AER/AGS Open File Report 2020-03

Formation-Top Offsets in West-Central Alberta and Their Implications for Subsurface Structure

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Alberta Geological Survey

October 2020

ISBN 978-1-4601-4509-8

Mei, S. (2020): Formation-top offsets in west-central Alberta and their implications for subsurface structure; Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Open File Report 2020-03, 25 p.

Published October 2020 by:
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Acknowledgements

The author wishes to thank Hilary Corlett for picks of the Devonian horizons, and Tiffany Playter for assistance in accessing the picks of the Alberta Geological Survey's Provincial Geological Framework Model of Alberta. The author thanks Dinu Pană, Tyler Hauck, Ryan Schultz, Kelsey MacCormack, and Dan Palombi for editorial review and technical commentaries that have considerably improved the manuscript.

Abstract

Subsurface bedrock formation-top offsets were mapped in west-central Alberta, Canada. The methodology used well-log data and geostatistical analysis to map the offsets. Five stratigraphic horizons were selected for mapping subsurface bedrock offsets; they are in descending order the flooding surface near the top of the First White Speckled Shale (Wapiabi Formation), the base of the Fish Scales Formation, the top of the Wabamun Group, the top of the Graminia Formation, and the 'Z marker' in the Ireton Formation. Across the mapped bedrock offset lineaments, consistent elevation differences were observed at the top of the analyzed formations. The selected surfaces represent, or are close to, the marine flooding surfaces in this area that are considered to have been originally close to horizontal and, therefore, are ideal for mapping formation-top offsets. Numerous local offsets were recognized and highlighted using residual maps of these surfaces, and an isochore map of the interval from the base of the Fish Scales Formation to the flooding surface near the top of the First White Speckled Shale. The lineaments detected in the stratigraphic succession were then compared to interpreted/inferred faults from previous publications; the elevation differences across some of the offset lineaments are interpreted as vertical offset across faults. The maps of offsets generated in this report can be used as a starting point for more detailed analyses of potential faults in west-central Alberta.

1 Introduction

In recent years, the Devonian Duvernay Formation and Lower Triassic Montney Formation, both extending over a large area of west-central Alberta, have become major drilling targets for unconventional oil and gas, which includes a significant amount of natural gas liquids. The increased activity warrants the study of the bedrock structure to help understand the structural setting and subsurface risks in the area.

This study attempts to map subsurface formation-top offsets in west-central Alberta using well-log data and geostatistical analysis. An offset is defined as any interpreted lineament of relatively abrupt elevation change in a formation top or bedrock horizon, which can be detected using well-log data and geostatistical analysis with the methodology first proposed by Mei (2009); a linear offset may represent a potential fault. This methodology allows for recognition of possible faults with offsets that are beyond the resolution of conventional structure contour maps, seismic reflection profiles, and well-log cross-sections.

This report presents the results of subsurface bedrock offset mapping in west-central Alberta. The study area extends from Twp. 51 to 71 and from Rge. 5, W 5th Mer., to Rge. 7, W 6th Mer., with the southwestern boundary of the study area corresponding to the deformation front of the Rocky Mountain fold-and-thrust belt (Figure 1). Five horizons were selected for mapping subsurface bedrock offsets, including, in stratigraphic descending order, the flooding surface near the top of the First White Speckled Shale (FWSS; Wapiabi Formation), the base of the Fish Scales Formation (BFS), the top of the Wabamun Group, the top of the Graminia Formation, and the Ireton 'Z marker' (Figure 2). Numerous possible linear offset structures were recognized and highlighted from these surfaces. Some of the mapped offsets coincide with previously reported faults in various studies, and may suggest basement control.

2 Geological Background and Previous Work

The study area (Figure 1) is located near the centre of the Alberta Basin, which is defined by the Rocky Mountain Trench to the west and southwest, the Canadian Precambrian shield to the northeast and separated from the Williston Basin by the Bow Island Arch to the southeast (Wright et al., 1994, Figure 3.1). The study area is confined to the west by the eastern limit of the Rocky Mountain fold-and-thrust belt and to the north by the Peace River Arch. The stratigraphic succession in the study area comprises Paleozoic to early Cenozoic sedimentary rocks deposited on top of the Precambrian crystalline basement of the North American craton.

Sedimentary rocks in the study area consist of two sequences with markedly different depositional history and lithology (Figures 2–4). The lower sequence was deposited on a passive continental margin and includes a succession of Cambrian, Devonian, Carboniferous, Permian, Triassic, and Middle Jurassic rocks, which are dominated by marine carbonates including reefs, and evaporites with some basin-filling deeper water shales. The upper sequence was deposited within a foreland basin from the Late Jurassic to Paleogene and is dominated by synorogenic siliciclastic rocks.

During the latest Devonian and earliest Carboniferous, the Prophet Trough developed along the western Canadian cratonic margin as an extension of the Antler foreland basin (Richards, 1989). A marine embayment also developed at the former site of the Peace River Arch in the northern part of the cratonic platform margin and subsequently became connected to the Prophet Trough. These developments resulted in different sedimentary patterns during the Carboniferous, with marine carbonates deposited in a narrow belt along the passive margin, with facies changing from shelf to basin towards the west and northwest (Kent, 1994, Figures 7.10, 7.11).

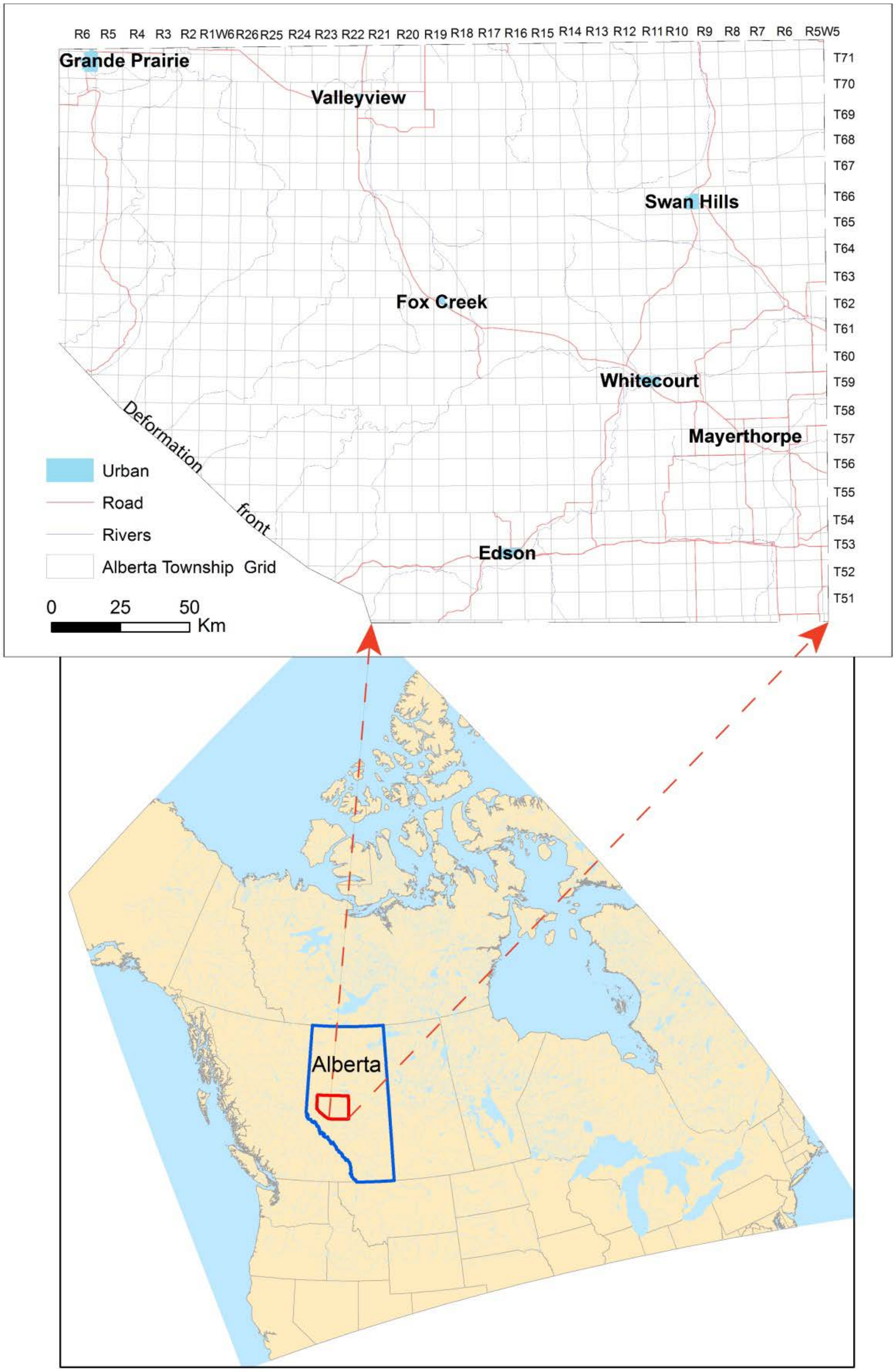

Figure 1. Location of the study area.

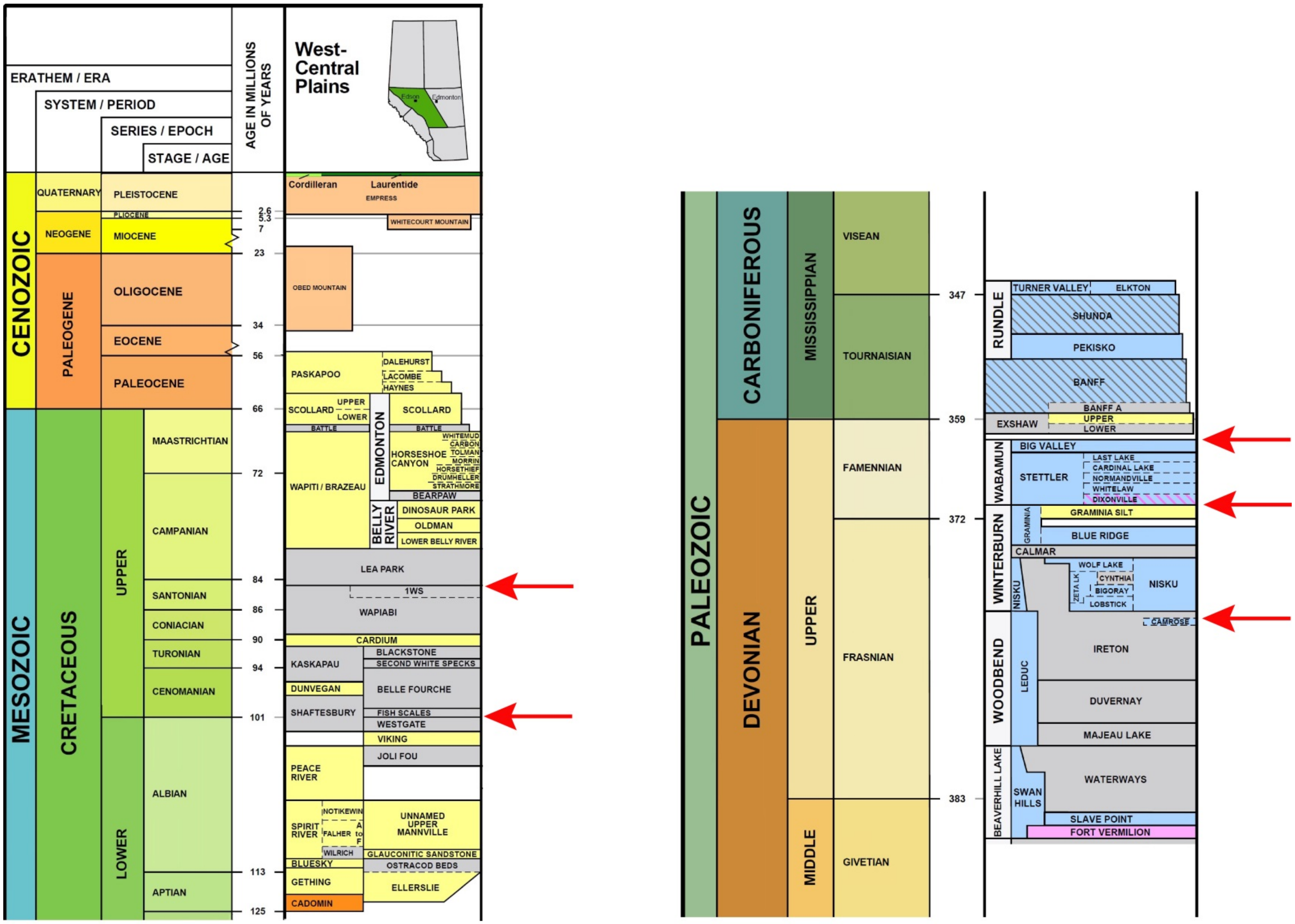

Figure 2. Stratigraphic nomenclature for the study area, west-central Alberta (modified from Alberta Geological Survey, 2019). The strata between the lower Cretaceous and the Mississippian and Devonian are confined to the southwestern part of the study area and not shown here. Red arrows indicate the five horizons analyzed in this study. Abbreviation: 1WS, First White Speckled Shale.

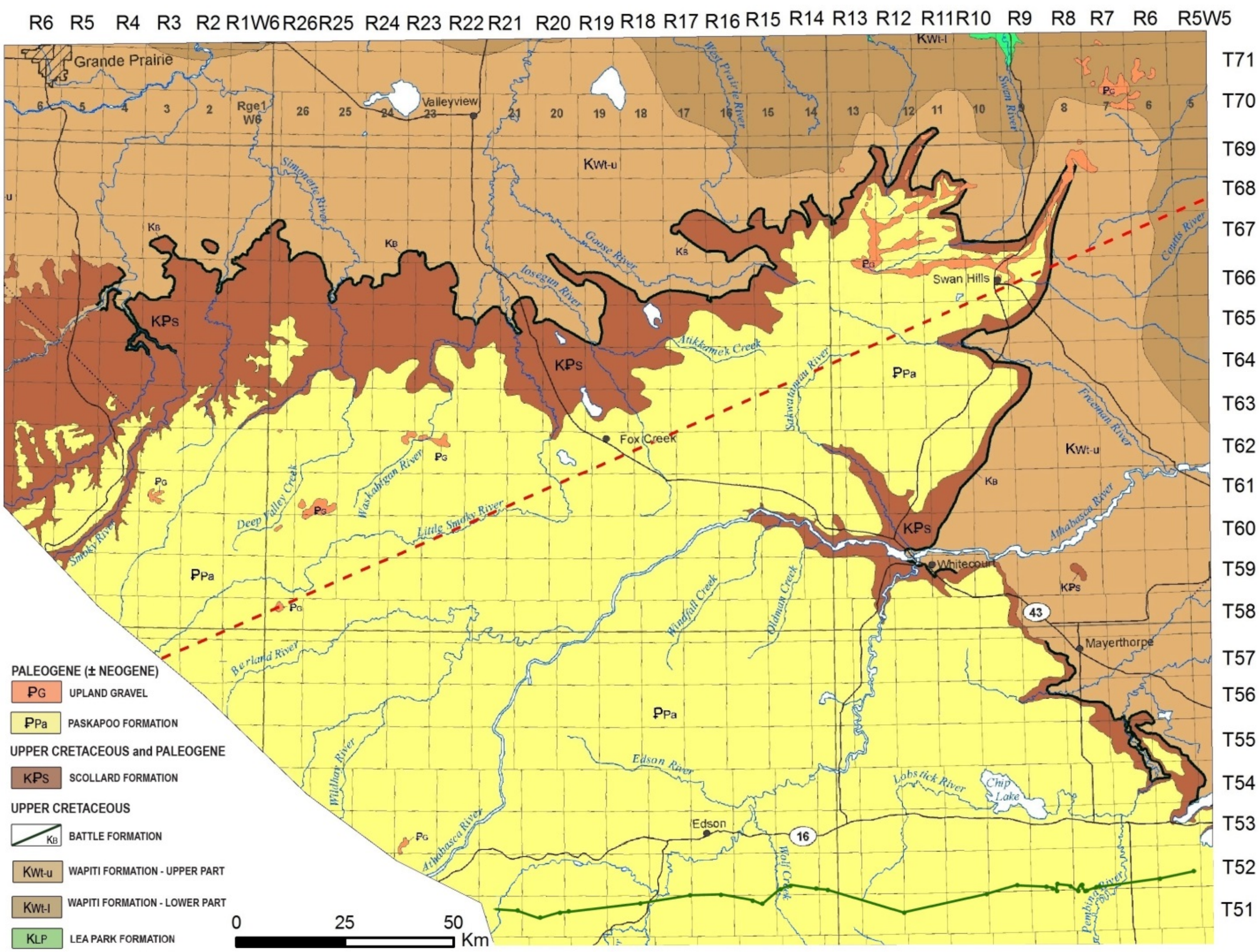

Figure 3. Bedrock geology map of the study area (modified from Prior et al., 2013), west-central Alberta. The red dash line indicates the location of the cross-section in Figure 4, and the green solid line and dots indicate the location of the well-log cross-section in Figure 11.

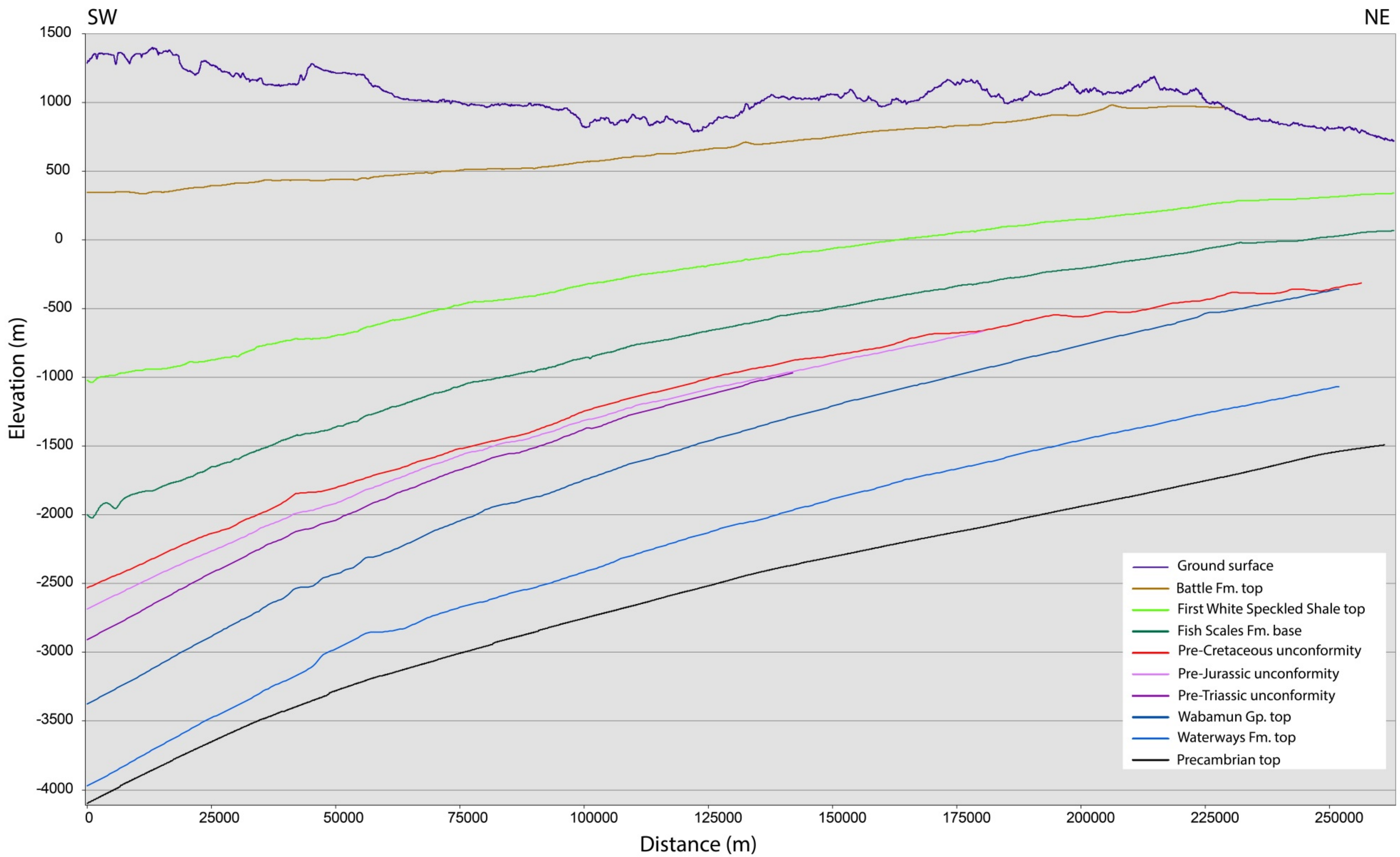

Figure 4. Generalized structure cross-section of the study area, west-central Alberta. The location of the cross-section is indicated by the red dashed line on Figure 1. Abbreviations: NE, northeast; SW, southwest.

The Wabamun Group is overlain by the black shale of the Exshaw Formation, which records the culmination of a regional transgression straddling the Devonian–Carboniferous boundary. Afterwards, sea-level change during the Carboniferous is characterized by a general trend of regression as indicated by the inferred coastline moving back towards the western basin (Kent, 1994, Figures 7.10, 7.12). The regressive trend continued and climaxed within the Permian with a significant drop in sea level, resulting in sedimentation being confined mainly to the Peace River Embayment and the Prophet Trough.

The low stand of sea level continued during the Triassic followed by a minor transgression (Kent, 1994, Figures 7.13, 7.14). The marine transgression during the Early Jurassic led to deposition of the lower Fernie Formation, which includes platformal limestone and chert, and widespread phosphatic, organic-rich shale deposited on a starved shelf. As a result, the Triassic is overlain unconformably by marine strata of Jurassic age throughout most of the Alberta Basin (Edwards et al., 1994). In western Alberta, the sub-Jurassic unconformity truncates successively older beds eastward onto the craton, from Triassic and Permian in the west, to Carboniferous in the east (Figure 4).

The transgression in the Early Jurassic was of short duration and ceased with the initiation of the terrane accretion to North America. This was followed by tectonic loading of the cratonic platform during the Middle–Late Jurassic. The ensuing isostatic flexuring of the lithosphere tilted the cratonic platform towards the southwest and led to the development of an elongated foreland basin in front of the advancing orogen. This was followed by a period of relative tectonic and magmatic quiescence in the Canadian Cordillera from about 140 to 125 Ma, which corresponds to lithospheric rebound/uplift of the foreland system resulting in significant erosion (Leckie, 2009). As a result, a major time-transgressive unconformity, known as the ‘sub-Cretaceous unconformity’, was formed throughout most of Alberta separating the overlying Cretaceous to Eocene foreland basin succession from the underlying passive margin succession (Figure 4).

The foreland basin succession has been variously assigned to two flysch–molasse cycles (Eisbacher et al., 1974), or two developmental stages triggered by two collisions (Porter et al., 1982), and three (Stott, 1984) or more (Leckie and Smith, 1992; Stockmal et al., 1992) depositional cycles/clastic wedges. The lower part of the succession is represented in ascending order mainly by the Nikanassin, Cadomin, Gething, Bluesky, Spirit River, and Peace River formations, and was deposited during the early phases of the orogeny. Deposits are characterized by fluvial and estuarine valley-fill sedimentary rocks, and sheet sandstone and shale deposited by repeated marine transgression-regression cycles. The middle part of the succession is represented predominantly by thick shale with some intervening thin sandstone of the Colorado Group and Lea Park Formation, and was deposited during an early Late Cretaceous tectonic lull when the basin was subject to a widespread marine transgression of the Cretaceous Western Interior Seaway (Caldwell, 1984). The upper part of the foreland basin succession was deposited during the Late Cretaceous–Paleogene Laramide orogeny, and includes nonmarine fluvial clastic rocks of the Wapiti Formation overlain by the Scollard and Paskapoo formations, with a thin layer of lacustrine mudstone of the Battle Formation separating the Wapiti Formation from the Scollard Formation (Figures 2–4).

All the sedimentary rocks in the study area dip toward the southwest (Figure 4), caused by lithospheric loading and isostatic flexure during the Cordilleran orogeny, with the passive-margin sequences dipping at a greater angle than the overlying foreland-basin sequence.

Previously, Jones (1980) recognized two linear hydrocarbon trends in the area, from Twp. 61 to 74, Rge. 5 to 25, W 5th Mer., each being interpreted as being composed of a main fault and several associated parallel faults with smaller lengths (Figure 5). The two main faults were interpreted as being associated with a vertical throw ranging from 4.6 to 12 m on well-log cross-section (Jones, 1980, Figures 7–9). It was inferred that these faults controlled the distribution of Late Devonian to Late Cretaceous hydrocarbon fields. To the northwest of the study area, Hart and Plint (1990) recognized four faults that offset the Cardium Formation from well-log cross-section; one of them, if projected to the southeast, is colinear with one of the faults inferred by Jones (1980).

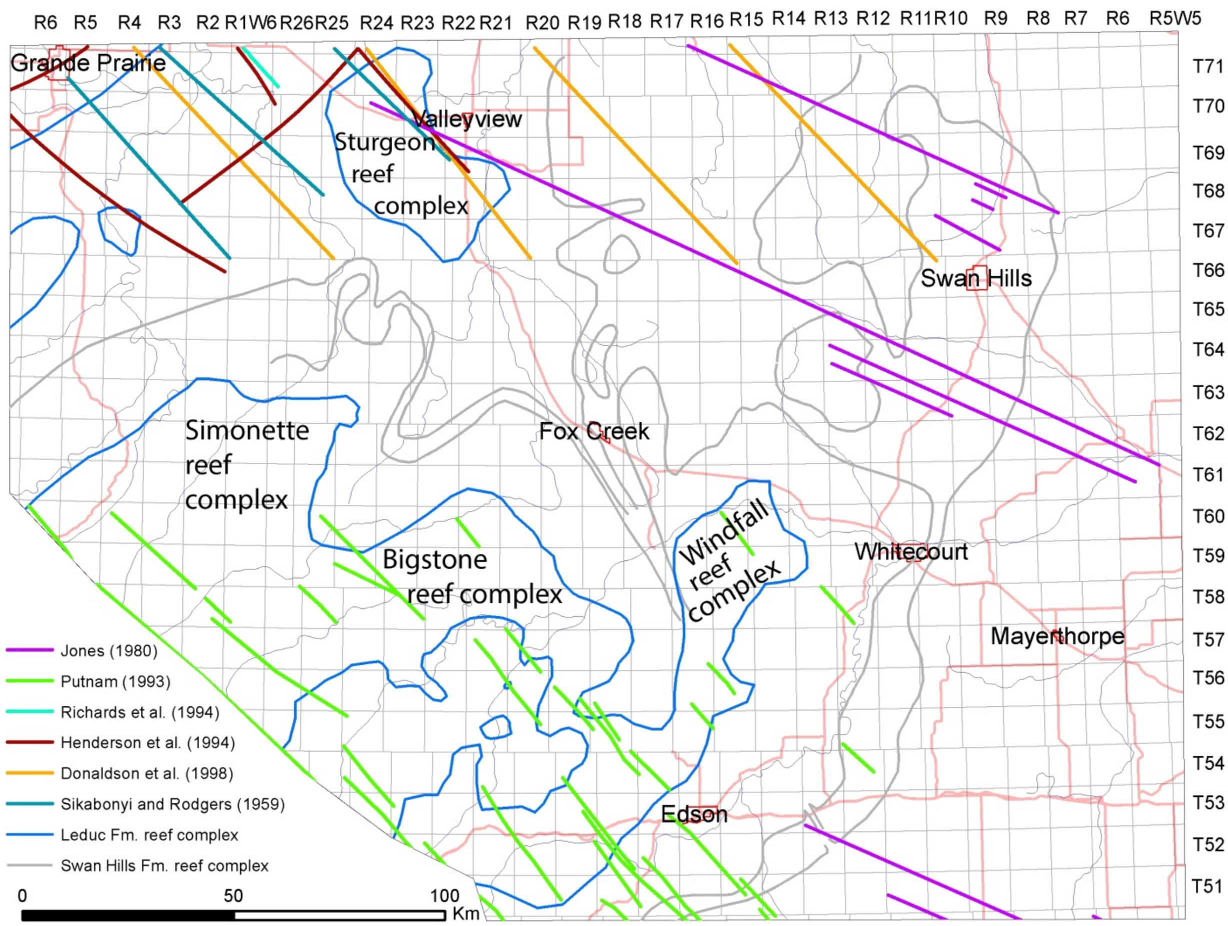

Figure 5. Previously interpreted faults and Devonian reef outlines in the study area, west-central Alberta. The thin red lines are roads and the thin light grey lines are rivers.

Putnam (1993) inferred several northwest-trending faults on top of the Chungo Member of the Wapiabi Formation based on well control only (Figure 5), and Murray et al. (1994) interpreted faults from the top of the Cardium Formation. To the northwest and south of the study area, Gardiner et al. (1990), Putnam (1993), and Hart et al. (2007) recognized fault-repeated Cardium Formation sandstone units, caused by shallow thrust faults typical of the Alberta Rocky Mountain Foothills (Bally et al., 1966), in both well-log and seismic data. In addition, Putnam (1993) reported linear structures that are oriented orthogonal to the disturbed belt and interpreted them to represent fracture systems parallel to the principle stress direction associated with the Laramide orogeny (Bell and Babcock, 1986).

In the northern part of the study area, Donaldson et al. (1998) documented four southeast-trending linear zones that record minor stratal drape of 5–20 m and rapid thickness and/or facies change in the Bad Heart Formation (Figure 5); they were interpreted to be basement-controlled bounding faults of deeper horst and graben structures.

To the north of the study area is the Peace River Arch, where numerous faults have been documented for the Carboniferous and Permian rocks overlying the arch and its southern flank, which overlaps with the northern part of the study area (Sikabonyi and Rodgers, 1959; Henderson et al., 1994; Richards et al., 1994; see Figure 5).

3 Data and Sources of Error

3.1 Data

The data used for structural mapping in this study are stratigraphic picks of five horizons in stratigraphic descending order: the flooding surface near the top of the FWSS, the base of the Fish Scales Formation (BFS), the top of the Wabamun Group, the top of the Graminia Formation, and the Ireton Z marker. The FWSS is composed of a calcareous mudstone with subordinate amounts of bentonite, fish remains, nodular phosphate, and concretions of siderite and calcite (Leckie et al., 1994). The FWSS is widespread and was deposited under warm-temperate, open-marine conditions during the maximum marine transgression following deposition of the Cardium Formation (McNeil and Caldwell, 1981). The flooding surface in the FWSS can be recognized by a high deflection/spike on gamma-ray logs due to its high radioactive uranium content associated with abundant kerogen and bentonites deposited in the shale.

Similarly, the Fish Scales Formation is also a basin-wide marker and contains abundant fish remains (scales and skeletal material) within finely laminated, generally nonbioturbated sandstone and siltstone (Leckie et al., 1994). It is characterized by high organic-carbon contents and a low concentration of benthic foraminifera, and is generally considered to have been deposited under poorly oxygenated bottom-water conditions during a peak transgression of the Cretaceous Western Interior Seaway (Caldwell, 1984). The BFS can be consistently picked by sharp increases on gamma-ray logs caused by its high radioactive content associated with abundant kerogen.

The top of the Wabamun Group is the base of the Exshaw Formation. The Exshaw Formation comprises mainly shale, tuff, and siltstone, which were deposited in a euxinic basin, from well below storm wave base up to shallow-neritic environments, during the late Famennian and earliest Tournaisian (Hays, 1985; Richards and Higgins, 1988). The black shale in the lower Exshaw Formation records the culmination of a regional transgression, which commenced with deposition of the uppermost Wabamun Group (Richards et al., 1991, 1994); it indicates widespread anoxic conditions and rapid deepening of water that coincide with the latest Devonian relative sea-level rise (Sandberg et al., 1988). The top of the Wabamun Group is considered conformable or a minor unconformity caused largely by transgressive ravinement (Richards, 1989). It is easiest to recognize on density and gamma-ray logs by the sharp contrast between the dense, nonradioactive carbonates of the Wabamun Group and the overlying radioactive black shale of the lower Exshaw Formation.

The Graminia Formation comprises the upper Graminia Silt member and the lower Blue Ridge Member. The widespread Graminia Silt is easily recognized on gamma-ray and density logs as it is composed of radioactive greenish-grey, reddish-brown mottled silty carbonates, dolomitic siltstone, and shale (Meijer Drees et al., 1998). The siltstone of the Graminia Formation shows evidence of minor reworking during Wabuman Group deposition, making the upper contact of the Graminia Formation conformable with the overlying Wabamun Group. The Blue Ridge Member underlies the Graminia Silt member and represents the last widespread carbonate cycle during the Frasnian (Switzer et al., 1994).

The Z marker is an easily recognized horizon in the shale of the Ireton Formation. This marker extends throughout the study area. The Z marker has traditionally been included within the Ireton Formation as part of the Woodbend Group; however, there are several publications that identify the Z marker as the transition from Woodbend to Winterburn Group deposition (Stoakes, 1980, 1992; Wendte et al., 1995). The Z marker is recognized by high gamma radiation and interval transit time on sonic logs (Wendte et al., 1995). Reference wells from Wendte et al. (1995) were used to correlate the Z marker within the Ireton Formation.

The horizons mentioned above were selected for offset mapping because 1) they are distinct on geophysical well logs and, thus, can be picked consistently, which reduces error in picking, and 2) they either represent or are close to the marine flooding surfaces in this area and can be considered to have been deposited horizontally near the sea surface, therefore, are ideal for structure mapping. For this report, 39 748 picks were used for the flooding surface near the top of the FWSS, 37 668 picks for the BFS, 8599 picks for the top of the Wabamun Group, 8568 picks for the top of the Graminia Formation and 1145 picks for the Ireton Z marker.

3.2 Sources of Error

A stratigraphic pick in a well is a point defined in three dimensions, where the wellbore intersects the top of a stratigraphic surface. IHS Markit's Petra™ software was used for analyzing geophysical well logs and for making picks in this study. As with other well-log software, when a surface is picked on the geophysical well log, the measured depth of the pick is automatically recorded. The measured depth represents the distance along the wellbore path from the kelly bushing (KB) on the drilling platform to the surface of interest. In a vertical well, the measured depth of the pick is the same as the true vertical depth (TVD) from the KB, and the x,y location of the pick is the same as the wellhead location. When a well is deviated, the measured depth (MD) along the wellbore is greater in value than the vertical depth of the pick; the x,y location of the pick is also different from that of the wellhead. In making stratigraphic correlations and structural maps, it is the elevation of the pick that is used. The elevation of a pick in a vertical well is calculated by taking the elevation of the KB and subtracting the MD of the pick. In a deviated well, the x,y location and vertical depth of the pick can be calculated if a deviation survey is available. The first source of error is commonly found to be caused by confusing the TVD with the MD of picks for deviated wells due to missing deviation survey data. In this study, deviated wells without deviation survey data were not included.

The second source of uncertainty in the elevation of picks is the potential error found in the elevation of the KB, from which the pick elevation is calculated. The error in KB could be caused by errors in surveying the ground elevation of the wellsite because the KB elevation is usually derived from adding the height of the drilling platform above the ground surface to the surveyed ground elevation.

The third source of error is human error. The most common error is inconsistent or incorrect placement of the pick on the well log. This can result from inconsistent application of a correlation model (e.g., lithostratigraphic versus sequence stratigraphic model; see Tinker, 1996), limited availability and poor resolution of logs, and complexity in facies changes.

The fourth source of error is the uncertainty in well location. In western Canada, wells are licensed based on the bottomhole location, and the coordinates that define the location are based on a survey grid that is tied to known markers. In Alberta, the grid currently used by the petroleum industry is the Alberta Township Survey version 4.1 (ATS 4.1), which can be downloaded from AltaLIS (http://www.altalis.com/products/property/ats.html). The ATS grid has gone through several revisions, and each revision has resulted in corrections to previously derived grid points. The accuracy for the ATS 4.1 is ±3 m. The surfacehole location is first defined as metes and bounds based on the ATS grid, which are the offsets relative to the southeast corner of the section in a township. Then, the bottomhole location is calculated based on the shifts from the directional survey and the surfacehole coordinates. Some uncertainty in well location is inevitably introduced in these calculations and conversions, and will translate into uncertainty in the elevation of picks.

Other potential sources of error include data entry mistakes and incorrect well-log depth calibration.

The errors associated with picks cannot be completely removed but can be reduced and managed to an acceptable level.

4 Methodology

The methodology used in this study is based on stratigraphic picks from well-log analysis, and geostatistical analysis of the picks. The method was proposed by Mei (2009) and includes steps for data cleaning, refinement, and offset mapping. It has been described in detail by Mei and Schultz (2020) and demonstrated by them in mapping offsets in southwestern Alberta. This methodology has a higher resolution and accuracy in mapping formation-top offsets than previous methods using well-log cross-sections, and structure contour and isopach maps (e.g., Lukie et al., 2002). It also allows recognition of metre-scale formation-top offsets that are below the detection or resolution limits of conventional seismic surveys (Mei, 2009; Mei and Schultz, 2020).

5 Results

Numerous possible linear offsets have been identified from near the top of the FWSS, the BFS, the top of the Wabamun Group, the top of the Graminia Formation, and the Ireton Z marker. In the northwestern quadrant of the study area, these lineaments appear to strike south-southeast, then, in the southwest, the linear offsets turn to strike southeast. This general southeast-trend appears to be crosscut and/or possibly displaced by a number of shorter northeast-trending lineaments/zones (Figures 6–8). In the central, east-central, and southeastern portions of the study area, the offsets are characterized by a dominant northeast trend, and are associated with a smaller amount of offset compared to the western portion of the study area. In the northeast, the offsets strike southeast and coincide with one of the trends mapped by Jones (1980).

The Leduc Formation reefs (see Figure 5), especially the Sturgeon reef complex in the northwest and the Windfall reef complex in the south-central are clearly recognizable on all the mapped surfaces (Figures 6–10). In contrast, the area that coincides with the Simonette and Bigstone reef complexes are found to be extensively fragmented by offsets on both the flooding surface near the top of the FWSS and the BFS; as a result, these two reefs are not recognizable on the two mapped surfaces (Figures 6, 7). However, the Simonette and Bigstone reef complexes are recognizable on the three Devonian surfaces (Figures 8–10).

Observations of the Sturgeon and Windfall reef complexes this far up section on both the flooding surface near the top of the FWSS and the BFS, which is at least 1 km above the reef top, may indicate that in addition to differential compaction, it is possible that they are partially fault-controlled as suggested by Greggs and Greggs (1989).

In the east of the study area, a series of relative lows can be recognized on the flooding surface near the top of the FWSS and the BFS (Figures 6b, 7b); these are interpreted to represent the reprints of the Edmonton Valley trend and its distributaries, which developed on the pre-Cretaceous unconformity surface (Mei et al., 2015; Peterson et al., 2016). Some mapped offsets are parallel to parts of the thalweg of the Edmonton Valley, suggesting that the bank of the river valley may have been controlled by potential faults.

There are less offsets detected from the deeper Devonian horizons due to a decreasing number of well penetrations with depth.

Some of the linear offsets recognized from these surfaces were validated with well-log cross-sections; this confirmed that the method used to map the offsets for the entire study area was valid. Figure 11 shows an example of a well-log cross-section and the log characteristics of selected surfaces. Repeated sections were recognized in well 00/04-25-051-21W5/0; a thrust fault was interpreted between the repeated sections.

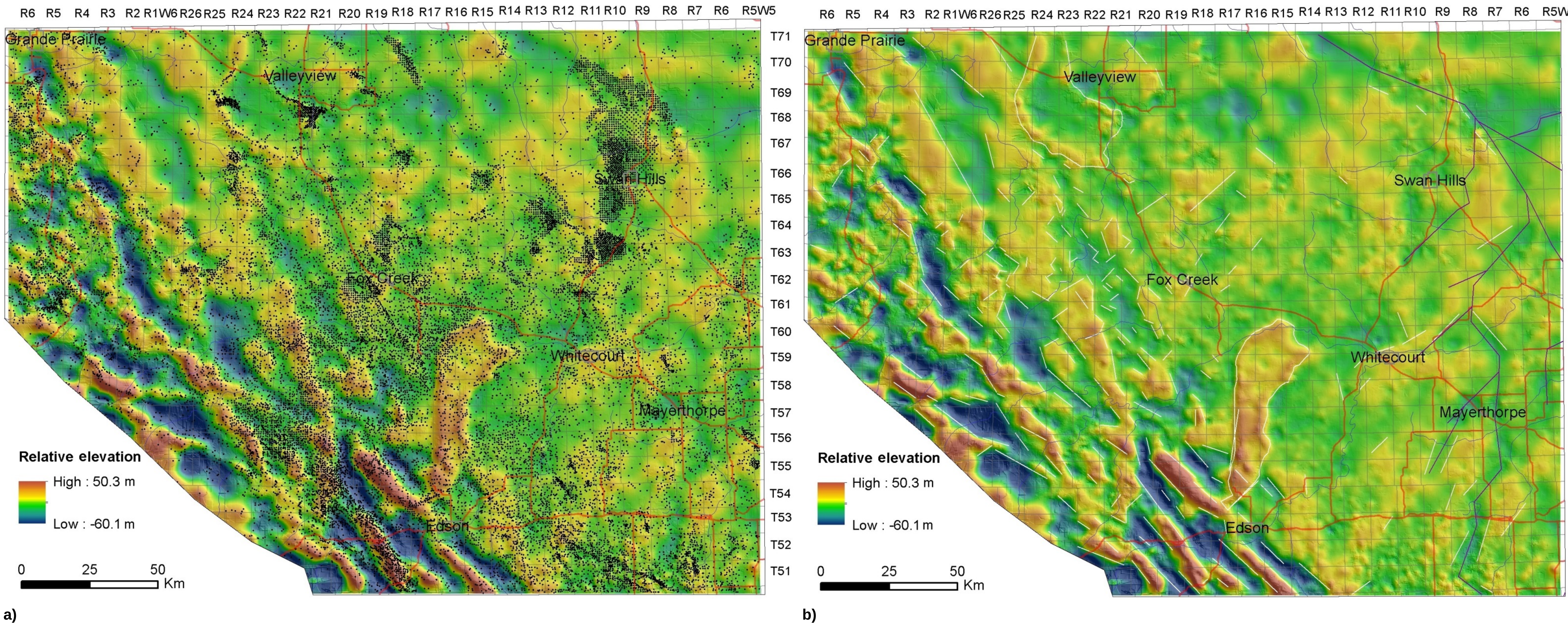

Figure 6. Residual map of the flooding surface near the top of the First White Speckled Shale (Wapiabi Formation), west-central Alberta: a) includes control wells (black dots) and b) includes interpreted offsets (white lines) and the thalweg of Edmonton Valley and its distributaries (purple lines). The red lines are roads and light blue lines are rivers.

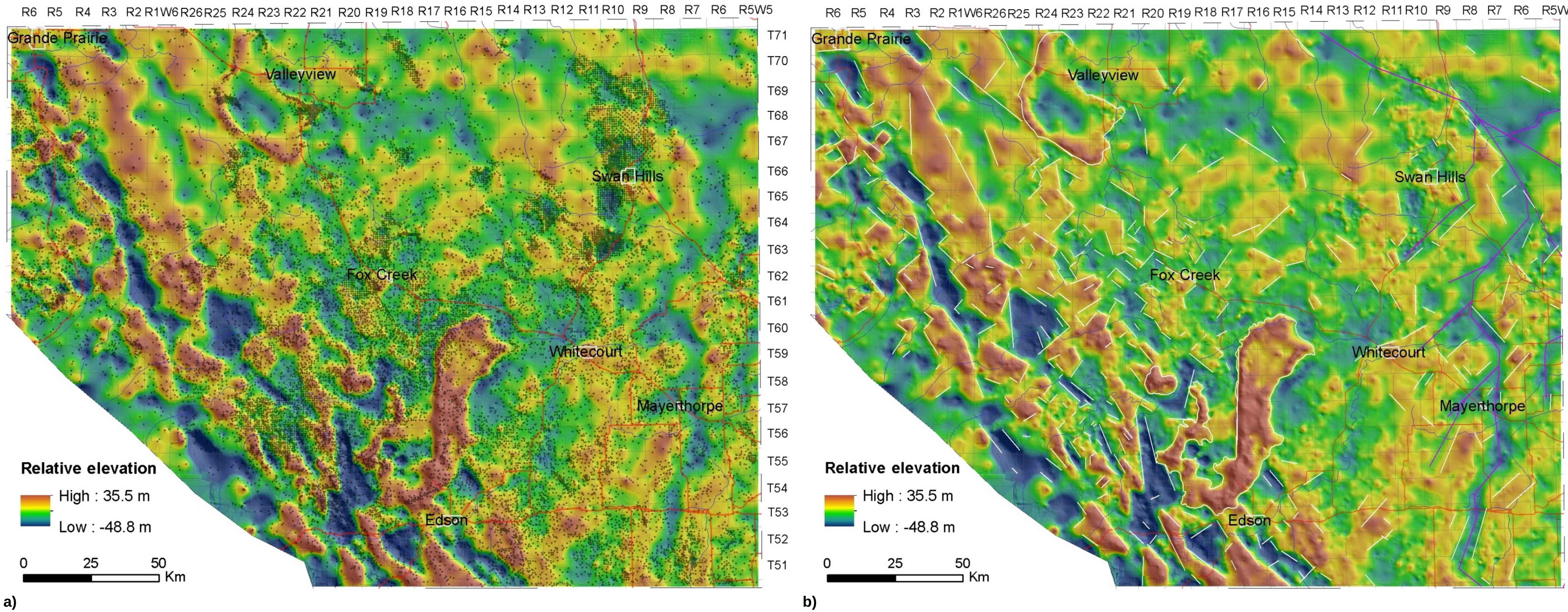

Figure 7. Residual map of the base of the Fish Scales Formation, west-central Alberta: a) includes control wells (black dots) and b) includes interpreted offsets (white lines) and the thalweg of Edmonton Valley and its distributaries (purple lines). The red lines are roads and light blue lines are rivers.

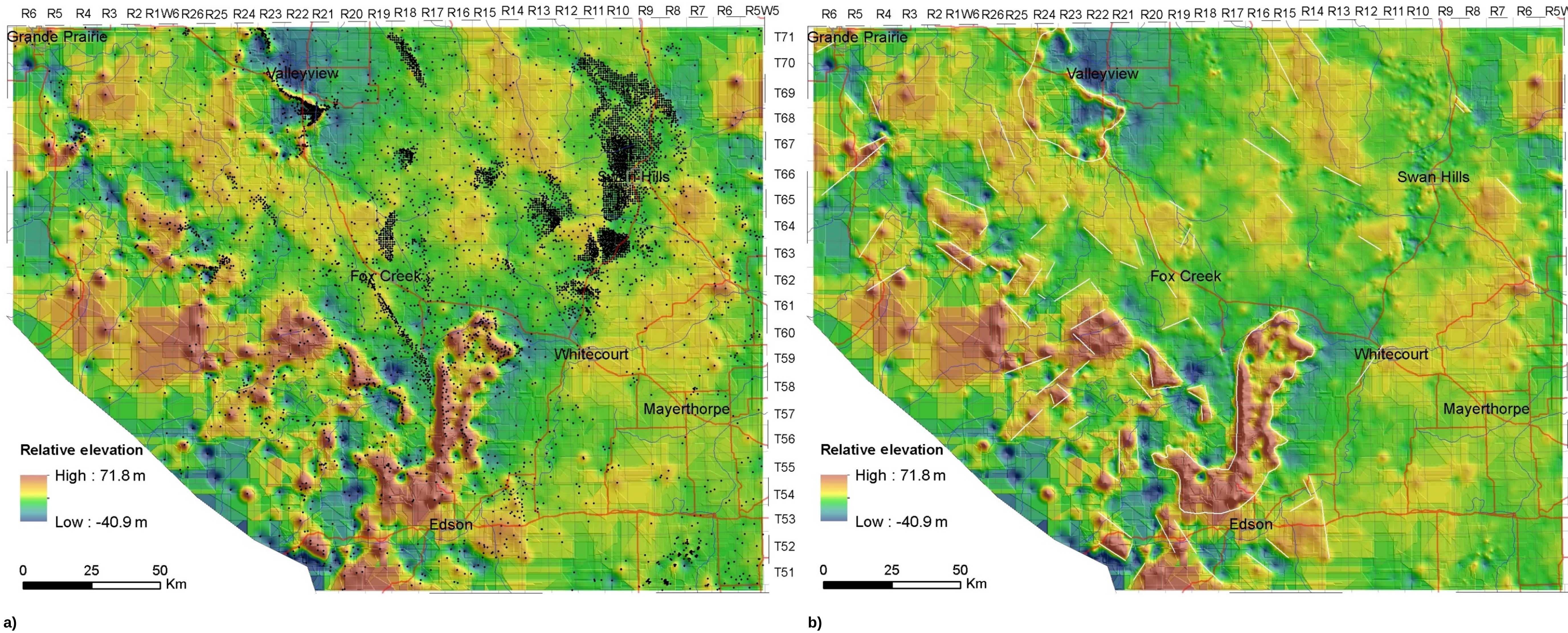

Figure 8. Residual map of the top of the Wabamun Group, west-central Alberta: a) includes control wells (black dots) and b) includes interpreted offsets (white lines). The red lines are roads and light blue lines are rivers.

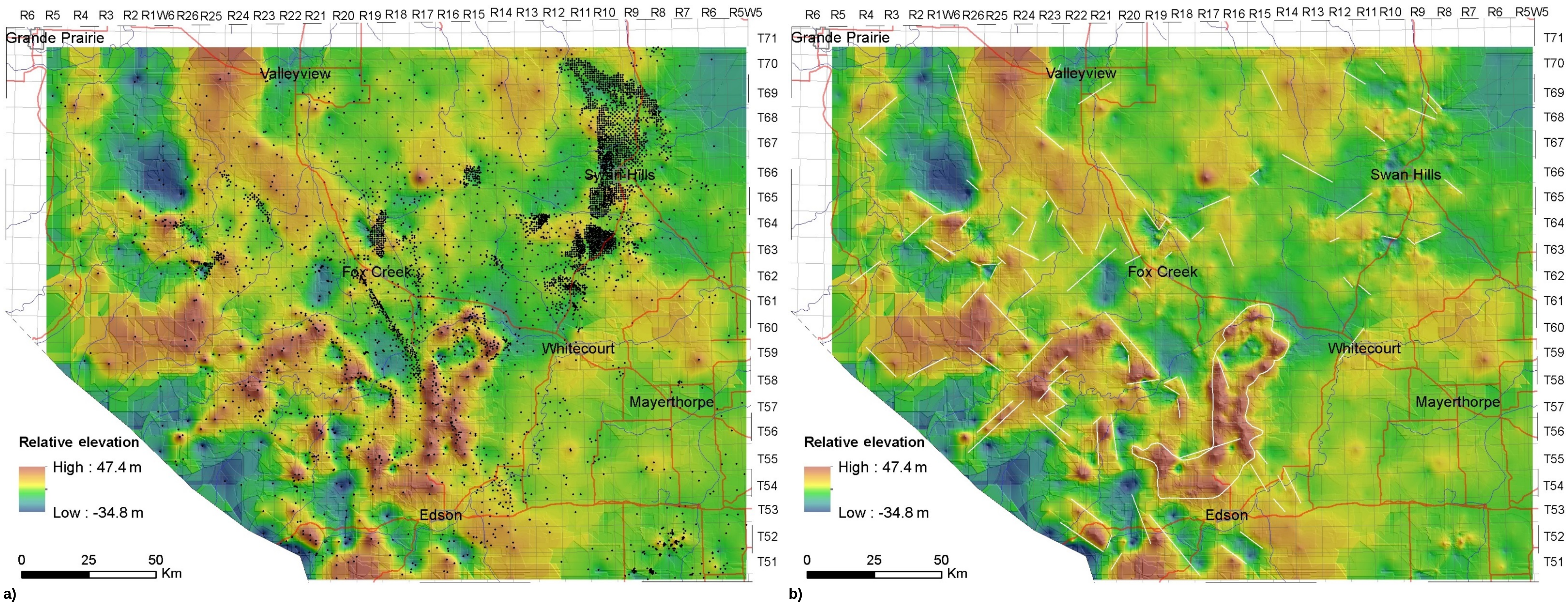

Figure 9. Residual map of the top of the Graminia Formation, west-central Alberta: a) includes control wells (black dots) and b) includes interpreted offsets (white lines). The red lines are roads and light blue lines are rivers.

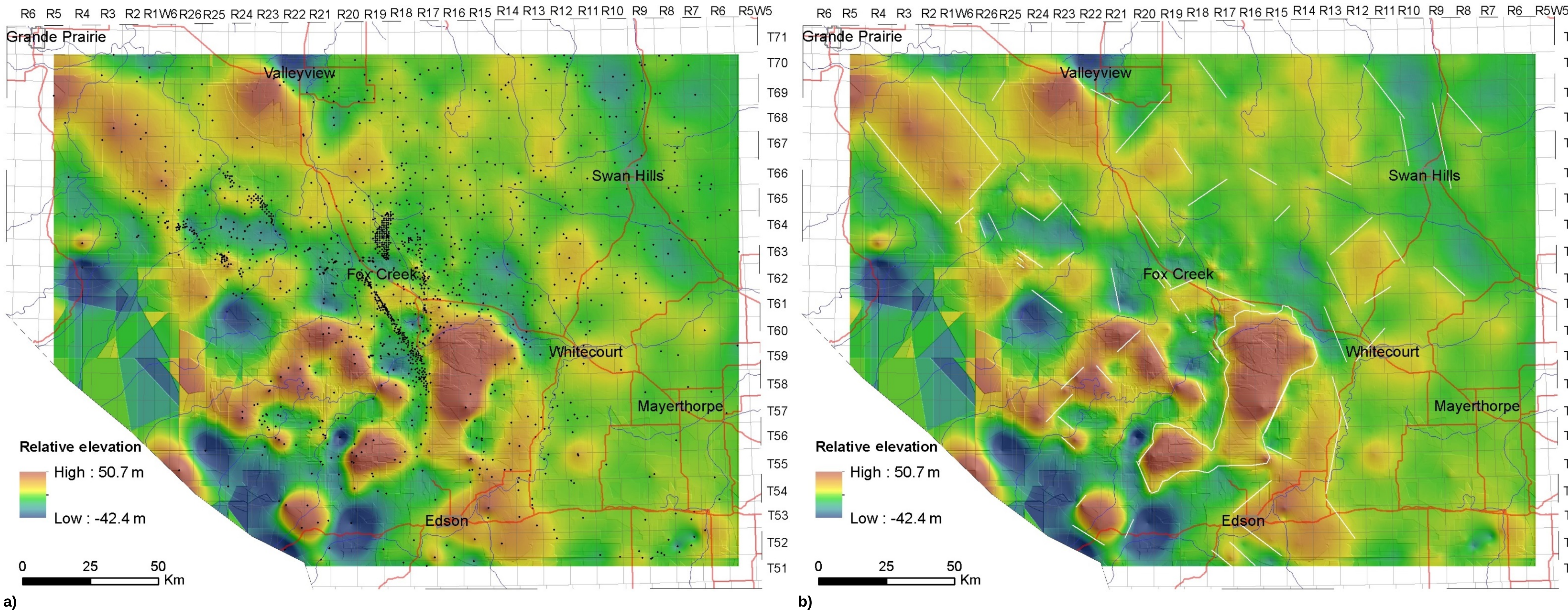

Figure 10. Residual map of the Ireton Z marker, west-central Alberta: a) includes control wells (black dots) and b) includes interpreted offsets (white lines). The red lines are roads and light blue lines are rivers.

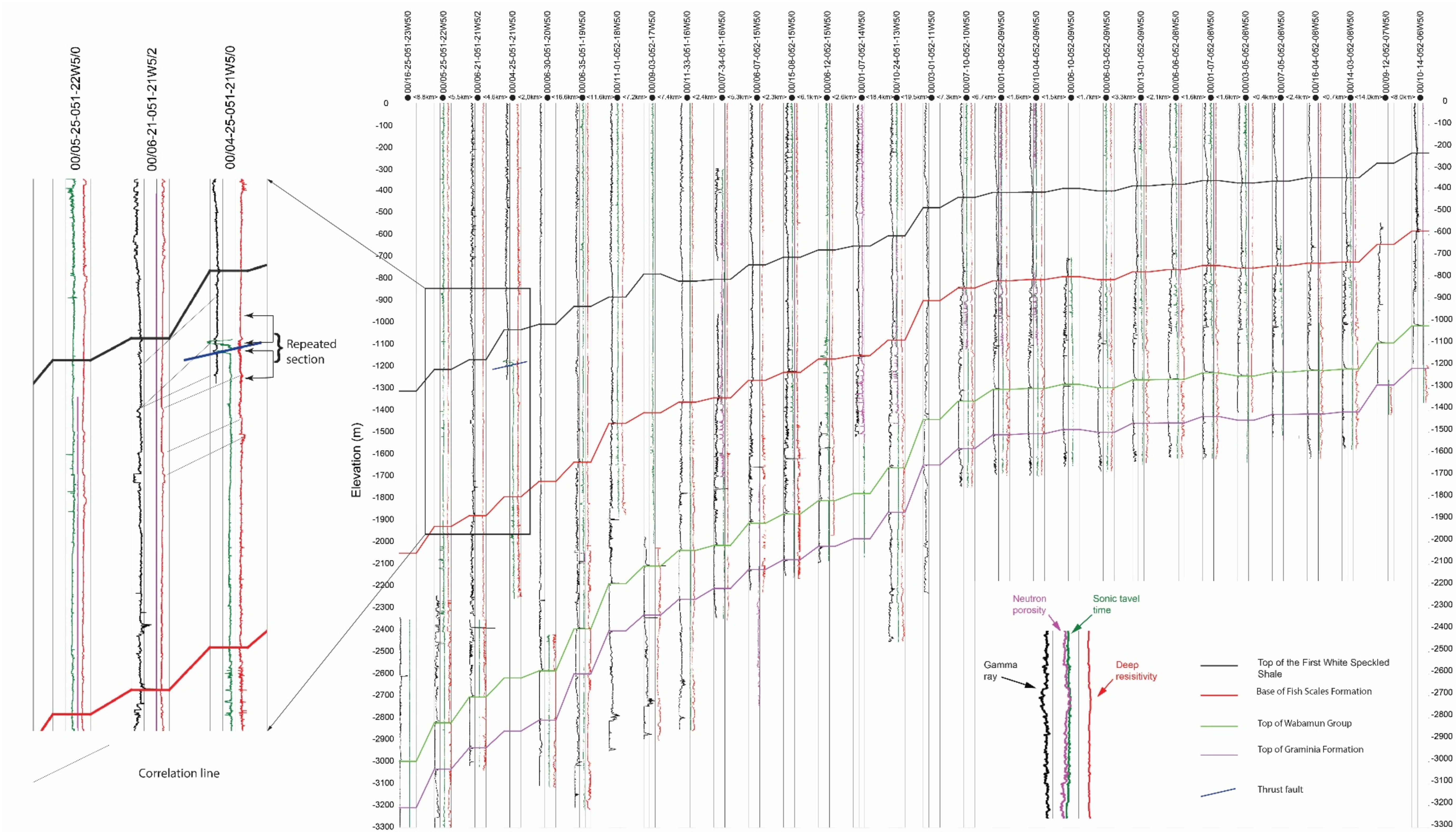

Figure 11. Structure cross-section showing the log characteristics of the flooding surface near the top of the First White Speckled Shale (Wapiabi Formation; black line), the base of the Fish Scales Formation (red line), the top of the Wabamun Group (green line), and the top of the Graminia Formation (purple line), west-central Alberta. The location of the cross-section and its wells are shown on Figure 3.

The mapped offsets were also examined by comparing them to patterns recognized from the isochore map of the interval from the BSF to the flooding surface near the top of the FWSS. Commonly, isochore maps are improperly referred to as ‘isopach’ maps, a term that should be restricted to true stratigraphic thickness unless the strata is flat and horizontal, in which case the isochore and isopach are the same. Figure 12 shows a residual map for the isochore of the interval from the BFS to the flooding surface near the top of the FWSS, where the effect of stratigraphic dipping, which caused the isochore and isopach to differ, was mostly removed with the trend. The residual isochore map was created to assess whether the interpreted linear offsets represent potential syndepositional growth faults. By comparing the offsets and the residual isochore map, syndepositional faults can be recognized by the thickness difference of a given stratigraphic unit across the fault. In areas over the Sturgeon and Windfall reef complexes of the Leduc Formation (see Figure 5), the isopach decreases, especially over the reef margins; this may indicate 1) positive relief over the reefs, and less subsidence caused by differential compaction of the offreef shaly strata during deposition, 2) growth faulting along the reef margins, or 3) both. Over many parts of the distributaries of the Edmonton Valley, the residual isochore appears to increase (Figure 12b), possibly indicating less compaction compared to other areas.

Figure 13 shows the lineaments interpreted from the top of the FWSS and the BFS and the background is the residual map for the isochore of the interval from the BFS to the flooding surface near the top of the FWSS. Many of the linear offsets interpreted from the two surfaces coincide very well with each other, suggesting that these interpreted offsets impacted both surfaces. Some of the linear offsets overlap with the lineaments interpreted from the residual isopach map (Figure 12), suggesting these offsets may indicate differential compaction across them, or may represent growth faults that accommodated differential subsidence during the deposition of the interval from the BFS to the top of the FWSS. In addition, stratigraphic thickening was found to be caused by shallow thrust faults (Figure 11), typical of the Foothills (Bally et al., 1966). A good example is the area extending southeasterly from approximately Twp. 62, Rge. 3–6, W 6th Mer. to Twp. 51, Rge. 16–22, W 5th Mer., where the thickness of this interval is clearly greater over the upthrown block of the offsets than over the downthrown block (compare Figures 6 and 12). This area may represent the eastward extension of the Foothills deformation belt. In the southern portion of this area, the offset pattern is quite different between the top of the FWSS and the BFS (compare Figures 6 and 7), suggesting that the thrusting probably occurs mainly in the stratigraphic section above the BFS.

Figure 14 shows all the lineaments interpreted separately from the five selected horizons. Some of the lineaments are clustered at approximately the same location with similar orientations, forming linear patterns; these linear patterns may be expressions of potential faults that affected the mapped horizons. Generally speaking, the interpretation is that the greater number of offset lines in a cluster, the higher level of confidence that it may represent a fault. The small discrepancy in location and orientation of interpreted lineaments within a linear pattern may be caused by 1) the dipping of the fault surface or an undulating fault surface, and 2) uncertainty in determining the position and direction of the fault due to inadequate density of the data points and/or accuracy in the pick. One type of linear pattern includes short-offset lineaments that are aligned in the same direction but with non-offset breaks in between and they occur over a much longer distance; some of these patterns may indicate a potential strike-slip fault. Vertical offsets can occur where a strike-slip fault cuts through and horizontally offsets a normal fault. The isolated, single-line linear patterns represent offsets that were identified only from a single horizon, and therefore may not necessarily indicate the presence of a fault, but may represent only local undulations in the horizon probably caused by depositional topography, local erosion, or differential compaction throughout the sedimentary succession.

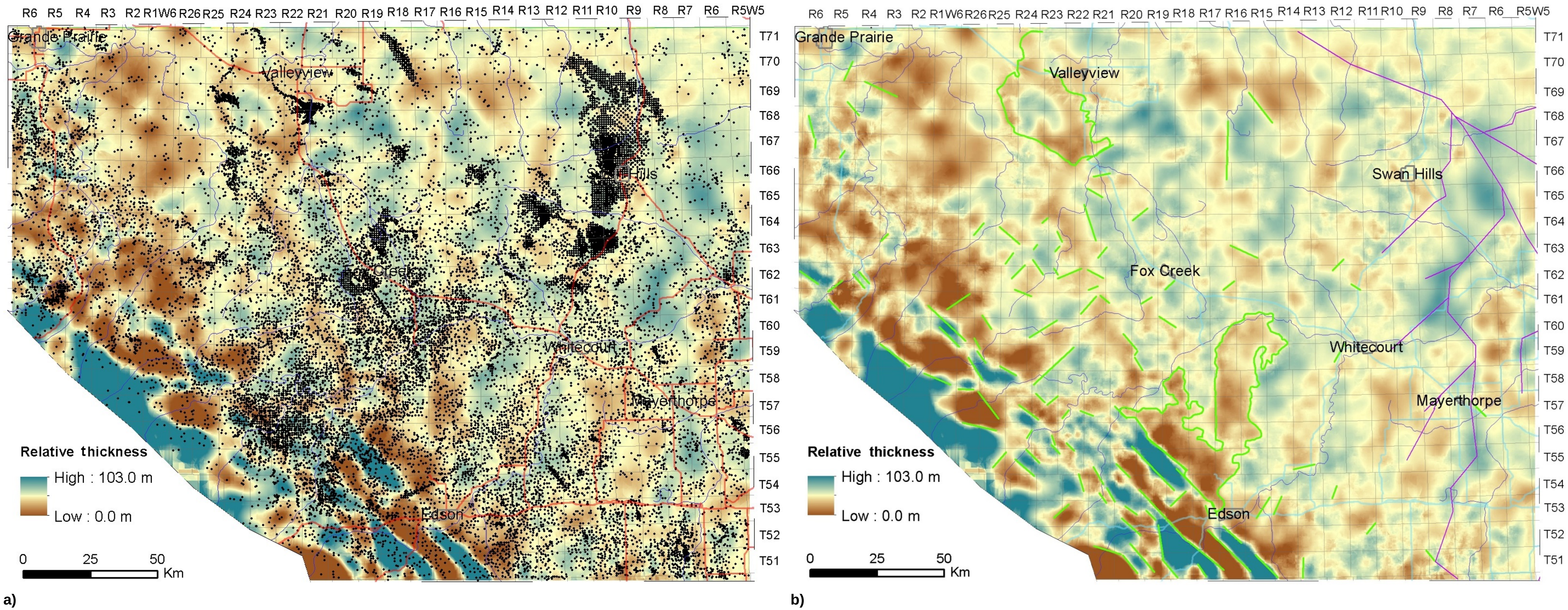

Figure 12. Residual map for the isochore of the interval from the flooding surface near the top of the First White Speckled Shale (Wapiabi Formation) to the base of the Fish Scales Formation, west-central Alberta: a) includes control wells (black dots) and b) includes some of the lineaments (green lines) interpreted from the residual isochore map and the thalweg of Edmonton Valley and its distributaries (purple lines). The red lines in map a) and cyan lines in map b) are roads, and the light blue lines are rivers.

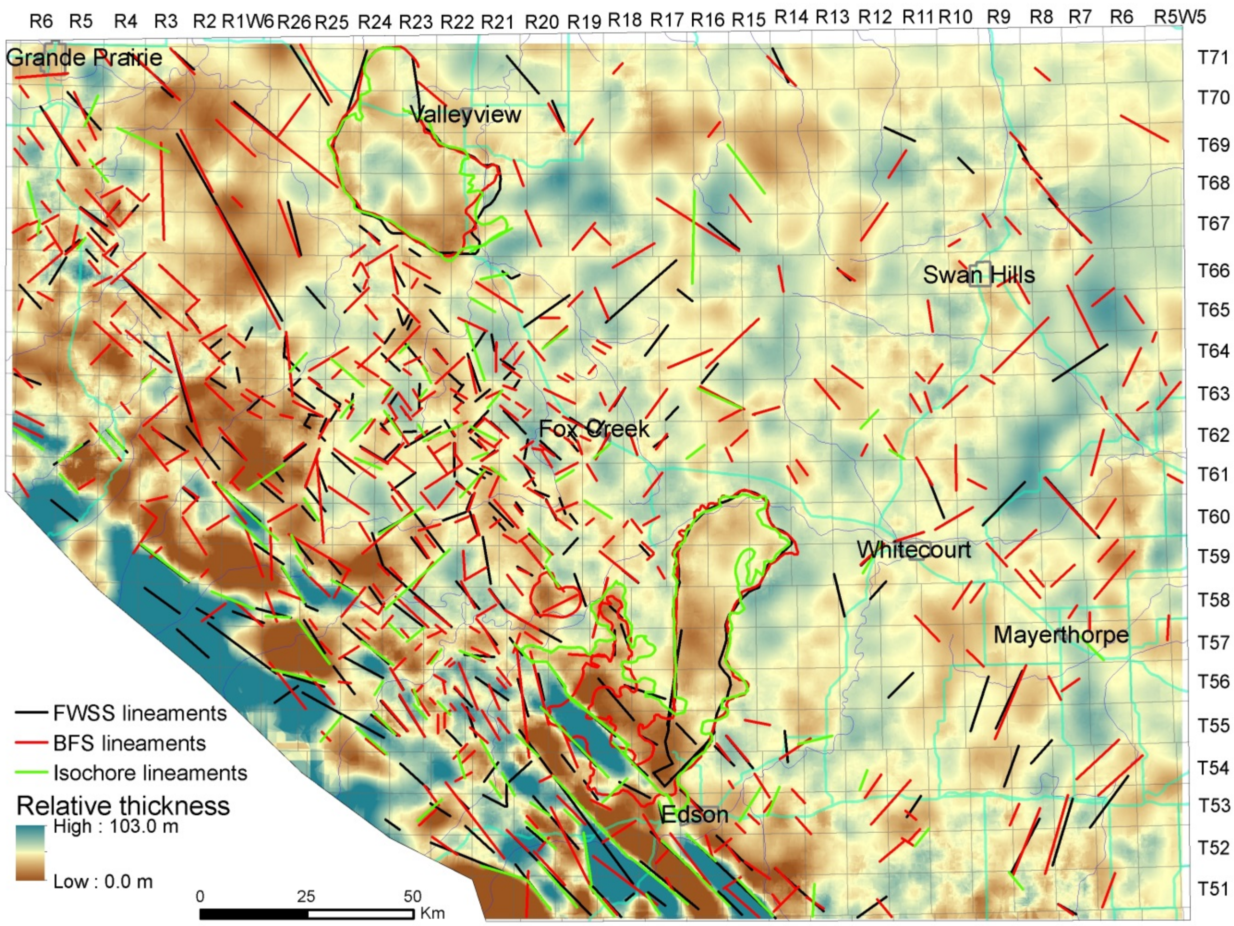

Figure 13. Interpreted offsets from the First White Speckled Shale (FWSS; Wapiabi Formation), the base of the Fish Scales Formation (BFS), and the residual isochore map, west-central Alberta. The residual isochore map is used as the background and represents the interval from the flooding surface near the top of the FWSS to the BFS. The cyan lines are roads and light blue lines are rivers.

5.1 Comparison to Previously Reported Faults

Previously, faults have been inferred from structure contour maps, isopach maps, well-log cross-sections, and linear hydrocarbon accumulation trends by numerous authors based on well-log data available at the time of their studies (Figure 5; Sikabonyi and Rodgers, 1959; Jones, 1980; Hart and Plint, 1990; Putnam, 1993; Henderson et al., 1994; Richards et al., 1994; Donaldson et al., 1998). Comparison of this study's lineaments with previously inferred faults is not straightforward because the two sets of lineaments are inferred by different authors at different times, from different horizons, and using different datasets with different spacing and quality; this leads to some discrepancy in length, orientation, and location. Even though some of this study's lineaments are found to overlap approximately, if not exactly, with the previously inferred faults in orientation and/or location (compare Figures 5 and 14), more detailed work is still needed to establish the connection between the two; however, this is beyond the scope of the current study.

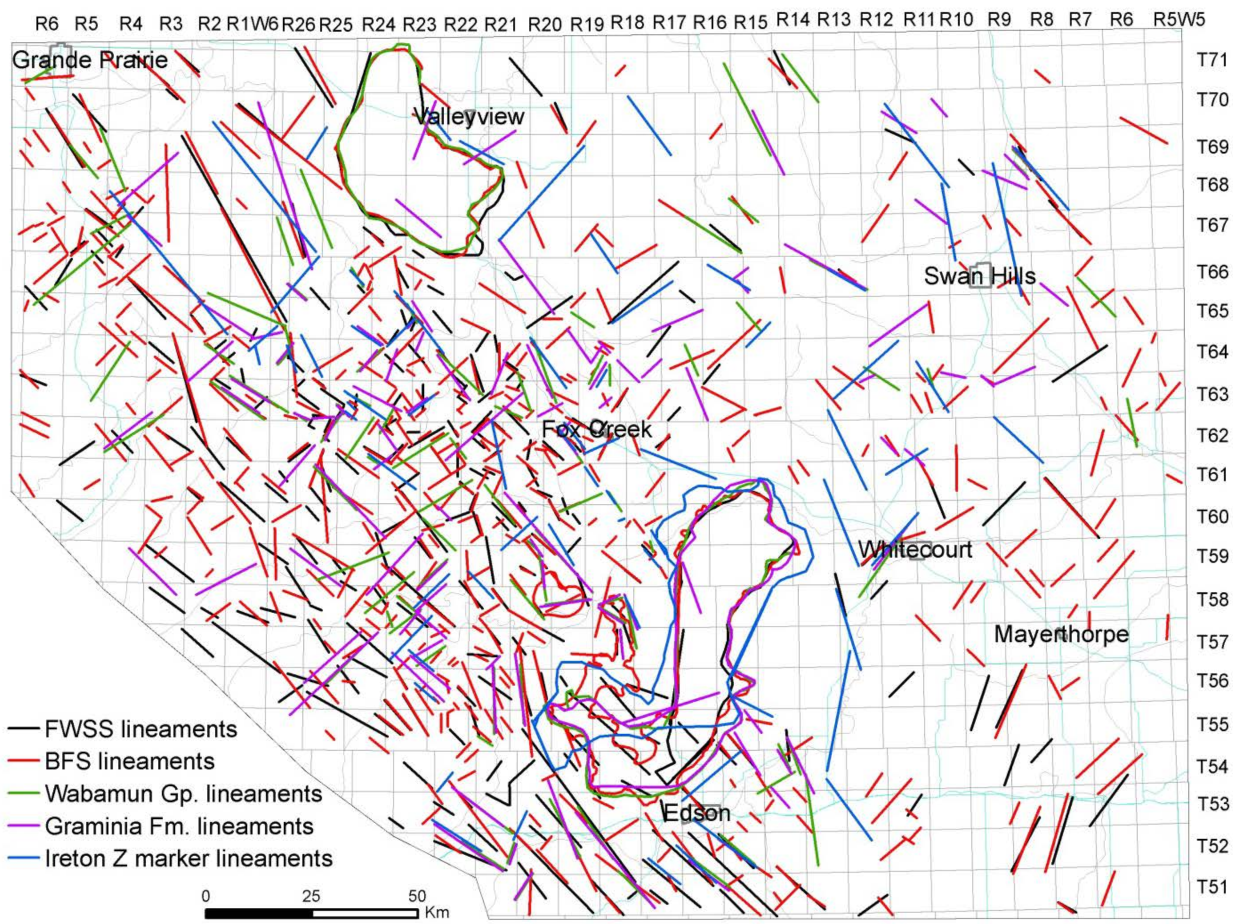

Figure 14. Interpreted offsets from the surfaces of the flooding surface near the top of the First White Speckled Shale (FWSS), the base of the Fish Scales Formation (BFS), the top of the Wabamun Group, the top of the Graminia Formation, and the Ireton Z marker, west-central Alberta. The cyan lines are roads and grey lines are rivers.

This study appears to confirm the existence of shallow thrust faults in the southwestern portion of the study area (Figures 6, 7, 11, 12), typical of the Foothills (Bally et al., 1966). This is in accordance with the findings of Gardiner et al. (1990) and Putnam (1993); they recognized fault-repeated Cardium Formation sandstone units near the deformation front to the south of the study area. To the northwest of the study area, Hart et al. (2007) also recognized shallow thrust faults and associated fault-related folds and tectonic thickening in the lower part of the Kaskapau Formation also near the deformation front. Lemieux (1999) and Mei and Schultz (2020) reported similar reverse faults in southwestern Alberta, also near the deformation front.

6 Concluding Remarks

Numerous linear offsets have been recognized in the subsurface of the west-central Alberta Plains. In general, these offsets trend in two dominant directions: southeasterly and northeasterly, except in some limited areas where some of the offsets are oriented away from these dominant directions. Offsets are generally denser in the southwestern portion of the study area compared to the northwestern. In the area from approximately Twp. 62, Rge. 3–6, W 6th Mer. to Twp. 51, Rge. 16–22, W 5th Mer., it is speculated that some of the offsets may represent potential shallow thrust faults, which is typical of the Foothills. In the rest of the study area, some of the offsets may represent potential normal and/or strike-slip faults.

Some of the offsets are interpreted to represent faults formed in response to deformation associated with the Laramide orogeny. Some of them may have formed initially under tensile conditions related to the development of a peripheral bulge in front of a zone of stacked thrust sheets during Laramide orogenesis. As the deformation front migrated eastwards, tensile stresses would have been replaced by northeast-oriented compressive stresses; this could have reversed some of the northwest-trending, originally normal faults in the southwestern margin of the study area, and generated new shallow thrust faults (fault inversion). Similar reverse faults were previously reported in southwestern Alberta.

Some of the discontinuous, northeast-trending linear offsets, which are oriented orthogonal to the disturbed belt, may represent potential strike-slip faults that are parallel to the principle stress direction associated with the Laramide orogeny. These faults are believed to be more prone to slip that may be induced by waste-water injection or hydraulic fracturing, which cause seismic events.

The Devonian reef trends, especially the Leduc Formation Sturgeon reef complex in the northwestern part of the study area and the Leduc Formation Windfall reef complex in the south-central part of the study area, were clearly recognizable as far up section as the flooding surface near the top of the First White Speckled Shale, which is at least 1 km above the underlying reef complexes. In addition, over these two reef trends, the isopach for the interval from the flooding surface near the top of the First White Speckled Shale to the base of the Fish Scales Formation is clearly thinner than the surrounding area, which may be a consequence of differential compaction; however, this data suggests that the location of the Leduc Formation reef trend may be at least partly fault controlled.

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