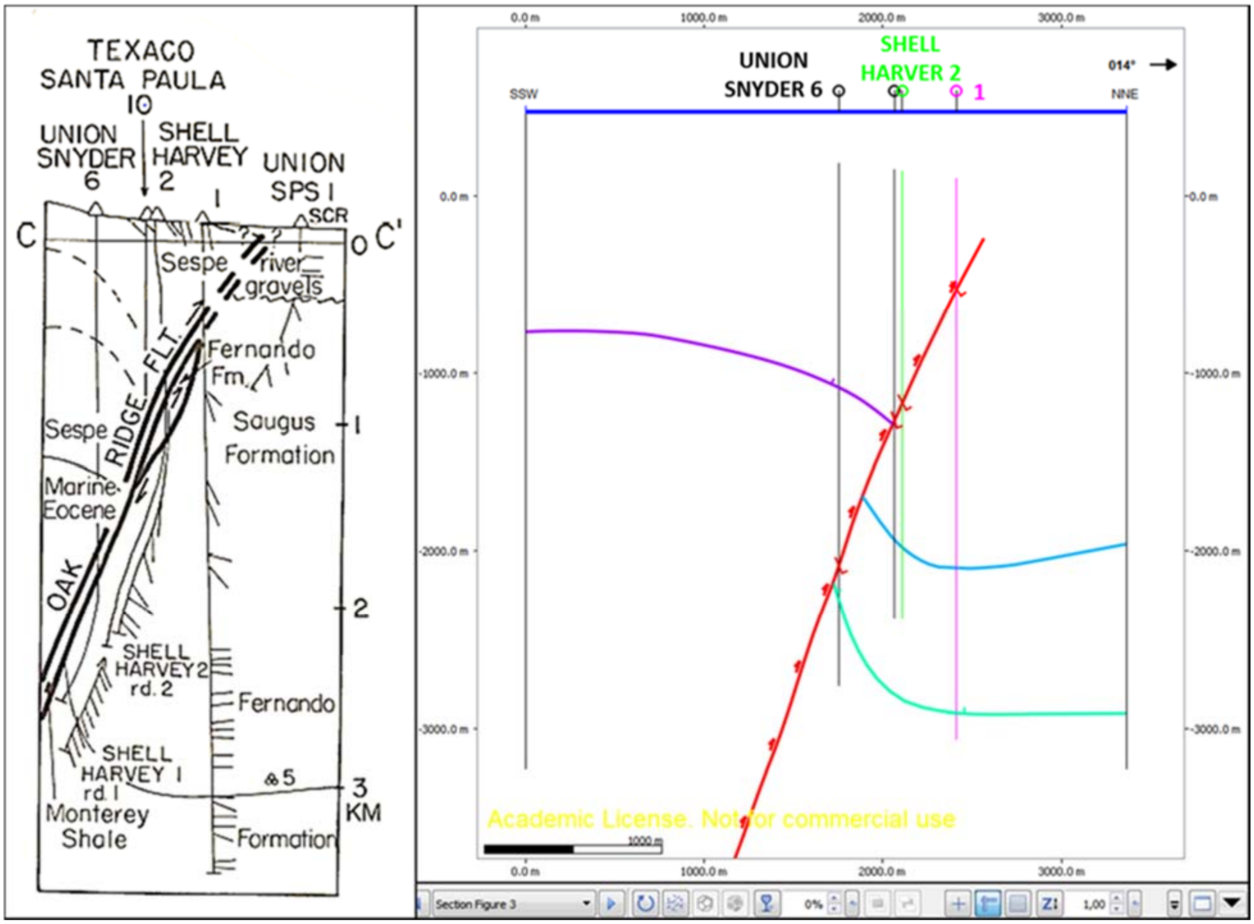

Figure 59. Interpreted cross section 12 and referred well correlation from report .Well correlation derived from Yeats (1988).

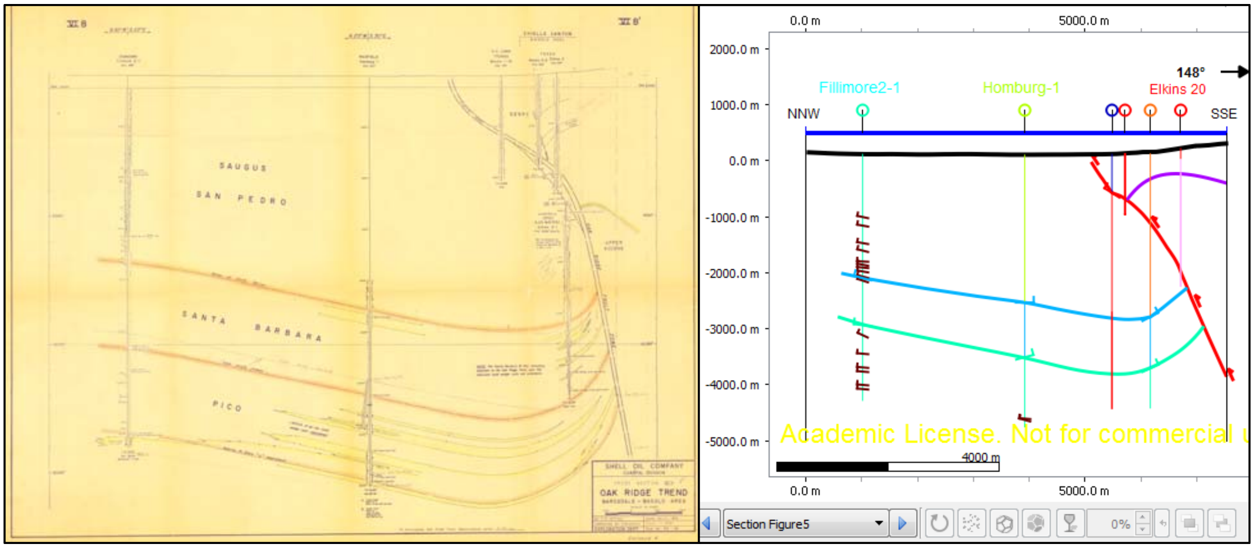

Figure 60. Interpreted cross section 14 (right) and referred well image from original Petrel project (left).

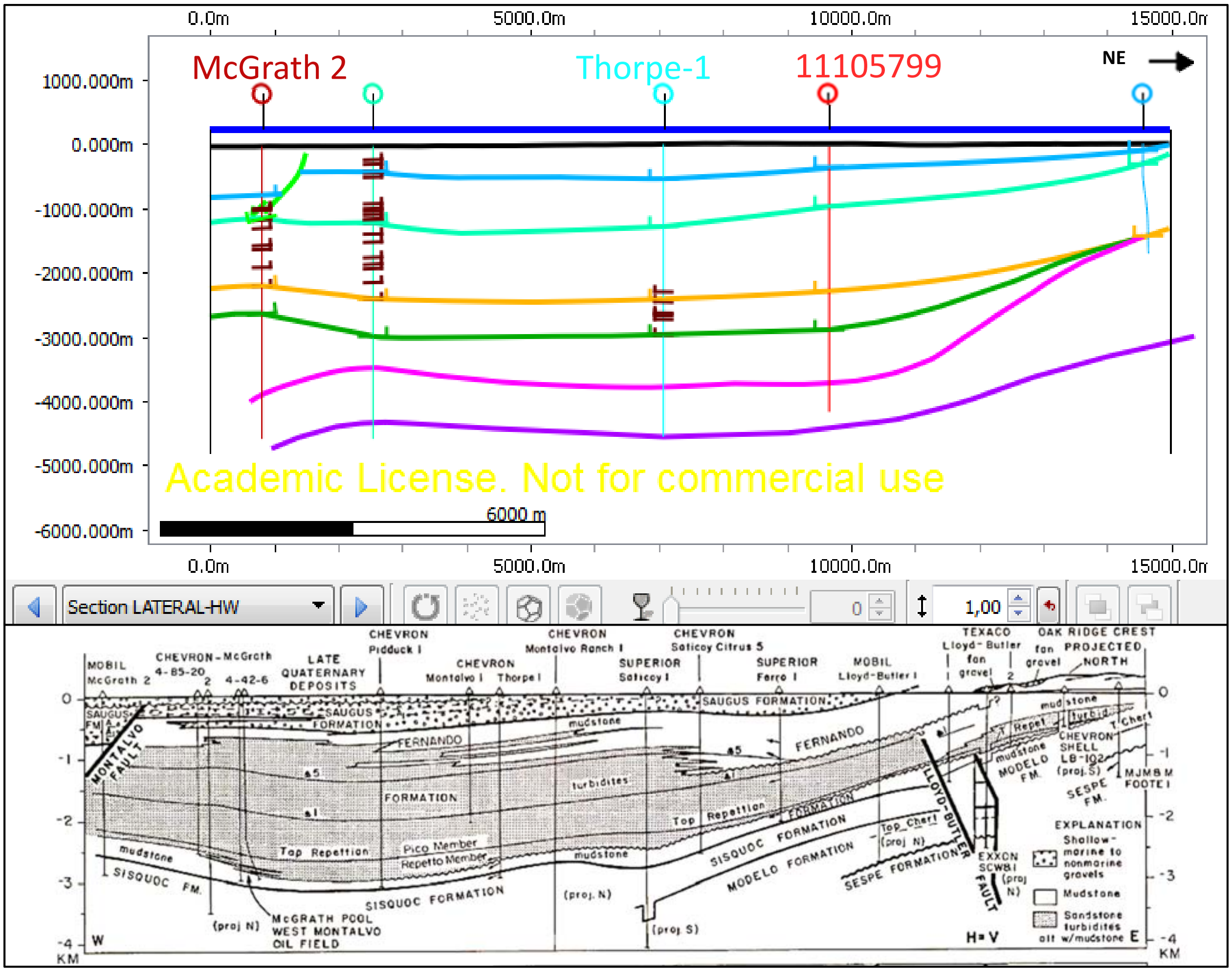

Figure 61. Interpreted cross section 8 and referred well correlation from report .Well correlation derived from Yeats (1988).

Secondly, the structural model is not smooth especially in the area where horizon depth changes rapidly (Figure 62). This is because I used the ‘Linear’ method to reconstruct the horizon by collecting the traces that appear consistent in all cross sections. Therefore, the interpolated surface does not change smoothly to follow the tendency of the horizon variation. This problem was highlighted on the QC cross sections (Figures 48 to 52). Two possible ways to solve this problem are: 1) Create more fake cross sections in this area to control the shape of the horizon. 2) Test other methods like Kriging to create smoother surface models. These solutions can be tested in future work to improve the structural model.

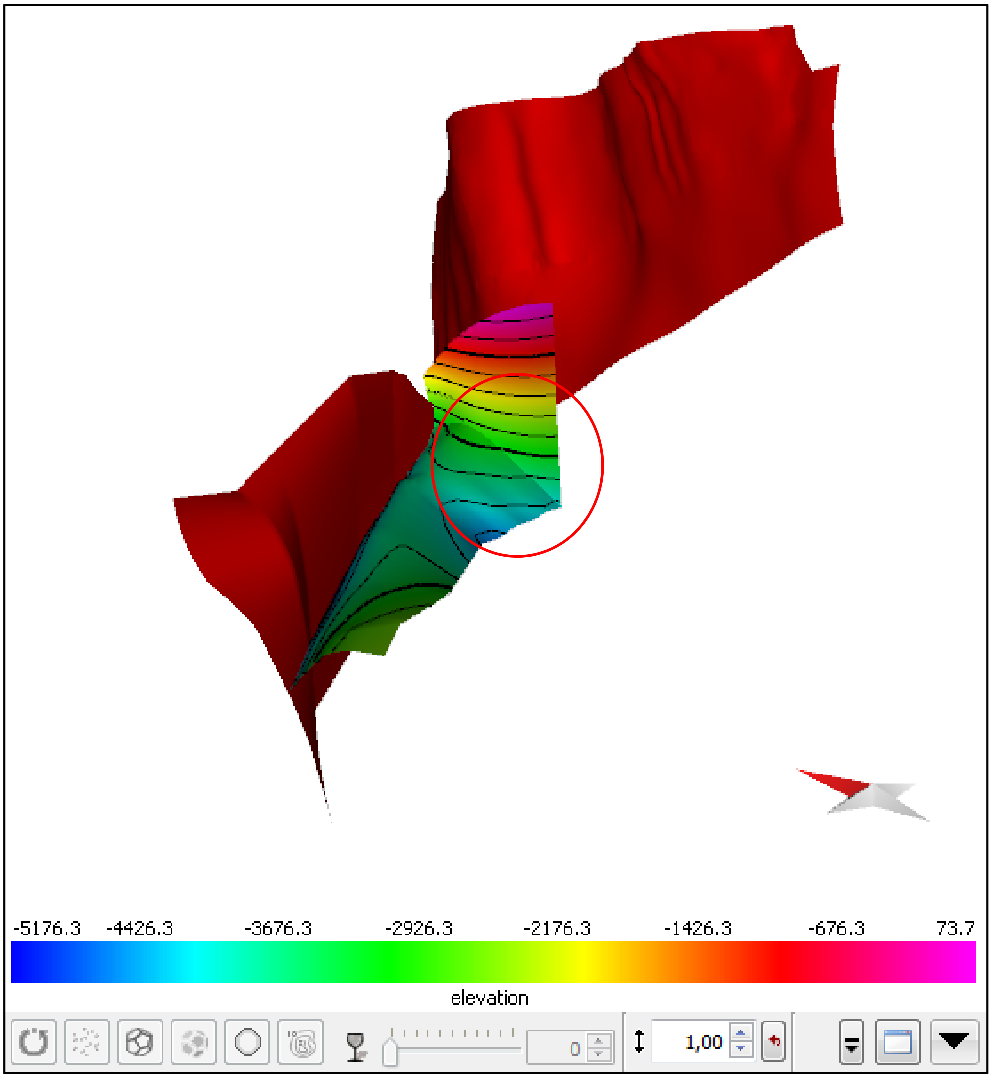

Figure 62. Example of Surface problem marked with red circle. Red surface is Oak Ridge fault. Colorful elevation map shows the Top Monterey surface.

7. Conclusion

In this research, 36 cross sections with well tops and dip meter data from the Oak Ridge fault were used to build two faults and six horizons surfaces in the study region using Move.

The Montalvo fault is a 58 to 84 degrees north dipping normal fault, which diverges southwest from the Oak Ridge Fault. The orientation of the Montalvo fault is NE-SW. This fault is formed in the coastal area and cuts the entire Santa Barbara Formation. Thicker Santa Barbara in the hanging wall block indicates that the Montalvo fault is a growth fault.

Based on the strike variation of the Oak Ridge fault, the fault was subdivided into four segments: (1) NE-SW striking coastal segment with an eastwards increased dip angle up to 80 degrees, (2) NE-SW striking segment dipping 85 degrees, (3) ENE-WSW striking segment with an eastwards decreasing dip angle from 80 degrees to 60 degrees, and (4) N-E striking segment with an eastward increasing dip angle from 60 to 80 degrees.

Horizon modeling was performed on both hanging wall and footwall from the coastal area to Santa Paula city where there was good well data control. To the east, the top Santa Barbara and top Pico surfaces were made in the footwall block, while only the top Sespe surface was made in the hanging wall due to the late Quaternary deformation in this region.

Unfaulted horizons show a monoclinal structure in the western area. To the east, the hanging wall Sespe horizon expresses an anticlinal structure due to uplift deformation, while the footwall Pico and Santa Barbara horizons show a synclinal structure.

Cross sections interpretation and final modeling show that the thickness of the Pliocene Pico and Pleistocene Santa Barbara formation on the hanging wall and footwall has different trends It decreases eastwards on the hanging wall block but increases eastwards on the footwall block from the coastal area to Santa Paula city.

The displacement of Oak Ridge fault generally decreases westwards. While the Montalvo fault has a displacement increasing westward.

Reference

Atwater, T., Stock, J., 1998. Pacific-North America plate tectonics of the Neogene southwestern United States: an update. International Geology Review, 40(5): 375-402.

Atwater, T.M., 1998. Plate tectonic history of southern California with emphasis on the western Transverse Ranges and northern Channel Islands, 45: 1-8.

Bohannon, R.G., Geist, E., 1998. Upper crustal structure and Neogene tectonic development of the California continental borderland. Geological Society of America Bulletin, 110(6): 779-800.

Bohannon, R.G., Parsons, T., 1995. Tectonic implications of post–30 Ma Pacific and North American relative plate motions. Geological Society of America Bulletin, 107(8): 937-959.

Crouch, J.K., 1979. Neogene tectonic evolution of the California Continental Borderland and western Transverse Ranges. Geological Society of America Bulletin, 90(4): 338-345.

Fossen, H., 2010. Structural geology. Cambridge University Press, 463.

Harding, T., Tuminas, A., 1988. Interpretation of footwall (lowside) fault traps sealed by reverse faults and convergent wrench faults. AAPG Bulletin, 72(6): 738-757.

Higgins, J.W., 1958. A Guide to the Geology and Oil Fields of the Los Angeles and Ventura Regions: For Annual Meeting AAPG-SEPM, Los Angeles, Calif., March 10-13, 1958. Pacific Section American Association of Petroleum Geologists.

Huftile, G., 1988. Structural geology of the Upper Ojai Valley and Chaffee Canyon areas Ventura County, California. unpublished Master's Thesis, Oregon State University, Corvallis.

Huftile, G.J., Yeats, R.S., 1995. Convergence rates across a displacement transfer zone in the western Transverse Ranges, Ventura basin, California. Journal of Geophysical Research: Solid Earth, 100(B2): 2043-2067.

Jackson, J., Molnar, P., 1990. Active faulting and block rotations in the western Transverse Ranges, California. Journal of Geophysical Research: Solid Earth, 95(B13): 22073-22087.

Jackson, P.A., Yeats, R.S., 1982. Structural evolution of Carpinteria Basin, western transverse ranges, California. AAPG Bulletin, 66(7): 805-829.

Kamerling, M.J., Luyendyk, B.P., 1985. Paleomagnetism and Neogene tectonics of the northern Channel Islands, California. Journal of Geophysical Research: Solid Earth, 90(B14): 12485-12502.

Kew, W.S.W., 1924. Geology and oil resources of a part of Los Angeles and Ventura Counties, California. US Government Printing Office.

Luyendyk, B.P., 1991. A model for Neogene crustal rotations, transtension, and transpression in southern California. Geological Society of America Bulletin, 103(11): 1528-1536.

Marshall, S.T., Funning, G.J., Owen, S.E., 2013. Fault slip rates and interseismic deformation in the western Transverse Ranges, California. Journal of Geophysical Research: Solid Earth, 118(8): 4511-4534.

Nagle, H., Parker, E., 1971. Future Oil and Gas Potential of Onshore Ventura Basin, California: Region 2.

Nicholson, C., Sorlien, C.C., Atwater, T., Crowell, J.C., Luyendyk, B.P., 1994. Microplate capture, rotation of the western Transverse Ranges, and initiation of the San Andreas transform as a low-angle fault system. Geology, 22(6): 491-495.

Rotzien, J.R., Lowe, D.R., King, P.R., Browne, G.H., 2015. Stratigraphic architecture and evolution of a deep-water slope channel-levee and overbank apron: The Upper Miocene Upper Mount Messenger Formation, Taranaki Basin. Marine and Petroleum Geology, 52: 22-41.

Schlueter, J.C., 1976. Geology of the Upper Ojai-Timber Canyon Area Ventura County, California.

Share, D.J., 2015. Written In Stone...seen through my lens [Blog]. Retrieved from http://written-in-stone-seen-through my lens.blogs po t .no/2015_12 _01_ archiv -e. html.

Shearer, P.M., 1998. Evidence from a cluster of small earthquakes for a fault at 18 km depth beneath Oak Ridge, southern California. Bulletin of the Seismological Society of America, 88(6): 1327-1336.

Sorlien, C.C., Gratier, J.-P., Luyendyk, B.P., Hornafius, J.S., Hopps, T.E., 2000. Map restoration of folded and faulted late Cenozoic strata across the Oak Ridge fault, onshore and offshore Ventura basin, California. Geological Society of America Bulletin, 112(7): 1080-1090.

Yeats, R.S., 1988. Oak ridge fault, Ventura basin, California: slip rates and late Quaternary history. 2331-1258, US Geological Survey.

Yeats, R.S., Clark, M.N., Keller, E.A., Rockwell, T.K., 1981. Active fault hazard in southern California: Ground rupture versus seismic shaking. Geological Society of America Bulletin, 92(4): 189-196.

Yeats, R.S., Huftile, G.J., Grigsby, F.B., 1988. Oak Ridge fault, Ventura fold belt, and the Sisar decollement, Ventura basin, California.

Yeats, R.S., Taylor, J.C., 1990. Saticoy Oil Field--USA, Ventura Basin, California. American Association of Petroleum Geologists Bulletin, 78: 199-219.

Appendix

Well correlations collected from publications.

1. Location of well correlation for Section 4 and 7 interpretation (cross section AB and EF).

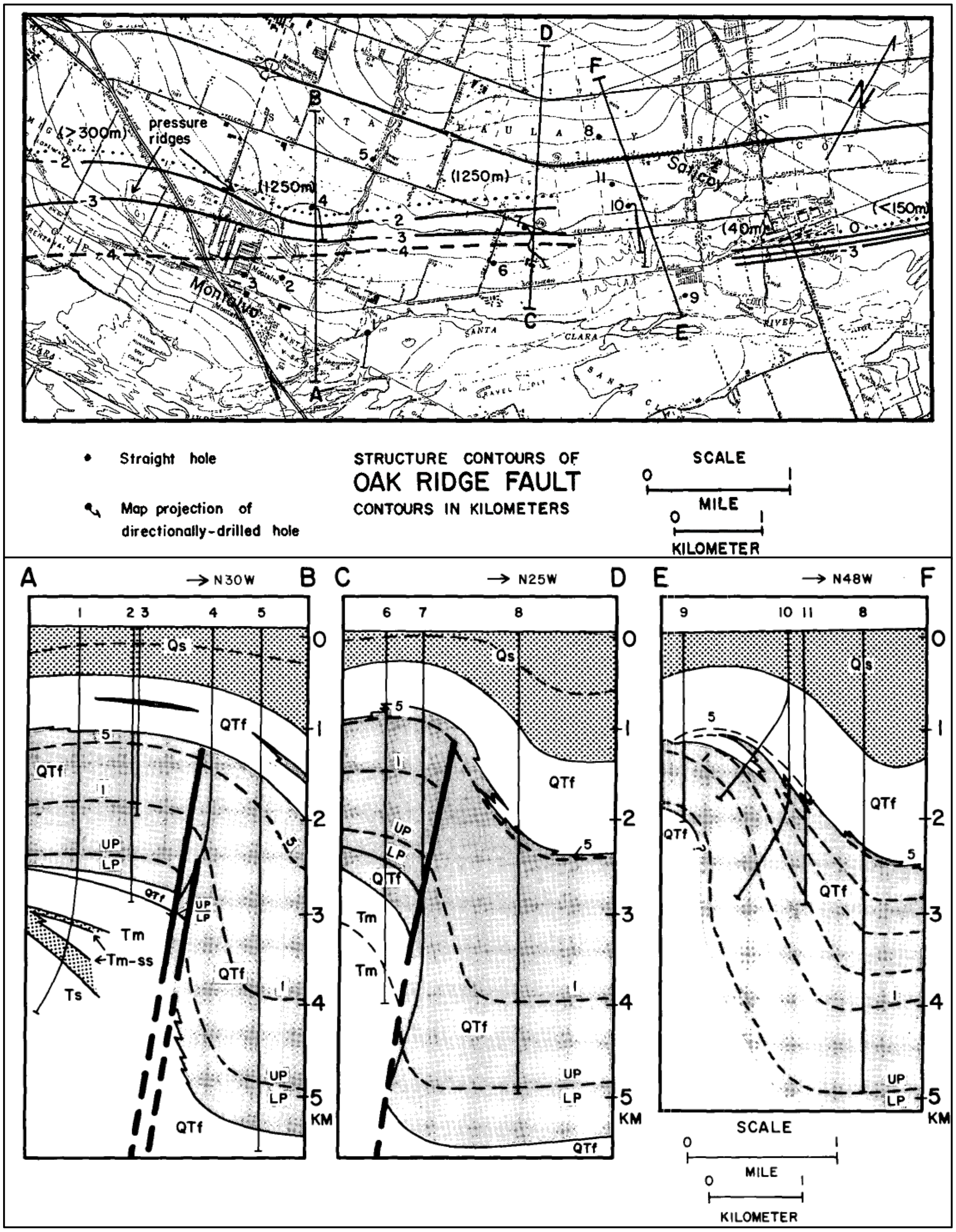

Figure 63. Structure contours on Oak Ridge fault near coast and referred cross sections. Adapted from Yeats (1981).

2. Location of well correlation for Section 8 interpretation.

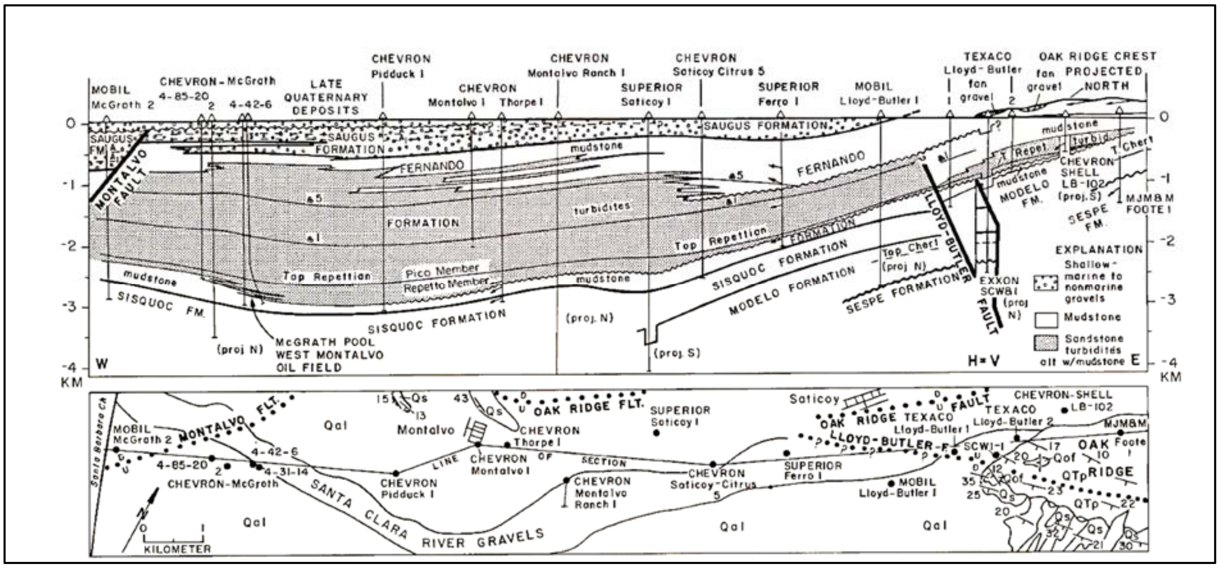

Figure 64. Cross section of hanging wall of Oak Ridge fault and location map. Adapted from Yeats (1988).

3. Location of well correlation for Sections 3, 5, 12 to 15 interpretation.

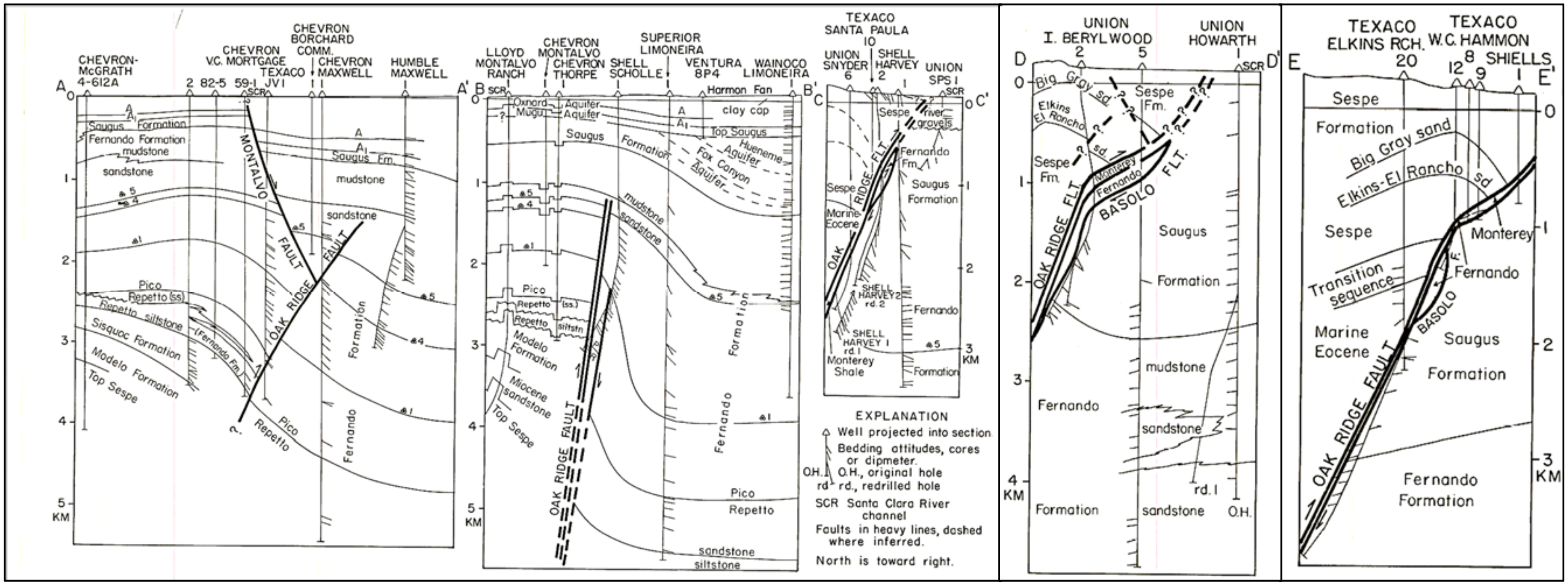

Figure 65.Cross sections of Oak Ridge fault. Sections located in Figure 66 (Red line). Adapted from Yeats (1988).

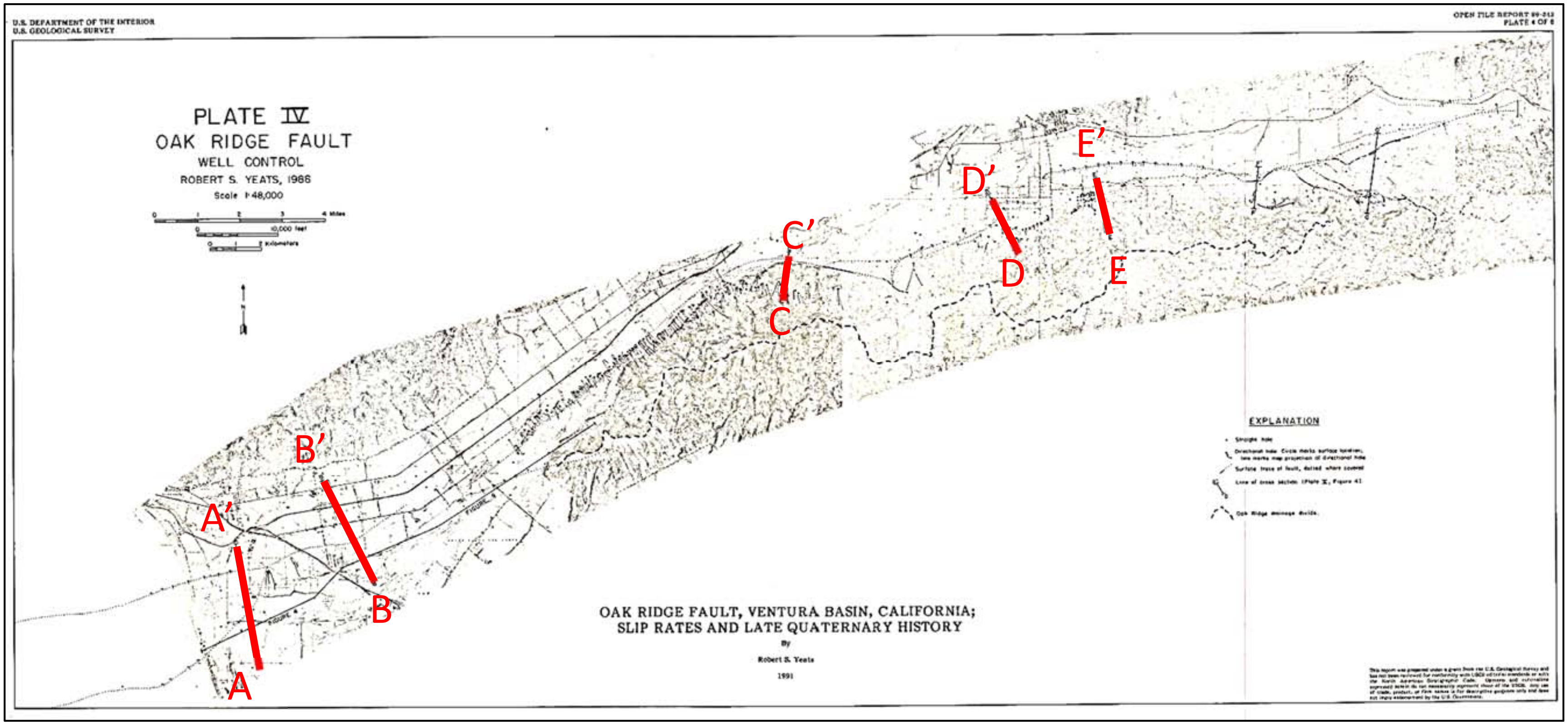

Figure 66. Cross section location map. Adapted from Yeats (1988).