3D stratigraphic architecture of the Lower and Middle Triassic strata of Western Canada: evidences for a major basin structural reorganization

Sera soumis à : Basin Research

Résumé

Cette étude se focalise sur les Formations triasiques de Montney et Doig du bassin d'avant pays de la cordillère canadienne (Alberta et Colombie Britannique). Basée sur des descriptions sédimentaires de carottes et d'affleurements (Crombez et al., soumis) et sur la corrélation de 400 forages, cette étude présente l'architecture stratigraphique 3D de ces formations à l'échelle du bassin.

Ce travail fait ressortir quatre séquences regroupées en deux cycles de deuxième ordre datant du Trias inférieur et moyen (séquences A et B). Il met en avant un hiatus de 2.5 Ma entre ces deux séquences qui enregistre une réorganisation majeure du bassin. Au cours de la séquence A, les apports sédimentaires proviennent de l'Est (du continent) alors qu'au cours de la séquence B ils proviennent de l'Est et de l'Ouest (du continent et des premiers reliefs de la cordillère canadienne). De plus cette étude montre que l'évolution de l'architecture stratigraphique est en partie contrôlée par l'évolution géodynamique de la région.

Dans de précédents travaux, le dépôt des Formations de Montney et Doig était présenté comme ayant eu lieu sur la marge passive ouest de la Pangée (Davies et al, 1997; Monger et Price, 2002), cette étude suggère qu'il a eu lieu dans un contexte structural plus complexe.

Abstract

This study focuses on the Lower and Middle Triassic Montney and Doig Formations from the foreland basin of the Canadian Cordillera (Alberta and British Columbia). Based on core and outcrop descriptions (Crombez et al., submitted) and on the correlation of 400 wells, this study presents the basin scale 3D stratigraphic architecture of these formations.

This work highlights four sequences gathered in two second order cycles (sequence A and B) from the Lower and the Middle Triassic. It emphasizes a major time gap of 2.5 My between these two cycles that records a major reorganization of the basin. During sequence A, sediments come from the East (continent) whereas in sequence B they come from both the East and the West (the continent and the proto Canadian Cordillera). Moreover this study show that the evolution of the Montney and Doig stratigraphic architecture is party controlled by the regional geodynamic evolutions.

In the past, the Montney and Doig Formation were interpreted to be deposited on the western passive margin of Pangaea (Davies et al, 1997; Monger and Price, 2002), this study suggests a more complex structural framework during the deposition of these formation.

I. Introduction

The geodynamic evolution of the Western Canada Sedimentary Basin is generally divided in two stages: (1) a passive margin before Jurassic and (2) a foreland basin from Jurassic to present day (Price, 1994, Monger and Price, 2002). Nonetheless, recent studies on the Triassic strata from the WCSB (Golding et al., 2015b, Onoue et al., 2015) and on the regional geodynamic evolution of Western Canada during the early Mesozoic (Beranek et Mortensen, 2011) present a more complex geodynamic and paleogeographic contexts during that time interval. However, these previous work did not integrate a detailed 3-D stratigraphic architecture of the lower and middle Triassic into their analysis of the basin evolution. The present work focuses on the Triassic Montney and Doig Formations from the Western Canada Sedimentary Basin. The workflow developed here is divided in three main steps: (1) a study of the 3D stratigraphic architecture of the Lower and Middle Triassic strata based on sedimentary description of core and outcrops (Posamentier et Waker, 1992; Catuneanu 2006), (2) a time calibration of the sequence based on previous works on biostratigraphy (Orchard and Zonneveld, 2009; Golding et al., 2015a) and (3) An analysis of the relationship between the main sequence boundaries and the regional context. This analysis provides insight into the regional and local controls of geodynamics on the paleogeographic evolution and stratigraphic architecture of the Montney and Doig Formation in the Western Canada Sedimentary Basin.

II. The Lower and Middle Triassic strata of the Alberta basin

In Western Canada, Triassic strata are present in two basins: (1) the Alberta basin (**Figure V - 1**) and (2) the Williston Basin (North Dakota and South Saskatchewan, Edwards et al., 1994). In the Williston basin, the Triassic interval is only composed of non-marine deposits (Cumming, 1956; Carlson, 1968; Edwards et al., 1994) whereas in the Alberta basin, the Lower to Middle Triassic strata records marine environments (Armitage, 1962, Davies, 1997; Davies et al., 1997; Orchard and Zonneveld, 2009). In this basin, the marine deposits of the Lower and Middle Triassic (approx. duration of 15 My) are divided into three formations from older to younger: the Montney, Doig and Halfway Formations.

In the foreland basin of the Canadian cordillera (WCSB on **Figure V - 1**), the Lower and Middle Triassic strata are stratigraphically between the Permian Belloy Formation and the Upper Triassic Charlie Lake Formation or the Jurassic erosive unconformity. The studied formations are mainly composed of fine-grained sandstones, siltstones and shales (Armitage, 1962, Gibson, 1974;

Gibson, 1975; Davies, 1997; Gibson and Edwards, 1990; Davies et al., 1997; Zonneveld et al., 2010, Crombez et al., submitted). Studies on the sedimentology and depositional environments of this interval highlight a wave dominated environments, including phosphatic shales layers (Armitage, 1962, Gibson, 1974; Gibson, 1975; Evoy and Moslow, 1995; Davies et al., 1997; Evoy, 1997; Zonneveld et al., 2010, Golding et al., 2014; Crombez et al., submitted), turbiditic deposits (Moslow and Davies, 1997; Crombez et al., submitted) and evaporitic environments for the top of the Middle Triassic deposits (Davies, 1997; Zonneveld, 1999). Various works on biostratigraphy (Orchard and Tozer, 1997, Orchard and Zonneveld, 2009; Golding et al., 2015a) show that the Montney Formation was deposited in the Lower Triassic and the Doig-Halfway Formations were deposited in the Middle Triassic. The geodynamic setting during the deposition of the Lower and Middle Triassic strata is still a matter of debate. According to Davies et al. (1997), the Montney and Doig Formations were deposited on the western passive margin of the Pangea, whereas Golding et al. (2015b) suggested that these formations were deposited in an early foreland basin.

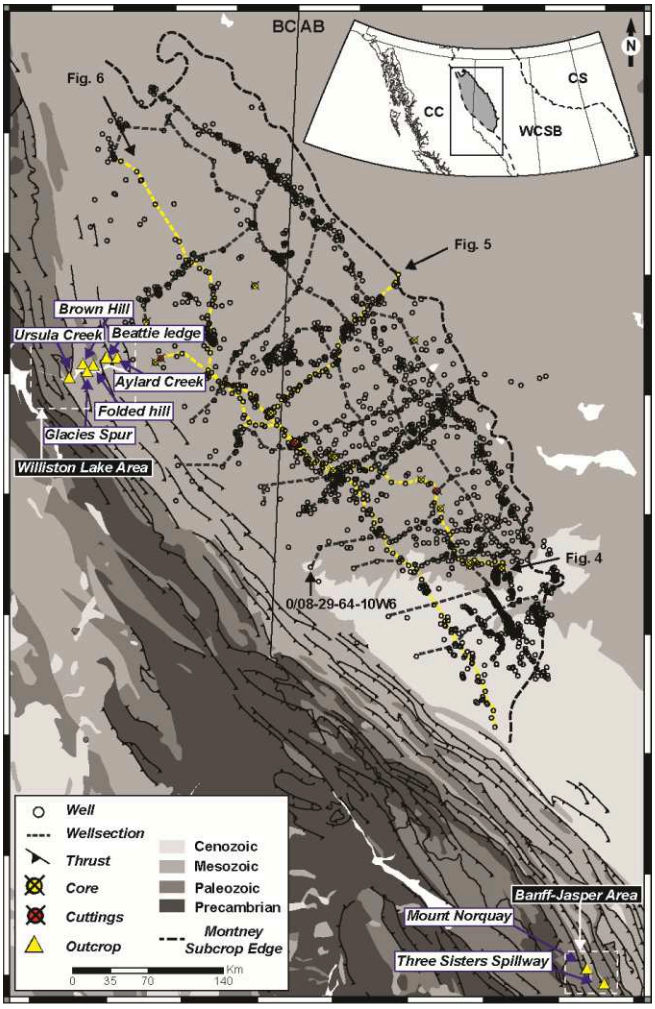

Figure V - 1: Location of the study area and of the data available for this study (geological map from Reed et al., 2005, Triassic subcrop edges from Edwards et al., 1994; basin limits from Wright et al., 1994).

In the past, numerous studies focused on subregional stratigraphic architecture of the Montney (e.g. Markhasin, 1997; Kendall, 1999; Panek, 2000) or Doig Formations (Evoy, 1995; Harris, 2000, Golding et al., 2015a). More regional and older studies provided a stratigraphic framework for the Montney and Doig Formations (Embry, 1988; Gibson and Barclay 1989; Embry and Gibson, 1995; Embry, 1997; Davies et al., 1997), but didn't benefit from the new wealth of data made available by the recent development of the distal unconventional part of the play. These studies highlight two second order cycles: one in the Montney Formation and another one in the Doig-Halfway Formations and several third order sequences within them.

III. Data and methods

1. Data

The present work is based on publicly available data from more than 2000 wells (Geowebworks, IHS Data Manager and Divestco Energisite) collected and gathered in a PETREL database. These well logs were completed by 22 sedimentological sections from 18 cores and 4 outcrops (**Figure V - 1**). This database also includes cuttings samples from the studied interval coming from three wells (**Figure V - 1**). From this database, 400 wells were selected along 18 regional cross-sections in order to reconstruct the stratigraphic architecture of the Lower and Middle Triassic.

2. Methods

a. Sedimentology and sequence stratigraphy

This study is based on facies descriptions from cores, interpretation of depositional environments and upscaling to well log data (Gamma Ray) for regional correlation (Crombez et al., submitted). This interpretation also benefits from the description and analysis of outcrop sections of Middle Triassic strata. The analysis of the stacking pattern and spatial distribution of depositional environments makes it possible to define shoreline trajectories (Helland-Hansen and Martinsen, 1996; Helland-Hansen and Hampson, 2009) and to identify the major time surfaces: end of regression, end of transgression, onset of base level fall and end of base level fall (Catuneanu, 2006, Catuneanu et al., 2009). Following the terminology proposed by Hunt and Tucker (1992) and Helland-Hansen and Gjelberg (1994), these time surfaces were used to reconstruct the 3D stratigraphic architecture of the studied interval.

b. Mineralogical analyses

In addition to core and outcrop descriptions, cuttings from three wells were sampled in order to quantify the mineralogy of the Triassic strata. QEMSCAN analyses (Gottlieb et al., 2000) were performed by SGS Canada Inc. on 201 samples. QEMSCAN is based on backscattered-electron imaging and energy dispersive X-ray spectroscopy techniques.

IV. Results

1. Sedimentary environments and depositional model

Detailed descriptions of the sedimentary facies were presented in a previous paper (Crombez et al., submitted). In the present study, two additional environments were highlighted: (1) fluvial deposits; characterized by fine- to medium-grained well sorted sandstones, with through cross stratification and erosional bases, (2) sebkha deposits, characterized by heterolitic, reddish sandstones and clays with gypsum nodules.

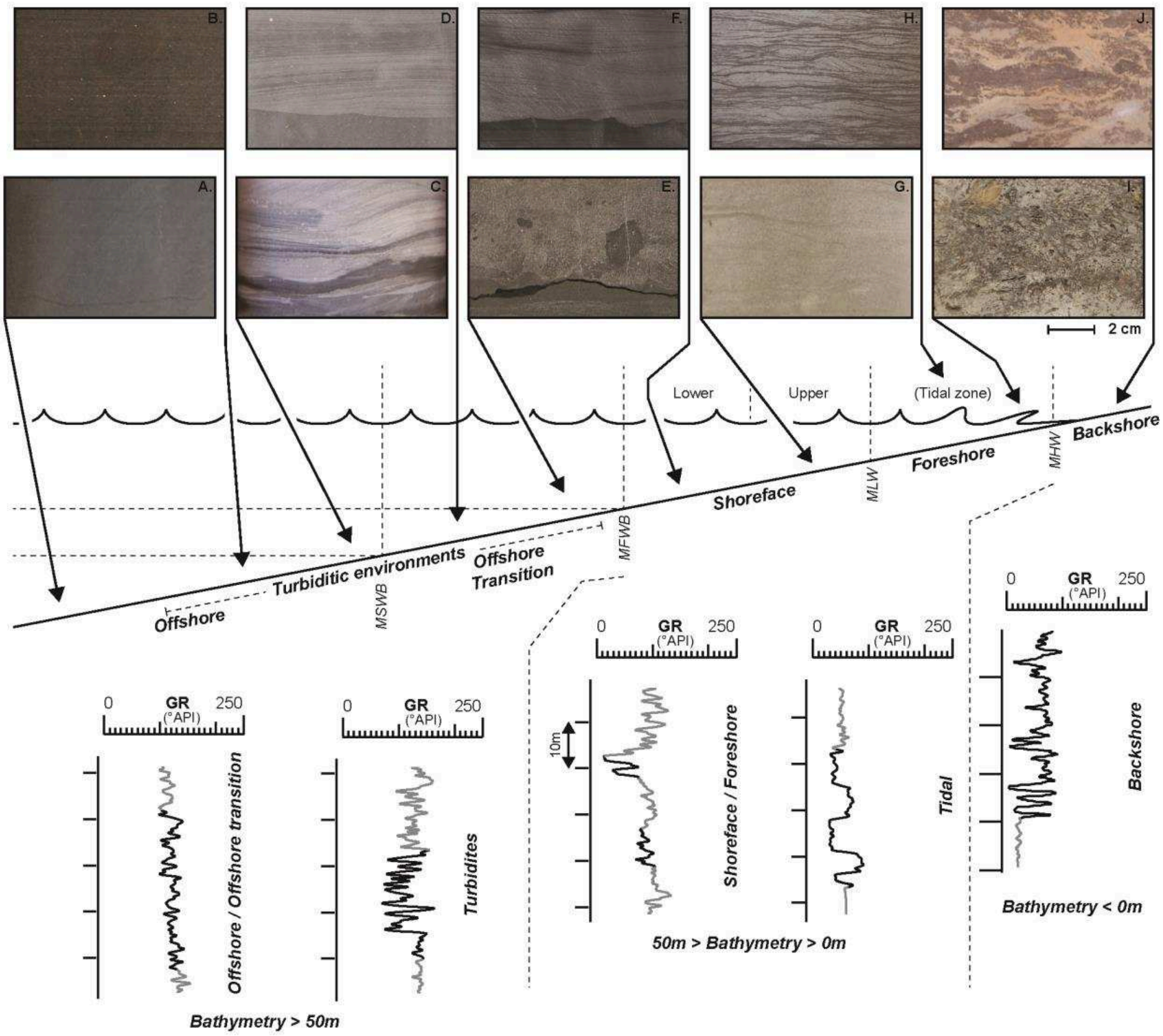

Figure V - 2: Facies, major sedimentary environment and their Gamma Ray pattern.
A. Submassive dark grey siltstone, B. Planar laminated dark grey siltstone, C. Heterolitic siltstones and sandstones with climbing ripples, D. Wavy bedded heterolitic siltstones and sandstones, E. Transgressive deposits, F. Wavy bedded heterolitic siltstones and sandstones, G. medium-grained sandstones, H. Heterolitic siltstones and sandstones with bidirectional current ripples, I. Bioclastic sandstone, J. Reddish heterolitic siltstones and clay with anhydrite nodules.

Figure V - 2 illustrates the different depositional environments along a depositional profile from backshore to offshore, with representative core photos and well log patterns. In the Lower and

Middle Triassic, eight main sedimentary environments are recognized: (1) offshore environments, characterized by massive to planar laminated dark grey siltstones (**Figure V - 2A and B**), (2) turbiditic environments, characterized by massive to heterolitic fine-grained sandstones with current and climbing ripples (**Figure V - 2C**), (3) offshore transition environments, characterized by fine-grained heterolitic sandstones and siltstones with hummocky cross stratification (**Figure V - 2D**), (4) shoreface environments, characterized by massive to heterolitic fine-grained sandstones and siltstones with swalley cross stratification or low angle cross-stratification (**Figure V - 2F and G**), (5) tidal environments, characterize by heterolitic sandstones and siltstones with bidirectional current ripples (**Figure V - 2H**), (6) foreshore environments mainly characterized by bioclastic sandstones (**Figure V - 2I**), (7) sebkha environments with reddish, heterolitic sandstone and clays with common gypsum nodules (**Figure V - 2J**) and (8) fluvial deposits, characterized by fine- to medium-grained well sorted sandstones, with through cross stratification and erosional bases. All the marine environments presented above are characteristic of a wave dominated shelf (Posamentier and Walker (eds), 1992). In our work, no clear evidences of deltaic environments were highlighted but previous studies identified these environments below the Jurassic unconformity along the erosional edge (Zonneveld et al., 2010).

On **Figure V - 2,** the typical Gamma Ray patterns of the main environments are presented. The figure shows that offshore and offshore transition facies present high Gamma Ray (GR>100°API) with coarsening upward trends. Shoreface and foreshore deposits present the same coarsening upward trend but with lower Gamma Ray values (shoreface GR<75°API, foreshore environments GR<50°API) interpreted to be linked to the higher sand content. Turbiditic deposits are characterized by a major drop in the Gamma Ray interpreted to represent the sharp depositional contact of sandstones above offshore facies. Unlike shoreface and foreshore environments, turbiditic deposits often present fining upward trends, interpreted to represent the lateral migration and/or waning of the turbiditic system. Turbiditic deposits also typically show high amplitude GR variations associated with high frequency changes in depositional energy. Tidal deposits present a blocky pattern that is interpreted to represent the sharp transition between heterolitic tidal flats deposits with sandy tidal channel deposits. The recognition of these distinctive patterns provides a mean to identify depositional environments and therefore vertical changes in relative depositional bathymetry on well logs.

2. Stratigraphic architecture along the 2D well sections

The synthetic stratigraphic architecture of the Montney, Doig and Halfway Formations is presented on **Figure V - 3**. On this figure, the first three sequences that compose the Montney Formation are interpreted to be part of the first second order cycle (Sequence A) described by previous studies (Gibson and Barclay 1990; Edwards et al., 1994; Davies, 1997) and the last sequence, that compose the Doig-Halfway Formations is part of a the second cycle (Sequence B).

Out of the eighteen sections realized for the present study, three are presented in this study. **Figure V - 4** presents a 375km long SE-NW section with 25 wells, **Figure V - 5** presents a 275km long NE-SW section with 18 wells and **Figure V - 6** present a 625 km long SSE-NNW with 25 wells. All sections cross the entire Lower and Middle Triassic strata of the Alberta basin. On the sections the studied interval rests on the Permian Belloy Formation. In the Eastern part of the basin, the studied interval is truncated by the Jurassic Nordegg Formation and by the Middle Triassic Copplin unconformity, whereas in the western part, it is capped by the upper Middle Triassic Charlie Lake Formation. In the present work, all sections are flattened on the sequence boundary 4 (SB4).

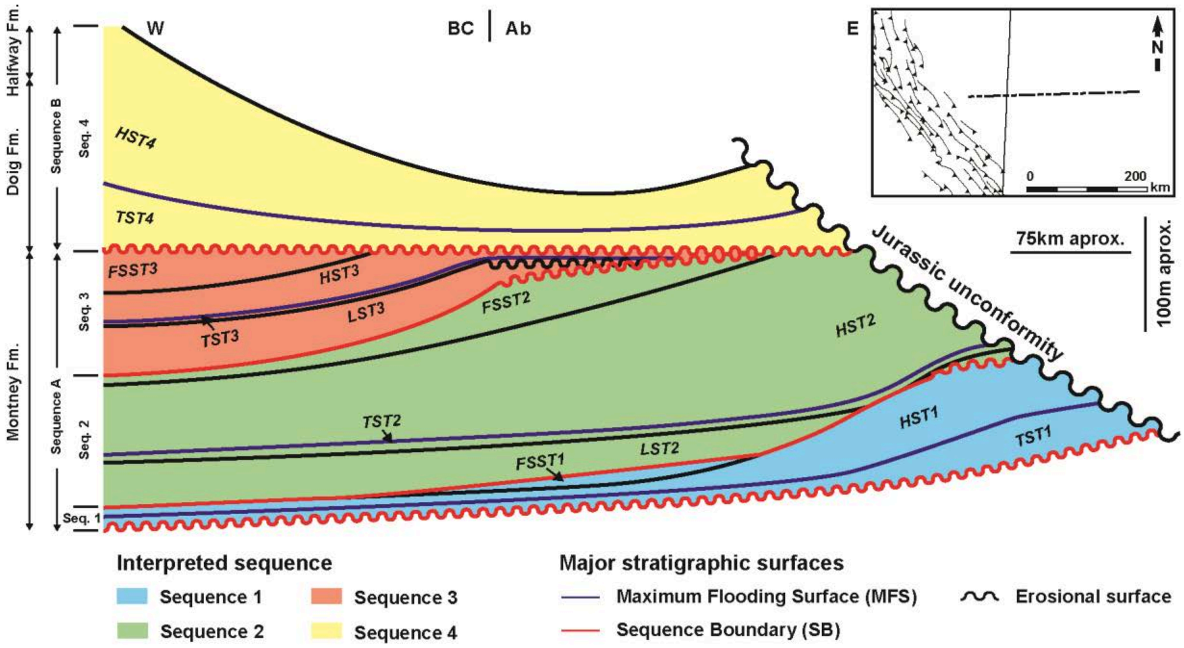

Figure V - 3: Synthetic stratigraphic framework of the Lower and Middle Triassic formation. In the present study four sequences are highlighted.

The stratigraphic architecture illustrated on these cross-sections suggests that sequence 1, 2 and 3 are sourced from the East and South, whereas sequence 4 might also be sourced by sediments coming from the west and/or South-West. On all well sections, sequence 1 is almost completely preserved, the proximal parts of sequence 2 are missing due to the Jurassic and SB4 erosions, sequence 3 is only preserved in the deepest part of the basin where it only presents distal deposits below an erosional truncation. Lastly, sequence 4 is well preserved in the western part of the basin.

On all sections, it is apparent that the maximum flooding surface of the sequence 2 (MFS2) induced a stronger backstep of the shoreline than the MSF of the sequence 1. Above MFS2, it seems that the basin presents a major regression trend until the SB4. In sequence A, MFS is therefore interpreted to be the MFS2. As sequence B is only composed by sequence 4, the maximum backstep of the sedimentary system is therefore recorded during MFS4.

3. 3D stratigraphic evolution

a. Sequence A

The **Figure V - 4, 5 and 6** illustrate the stratigraphic evolution along two 2D profiles. The correlation of 400 wells throughout the basin provided the database to map the thickness variations of the Lower and Middle Triassic sequences and their system tracts. The **Figure V - 7** presents the distribution of the sedimentary deposits during the third order systems tracts of sequence A.

Sequence 1

On **Figure V - 7** the TST1 maximum thickness occurs along the eastern part of the basin. Here it is mainly composed of foreshore to shoreface deposits and the thickness can reach up to 80m. In the HST1 (**Figure V - 7B**), the maximum thickness is located in the northern part of the basin, where thickness can locally reach up to 120m. The falling stage system tract 1 (FSST1) (**Figure V - 7C**) is poorly developped and only preserved in the central part of the basin where it consists of massive turbiditic deposits.

Sequence 2

The lowstand deposits of sequence 2 are mainly present in the central part of the basin (**Figure V - 7D**) where fine-grained turbidites interbedded with offshore deposits are present (up to 90m). The North-South depositional fairway extending from the cordillera to the South to the LST2 depocenter to the North mainly consists of turbiditic channel deposits. This suggest that during this lowstand it seems that the a large part of the sedimentary inputs came from the South. The TST2 only present starved deposits in the basin (**Figure V - 7E**), the maximum thickness areas probably located a few kilometers beyond the Jurassic erosion edge to the East. The HST2 records a significant progradation of the sedimentary system (**Figure V - 7F**), but the maximum thickness is still located on the eastern part of the basin and can reach up to 100m. Above the HST2, the FSST2 is poorly preserved due to the erosion below SB3 and SB4. In the basin it can locally reach 40m in thickness (**Figure V - 7G**).

Sequence 3

The **Figure V - 7H, I J and K** present the deposit thickness of sequence 3. On this figure, it is apparent that most of the preserved part of the sequence 3 is located below the erosion of the SB4. The maximum thickness of LST3 (**Figure V - 7H**) is located in the western part of the basin, along the deformation limit. Shoreface and offshore deposits can reach thickness up to 100m. The TST3 only presents distal, starved sedimentation and is only preserved in the West-central part of the basin (**Figure V - 7I**). Both HST3 and FSST3 (**Figure V - 7J and K**) are also preserved in the western part of the basin, where mainly offshore deposits can reach thicknesses up to 70m.

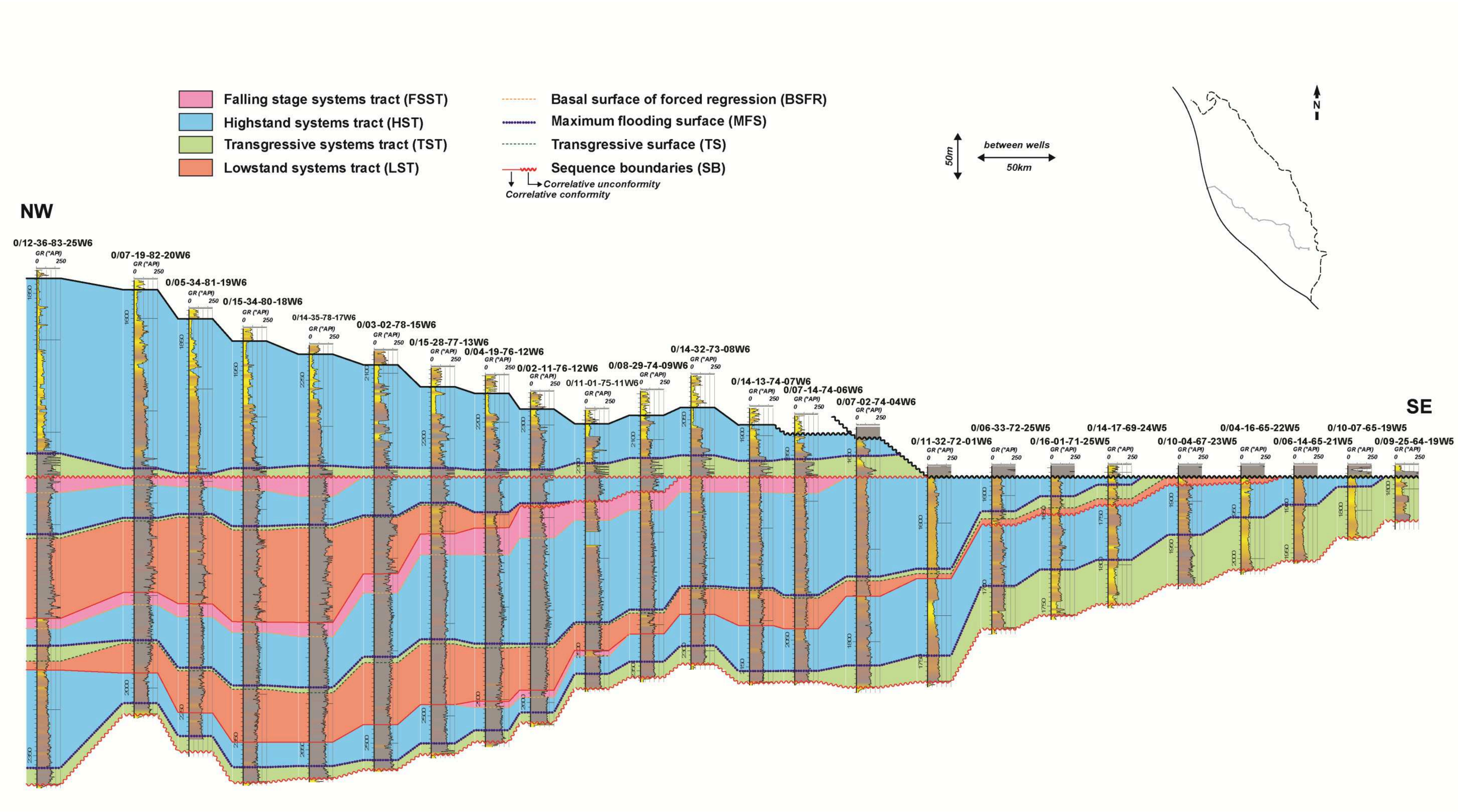

Figure V - 4: SE-NW well section with stratigraphic correlations
Note that the average distance between well is 15 km.

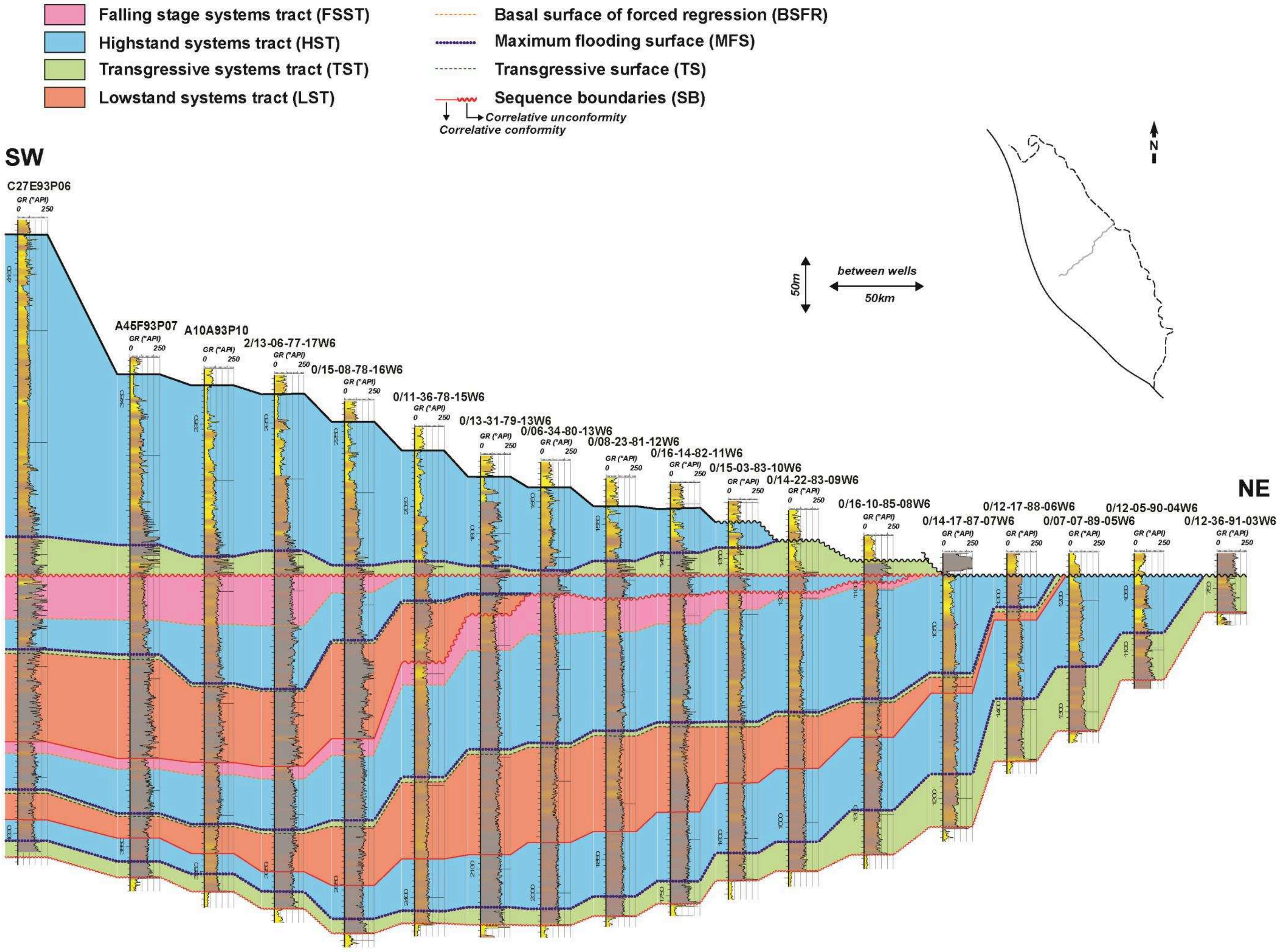

Figure V - 5: NE-SW well section with stratigraphic correlations.
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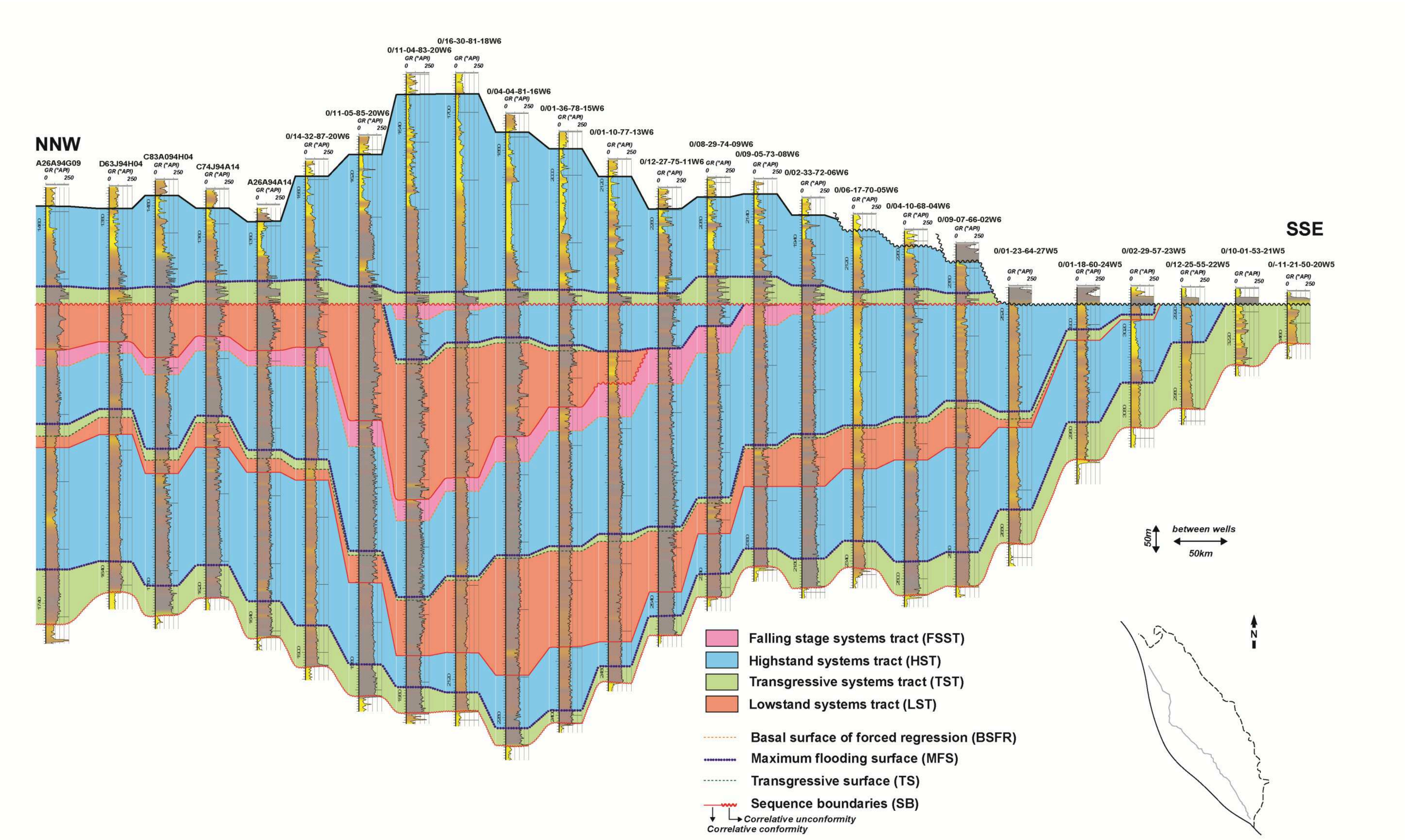

Figure V - 6: SSE-NNW well section with stratigraphic correlations.
Note that the average distance between well is 25 km.

The **Figure V - 8A** presents the isopach maps of the three third order sequences within sequence A. It shows that these three sequences do not present the same areas of maximum sediment accumulation. During sequence 1, the maximum accumulation is located in the northern part and eastern margin of the basin. During sequence 2 the maximum accumulation is located in the central part of the basin. In sequence 3, the depocenter of the preserved parts of the sedimentary records are located in the western part of the basin. The **Figure V - 8A** also presents the location of the main structural elements below the Triassic strata: The Hay River shear zone and the inherited structure from the Peace River arch collapse (The Leduc reef indicates the location of the Peace River arch, O'Connell, 1994; Switzer et al., 1994; Wright et al., 1994).

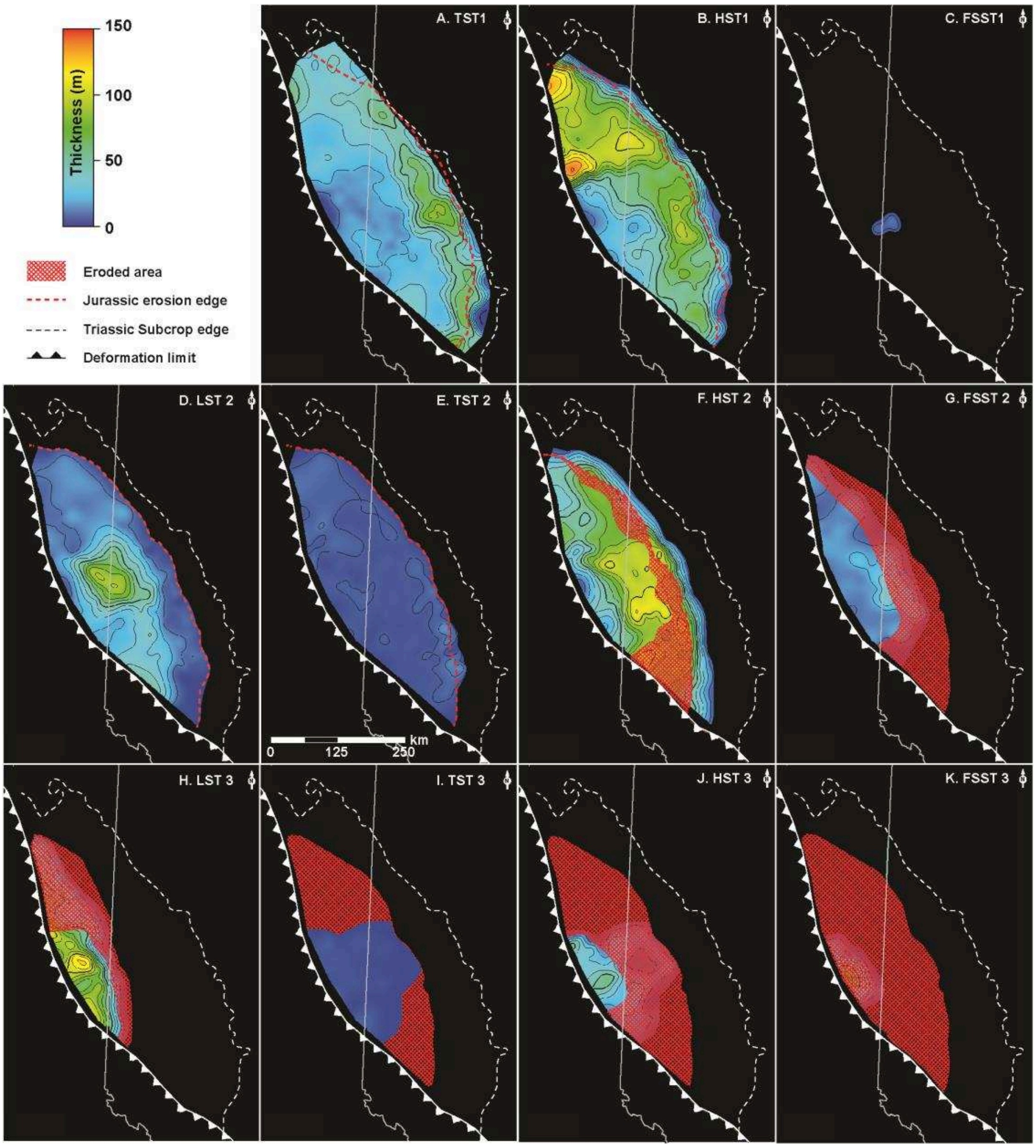

Figure V - 7: Systems tracts evolution of sequence 1, 2, and 3.

On **Figure V - 8** it is apparent that the maximum thickness of sequence 1 occurs above the Hay River shear zone. The **Figure V - 8** suggests that the maximum deposits of sequence 2 were deposited in the basin center above the former Peace River arch. The **Figure V - 8** shows that the preserved parts of the sequence 3 are also located above the Peace River arch. Based on the upscalling of the sedimentary facies, the **Figure V - 8B** presents schematic paleogeographic maps of sequence A. they all represent a snapshot of the paleogeography at the end of the lowstand. Black arrows illustrate dominant sedimentary inputs from the Northeast, the East and the Southeast during sequence A (**Figure V - 8B**).

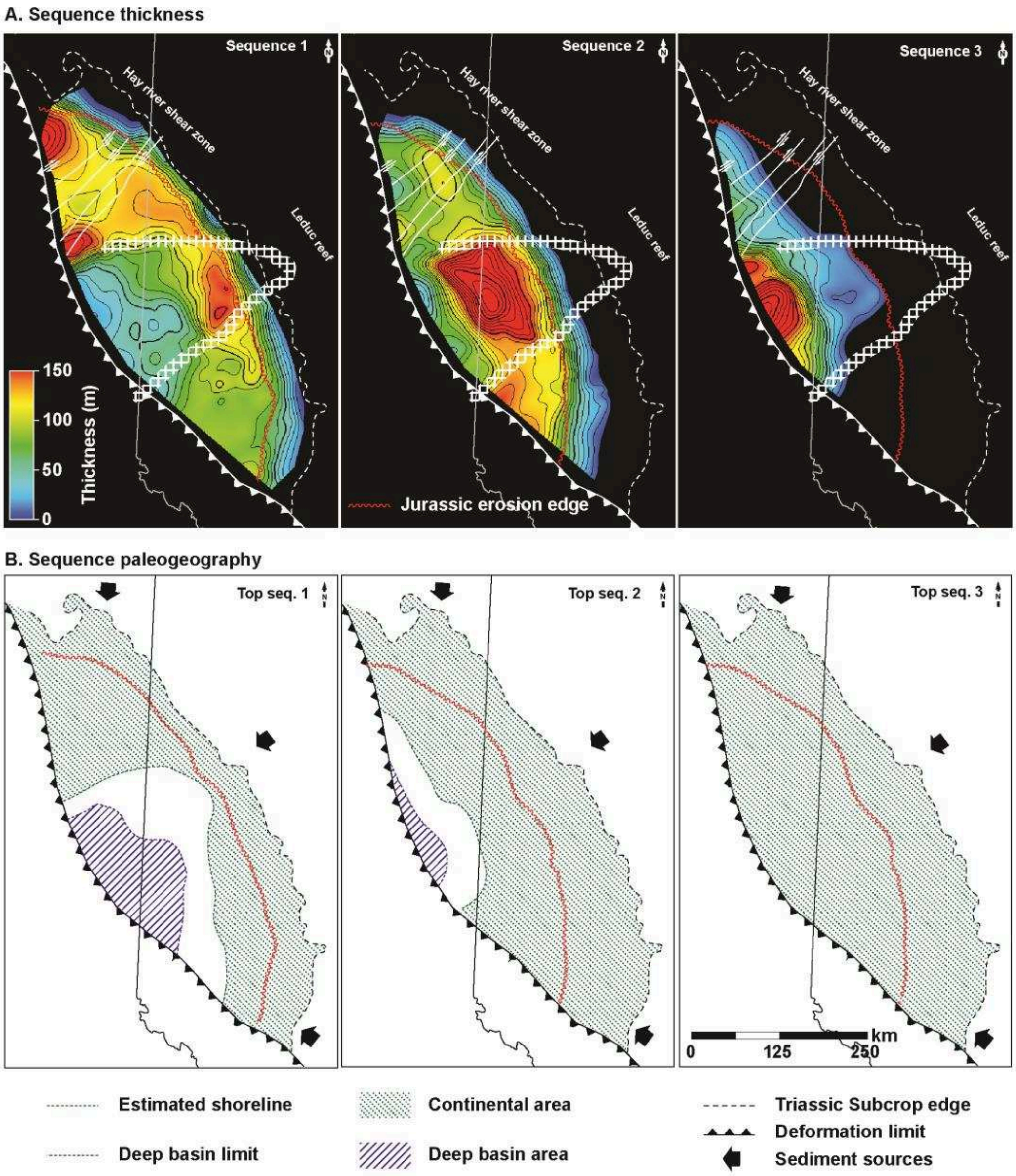

Figure V - 8: A. thickness evolution in each systems tract in the sequence A;
B. Paleogeographic maps of sequence A.
(structural elements from Berger et al., 2008 and Leduc trend from Switzer et al., 1994).
Note that the sedimentary inputs come from the continent.

b. Sequence B

The LST4 is not preserved in the subsurface of the Alberta basin (**Figure V - 9A**). The **Figure V - 9A** shows that the TST4 maximum thickness presents a halo shape and it maximum thickness can reach up to 40m. This figure also shows that during the HST4 the maximum thickness is recorded along the present day deformation limit in the western part of the basin, where the thickness can reach up to 225m. In sequence B the maximum sediment accumulations are located in the western part of the basin, along the deformation limit. The thickening of this sequence near the deformation limit tends to show that sedimentary inputs also come from the West. Lastly, **Figure V - 9A** does not show any evidences of a strong control of the major structural elements on the depositional thickness.

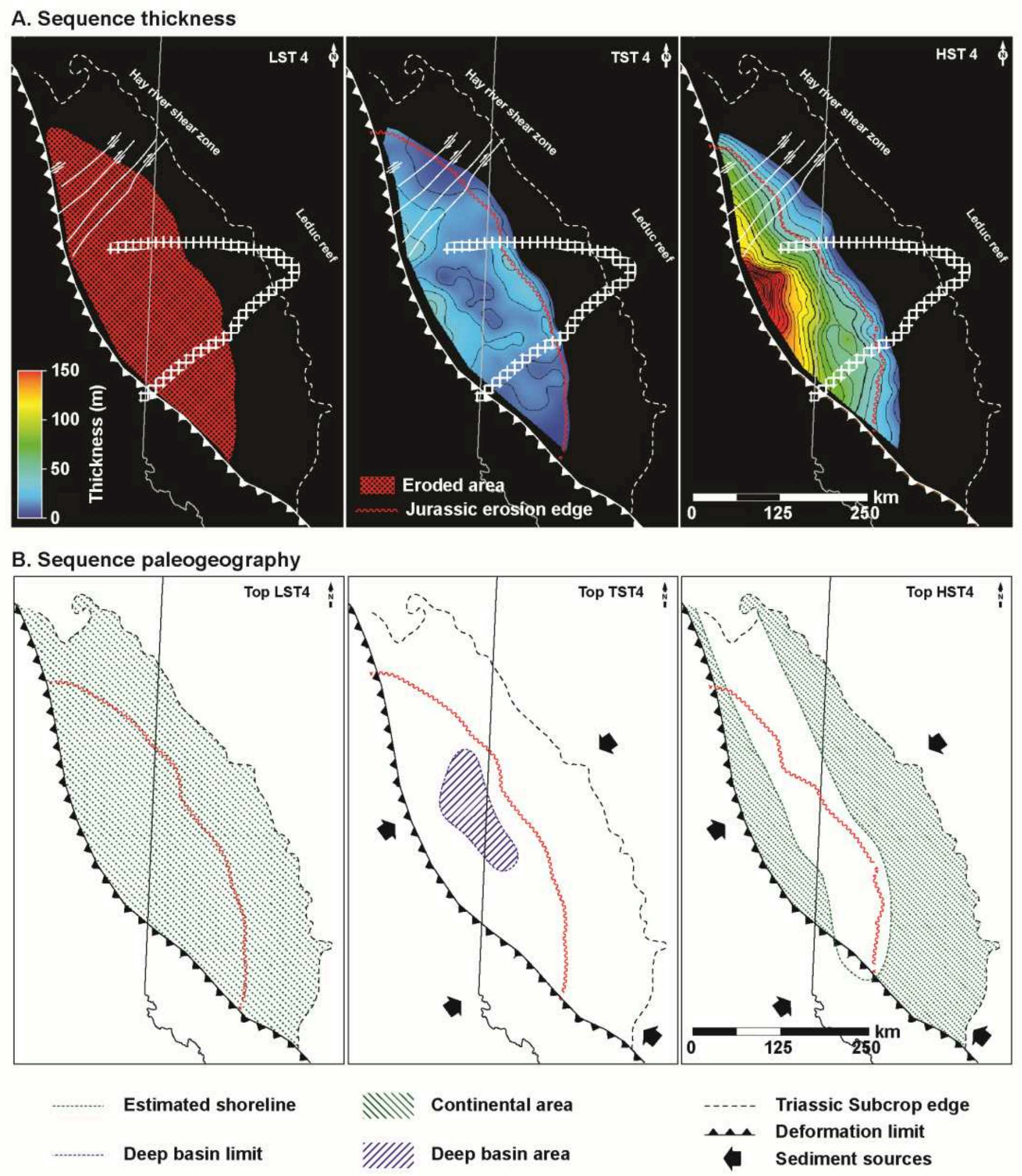

Figure V - 9: A. thickness evolution in each systems tract in the sequence B;
B. Paleogeographic maps of sequence B.
(structural elements from Berger et al., 2008 and Leduc trend from Switzer et al., 1994).

The reconstruction of the stratigraphic architecture on the Montney, Doig and Halfway Formations show that sequence A and sequence B are separated by a major erosional surface. In sequence A, the basin shows a progradation of the shoreline between the MFS2 up to the SB4. At the end of sequence 3, it seems that the basin undergoes a major subaerial exposure. In sequence B, the **Figure V - 9** suggests a completely different paleogeography. Our interpretation suggests that during this sequence, the Western Canada sedimentary basin presents sedimentary inputs not only from the continent to the East but also from a western source (**Figure V - 4, 5 and 6**). Above SB4, stratigraphic correlations suggest that the basin was becoming more and more restricted up to the deposition of sebkha environments in the Charlie Lake Formation (**Figure V - 4, 5 and 6**).

4. Evidences from the fold and thrusts belts outcrop

In the fold and thrusts belt of the Canadian cordillera, several outcrop sections located in the Williston Lake and Banff areas were used to describe the Lower and Middle Triassic strata (**Figure V - 1**).

a. Williston Lake area

Glacier Spur, Brown Hill and Folded Hill

In Williston Lake, the Brown Hill outcrop presents a similar facies evolution than a well located 275km southeast, in the Alberta basin. This section displays Montney, Doig, Halfway and Charlie Lake Formations time equivalent strata (**Figure V - 10**). Biostratigraphic data (Zonneveld, 1999) show that the upper part of the section (above 250m) was deposited during the Middle Triassic, whereas the absence of biostratigraphic markers does not allow dating the lower part of the section. On Brown Hill, the lower part of the outcrop presents an interval of turbiditic deposits from 10 to 50 m and fluvial deposits above a major erosional surface from 160 to 175 m. The upper part of the section presents two main prograding cycles that range from offshore to sebkha deposits in the Charlie Lake. On this section the major unconformity below the fluvial deposits is interpreted to correspond to the SB4. According to our interpretation, the turbiditic deposits at the bottom of the Brown Hill section correspond to the LST2 (**Figure V - 10**).

The **Figure V - 11** presents simplified correlations of the facies that are present above fluvial deposits along three outcrop sections in the Williston Lake area. This figure emphasizes a thinning of the continental, tidal and shoreface deposits to the East. Moreover, on Folded hill, raindrops marks and snails tracks are present. These observations suggest that the sedimentary system prograded from West to East after the major subaerial exposure of SB4.

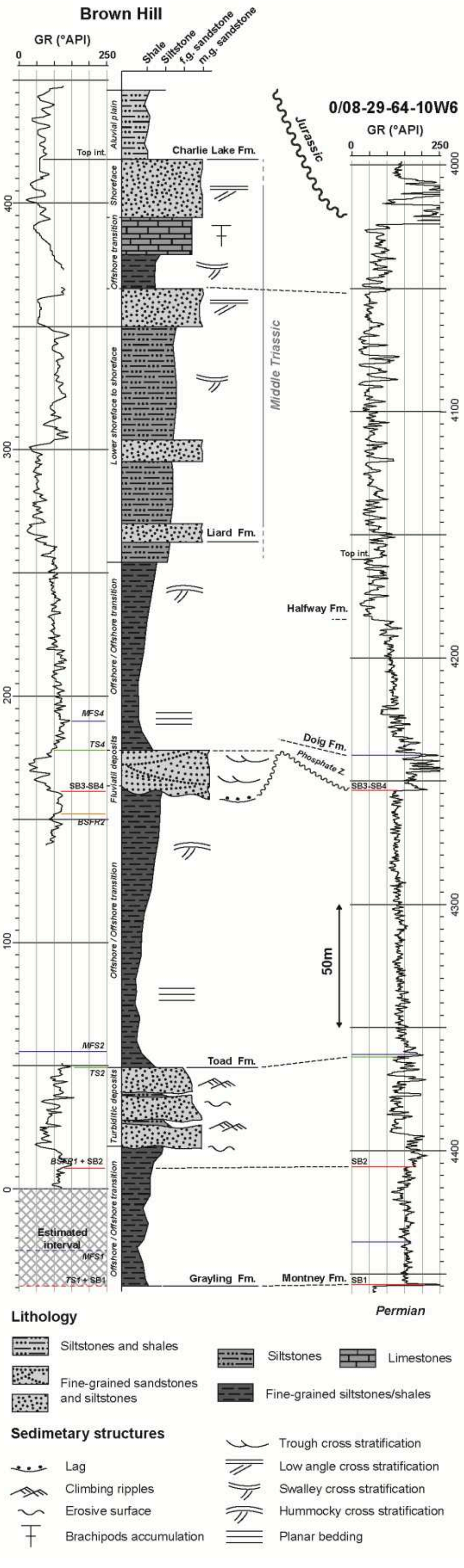

Figure V - 10: Synthetic sedimentary section of Brown Hill outcrop.

Note the similarities between Brown Hill and a well located in the Alberta Basin.

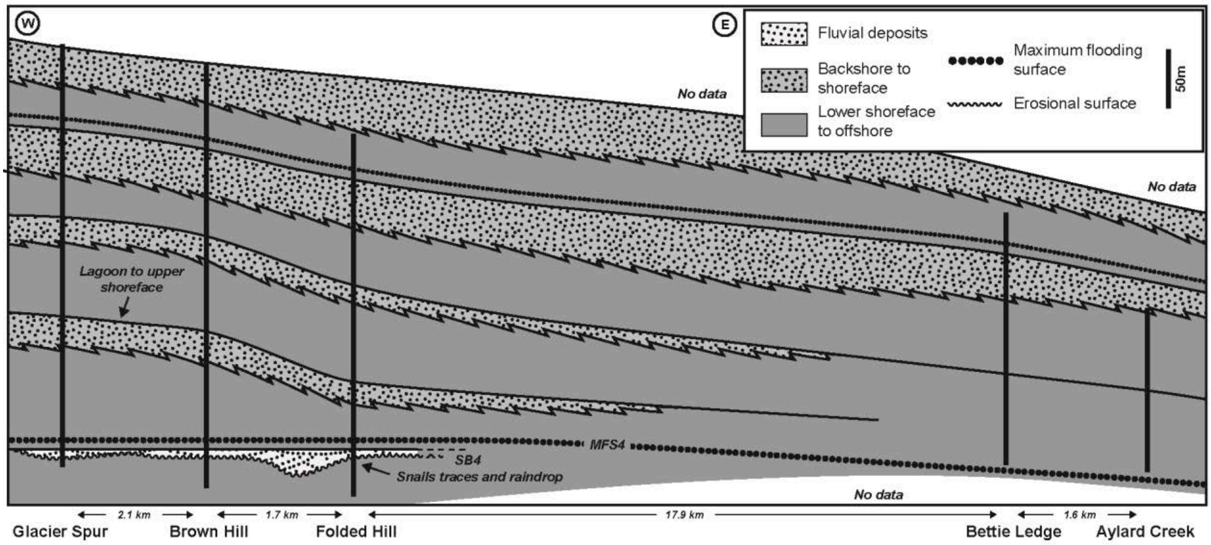

Figure V - 11: Outcrop correlation from the Williston Lake area.
Note the thinning of the continental, tidal and shoreface deposits from West to East.

Ursula Creek

At this location, the outcrop only displays the Montney and Doig time equivalent strata. Here the Triassic strata rest above the Permian and below the Carnian unconformity. Biostratigraphic data (Zonneveld, 1999) also show that Ursula Creek section records from 0m to 70m of Lower Triassic deposits and from 70m to 120m of Middle Triassic deposits. Unlike other outcrop described in this study, Ursula Creek section only presents distal fine-grained offshore deposits.. On top of Ursula Creek an interval with phosphate is present from 75m to 100m, but unlike in the Alberta basin, no major surface of erosion is recorded below the phosphates zone. The only unconformity that is present is at the top of the section, below Carnian carbonates.

b. Banff area

In southern Alberta, two sections with Triassic deposits were described for the present work: Mount Norquay and Three Sisters Spillway. These sections do not present the basal contact between the Lower Triassic and the Paleozoic or the contact between the Middle Triassic and the Upper Triassic. On both sections, the sedimentary description highlight offshore to tidal environments. No major turbiditic intervals or evaporitic deposits are present. On both outcrops, no major erosional surface can be interpreted as a subaerial unconformity.

5. Mineralogy

The results of the QEMSCAN analysis are presented on **Figure V - 12**. On this figure, sequences are represented by different shades of grey and each symbol corresponds to a different well. The **Figure V - 12A** shows that in the studied interval, clay content is low (average of 14 wt %) but can reach up to 35 wt %. It also shows that quartz, feldspars and micas are the dominant minerals (average of 55 wt %) and that carbonates represent 27 wt % in average. On **Figure V - 12A**, the sequence B (Q-F-M = 49 wt %, clays = 7 wt % and carbonates = 27 wt %) presents a different average mineralogy than sequence A (Q-F-M = 57 wt %, clays = 16 wt % and carbonates = 24 wt %). The **Figure V - 12B** confirms the presence of two different trends of quartz versus carbonates in sequence A and B. Sequence A presents less carbonates than sequence B.

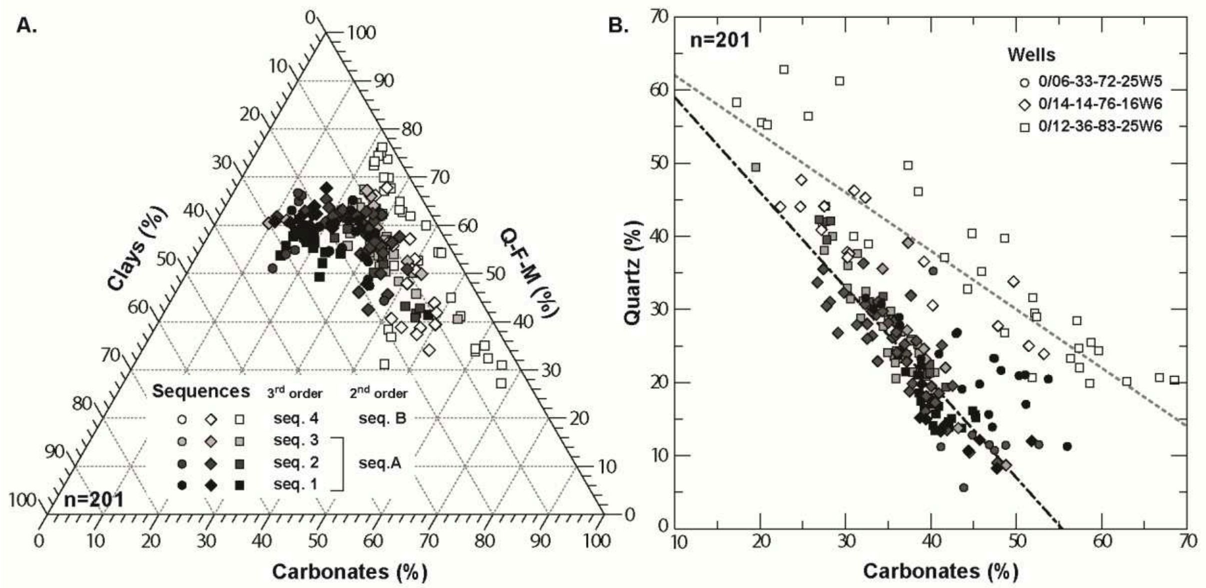

Figure V - 12: results of the QEMSCAN analysis.
A. Ternary diagram of the quartz-feldspar-micas, carbonates and clay content in the samples, B. quartz versus carbonates cross plot of the analyzed samples. Note the two different trends between sequences A and B.

V. Discussions

This work built upon previous published studies and aims at bringing the interpretation a step further by building sequence and system tract thickness maps as well as paleogeographic maps at the scale of the basin. Ultimately, these maps provide a mean to better understand the geological controls on the 3D stratigraphic architecture of the Lower and Middle Triassic in Western Canada.

1. Stratigraphic record and global eustatic variations

In the present study, we highlighted 4 sequences (**Figure V - 3**). Three are located in the Montney Formations and one in the Doig-Halfway Formations. Previous studies on biostratigraphy (Orchard and Tozer, 1997; Orchard and Zonneveld, 2009; Golding et al., 2014, Golding et al., 2015a) provide a chronostratigraphic framework to these sequences. Based on these studies, the three sequences that correspond to the Montney Formation were deposited during the Lower Triassic and the sequence encompassing the Doig and Halfway Formations was deposited during the Middle Triassic. In an attempt to better calibrate the ages of the third order sequences within the Montney

Formation, the **Figure V - 13** presents the high frequency variations of the eustatic sea-level (Hardenbol et al., 1998). As the Montney, Doig and Halfway Formations records marine deposits, the relative variations of the sea level recorded in the sedimentary deposits are linked to the global variations of the sea level combined with regional tectonic subsidence and uplift. The **Figure V - 13** presents three rise-fall cycles in the Lower Triassic and three in the Middle Triassic. In the present work, as no major time gap was highlighted between sequence 1, 2 and 3, it is assumed that the three high sea levels of the Lower Triassic were approximately recorded during the MFS1, 2 and 3. According to our interpretation, sequence 2 and 3 represent respectively the HST and FSST of the sequence A and the major erosional surface SB4 corresponds to the subaerial sequence boundary of sequence B.

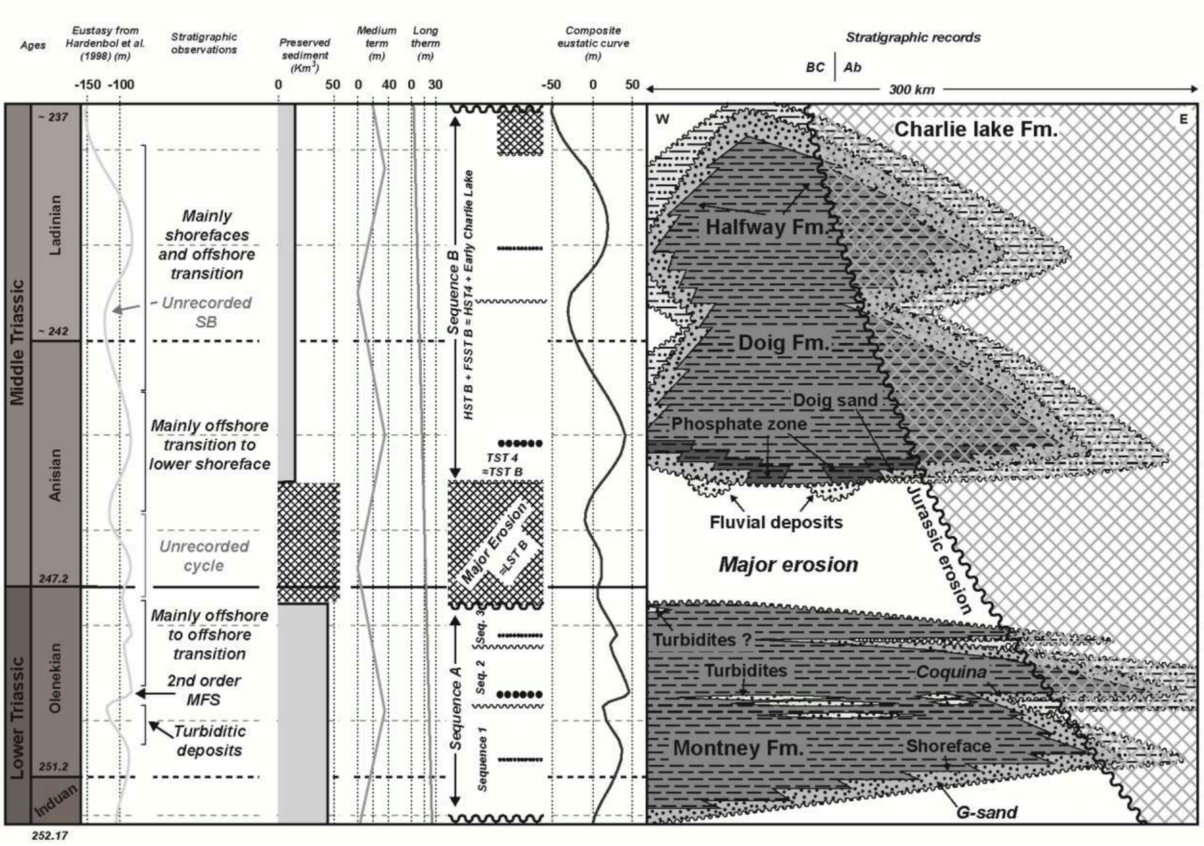

Figure V - 13: stratigraphic framework of the Lower and Middle Triassic strata of western Canada (modified from Davies et al., 1997). It presents the major stratigraphic observation of this work and the composite relative sea level curve (modified from Hardenbol et al., 1998) that corresponds to the stratigraphic evolution.

Recent work on the Doig phosphates zone (Golding et al., 2015a) concluded that the deposition of this interval was diachronous with Early Anisian deposits to the West and Middle Anisian deposits to the East of their studied area. On **Figure V - 13** a long rise of the sea level is present in the Middle Triassic and is therefore interpreted to be linked to the TST4. The association of this transgression with the TST4 implies that a Lower Anisian eustatic cycle was not recorded in the sedimentation. In the present work, this unrecorded cycle is interpreted to be the second order LST of sequence B at the boundary between the Lower and the Middle Triassic cycles. This interpretation is supported by the fact that in the Williston lake area, a major unconformity incising down to the sequence 2 (**Figure V - 11**) which therefore shows the occurrence of a major lowstand condition below the Middle Triassic strata. In the Alberta basin, we therefore think that no Early Anisian marine sediments are deposited. In the work of Golding et al. (2015a) all the biostratigraphic markers found in the phosphates zone were assumed to be in place and not reworked. Our study suggests that the Early Anisian faunas found in the Doig phosphate may derive from reworked sediments. In fact, the major turnover in the sediment sources highlighted by this study may allow the reworking of Early Anisian sediment that were deposited during the second order LST in an area that was, at that time, located under the actual Canadian cordillera. Here, the occurrence of faunas with different ages in different locations of the TST4 can be interpreted as a consequence of the multiple sediment sources: on the western part, the TST4 is mainly sourced by the West and maybe by Early Anisian reworked sediment whereas the Eastern part is mainly sourced by the continent and will only Middle to Late Anisian faunas present. We do not question the diachronism of the Doig phosphates zone. The TST4 depicting a second order transgression, the Doig phosphate will be deposited from the Middle Anisian up to the lower Late Anisian. We suggest that major erosion occurs during the Early Anisian and that no deposits of that age are present in the preserved part of the basin.

Over the Doig phosphate and the MFS4, the eustatic curve presents two episode of sea level fall (**Figure V - 13**). As the in sequence A, the regression of the Middle Triassic cycle may be composed of several third order sequences. In the Anisian and Ladinien, no major sequence boundary was highlighted at basin-scale, but the two eustatic cycles may correspond to the two prograding cycles present in the Williston lake area (**Figure V - 11**) and elsewhere as reported in previous studies (Embry and Gibson, 1995; Davies et al., 1997; Embry, 1997, Gibson and Barclay, 1999).

2. Relations between the stratigraphy and the regional geodynamic evolution

The **Figure V - 13** summarizes our sequence stratigraphic interpretation of the Lower and Middle Triassic in Western Canada. It shows that the eustatic variations of the sea level (left track on **Figure V - 13**) do not fit with stratigraphic observations: (1) the highest sea level of sequence A does not coincide with MFS2, (2) the unrecorded cycle does not correspond to a major drop of sea level (3) sequence B, presents two high amplitude rises of the sea level.

In order to fit a composite eustatic curve with the stratigraphic observations, two curves were added to the eustatic level of Hardenbol et al. (1998): (1) a medium term curve, with a period of 5.5 My and an amplitude of 35m and (2) a long term curve, with an amplitude of 25m. In this work, those curves are interpreted to represent the impact of the regional geodynamic and structural evolution on the relative sea level. The long term curve is interpreted as a small continuous uplift of the basin whereas the medium term is interpreted to be linked to more punctual structural uplift and subsidence (Haq et al., 1987). On **Figure V - 13**, it is apparent that the major lowstand conditions between sequence A and sequence B are induced by a minimum in the medium term curve. This suggests that this sequence boundary is controlled by the regional tectonic evolution and probably the early Canadian Cordillera orogeny (Beranek et Mortensen, 2011; Golding et al., 2015b).

3. Sediment inputs

The integration of the stratigraphic architecture in a chronostratigraphic framework shows that the three sequences of the Montney Formation were deposited in approximately 5 My (1.6 My each) whereas the sequence of the Middle Triassic time was deposited in more than 8 My. The isopach maps allow computing the volume of sediment preserved in the sequence A and B. In sequence A, 44.10^3 km^3 of sediments are present in the subsurface of Alberta and British Columbia whereas in sequence B, only 15.10^3 km^3 are present. This volume does not include any estimation of the parts that were eroded by the Jurassic or the second order sequence boundary between sequence A and B. Estimated average sediment fluxes in sequence A and B were computed based on preserved sediment volumes and sequence duration. It shows a major drop at the boundary between sequence A and sequence B (from 10.10^3 km^3/Ma to 2.10^3 km^3/Ma in sequence B).

Between the Lower and Middle Triassic, no major climatic changes are recorded (Hallam, 1985; Golonka et al., 1994; Davies, 1997a; Davies, 1997b; Sellwood and Valdes, 2006), suggesting that the drop of sediment supply between sequence A and B is not related to changes in the vegetal cover or increased runoff. Instead, we propose that this change in sedimentation rate is more likely related to modifications of the regional basin physiography (Dai and Trenberth, 2002).

During sequence A, the major part of the sediment input comes from the Canadian Shield (**Figure V - 8**) which is consistent with the occurrence of ephemeral (Zonneveld et al. 2010) and perennial (Zonneveld and Moslow, 2014) deltas on the eastern margin of the basin during the deposition of the Montney Formation (sequence A). In the Doig and Halfway Formations, evidences from Golding et al. (2015b) and Harris (2000) suggested sediment inputs from the West. In the present work, the 3D stratigraphic architecture of sequence B confirms the occurrence of sedimentary sources from the West during Middle Triassic (**Figure V - 9**). The study of the stratigraphic architecture of sequence A and B emphasizes a change of the sedimentary sources from sequence A to sequence B. It suggests a major reorganization of the regional paleogeography during SB4.

This turnover is also highlighted by the mineralogy: sequence B presents more carbonate than sequence A. This further suggests a change of sediment sources. Price (1972) shows that Paleozoic formations are mainly carbonates and during Early Triassic the only crystalline areas that can source the lithic elements are located on the Canadian Shield (Burwarsh et al., 1994; Kent, 1994). These observations suggest a major change in the physiography of the basin resulting in the reworking of Paleozoic formations to the West with reduced sediment input from the Canadian Shield.

All the previous observations are not compatible with a passive margin setting as suggested by Edwards et al. (1994) and Davies et al. (1997). The present study tends to show that Middle Triassic formations were deposited in a basin that presents western sedimentary sources. Based on detrital zircons, Golding et al. (2015b) suggested the occurrence of western sources and the deposition of the Middle Triassic in an early foreland basin. Further investigations of regional subsidence rates are needed in order to define the precise basin type.

4. Depocenters and structural settings

For each sequence, the large scale tectonic control on sedimentation can be assessed through the spatial relationship between the major structural elements of the basin and the thickness distribution.

The Hay River shear zone, is reported to be active in the Precambrian times (Hoffman, 1987, Wright et al., 1994) and to have only little impact of the Triassic strata (Strurrock and Dawson, 1990). Here, the location of the sequence 1 maximum thickness suggests that the Hay River shear zone may increase the local subsidence and therefore influence the deposition of the early Lower Triassic.

Numerous works focus on the relative movements of the Peace River arch (Cant, 1988; Barclay et al., 1990; McMechan 1990; O'Connell et al., 1990; Ross, 1990; Eaton et al., 1999), and agreed that the Peace River arch rose during the Precambrian and then started to collapse in the Carboniferous. Other studies suggest that the Peace River embayment affects the depositon of the first Triassic deposits (Barclay et al., 1990, Gibson and Edwards, 1990; Davies et al., 1997, Moslow and Davies, 1997). In the present work, the maximum thickness of sequence 2 that is present above the former Peace River arch may suggest the occurrence of bathymetric heritage from the arch collaps. Here three scenarios are possible: (1) a bathymetric low that is induced by the Fort St John graben, however, even if LST2 maximum thisckness is located above this structure, the sequence 1 do not present any thickening in this area, (2) an irregular bathymetry induced by the differencial compaction of the underlying formations and (3) differential subsidence between sequence 1 and 2: the north of the bassin (above the Hay River shear zone) subsided during sequence 1 and the centre of the basin (above the former peace river arch) subsided during sequence 2 (Moslow and Zaitlin, 2008). Further studies on the detail systems tract thickness is needed in this area in order to choose between these options.

Lastly, on **Figure V - 12C**, it is apparent that the preserved part of the sequence 3 is located above the Peace River arch. The present work suggest that the SB4 was induced by a regional uplift, the preservation of the sequence 3 above the Peace River arch is therefore interpreted as being related to a reactivation of the ancient structures of the Dawson Creek Graben Complex during the uplift. This reactivation creates a differential subsidence that increased the preservation of the sequence 3 within these structures.

5. Regional paleogeography

The similarities between the outcrop section of Brown hill and a well (0/08-29-64-10W6, **Figure V - 10**) located 275km southeast, in the basin near the deformation limit, suggest that the outcrops of the Williston Lake area are not at their syn-depositional location. Price (1994) shows the occurrence of major (> 500 km) South to North displacement of terranes during the cordilleran orogeny.The similarities between the well and the outcrop suggest that the initial position of Brown Hill was around 200 km southeast from its present-day location (**Figure V - 14**). As Ursula Creek section is separated from Brown Hill by a major structural suture, it is assumed that an even greater displacement may also affect to Ursula Creek (**Figure V - 14**).

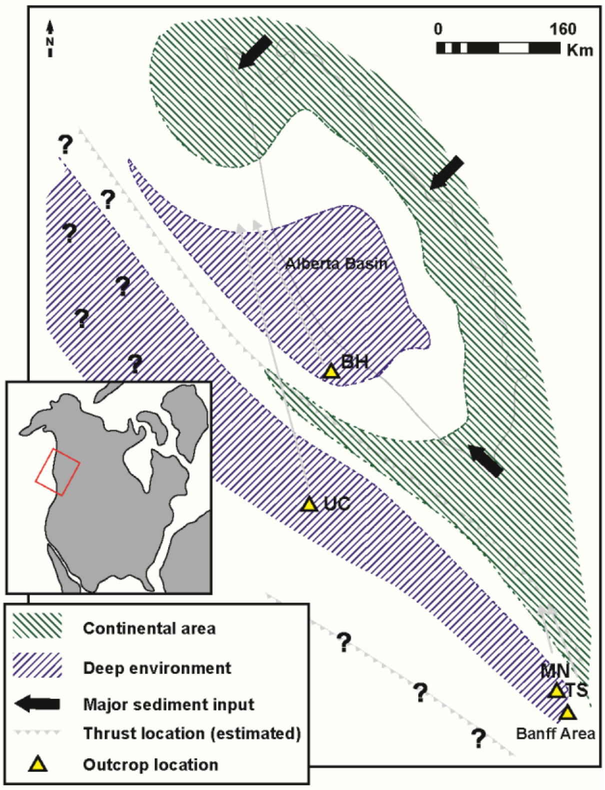

Figure V - 14: schematic reconstruction of the paleogeography of Western Canada during lower Triassic.
Note the occurrence of two basins separated by a topographic high. BH: Brown Hill, UC: Ursula Creek, MN: Mount Norquay, TS: Three Sister Spillway.

The sedimentary description of Ursula Creek does not highlight a major subaerial unconformity as opposed to Brown Hill, Glacier Spur, Folded Hill or in the basin. Below the phosphates zone of Ursula Creek, offshore transition facies were deposited. They are interpreted to be the LST4 deposits (Early Anisian) that is contemporaneous of the SB4 in the Alberta basin. This interpretation suggests that Ursula Creek was initially located in a deeper part of the basin that did not record the subaerial exposure during the LST4 (**Figure V - 14**).

In the southern part of Alberta, in the Banff area, the sections of Mount Norquay and Three Sister Spillway present marine deposits. Thereby, in the basin during the LST2, the turbiditic deposits appear to come from the South. This last observation suggest the presence of emerged areas to the South of the basin probably located between the Alberta basin and the Banff area (**Figure V - 14**). In the present study the outcrop of the Banff area are interpreted to be in the same basin than Ursula Creek. The present study therefore suggests the occurrence of two Triassic basins on the western margin of Canada, separated by bathymetric highs or thin continental areas (**Figure V - 14**).

6. Stratigraphic architecture of the Lower and Middle Triassic marine strata of Western Canada

Based on previous observations and interpretations we propose a revised stratigraphic architecture of the Montney Doig and Halfway Formations (**Figure V - 13**). The **Figure V - 13** shows that the Montney Formation and the Doig-Halfway Formations are two different second order sequences separated by a major time gap (approx. 2.5 My) associated with an emersion and major erosion. In the Montney Formation previous studies suggested the occurrence of three sequences with a unique regressive trend (Embry and Gibson, 1995; Davies et al., 1997; Embry, 1997, Gibson and Barclay, 1999). In the present study, the correlation of over 400 wells throughout the basin shows that the maximum flooding surface of the Montney Formation (sequence A) occurred in the second 3rd order sequence. In the sequence 1, the TST1 occurred during a long and smooth rise of the sea level resulting in the deposition of backstepping shorefaces of the G-sand, described by Pannek (2000). In sequence 2, thick turbiditic interval was deposited during the lowstand sea level (**Figure V - 13**). Above the SB4, the present work emphasizes the occurrence of fluvial facies (**Figure V - 13**) that were deposited in incised valley during LST4. Above the SB4 the basin present sediment sources from the East and the West. In the present study, the two distinct prograding cycles of the Middle Triassic are only highlighted in Williston Lake and not in the basin due to the lack of detail in the HST4. However they are described in previous studies (Embry and Gibson, 1995; Davies et al., 1997; Embry, 1997, Gibson and Barclay, 1999) and therefore presented on **Figure V - 13**.

VI. Conclusions and perspectives

The 3D basin-scale stratigraphic architecture of the Lower and Middle Triassic strata in the Alberta Basin was reconstructed based on an extensive network of regional correlation cross-sections. The key outcomes of this reconstruction are summarized here below:

- The Lower and Middle Triassic strata are divided in two second order sequences (sequence A and B) that are separated by a major erosional surface.
- The limit between the two sequences records a major time gap. This 2.5 My long, subaerial exposure is interpreted to be linked to a regional uplift that was probably induced by the evolution of the proto-Canadian cordillera.
- The first second order sequence (Montney Formation) was mainly sourced by the continent, whereas the second one (Doig and Halfway Formations) presents sedimentary inputs from both the continent and the West. This turnover is associated with a major change of the paleogeographic settings between sequence A and sequence B.
- The deposition of the Lower and Middle Triassic strata took place in a tectonic active basin: (1) occurrence of regional uplifts, (2) significant sedimentary accumulation over the Hay River shear zone, (3) preservation of the sequence 3 above the Peace River arch, (4) changes in the paleogeography that induces changes of the sedimentary sources.
- A major reorganization of the basin took place between Lower and Middle Triassic due to the evolution of the Canadian Cordillera.