The Ten Stone Ranges Structural Complex of the central Mackenzie Mountains fold-and-thrust belt: a structural analysis with implications on the Plateau Fault and regional detachment level

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Science
in
Earth Sciences

Waterloo, Ontario, Canada, 2009

Authors Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The Cordilleran Orogen affected majority of the western margin of ancient continental North America in the Cretaceous, which is well recorded in the Foreland Belt. The Mackenzie Mountains fold-and-thrust belt is located primarily in the westernmost Northwest Territories and easternmost Yukon Territory in northern Canada. The mountains are often described as the northern extension of the Rocky Mountains to the south which are one of the world's best examples of a thin-skinned fold-and-thrust belt. Within the Mackenzie Mountains, Neo-Proterozoic through Cretaceous sedimentary rocks record the Laramide aged deformation, with a range of structures that vary in size and complexity. Previous mapping by the Geological Survey of Canada produced a series of reconnaissance maps that are still in use today, many of which are available in only black and white.

This study is focused on a part of the 1:250 000 scale NTS 106A Mount Eduni map sheet from Geological Survey of Canada reconnaissance mapping in 1974. The study involved re-mapping a large panel at 1:50 000 scale to better understand the structural geometry, regional shortening and the depth of the underlying detachment level. Through systematic geologic mapping and structural analyses, this study presents a balanced regional cross-section, numerous serial cross-sections and a detailed geologic map of the study area, the Ten Stone Ranges Structural Complex.

The serial cross-sections were used to define the geometry of the Cache Lake Fold, a large fault-bend-fold system that involves a folded thrust fault and complicated subsurface geometry. In addition to this, the sections confirmed that the TSRSC is a transfer zone whereby a series of thrust faults and décollement folds are responsible for much of the displacement and shortening in the Mount Eduni map sheet. The balanced regional cross-section was constructed across a number of key structural elements, in particular the Plateau Fault, a regional structure with a > 250 kilometer strike length and the subject of much debate as to its geometry. In addition to this structure, the cross-section transects the Cache Lake Fold and the Shattered Range Anticline, a regional box shaped anticline that was used for a "depth to detachment" calculation. By examining the regional detachment level estimated from the balanced cross-section and calculating the detachment depth using the Shattered Range Anticline the detachment depth was found to be – 11.3 kilometers below the current erosional level.

This study is the first structural analyses of the Mount Eduni map sheet, particularly the Ten Stone Ranges Structural Complex, and has resulted in an estimate of the detachment depth for the area, a shortening estimate of > 7 kilometers across the 50 kilometer line of section and a displacement estimate for the Plateau Thrust of > 20 kilometers.

Acknowledgements

First and foremost, I would like to thank my supervisor Dr. Shoufa Lin. His overwhelming passion for structural geology is obvious to anyone who has ever been in the field with him. You have inspired many students and I am happy to say I am one of them.

I would like to thank Dr. Steve Gordey for his unlimited patience and for all the knowledge he has passed on to me throughout the course of this project. He has been an outstanding mentor and I am truly thankful for the opportunity to work with such a fine geologist. I am also grateful to Drs. Karen Fallas and Charlie Roots for their constructive criticism, guidance and teaching me how to map in the mountains. I am also grateful to Edith Martel for getting me involved in this project, and for being a great geologist and project manager during our time in the Mackenzie's. I would also like to thank the SEKWI Mountain Team for all of their great field discussions. In addition, a large thanks to my colleagues at Waterloo, for open ears and great friendship throughout the course of this project.

I would like to sincerely thank my family for their support throughout my entire academic journey. To my parents, who always encouraged further education and learning, and supported my decisions along the way. Lastly, I would like to thank my Fiancée Kelsey, you are truly an amazing person and you have stood by my side and provided encouragement time and time again. This study was jointly funded by the Northwest Territories Geoscience Office as part of the SEKWI Mountain Project and by a Natural Sciences and Engineering Council of Canada operating grant to Shoufa Lin.

Dedication

For David and Richard…The best grandfathers a boy could ever know

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Chapter 1
Introduction

1.1 Introduction

1.1.1 Introduction

Geologists all over the world have long studied fold-and-thrust belts since the mid 1800's. The first scientist to observe the Rocky Mountain fold and thrust belt in Canada was Sir James Hector in 1859. Since then, the Canadian Rockies have been a world-class locality to study the structures that occur in these tectonic settings. The early workings of the Geological Survey of Canada (GSC) brought forth such techniques as the art of balancing cross sections, one that would prove to be very beneficial to scientists and especially the petroleum industry that now thrives in such settings, especially the foothills of the Rocky Mountains.

There are undoubtedly many different aspects and structural elements associated with fold and thrust belts, perhaps the most important of these structural elements are the large-scale, low angle thrust faults and associated décollement folds that dominate these settings, and are responsible for much of the shortening and deformation that occurs there.

1.1.2 Location and Access

The Mackenzie Mountains, located in northern Canada, are the northern extension of the Rocky Mountains in the northeastern Cordillera. They are located primarily in the Northwest Territories (NT) and straddle the Yukon-NT border for some 600 kilometers north of British Columbia. The mountains extend northwestward to the Peel Plateau and comprise part of the watershed for the Mackenzie River (east) and the Yukon River (west) and are the source for the Pelly River, a headstream of the Yukon River. They are bordered on the northeastern side by the Franklin Mountains and on the southwestern side by the Selwyn Mountains (Figure 1.1). The tree-line on the mountains is typically around 1200m elevation and peaks average from 1300-2500m with the highest peak in the mountains being Keele Peak at an elevation of 2972m. The high elevation, large seasonal snow pack and large river systems make access through the mountains very challenging.

Prior to WWII, the Mackenzie Mountains were largely underexplored due to their remote location and unforgiving topography. With the onset of WWII and the ongoing war in the Pacific, the Americans

Whitehorse, Yukon and eventually on to Alaska via the ALCAN highway. This monument of the Second World War was known as the CANOL Road ("Canadian Oil") and was abandoned shortly after its completion upon the Japanese surrender in 1945. Since its abandonment, the pipeline has been removed and the road has been turned into a heritage trail, however many of the pump houses and old equipment remain along the trail which serve as interesting sights for the tourists that hike the trail every summer. The study area of this thesis is located within NTS sheet 106A (Figure 1.2) which is the Mount Eduni map sheet. The access to the study area is possible only by fixed wing aircraft or helicopter from the Yukon side or Norman Wells, NWT. There are a number of game outfitters and mineral exploration companies in the study area that maintain several small airstrips suitable for a Twin Otter or smaller aircraft. Access can also be gained via the CANOL road from Whitehorse, Yukon to the Macmillan Pass staging area at the Yukon/NT border. However, a helicopter or fixed wing aircraft is required past this point as much of the road is deteriorated and is not passable even by ATV's (all terrain vehicles). Access to the area was gained by float plane from Norman Wells to Shale and McClure Lakes where the base camps were situated, and then by helicopter for ground traverses and two-person fly camps. It is understandable that the remoteness of this location resulted in mostly reconnaissance studies by the Geological Survey of Canada and exploration programs by mining and oil companies.

1.1.3 Previous Work

The earliest investigations of the Mackenzie Mountains involved following the Keele River (Keele, 1910) and the CANOL Road through the mountains by the Geological Survey of Canada. Helicopter reconnaissance mapping under GSC Operation Selwyn in 1963-1967 resulted in a series of 1:250 000 scale maps by Gabrielse et al. (1973a, b, c) and Blusson (1971, 1972) (after Roots and Martel, 2008). Later mapping during GSC Operation Norman in 1969-70 resulted in the first maps of the areas north and northeast of Sekwi Mountain (including Mount Eduni) by Aitken and Cook (1974a), Aitken et al. (1974) and Blusson (1974) (after Roots and Martel 2008). Later revision mapping in the area was undertaken by the territorial governments which resulted in a number of 1:50 000 scale maps for the Dal Lake area (Colpron and Augereau, 1998a, b; Colpron and Jefferson, 1998; Jefferson and Colpron, 1998) and a Nahanni National Park energy resource assessment project resulted in further work in the area (Wright et al, 2007) (after Roots and Martel, 2008). Overall, before the Sekwi Mountain Project, many areas had only uncolored 1:250 000 preliminary maps and unfortunately even after a project of this breadth, many of the maps in the northern Mackenzie Mountains are still only available in their uncolored original condition.

Figure 1.1: Physiographic map of northern Cordillera showing location of Mackenzie Mountains and northern Rocky Mountains (Colpron et al., 2006).

Figure 1.2: Location of 2005-2008 study area for SEKWI Mountain Project which is composed of NTS sheets 106A (blue box), 105P (red box), and part of 95M (red box). Black outline represents the Sahtu region of the Northwest Territories, black dashed line shows position of CANOL trail and red stars represent communities in the region (after Roots and Martel, 2008).

1.1.4 The SEKWI Mountain Project

This project which provided funding and access to the area was initiated by the Northwest Territories Geoscience Office as a need to assess the resource potential of the vastly underexplored Mackenzie Mountains which account for a significant amount of the NT's landmass. Many of the geology maps in the Mackenzie Mountains that were produced in the 1960's (Figure 1.3) were uncolored and each 1:250 000 reconnaissance scale map had its own legend making correlation of units across the mountains very difficult. This project involved collaborative studies with the Northwest Territories Geoscience Office, universities, the Geological Survey of Canada and industry and was conducted over a four year period from 2005-2008. As part of the SEKWI Mountain Project, a total of three M.Sc. projects were completed, the following of which is the structural analyses of the area. This project involved a mapping, structural-focused thesis that examined the structures adjacent to and related to a large, through-going dip-slip fault coined by previous workers as the Plateau Thrust (Gabrielse, 1973). By subsequent mapping along this fault an intensely deformed zone, the Ten Stone Ranges Structural Complex, was defined and mapped in detail for as part of this study.

1.1.5 Geologic Mapping of the Ten Stone Ranges Structural Complex

A total of two summers were spent in the Mackenzie Mountains both collecting data for this individual study as well as mapping other areas for the SEKWI Mountain Project. The first summer of field work involved defining the scope of the project by choosing a suitable map area based on the previous 1:250 000 Mount Eduni map by Aitken and Cook (1974a) and Blusson (1974) (Figure 1.4). The field area was chosen to incorporate a highly deformed panel in the center of the Mount Eduni map sheet in which there were numerous problem areas that needed detailed mapping. This deformed panel was later coined the Ten Stone Ranges Structural Complex (hereafter TSRSC) and was thoroughly mapped over the course of these two summers which resulted in the geologic map (Figure 1.5) and corresponding legend (Figure 1.6). The 1:50 000 scale geologic map and legend are located in the pocket.

The TSRSC runs from the southeast to the northwest and is roughly perpendicular to the Laramide transport direction, allowing for large scale, continuous structures to be studied along strike from southeast to northwest. The TSRSC is bound on the southwest side by the Plateau Fault, a large through-going structure, and on the northeast side by the Shattered Range Anticline, a regional scale box fold. The study area is located in the immediate footwall of the Plateau Fault and is intensely shortened by northeast vergent thrust faults and folds of varying structural complexity. The TSRSC extends southeast to the Wrigley Lake map sheet but this part of the complex was not included in this study (Figure 1.4).

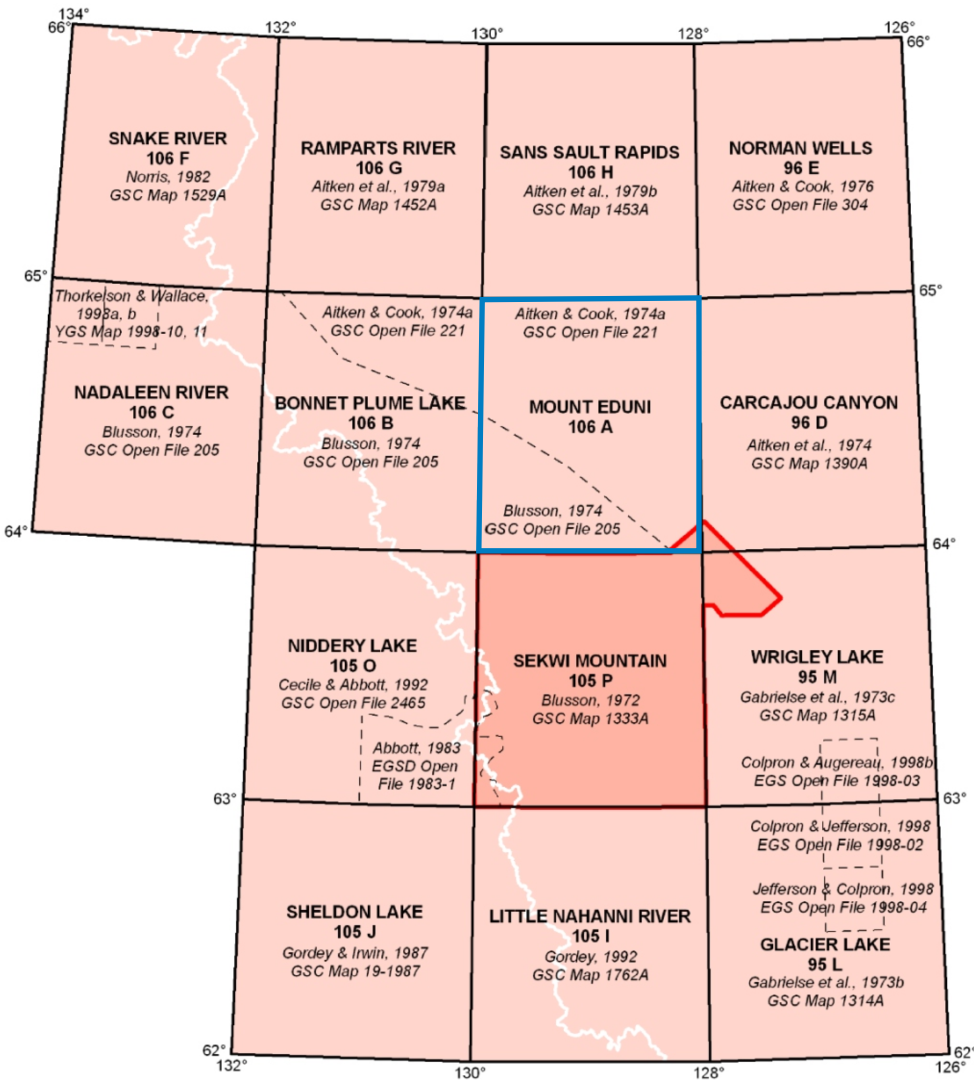

Figure 1.3: Distribution of available bedrock geology maps for the Mackenzie Mountains with shaded area (pink) representing work of the SEKWI project during 2005 and 2006. The field area for this study was located in the Mount Eduni map area, NTS sheet 106A to the north of 105P (blue outline) and was mapped during the 2006 and 2007 field work (after Roots and Martel, 2008).

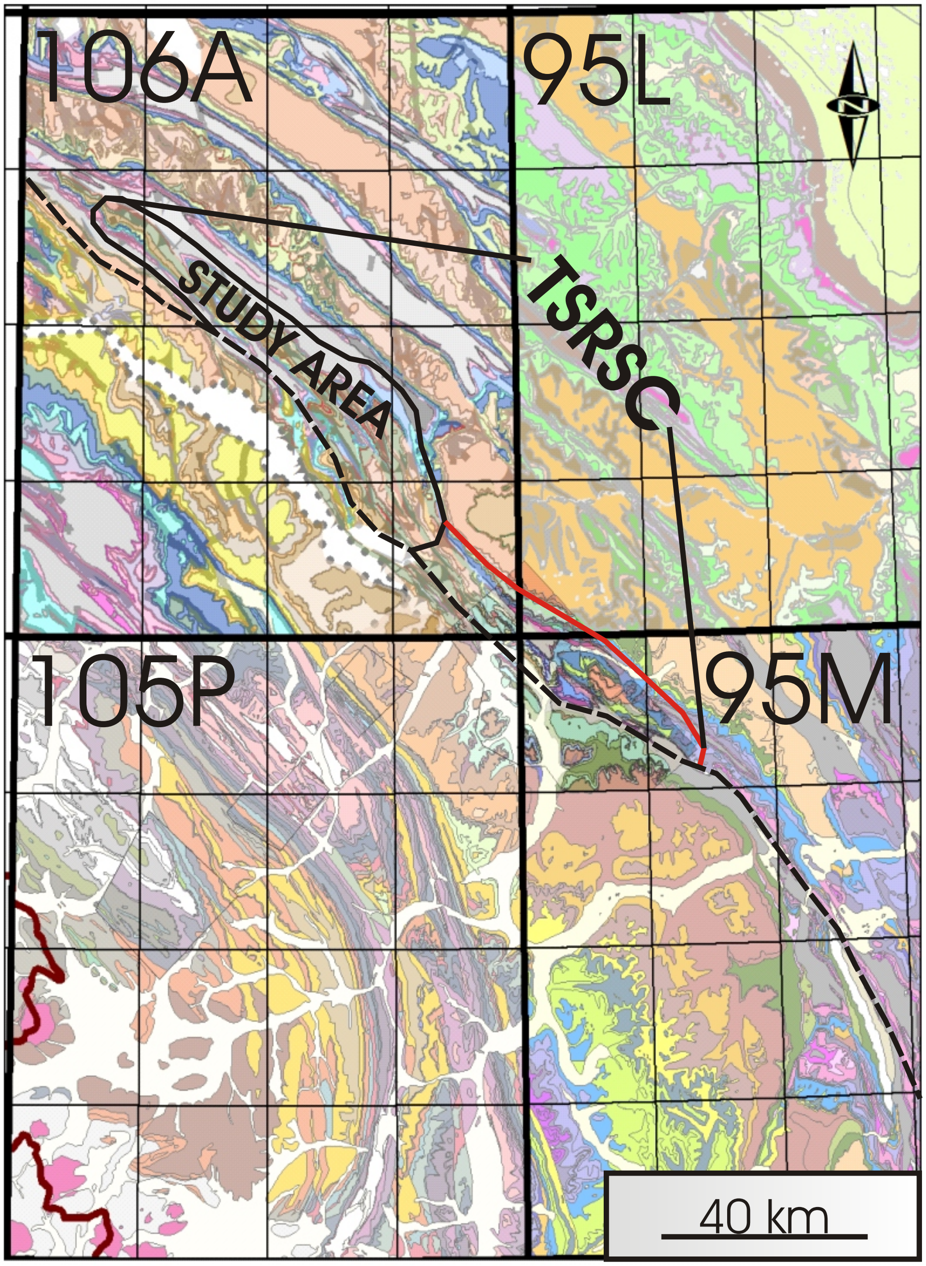

Figure 1.4: Location of the Ten Stone Ranges Structural Complex (TSRSC) where black polygon shows position of study area, red polygon is southeastern extension of TSRSC and dashed black line is approximate trace of Plateau Fault which serves as the western boundary of the TSRSC.

The latest mapping from the SEKWI Mountain Project in this area includes the “Four Corners” map from 2006, improvements on the Wrigley Lake map throughout 2006-2008 as well as selective mapping along the Plateau Fault in 2008 by the SEKWI project to fill in data gaps.

The “Four Corners” map area, a 1:50 000 map tile that was completed in the 2006 SEKWI program, displays the southeastern continuation of the TSRSC along its northwest-southeast trend (Figure 1.7). This area was mapped as an attempt to make a unified legend for four maps as it lies on each of the four corners of the 1:250 000 scale geological maps of 95M, 96D, 105P and 106A (Figure 1.8). The area was also chosen for more detailed work as it is where the footwall of the Plateau Fault outcrops so it presented many opportunities to study its structural and stratigraphic complexities (Roots et al., 2008). Farther to the southeast, in the Wrigley Lake map area (NTS 95M) the Plateau Fault continues along strike and has been investigated as part of the hydrocarbon potential of the Plateau Fault study undertaken by Fallas and MacNaughton throughout 2006-2008 (Figure 1.9).

The above work has been very important in understanding the southeastern area of the TSRSC providing diagrams and maps which help to answer such questions as the influence (if any) of the Plateau Fault on the TSRSC in the Mount Eduni map area, as well as the cross-sections and maps that were available for comparison of structures. Up to this point, little has been done to attempt to constrain the depth of the underlying detachment level(s) in the central Mackenzie’s, which is of utmost importance for understanding the regional geology and structures. Through this study, a number of questions have been put forth and are discussed systematically throughout the text.

1.2 Purpose of Study

1) Map in detail the structures present in the TSRSC to understand the overall geology of this area and its relationship to the adjacent domains in the Mount Eduni map sheet

2) Determine a reasonable estimate of the shortening in the region by using data collected through the SEKWI Mountain Project via the first ever balanced cross-section through the Mount Eduni map sheet

3) To better understand the detachment (s) that are present at depth and their effect on the structures observed in the map area and the Mount Eduni area

4) To understand the geometry of the Plateau Fault and its implications on the regional structural picture and if it is as significant as it has been previously postulated

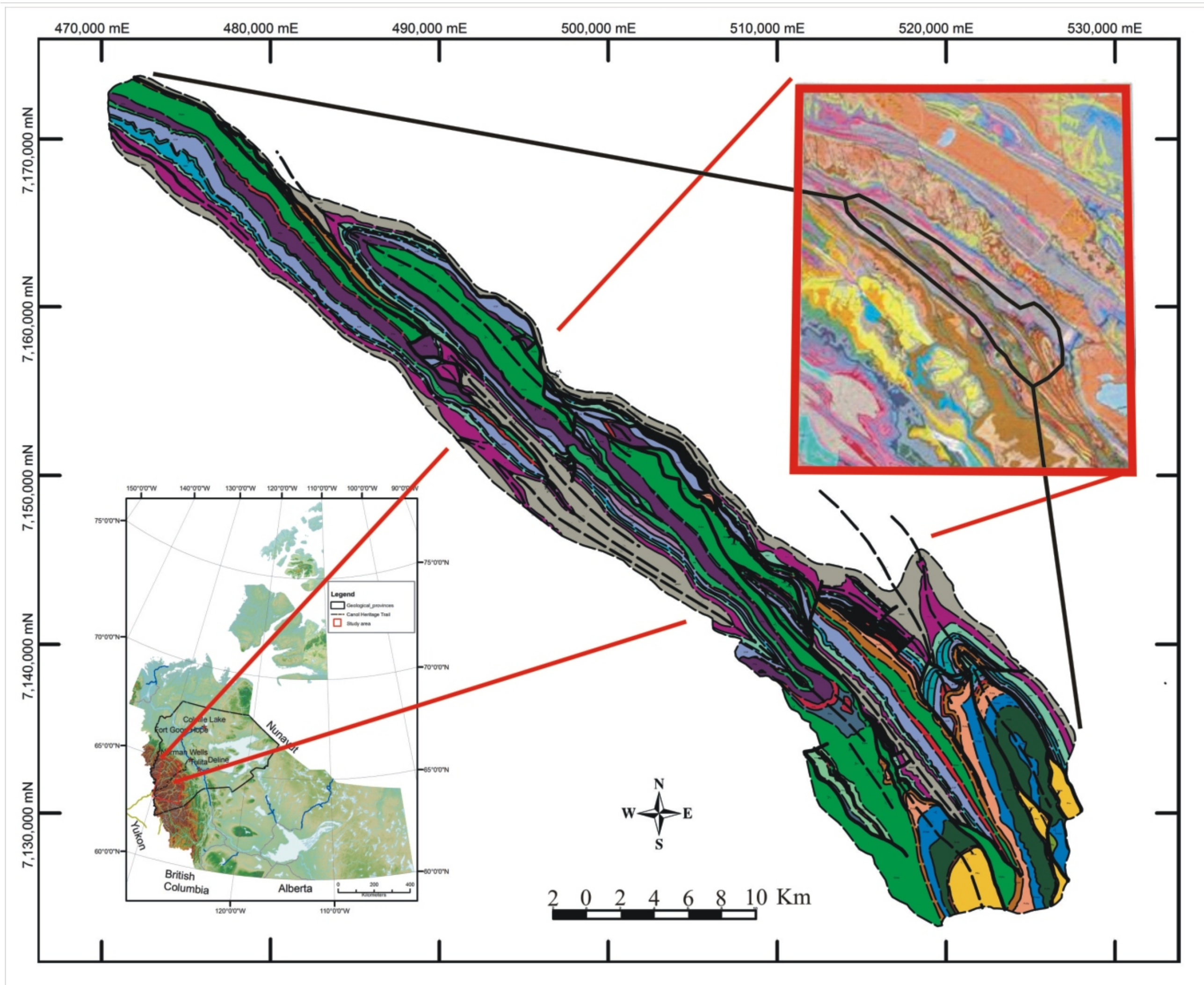

Figure 1.5: Simplified version of the 1:50 000 scale geologic map of study area (center) showing location within NTS sheet 106A (black polygon, top right) and within the Mackenzie Mountains (bottom left). The 1:50 000 scale map with legend is located in the back pocket. See figure 1.6 for legend.

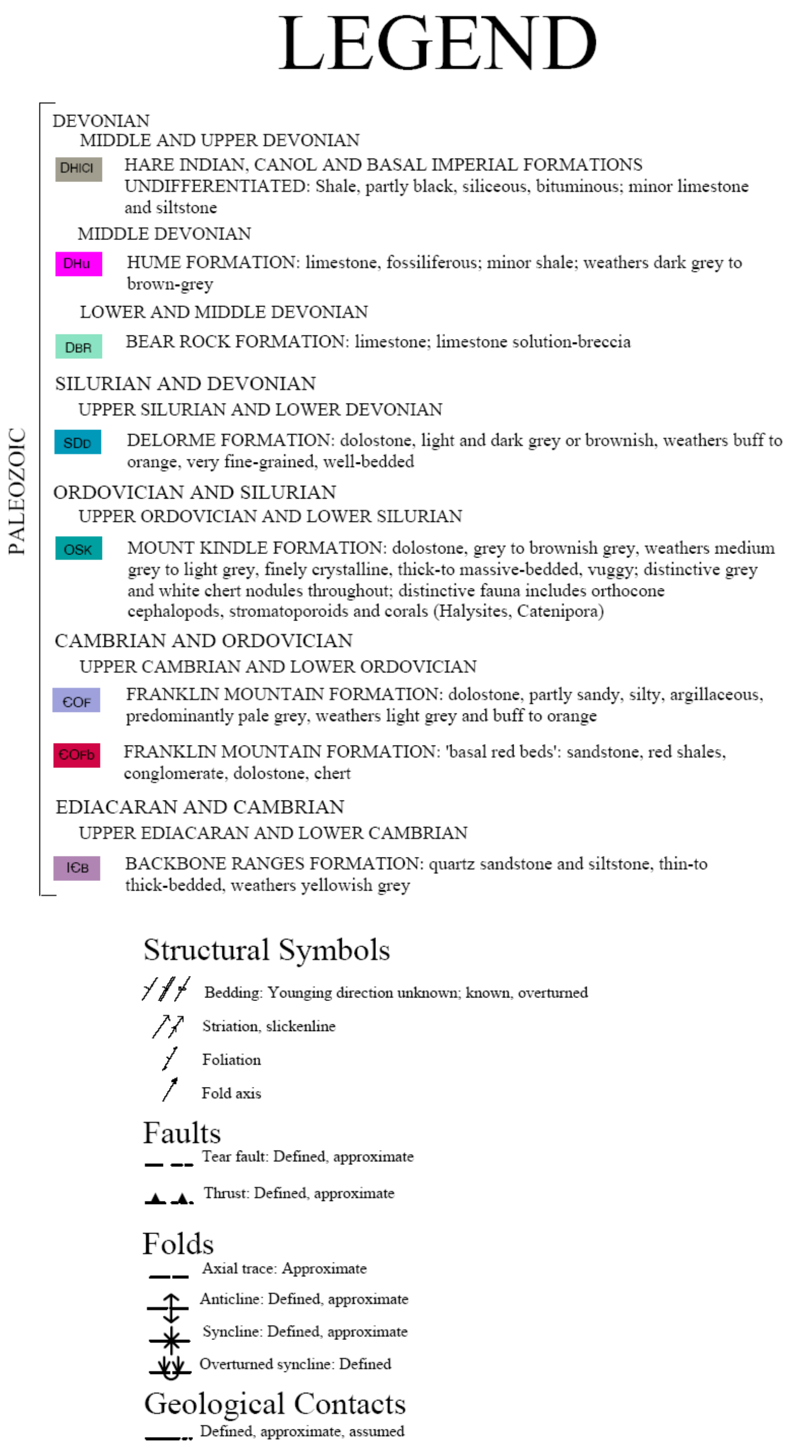

Figure 1.6a: Map legend with Paleozoic units found in map area (modified after Gordey et al., 2008). Same color scheme and abbreviations are used for all maps and cross-sections throughout the thesis unless otherwise indicated.

Figure 1.6b: Map legend with Proterozoic units found in map area (modified after Gordey et al., 2008). Same color scheme and abbreviations are used for all maps and cross-sections throughout the thesis unless otherwise indicated.

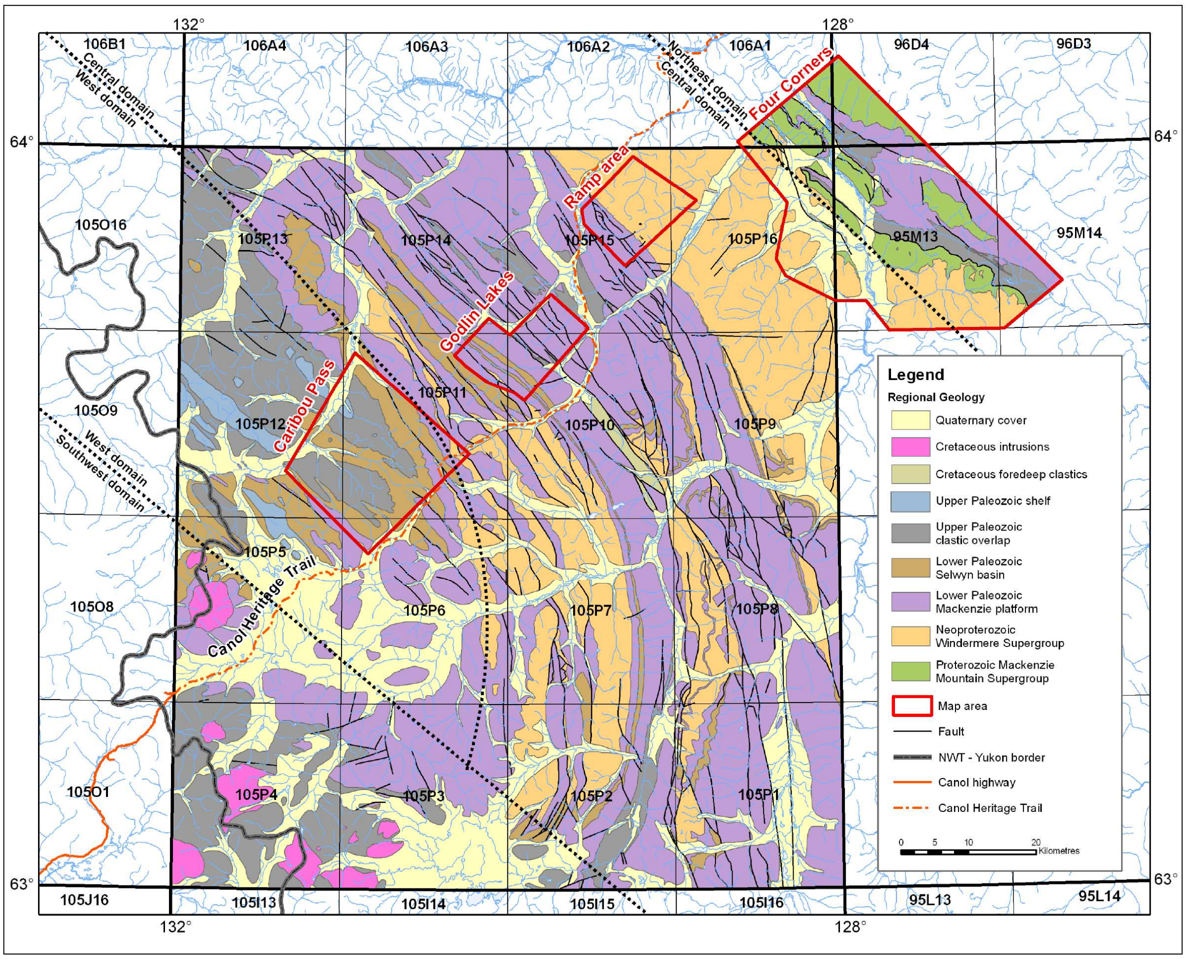

Figure 1.7: Simplified geology of the SEKWI Mountain map area (105P) with main areas of 2006 mapping outlined in red, major faults are represented by black solid lines and Yukon-NWT border shown in solid black to left of diagram (after Roots and Martel, 2008).

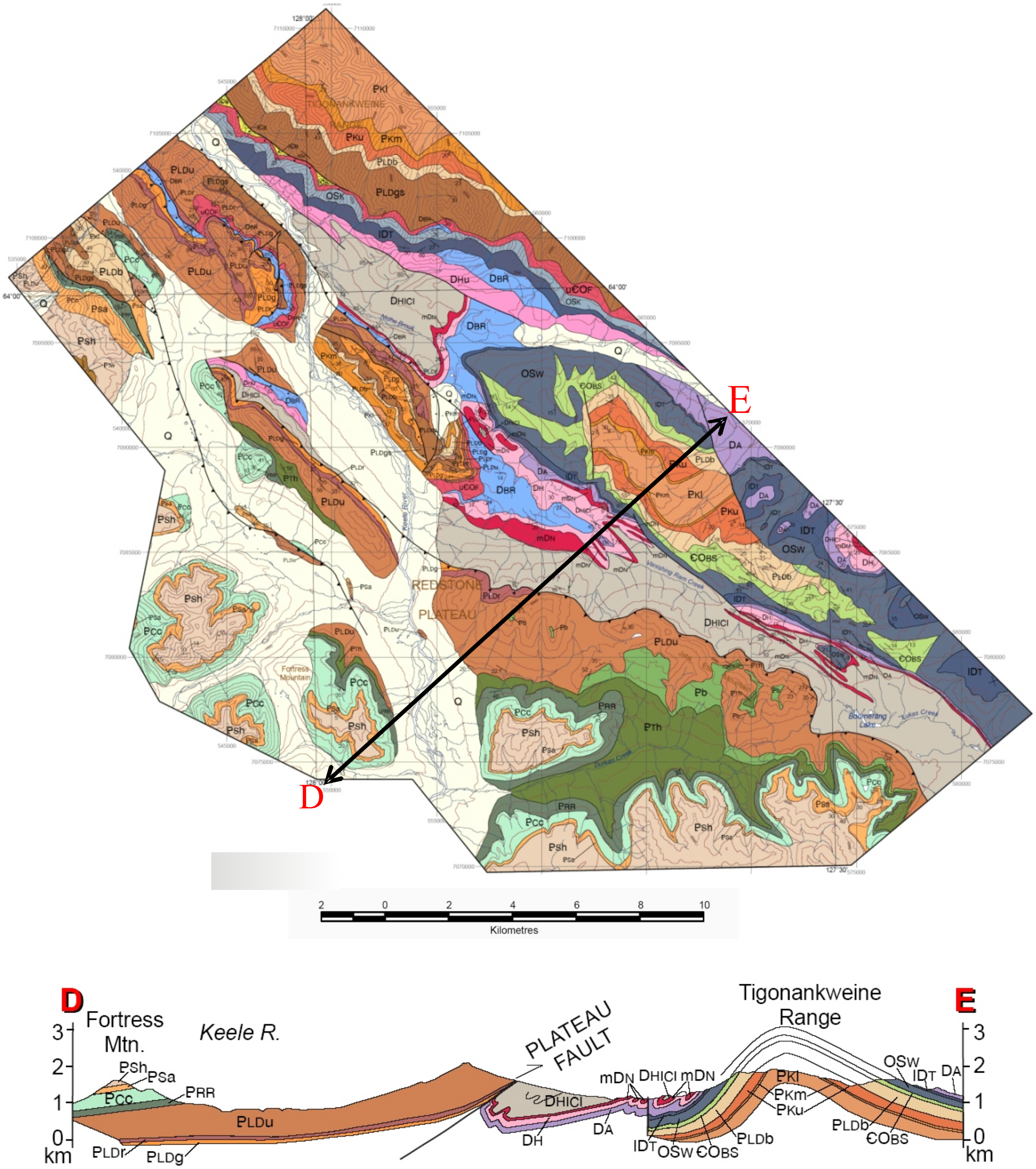

Figure 1.8: Geologic map of the Four Corners map area, with accompanying schematic cross-section portraying the Plateau Fault as a relatively low-angle structure with a slight listric component at its tip where it covers the Devonian clastic rocks (after Roots and Martel, 2008). Abbreviations are as in Figure 6a,b.

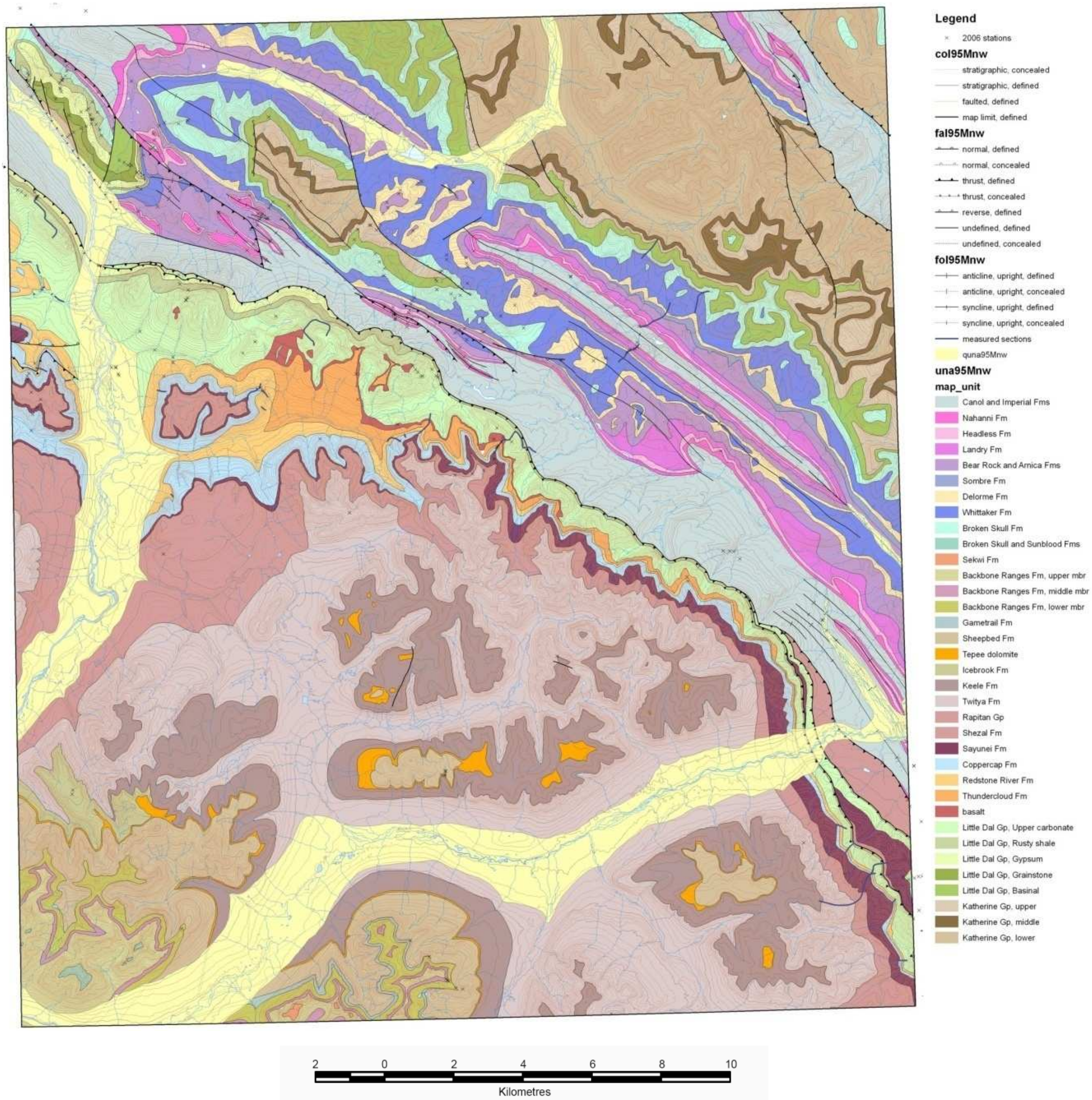

Figure 1.9: Geologic map of the northwest portion of NTS sheet 95M, Wrigley Lake map area (Fallas et al., 2008).

1.3 Geological Setting

The Canadian Cordillera encompasses an area of over 1.6 x 10 ^{6} km^{2} which extends from the base of the continental slope to the west to the western limit of undeformed strata of the Interior Plains (Gabrielse and Yorath., 1991). The northern and southern limits are the Beaufort Sea and the International Boundary with the United States. This area is composed of a collage of terranes that were accreted to the western margin of the North American craton between late Paleozoic and early Cenozoic time (after Colpron et al., 2006)(Figure 1.10). The Foreland Belt, the eastern limit of deformation, consists of the British, Richardson, Ogilvie, Wernecke, Mackenzie, Franklin and Rocky Mountains, all of which are composed primarily of sedimentary strata (Gabrielse and Yorath, 1991).

West of the Foreland Belt is the Omineca Belt, a package of stratigraphically equivalent rocks that have been intensely folded and intruded by granitic rocks to form the Selwyn, Kaska and Columbia Mountains (Gabrielse and Yorath, 1991). The Omineca Belt is transected (in the Yukon) and separated from the Foreland Belt (in British Columbia) by the transcurrent Tintina Fault, which extends to form the Northern Rocky Mountain Trench in northern British Columbia (Gabrielse and Yorath, 1991). In addition to these Belts are the Intermontane Belt of central British Columbia and southern Yukon, the Coast Belt which borders the Intermontane Belt to the west and the Insular Belt which spans from southwestern British Columbia to southwestern Yukon.

This study takes place in the north-central Foreland Belt, specifically the Mackenzie Mountain Fold-and-Thrust belt, which has been subjected to one phase of compressional deformation associated with Early to Middle Cretaceous northeast and east contraction. The layered sedimentary rocks of the Mackenzie Mountains are supracrustal in nature, and form an easterly tapering wedge of strata that range in age from NeoProterozoic to Devonian, with minor Cretaceous strata rarely preserved. The NeoProterozoic strata were deposited on a stable continental shelf that underwent periods of extension and glaciation. It has been suggested that several of the Proterozoic aged units in the Mackenzie Mountains (i.e. Katherine Group) contain sediment grains that have a Grenville provenance and were likely transported by large continent-scale river systems (Rainbird, 1997).

The early Paleozoic units observed in the Mackenzie Mountains almost all record a facies transition from platformal carbonate in the east to an argillaceous basin in the west. The late Devonian strata mark an influx of dark coarse-to-fine clastic sediment in the area which was succeeded by stable shelf sedimentation through Permian time (Roots and Martel, 2008).

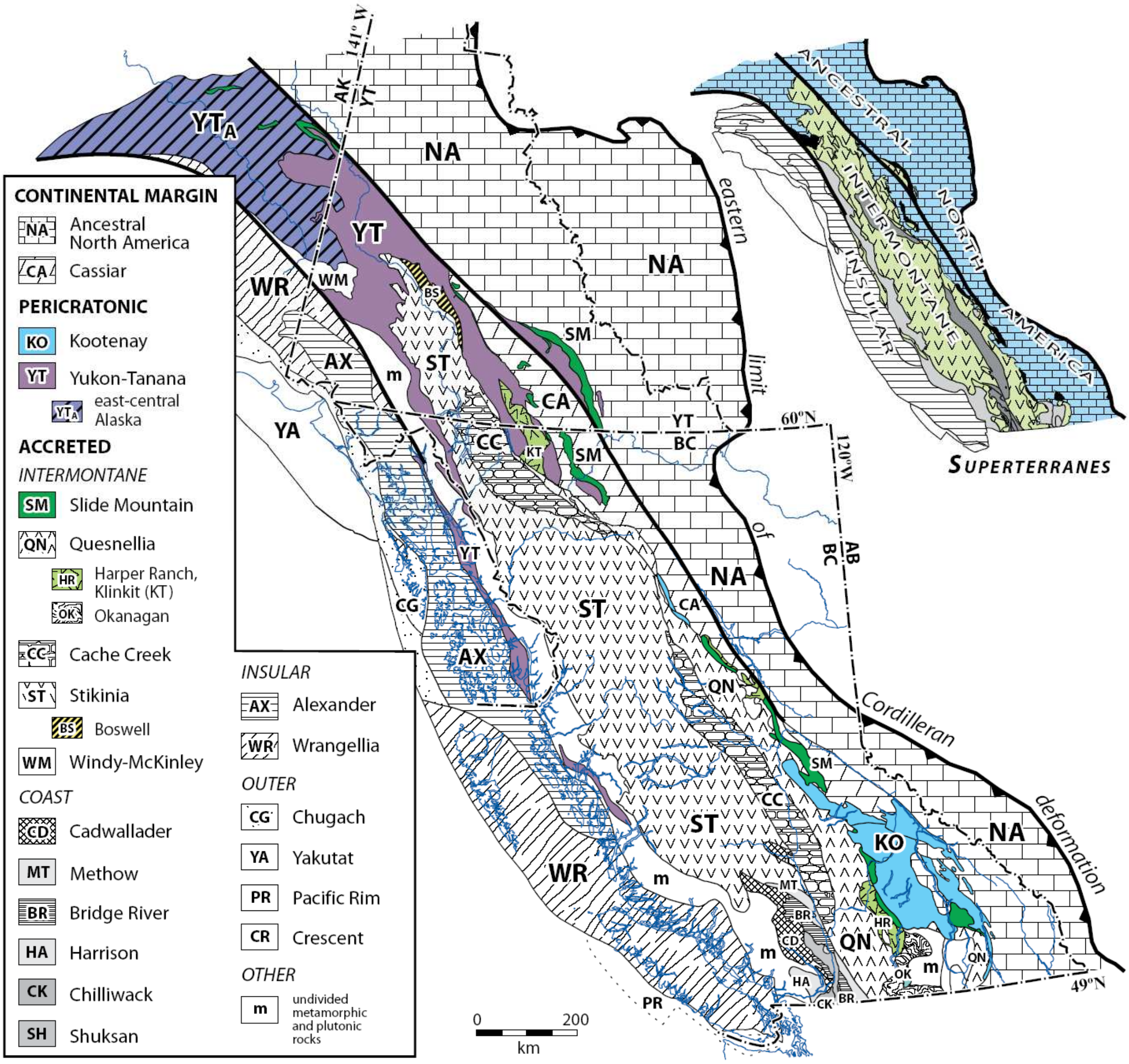

Figure 1.10: Terrane map of the Canadian Cordillera (modified after Colpron et al., 2002) showing the position of the Ancestral North American continental margin with the foreland belt at the northeastern limit and relative position of Mackenzie Mountains and Northern and Southern Rocky Mountains.

The study area for this thesis is located in the northcentral Mackenzie Mountains, in particular the central portion of NTS sheet 106A which has been introduced above as the TSRSC. This study area consists of some 27 informally named formations of NeoProterozoic to Devonian age sedimentary rocks and minor Proterozoic mafic dykes. A brief description of each formation and Group is given in chapter two.

1.4 Tectonic Setting

The foreland thrust-and-fold belt of the North American Cordillera follows the boundary of between the Cordilleran miogeocline and the North American craton from the Yukon Territory of Canada to southeastern California, USA (Price, 1981). From there, the belt continues on through the southwestern United States through Mexico and eventually on to Guatemala and Honduras. This Foreland Belt is a zone of easterly to northeasterly verging shallow thrust faulting and décollement folding that is up to 300 kilometers wide and is characteristic of a 'thin-skinned' deformation style (Price, 1981). The zone consists of a tectonically thickened, easterly tapering wedge of supracrustal rocks that was horizontally deformed above an undeformed craton.

The North American Foreland Belt is similar in tectonic setting and structural style to other foreland thrust-and-fold belts, such as the Helvetic and Jura Mountains in the northern Alps, the Valley and Ridge Province in the Western Appalachian Mountains of the United States and the Asiak fold and thrust belt between the Bear and Slave provinces in the northwestern Canadian Shield (Price, 1981). Foreland fold-and-thrust belts are widespread and appear similar in structural style to the imbricated fault zones that occur above subduction zones nearest the inner slope of trenches, however they are not. These zones are underlain by inter-plate displacements whereas in a foreland belt, there is no movement in the underlying plate (intra-plate) and shortening must happen above the physically continuous plate (Price, 1981). The shortening in a foreland belt is much less (d x 10^2 kilometers) than across a suture where one plate has overridden another (d x 10^3 kilometers) (Price, 1981). The North America Foreland Belt is a good example of an intra-plate shortening thrust-and-fold belt and although there are variations in structural style and tectonic setting from segment to segment throughout the Belt, it consistently maintains the criteria necessary to be classified as a foreland thrust-and-fold belt.

There are a number of distinguishable segments within the North American Foreland Belt, in particular the Southern Rocky Mountains, the Northern Rocky Mountains and the Mackenzie Mountains. The Southern Rocky Mountains are characterized by large-displacement, low-angle thrust faults and associated décollement folding that has resulted in up to 50 kilometers of lateral displacement on some thrusts (Price, 1981). Triangle zones are often developed where thrust and fold structures terminate at the leading edge of the autochthonous foreland basin deposits (Price, 1986). Duplex structures are common where enough shortening has taken place such that there is an upper detachment which is then met by subsequent thrusts that develop below it, such as with the Lewis Thrust in the Alberta Foothills (Jones, 1987).These structures are all indicative of the highly shortened southern Rocky Mountains.

In the northern Rocky Mountains, structures are dominated not by large imbricated thrust faults such as are seen in the southern Rocky Mountains, but by large amplitude box folds and chevron folds that deform above relatively flat lying detachments. Interestingly, in this area the large leading edge anticlines show no evidence for thrusting whatsoever, and only with key erosional features can one see that there is clearly an underlying detachment, however instead of ramping up through the leading edge of the folds, it is transformed into disharmonic folds at this detachment level in Devonian and Mississippian shales (Thompson, 1981).

In the Mackenzie Mountains, the deformation is primarily of fold-and-thrust style rather than thrust-and-fold such as the foothills to the south. The Mackenzie Mountains are overall consistent of low-displacement thrust faults and large amplitude box folds with wavelengths up to 10 kilometers in places that expose Proterozoic strata in their cores. Some regions are dominated by chevron folds and display strong evidence for tectonic wedging (Price, 1986) however this is not the case in the Mount Eduni sheet where this study takes place. The Mackenzie Mountains have been compared in structural style and overall tectonic shortening to the northern Rocky Mountains, where both allow for a 'preview' of Canadian Rocky Mountain evolution before the development of the spectacularly thrust faulted front ranges subprovince that characterizes the eastern portion of the southern Rocky Mountains (Thompson, 1981; Gordey, 1981).

1.5 Thesis Outline

This thesis is composed of four chapters, the first of which is the introduction. Chapter two will introduce and examine the stratigraphy of the Mackenzie Mountains, in particular the Mount Eduni map area where the study area was located. Chapter three will focus on the structural and tectonic aspects of the study, which include the presentation of numerous cross-sections and figures to explain the complexities in the Mount Eduni area and the Mackenzie Mountains. The remaining chapter is focused on explaining how the data collected during this project ties in with the regional picture and overall structural setting of the Mackenzie Mountains. A full scale map and cross-sections are located in the pocket.

Chapter 2

Stratigraphy

2.1 Introduction

The author would like to note that because this study is primarily structurally focused, majority of the stratigraphy chapter is based on several authors' publications, notably the works of Turner and Long, 2008, Aitken 1978a, 1981, MacNaughton et al., 2008 and Roots et al., 2008. The Proterozoic stratigraphy of western and northern Canada has been divided into three major packages (A, B, and C), corresponding to Mesoproterozoic, early Neoproterozoic, and late Neoproterozoic depositional ages, which are in turn separated by major subaerial unconformities at 1000 Ma (A–B) and 750 Ma (B–C) (Turner and Long, 2008).

The Mount Eduni map area is composed of a variety of sedimentary rocks ranging in age from Neo-Proterozoic to Devonian (Figure 2.1). The oldest strata in the area belong to the Mackenzie Mountain Supergroup (MMSG), which has a maximum depositional age of 1083 Ma, based on detrital zircon work on terrigenous units low in the succession (Turner and Long, 2008). The base of the MMSG is not exposed in the Mackenzie Mountains, but is believed to be exposed in the Wernecke and Ogilvie Mountains to the west, beneath unit D of the Pinguicula Group (Turner and Long, 2008).

A number of authors have suggested that the MMSG is underlain by several kilometers of 1.7-1.2 Ga sedimentary rocks that are equivalent to Sequence A (Turner and Long, 2008). The MMSG is thought to belong completely to the Sequence B package (Figure 2.2). These rocks are believed to be underlain by igneous and metamorphic rocks similar to those in the Thelon – Wopmay belt to the east, which was demonstrated by zircon analyses from granitic clasts found in the Ordovician Coates Lake diatreme with an inherited U-Pb age of at least 1.75 Ga (Turner and Long, 2008).The Mackenzie Mountain Supergroup is unconformably overlain by the Windermere Supergroup, which consists in this area of the Coates Lake Group containing the Redstone River and Copper Cap formations, and the Rapitan Group, which contains the Sayunei and Shezal formations. Overlying these groups are the Twitya, Keele and Sheepbed formations.

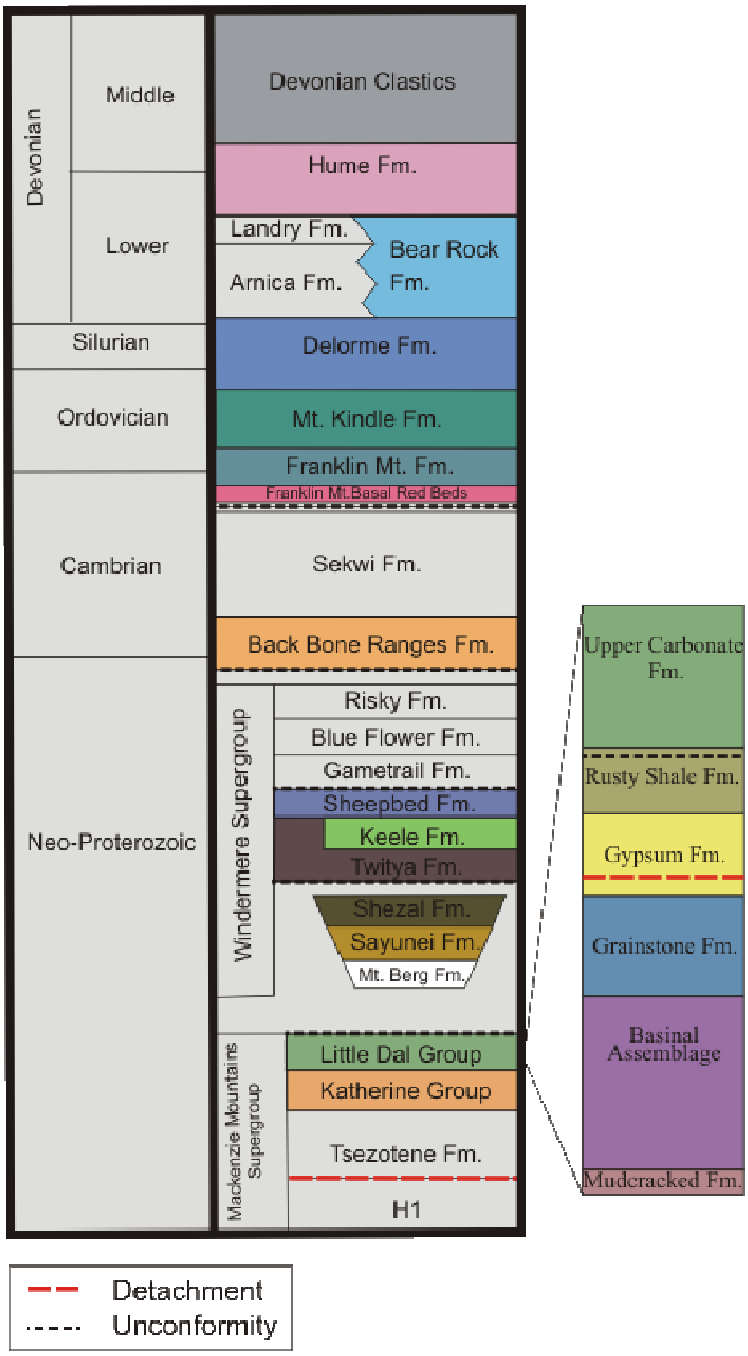

Figure 2.1: Stratigraphic column showing the relative ages of units present in the study area (colored) and positions of key unconformities and detachment levels (modified after Dewing, 2006).

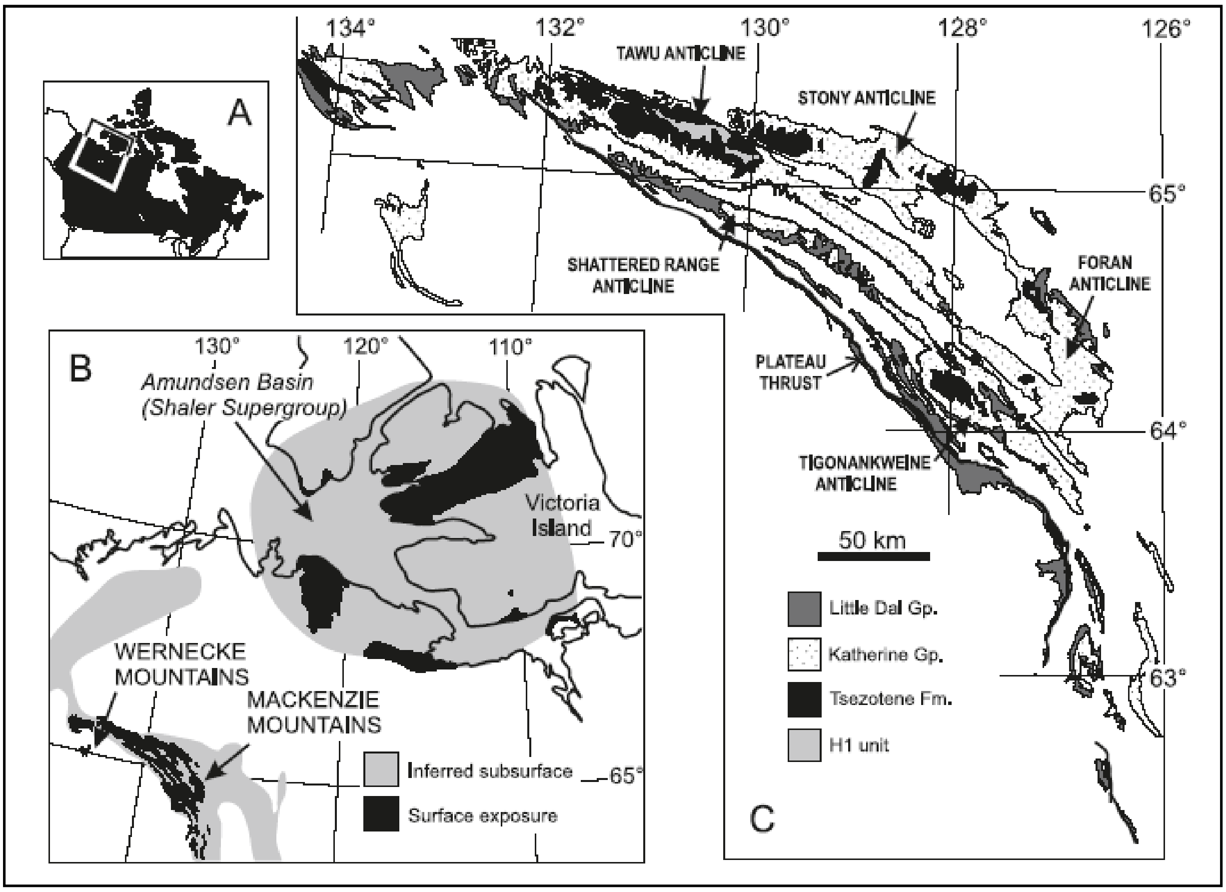

Figure 2.2: Location map of MMSG (Mackenzie Mountain Supergroup) outlined by square (A) with location of sequence B stratigraphy (inferred in white and surface exposure in black) (B) and distribution of individual groups, formations and units of the MMSG in the Mackenzie Mountains with Plateau Fault and major anticlines outlined (C)(Turner and Long, 2008).

The Paleozoic rocks in the area range from lower Cambrian to middle Devonian, the oldest being the Backbone Ranges formation. This is unconformably overlain by the Franklin Mountain basal red beds, Franklin Mountain Upper Carbonate, Mount Kindle, Delorme, Bear rock and Hume formations. The youngest rocks observed in this area are the Devonian clastic rocks of the Hare Indian, Canol and basal Imperial formations. These three formations are not always easily mapped due to intense deformation and poor exposure, so for the purpose of this study they have been grouped and will be referred to as the Devonian Clastics.

2.2 Description of Proterozoic Stratigraphy

2.2.1 Tonian

Tonian aged rocks in the Mount Eduni map area are restricted to the MMSG rocks which range in age from > 779 Ma to <1083 Ga (Turner and Long, 2008) and are approximately 5 kilometers thick in the Mackenzie Mountains and thicken toward the southwest (Figure 2.3).

2.2.1.1 Mackenzie Mountain Supergroup

The MMSG is composed of four divisible units of various sedimentary rocks: Map unit H1, the Tsezotene formation, the Katherine Group and the Little Dal Group. These units are dominated by mudstone, sandstone, carbonate rocks and minor evaporate rocks and are listed in Table 2.1 with unit descriptions and known thicknesses (Turner and Long, 2008).

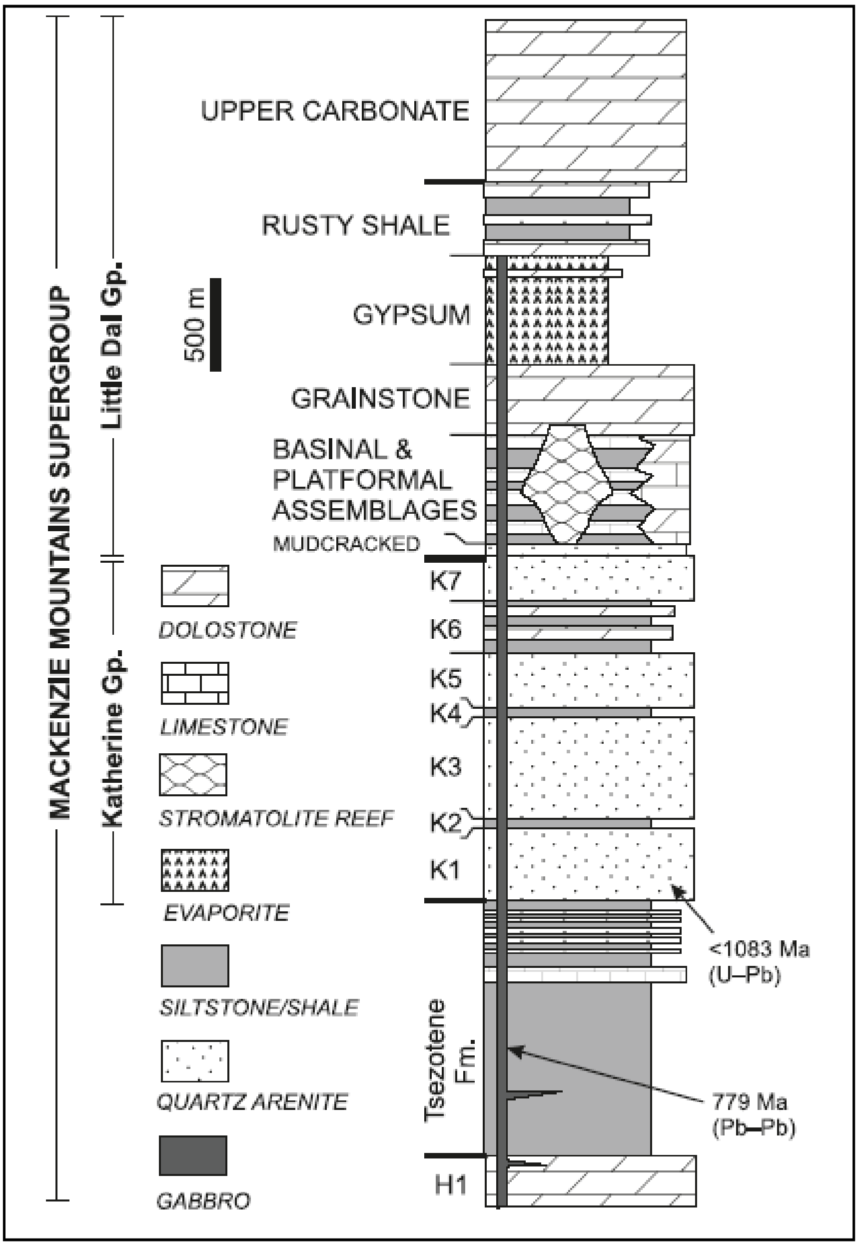

Figure 2.3: Stratigraphic column showing age constraints of the MMSG (Turner and Long, 2008).

Group	Formation (thickness)	Lithology, stratigraphic packaging, and contacts
Little Dal	Upper Carbonate (up to 720 m)	Dolomudstone, stromatolitic dolostone, and intraclast packstone–grainstone, with local chert. Basal contact conformable.
	Rusty Shale (*115–260 m)	Dolostone, siltstone, and quartz arenite. Basal contact abrupt but conformable.
	Gypsum (*500 m)	White gypsum with rare red siltstone–mudstone; *10 m thick carbonate marker near top. Basal contact may be unconformable.
	Grainstone (*425 m)	Dolomitic ooid grainstone; locally cherty. Conformable basal contact.
	Basinal (425–631 m)	Four shale-to-carbonate cycles; carbonate units are lime mudstone. Giant calcimicrobial stromatolite reefs in northwesternmost area. Conformable basal contact. Northwestern equivalent of platformal assemblage.
	Platformal (395–770 m)	Cyclic oolitic, intraclastic, molar-tooth and stromatolitic dolostone. Conformable basal contact. Southeastern equivalent of basinal assemblage. Conformable basal contact.
	Mudcracked (9–65 m)	Grey siltstone and shale and white quartz arenite. Orange oncoid-intraclast marker at top. Conformable basal contact.
Katherine	K1–K7 (*300–1716 m)	Seven informal members: odd-numbered members are quartz arenite; even-numbered members are predominantly siltstone–mudstone with minor carbonate. Two orange stromatolite marker units are present. Conformable basal contact.
(none)	Tsezotene (*600–1563 m)	Lower ‘‘grey’’ member of mudstone, siltstone, and minor carbonate; upper ‘‘red’’ member of variously coloured siltstone and sandstone. Limestone containing stromatolites separates the members. Basal contact abrupt and possibly unconformable.
(none)	H1 (>400 m)	Grey-weathering dolostone with black chert near top. Lower contact not exposed.

Table 2.1: The left side of the table displays relative thickness data for informal formations of the MMSG (Mackenzie Mountain Supergroup) with lithological descriptions provided on the right side of the table (Turner and Long, 2008).

2.2.1.1.1 Map Unit H1 and Tsezotene Formation

These units play an important role in the thickness of the overall stratigraphy in the Mackenzie Mountains but do not occur in the limits of the study area; however due to their presence in the region they play an important role in explaining the structure of the TSRSC.

The oldest strata exposed in the Mackenzie Mountains are part of the Map unit H1. This unit has been measured where exposed to be in excess of 400 meters and consists primarily of carbonate rocks. Thicknesses have been estimated to be 0.9 to 1.46 kilometers from an equivalent stratigraphic package farther to the east in the Mackenzie valley where seismic data is available. Equivalent strata in the Wernecke and Ogilvie Mountians to the west are on the order of a few hundred meters thick (Aitken et al., 1978a, b; Turner and Long, 2008).

The map unit H1 is overlain by the 763-2200 meter Tsezotene formation, which is composed of mudstone, sandstone and carbonate rock. The contact between the map unit H1 and the overlying Tsezotene represents a major flooding surface; with the Tsezotene formation being divisible into two members, a lower “grey member” and an upper “red member” (Turner and Long, 2008). The Tsezotene formation is overlain by the Katherine Group rocks, which have been, for the purpose of this study grouped into one unit.

2.2.1.1.2 Katherine Group

The Katherine Group is divisible into seven formation scale units K1-K7, which alternate between thin, recessive units of marine mudstone, carbonate rock and minor sandstone to thick successions of fluvial sandstone (Aitken, 1978a). For the purpose of this study, the Katherine Group is not subdivided and is assumed to have a relatively constant thickness of approximately 1000 meters for cross-section construction. The base of the Katherine Group is not exposed anywhere in the study area, but outcrops elsewhere in the Mount Eduni map sheet.

2.2.1.1.3 Little Dal Group

The Little Dal Group was divided by Aitken (1981) into seven informal units: Mudcracked formation, Basinal and lateral equivalent Platformal assemblages, Grainstone formation, Gypsum formation, Rusty Shale formation and Upper Carbonate formation. The platformal assemblage does not occur in the study area and thus will not be described.

The Mudcracked formation is a thin unit of interbedded sandstone and mudstone on the order of 9-65 meters that is conformable to the top of the Katherine Group. Due to the often minor thickness, the Mudcracked formation has been grouped with the Basinal assemblage for map and cross-sections.
The Basinal assemblage directly overlies the Mudcracked formation and consists of a 425-630 meter package of thinly interbedded lime mudstone with shale and large reefs (Aitken, 1981). Overlying the Basinal assemblage is the 300-450 meter thick Grainstone formation which is composed of massive beds of dolomitised ooidic grainstone that is robust and easily identifiable.

Above the Grainstone formation is the Gypsum formation, which is never fully exposed in the study area, and usually consists of tens to hundreds of meters of white to red gypsum that is often observed in the hangingwall of faults. The Gypsum formation is overlain by the Rusty Shale formation (Figure 2.4) which is a 115-260 meter thick package of sandstone, carbonates and mudstone which is a reddish brown color and again, is commonly identified in the hangingwall of faults in the study area.

At the top of the Little Dal Group is the thick Upper Carbonate formation, which is a ~700 meter thick package of grey dolostone that is commonly observed in the study area. The Little Dal Group rocks are very distinctive and are great marker units for determining the structure in complicated areas due to their rapid changes in thickness, rock type and color within the group.

2.2.2 Cryogenian

The MMSG is unconformably overlain by the Windermere Supergroup which records an extension on the margin of Laurentia with two glacial interludes (Roots et al., 2008).

2.2.2.1 Windermere Supergroup

In the study area, the Windermere Supergroup contains the Coates Lake Group, Rapitan Group and the Twitya formation.

2.2.2.1.1 Coates Lake Group

The Coates Lake Group is composed of three formations which are all sparsely exposed in the study area. The first of these formations, the Gabbro Dykes, are only exposed in two outcrops, where they were observed to cut the Little Dal Upper Carbonate formation as well as the Katherine Group. These dykes have been dated to 779 Ma (Heaman et al., 1992) and are also the lower age constraint on the MMSG. The gabbro dykes are coarse to finely crystalline and contain carbonate filled vesicles.
The Redstone River formation occurs as red to pink gypsum interbedded with thin beds of conglomerate, is ~75 meters thick in the study area, and is inferred to “pinch-out” laterally. The Copper Cap

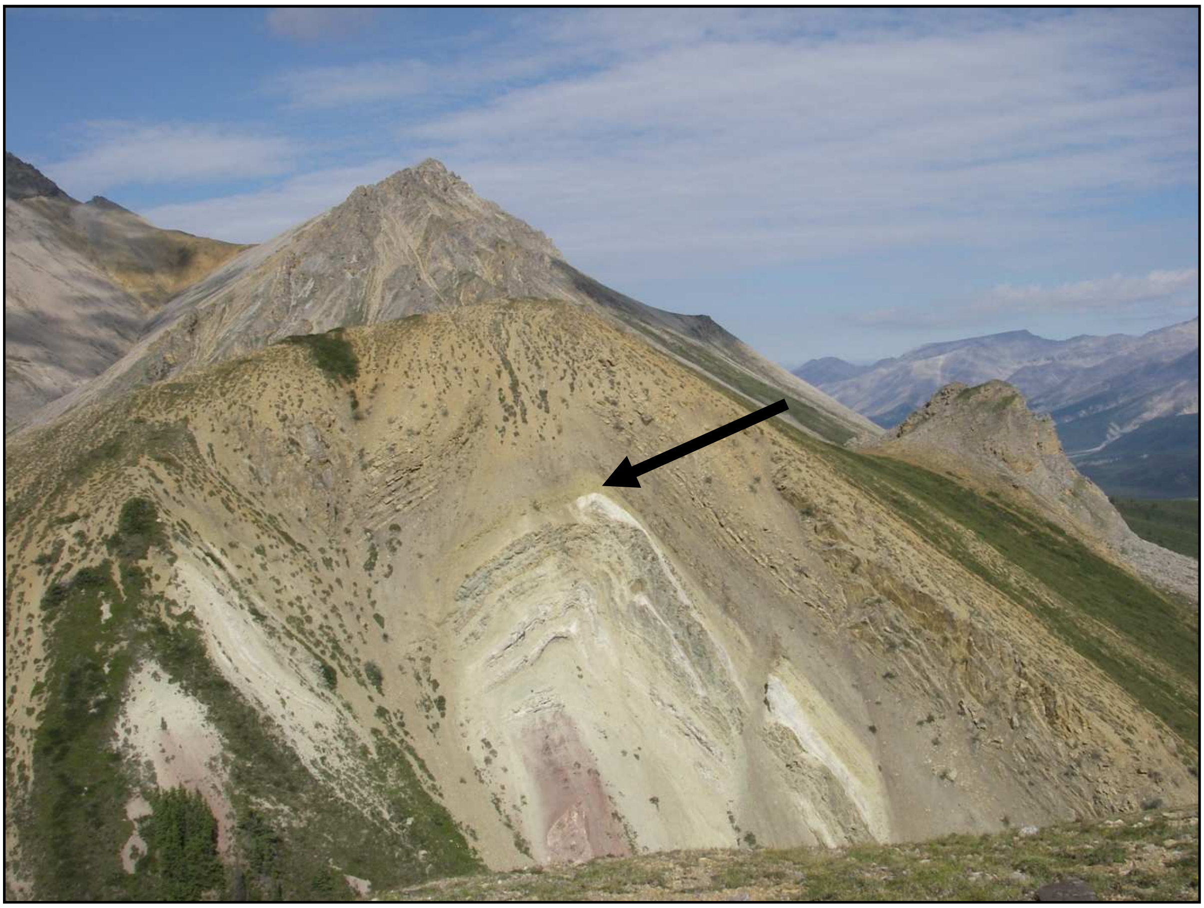

Figure 2.4: Picture looking northeast at folded contact (arrow) between underlying Little Dal Gypsum formation and overlying Little Dal Rusty Shale formation. Picture approximately 100 meters wide and view is to the northwest.

formation is composed of a fairly thin ~50 meter sequence of grey limestone that sits conformably above the Redstone River formation. The Copper Cap formation was also observed to "pinch-out" laterally with the Redstone River.

2.2.2.1.2 Rapitan Group

The Rapitan Group is composed of two formations, the Sayunei and Shezal. These formations are interpreted as glaciomarine deposits that were deposited in a series of sub-basins along the ice-covered continental margin (Roots et al., 2008). The formations are relatively thin in the study area, from 2-50 meters and usually "pinch-out" along their strike length due to unconformities and syn-sedimentary faulting which has a large effect on their thicknesses. These formations are typically composed of shales, mudrock and conglomerates and often preserve drop stones.

2.2.2.1.3 Twitya Formation

Overlying the Rapitan Group is the Twitya formation which is composed of a succession of thinly bedded mudrock, minor sandstone and siltstone that varies in thickness from several meters to > 100m.

2.2.3 Upper Cryogenian and Lower Ediacaran

2.2.3.1 Keele Formation

The Keele formation outcrops extensively in the study area, commonly as a thin (~20 meters) interval of sandstone and minor dolostone that conformably overlies the Twitya formation.

2.2.4 Middle Ediacaran

2.2.4.1 Sheepbed Formation

The Sheepbed formation is only present in one locality, where it sits conformably above the Keele formation. At this location, the unit is ~ 25 meters thick, recessive and is a thinly bedded dark grey-black shale. This formation is the youngest of the Proterozoic units in the map area and is overlain conformably by the Cambrian Backbone Ranges formation.

2.3 Description of Paleozoic Stratigraphy

The Paleozoic strata in the map area are primarily carbonate rocks and are fairly continuous along the strike of the bordering valleys.

2.3.1 Upper Ediacaran and Lower Cambrian

The Backbone Ranges formation conformably overlies the Proterozoic Sheepbed formation in locality of the study area. At this locality, the Backbone Ranges formation is only ~ 20 meters thick and is composed of a thick bedded coarse grained quartz sandstone.

2.3.2 Upper Cambrian and Lower Ordovician

Overlying the Backbone Ranges formation unconformably are the Franklin Mountain Basal Red Beds. This unit consists of thick bedded sandstone and thin bedded shale that has a reddish brown color and is erosive at its base. The unit can range in thickness up to 100 meters and is observed to unconformably overly a number of units as old as the Little Dal Rusty Shale formation.

Above the Franklin Mountain Basal Red Beds is the Franklin Mountain formation, a medium to thick bedded grey, homogeneous dolostone which is present throughout the entire map area and is easily identifiable. The thickness of this unit is variable throughout the map area with a range of 100 – 300 meters.

2.3.3 Upper Ordovician and Lower Silurian

The Mount Kindle formation, a < 200 meter thick grey dolostone, is present throughout the northeastern half of the map area, but "pinches-out" to the southwest. This unit serves as a great stratigraphic marker due to its distinctive silicification and suite of preserved fauna.

2.3.4 Upper Silurian and Lower Devonian

The Delorme formation overlies the Mount Kindle formation to the northeast and the Franklin Mountain formation to the southwest. This light grey to yellowish dolostone has no preserved body fossils and is commonly thin bedded and difficult to distinguish from the upper Franklin Mountain formation when the Mount Kindle formation is not present. The thickness of this unit is quite variable across the map area, but on average it is ~ 100 meters thick and can be as much as 180 meters thick.

2.3.5 Lower and Middle Devonian

The Bear Rock formation is a unique lithological unit which is interpreted to be a post-depositional solution collapse breccia possibly attributed to dissolution of evaporate strata (Roots et al., 2008). The Bear Rock breccia is commonly composed of limestone in the study area, and contains abundant calcite cement in the matrix. This unit is laterally equivalent to the Arnica formation (Morrow, 1991) and large blocks of preserved Arnica formation strata are typically observed and appear unaltered. From a mapping perspective, this unit is very unique and easily identifiable by its spire-forming erosional properties and texture. The average thickness is < 90 meters in the map area.

2.3.6 Middle Devonian

Overlying the Bear Rock formation is the Hume formation, a thin bedded, < 80 meter fossiliferous limestone that is present throughout the entire map area. The hume formation preserves excellent corals that can be used for "way-up" indicators while mapping these intensely deformed Paleozoic units.

2.3.7 Middle and Upper Devonian

The Middle and Upper Devonian represent a change is depositional environment with the widespread influx of dark marine turbiditic clastic sediments of the Hare Indian, Canol and Imperial formations (Roots et al., 2008). These three formations are composed of dark graptolitic shale, siltstone, sandstone and minor limestone which are always observed in the cores of major synclines in the Mount Eduni map sheet.

It is important to note that of some the Paleozoic strata have been investigated as potential source and reservoir rocks in the Mackenzie Mountains. The units of highest interest in the Mount Eduni map sheet are the Mount Kindle formation, which has been proposed to be an excellent reservoir rock due to its well developed porosity, the Canol formation which has been studied as a potential source rock in the area and the Imperial formation which is primarily sandstone and would be a good reservoir rock (MacNaughton and Fallas, 2008)

2.4 Unconformities and Stratigraphic Complications

A series of unconformities were observed by the author while mapping in the TSRSC, particularly at the base of the Franklin Mountain formation and in the Neo-Proterozoic strata (Figure 2.5). In the Cambrian strata, the Mount Kindle formation is absent in much of the field area due to an unconformity at the base of the Siluro-Devonian strata, particularly the Delorme formation.

The Upper Cambrian and Lower Ordovician Franklin Mountain formation and the associated Basal Red Beds unconformably overly numerous strata ranging in age from the Neo-Proterozoic Little Dal Rusty Shale formation to the Lower Cambrian Backbone Ranges formation. This unconformity is by far the largest and most extensive in the *TSRSC*, and is an artifact of the substantial erosion of the Mackenzie Arch before the middle Cambrian carbonates were deposited. Stratigraphically below this level, there was also a notable unconformity at the base of the Lower Cambrian Backbone Ranges formation.

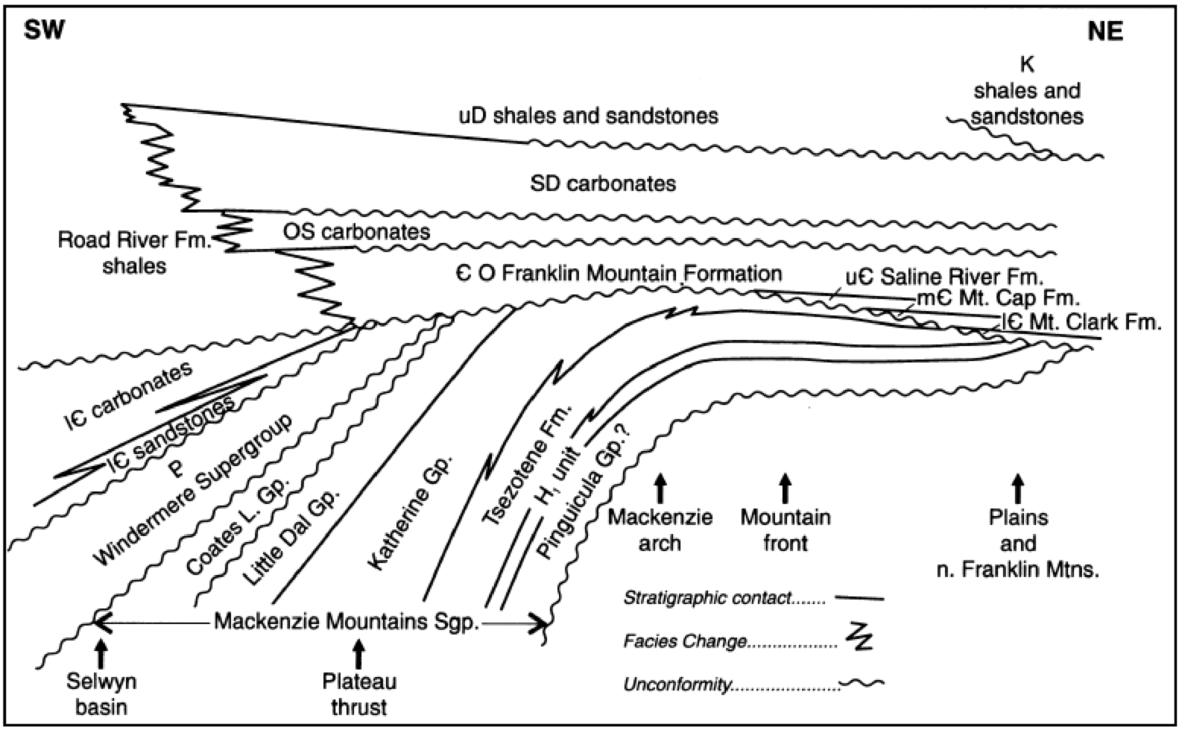

Figure 2.5: Schematic diagram outlining the unconformable relationships between stratigraphic units of the Neo-Proterozoic Mackenzie Arch and the overlying Paleozoic strata (after Cook and Mclean, 1991).

In addition to the above, there are numerous unconformities in the Neo-Proterozoic strata, particularly at the base of the Rapitan and Coates Lake groups which are responsible for major thickness changes along strike in these units.

2.5 Stratigraphy Summary

The oldest known strata in the Mackenzie Mountains are the Neo-Proterozoic sedimentary rocks of the Mackenzie Mountain Supergroup which are likely underlain by several kilometers of unknown strata which overlie the crystalline basement. The MMSG is overlain by late Neo-Proterozoic strata which mark a period of ongoing glacial events producing a number of unconformities and unique lithological units that are abundant in the Mount Eduni map area. The Neo-Proterozoic strata are unconformably overlain by a series of Paleozoic strata ranging from Cambrian to Devonian age which almost all mark a transition from a platformal setting in the northeast to a basinal setting in the southwest, nearest the Selwyn Basin. These rocks account for the 28 individual units that are recognized and mapped in the study area.

Chapter 3

Structure

3.1 Introduction

The Mount Eduni map area contains three structural domains: (1) a gently southwest dipping panel of hangingwall strata above the Plateau Fault, (2) a central fold-and-thrust belt (hereafter, Ten Stone Ranges Structural Complex, TSRSC), and (3) an area of broad open folds to the northeast of the central thrust-and-fold belt (Figure 3.1). The broad, open folds consist of large cylindrical synclines forming prominent valleys and large box shaped anticlines which, at their core expose some of the oldest strata in the map area, rocks of the Tsezotene formation and the Katherine Group. This study was conducted solely in the fold-and-thrust belt that extends from the southeast to the northwest corners of the NTS 106A 1:250 000 scale Mount Eduni map sheet (Figure 3.1).

These structures are believed to have formed during the northeast-southwest compression in the early Cretaceous as Cordilleran fold and thrust belt deformation migrated through the region (Roots et al., 2008). The deformation, which ranged broadly from Lower Cretaceous to Tertiary, may have happened in one event or a series of pulses, the answer to this is unknown and individual structures cannot be dated exactly with the current data set (Gordey, 1981). Techniques do exist for dating faults by examining fluid inclusions in calcite and quartz crystals that seal the faults; however, this is beyond the scope of this thesis.

There are three constraints on the age of the deformation: (1) the existence of deformed Early Cretaceous strata within the fault-bounded panel near Godlin Lakes in NTS sheet 105P, (2) the intrusion of undeformed, cross-cutting Middle Cretaceous plutons in the southwest portion of 105P into folded strata, and (3) the existence of gently inclined (20 degrees) Tertiary strata in the Fort Norman area which is the eastern limit of deformation (Roots et al., 2008; Gordey, 1981; Aitken and Cook., 1974).

The southwest portion of the Mount Eduni map sheet displays a very different map pattern than the central Ten Stone Ranges area where this study was undertaken. The gentle dips (5-10 degrees) of the southwest panel leave map units well exposed in cliff faces and strata here generally thickened as they transform from the platformal assemblages to the northeast to more basinal assemblages in this area. For instance, the Cambrian Backbone Ranges formation that is only sparsely exposed in the central thrust-and-fold belt of the TSRSC is well exposed in this area, to the south and north and separable into three distinct members, several hundred meters in thickness (MacNaughton et al., 2008). The northeast boundary to this gently dipping panel is the Plateau Fault. Cecile and Cook (1981) interpreted the Plateau

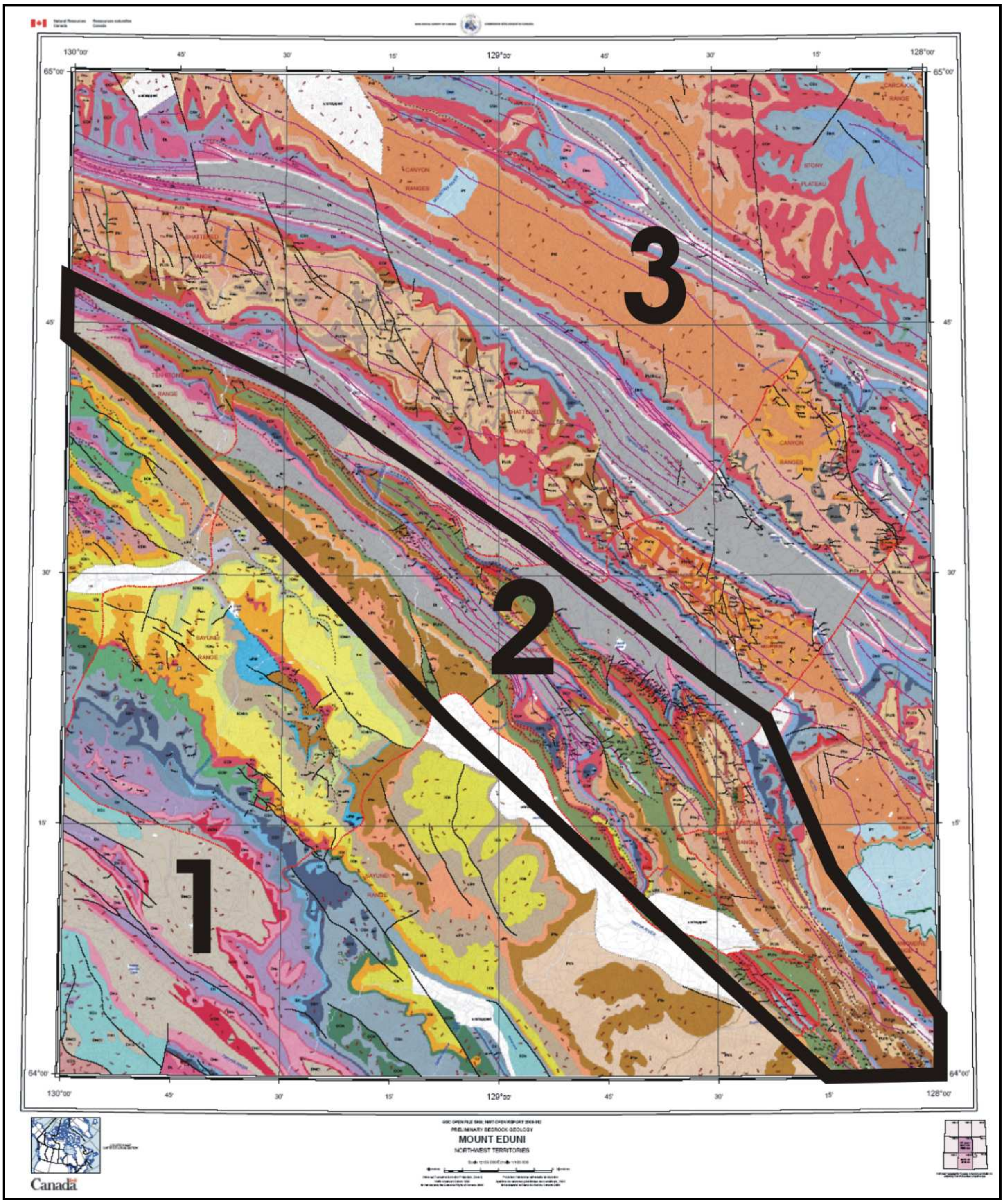

Figure 3.1: In progress geologic map of Mount Eduni area showing relative location of structural domains 1-3 in the field area (modified after Gordey et al., 2008).

Fault as a thrust fault having some 35-55 kilometers of overlap atop the Paleozoic strata in the northeast Sekwi Mountain map sheet, directly to the south of Mount Eduni. This was later investigated by Roots et al. (2008) who found no evidence for significant facies changes in Proterozoic strata between the hangingwall and the footwall of the fault and thus concluded that such a large displacement was unlikely.

In the Mount Eduni sheet, the Plateau Fault behaves as a boundary between the more deformed footwall area containing the thrust-and-fold belt and the generally undeformed hangingwall of gently dipping strata. The TSRSC is dominated by northeast trending dip-slip faults, some of which are low angle enough to be thrust faults that show evidence for hundreds to thousands of meters of stratigraphic separation, based on thicknesses of Proterozoic units in the area recorded while mapping and measured during the SEKWI project. These faults are in most cases rooted at a structural level below that of the Little Dal Gypsum formation detachment (hereafter, Gypsum detachment), and are likely related to a detachment somewhere below this level in the crust. Evidence for this is seen in the southeast of the Mount Eduni map area where Tsezotene formation outcrops in the core of a box anticline, thus suggesting a detachment level in or below the Tsezotene formation. In addition to this, majority of the faults in the area eventually expose (along strike) Proterozoic strata that are older than the Little Dal Gypsum formation. In relation to this, Gordey (1981) suggested that the high structural relief of the Redstone Plateau, a large flat-lying area of Proterozoic strata, in the Wrigley Lake NTS sheet 95M to the southeast of Mount Eduni, is related to a northeastward detachment above a basement-controlled ramp that itself appears to be controlled by significant thickening of Rapitan-aged strata to the west (Gordey, 1981). This detachment level is likely the décollement surface where many, if not all the faults in the TSRSC are rooted and is likely located in or below the Tsezotene, or possibly as deep as the H1 unit.

3.2 Structure of Study Area

3.2.1 Introduction

The TSRSC is a thin zone in the footwall of the Plateau Fault that has a distinctive map pattern due to the density of thrust faults and map scale fold structures that occur there. There are several structures observed that are important for determination of the structural style as well as shortening of the rocks in the Mount Eduni map sheet in this particular part of the Mackenzie Mountains.

The structures observed in the Mount Eduni map area are akin to those of a foreland fold and thrust belt such as the southern Rocky Mountains in Alberta or the Appalachian Mountains in the eastern

United States. Due to the abundance of petroleum resources in the Rocky Mountains, they have been thoroughly studied by industry and academia by means of seismic imaging, surface mapping and well data. This quantitative data is evidence for the existence of structures that can only be observed in part on the surface, thus solidifying hypothesis derived from geologic mapping. Given that the Mackenzie Mountains are the northern extension of the Rocky Mountains and are of Laramide age deformation, the observed structures will later be compared to several structures in the Rockies which are well documented and for which interpretations are widely accepted.

3.2.2 Folding and Faulting

The TSRSC contains a range of folds from small scale parasitic folds up to 1:250,000 scale regional features of varying complexity. Fold vergence is primarily toward the foreland, which in the case of the Cordilleran Orogen is to the northeast. Overall, the area is characterized by northwest and southeast, shallow to moderately plunging (10-60°) concentric cylindrical and conical folds associated with underlying décollement surfaces.

The northwest-southeast trending valleys that border the study area on either side are primarily composed of Devonian clastic rocks of the Hare Indian, Canol and Imperial formations, however there are common outcroppings of Devonian carbonates of the Hume and Bear Rock formations as well. The Devonian carbonates of the Hume formation are commonly tightly folded in places, with shallow to steep plunges that can vary from the common northwest/southeast direction (Figure 3.2a). The clastic rocks in this area are commonly tightly folded and highly deformed, with common box, chevron and tight asymmetric concentric folds developed (Figure 3.2b). These folds rarely display axial planar cleavage with northwest/southeast trend and shallow to steep northeast to southwest dips. The Devonian clastic rocks are often difficult to separate into their respective units due to the similarity of the lithologies and the intense deformation they have undergone, thus for the purposes of the 1:50,000 scale mapping these lithologies were grouped as was previously mentioned.

Flextural slip folding in the Paleozoic rocks, particularly the carbonate rocks, is usually intense and coupled with minor accommodation faulting. Due to the similarity of these units, detailed mapping and tight traversing was required to sort out the stratigraphy and structure in these areas. Folds range from mountain scale, often chevron type anticlines to open synclines, often with an overturned limb when in the footwall of a thrust (Figure 3.3), to meter scale parasitic folds of “S”, “Z”, “M” and “W” asymmetry.

(a)

(b)

Figure 3.2a and 3.2b: Image (a) shows isoclinal to tight folding in limestone of the Devonian Hume formation. Image (b) shows intense kink folding in the Devonian Imperial formation, person for scale in lower left of image.

The study area contains two very important folds, both anticlinal with shallow (10-15°) plunges to the northwest: the Mountain River Fold and the Cache Lake Fold.

3.2.2.1 Mountain River Fold

The Mountain River Fold is a fault bend fold that is approximately 15 km long and 3.5 km wide and sits in the footwall of a large thrust (Figure 3.4). The northeast limb of the fold develops into a thrust fault toward the southeast with an oblique ramp resulting in the thrust cutting progressively down section in the hanging wall from the Devonian clastic rocks to the Little Dal Upper Carbonate formation. On the southwest limb, a large thrust fault bounds the fold at the level of the Little Dal Gypsum and Rusty Shale formations which results in the southwest limb of the fold continuing under the thrust where it is truncated in the footwall (Figure 3.5). The core of the large anticline is composed of Little Dal Upper Carbonate formation which is parasitically folded throughout and this formation is unconformably overlain by the Shezal and Twitya formations which change in thickness along strike from several meters to > 100 meters. The Mountain River Fold will be discussed in further detail in section 3.3.3 where a cross-section through the fold is described in detail.

3.2.2.2 Cache Lake Fold

The Cache Lake Fold is another large anticline with a gentle northwest plunge; however it is far more complex than that of the Mountain River Fold. The fold itself is well defined by the northeast limb and fold nose, as they are comprised primarily of Paleozoic carbonate rocks of the Franklin Mountain, Mount Kindle, Delorme, Bear Rock and Hume formations. The southwest side of the fold has been truncated by a large thrust fault that results in a “fish hook” like map pattern (Figure 3.6). The topography of the area makes for poor exposure in the core of the fold, as it is a grass filled valley with sparse outcrop so exact interpretation of contacts is difficult (Figure 3.7).

The Cache Lake Fold is a fault bend fold that is controlled by a series of thrust faults that are numbered 3, 4 and 5 on Figure 3.6 above with fault 3 to the southwest and fault 5 to the northeast. Fault 3 is observed to truncate the fold and is rooted in the Gypsum detachment level. This fault dies out to the southeast at the contact between the Little Dal Gypsum and Rusty Shale formations. Fault 4, also known as the Cache Lake Fault, is later truncated by fault 5 in the core of the anticline. In the south portion of fault 4, it is apparent that the Katherine Group in the hanging wall is in thrust contact with the Little Dal Basinal Assemblage and Grainstone formation. Moving northeast along strike of the fault, the obliqueness

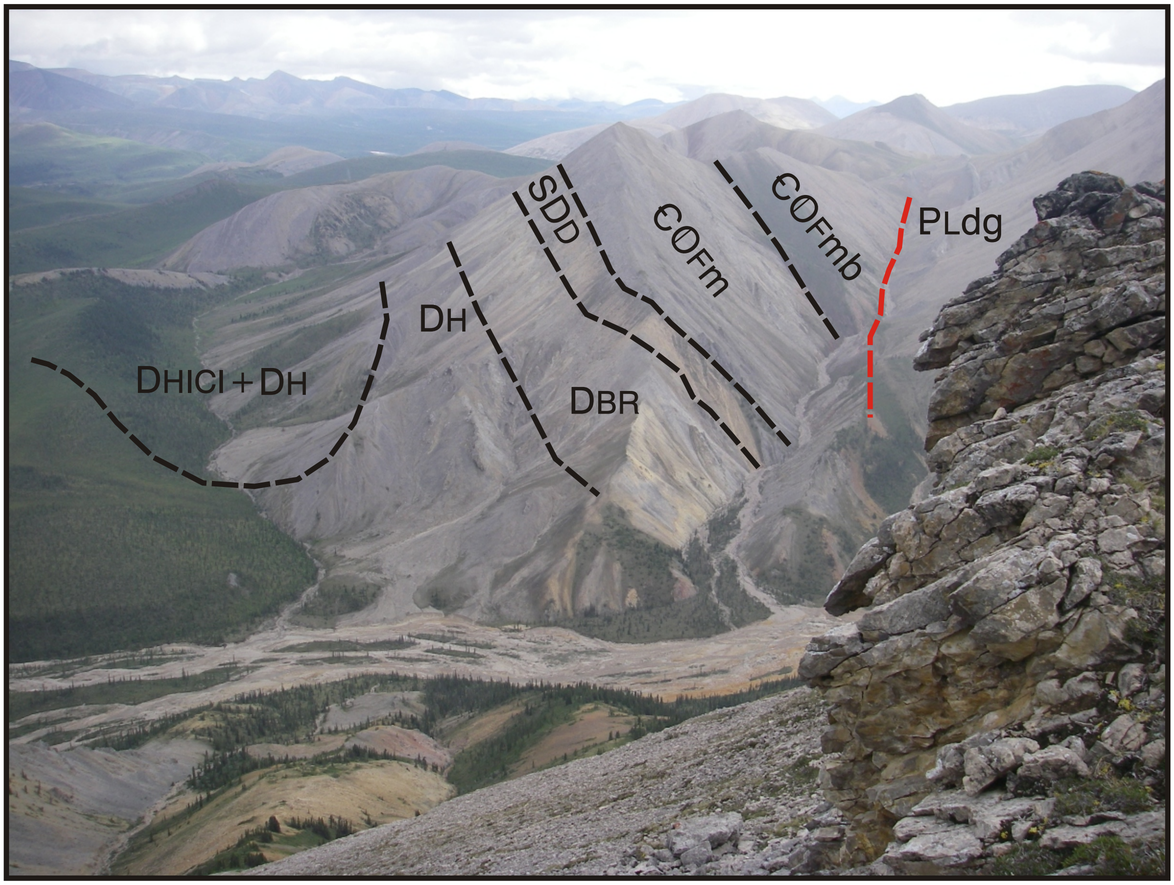

Figure 3.3: View looking southeast at a footwall syncline with southwest limb overturned. Red line defines a thrust fault at the level of the Little Dal Gypsum detachment resulting in Cambrian-Ordovician rocks of the Franklin Mountain formation in the footwall structurally overlying progressively younger strata toward the northeast. See figure 1.6a,b for unit abbreviations.

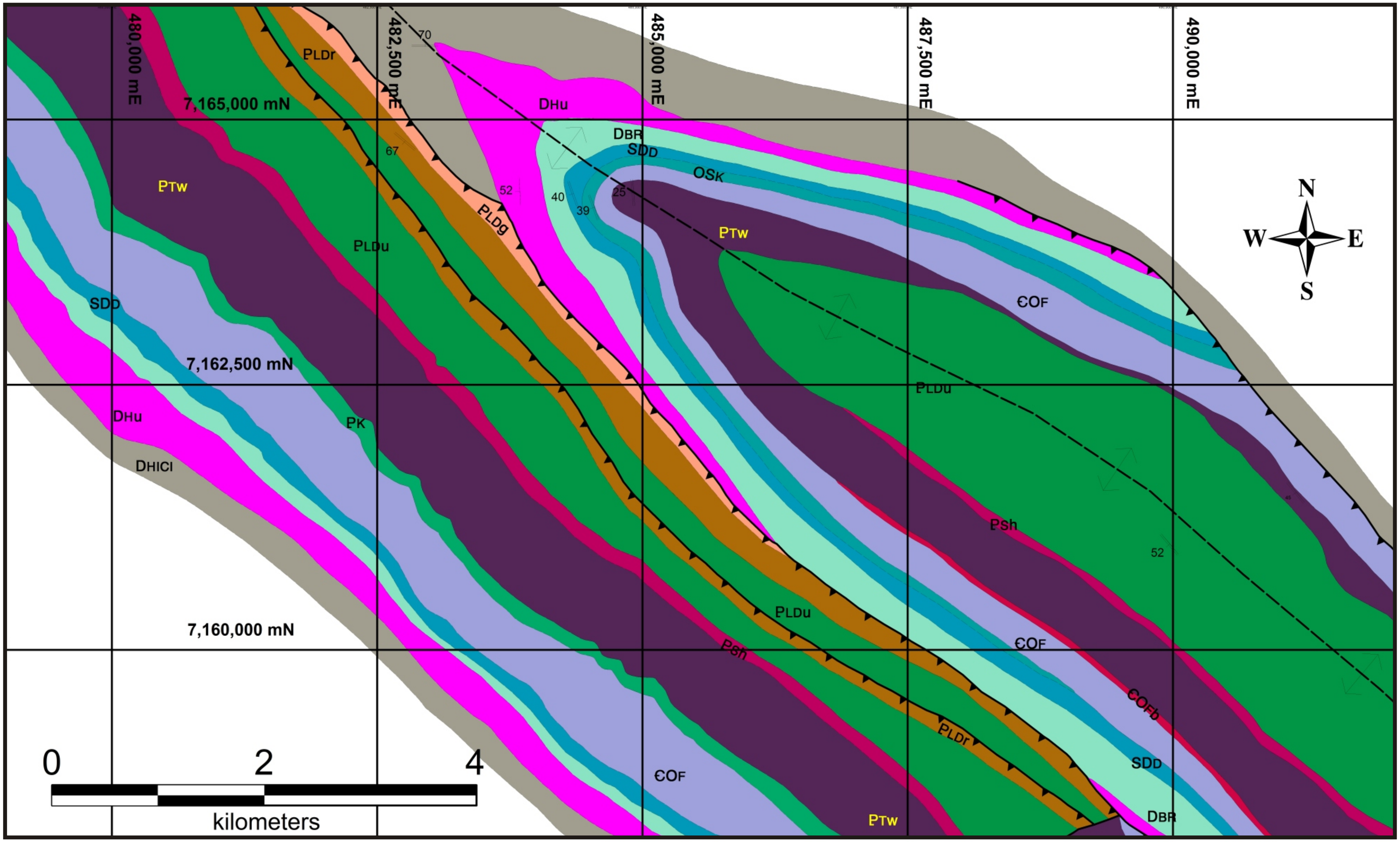

Figure 3.4: Simplified geologic map of the Mountain River Fold, with Little Dal Upper Carbonate formation in the core of the anticline and Paleozoic rocks comprising the limbs and nose of the fold. See Figure 1.6a,b for map legend. 1:50 000 scale map located in pocket.

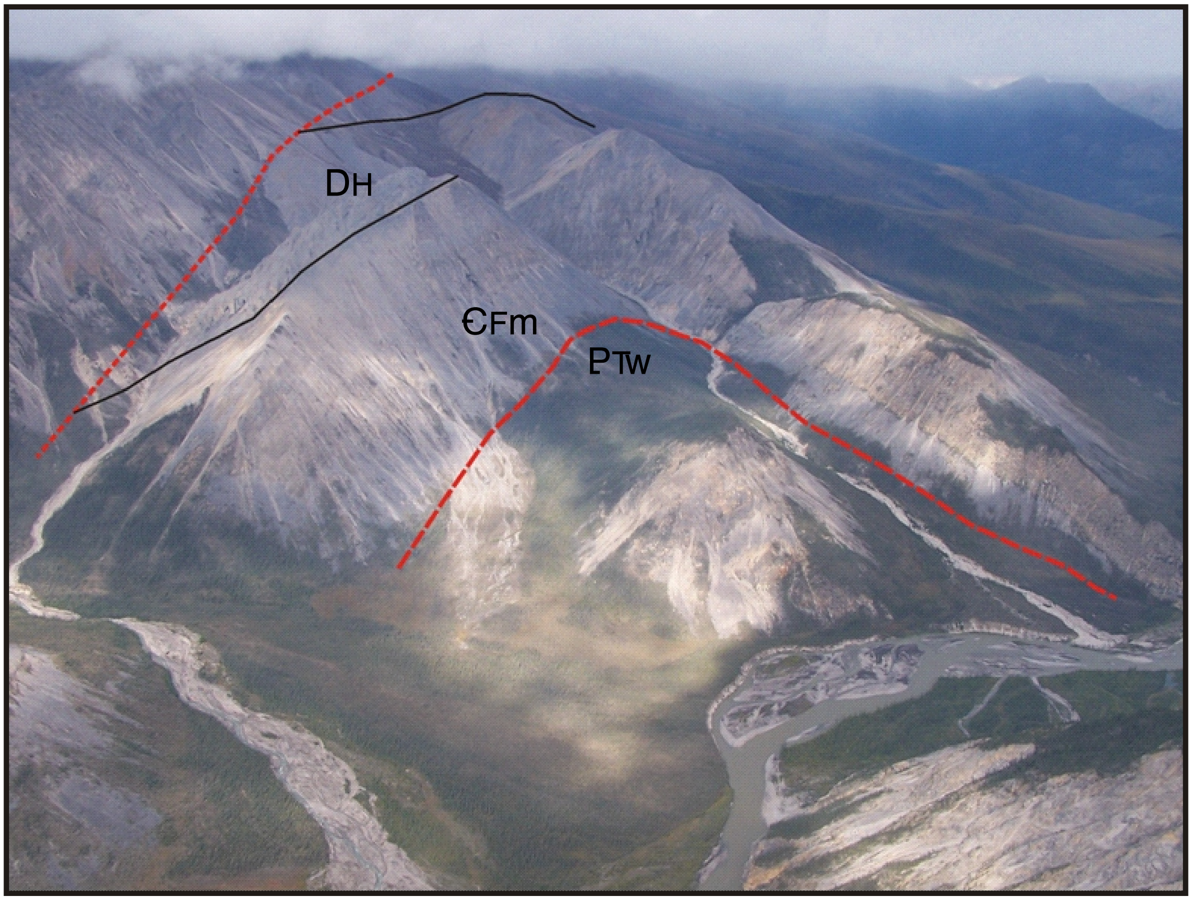

Figure 3.5: An aerial view looking northwest of the Mountain River fold with red line on the left showing the position of the thrust fault at the level of the Gypsum detachment which truncates the fold. The black lines define the contact of the top and bottom of the Devonian Hume formation (DH); the red line in the fold nose defines the unconformable contact between the Neo-Proterozoic Twitya formation (PTw) and the overlying Paleozoic Franklin Mountain formation.

of the ramp results in the thrust cutting upsection in the hangingwall through the Katherine Group, Little Dal Mudcracked, Basinal assemblage, Grainstone and Gypsum formations before remaining at this level on the west side of the fold nose. Moving east along the nose of the fold, the fault remains at the Gypsum/Rusty Shale formation level, and continues at this level until it cuts upsection in the hangingwall through the Paleozoic rocks under the northeast limb of the fold. The fault is then inferred to die out in the Devonian clastic rocks which absorb the displacement by folding and minor shearing.

At some point after fault 4 develops, fault 5 manifests itself in the core of the Cache Lake Fold as a splay off of fault 4. This fault causes the core of the anticline to fold, resulting in a fold within a fold that is again plunging shallowly to the northwest. As fault 4 propagates, the fold in the core of the anticline is forming and because the ramp is oblique, this footwall anticline gets sliced down-section so that the resultant map pattern displays Paleozoic rocks in the core of the Cache Lake Fold (Figure 3.8) that cut down-section to Proterozoic Little Dal Group in the south portion of the core. As fault 5 develops further, it eventually breaks through and because the ramp for this fault is also oblique, the map pattern shows the hangingwall is cut down-section from the Little Dal Gypsum formation to the Katherine Group level. This package is thrust atop the Paleozoic rocks in the northeast limb of the Cache Lake Fold which results in the truncation of fault 4 (Cache Lake Fault) on the northeast side of the Cache Lake Fold.
The substantial difference between the Mountain River Fold and the Cache Lake Fold is the presence of a well developed folded thrust (fault 4) beneath the Cache Lake Fold. The interpretation of the Cache Lake Fold is based entirely on the presence of Bear Rock formation in several outcrops in the fold nose that sit directly below the Little Dal Gypsum and Rusty Shale formations which are well exposed in the fold nose. The presence of Bear Rock formation, which is interpreted to be a solution collapse breccia with angular limestone clasts thus making it very unique and easily identifiable, is coupled with small outcroppings of Franklin Mountain formation farther to the south in the core of the fold. If this were a simple fold akin to the Mountain River Fold, one would expect to find only Proterozoic rocks in this location, not competent outcrops of Paleozoic rocks.

Although the Mountain River Fold is much less complex, when comparing it with the Cache Lake Fold, it has a similar geometry to the early stages of the Cache Lake Fold. If the thrust that was developing on the northeast limb of the Mountain River fold were to continue, it would likely end up covering the Paleozoic rocks in the valley with the Neo-Proterozoic rocks of the core.

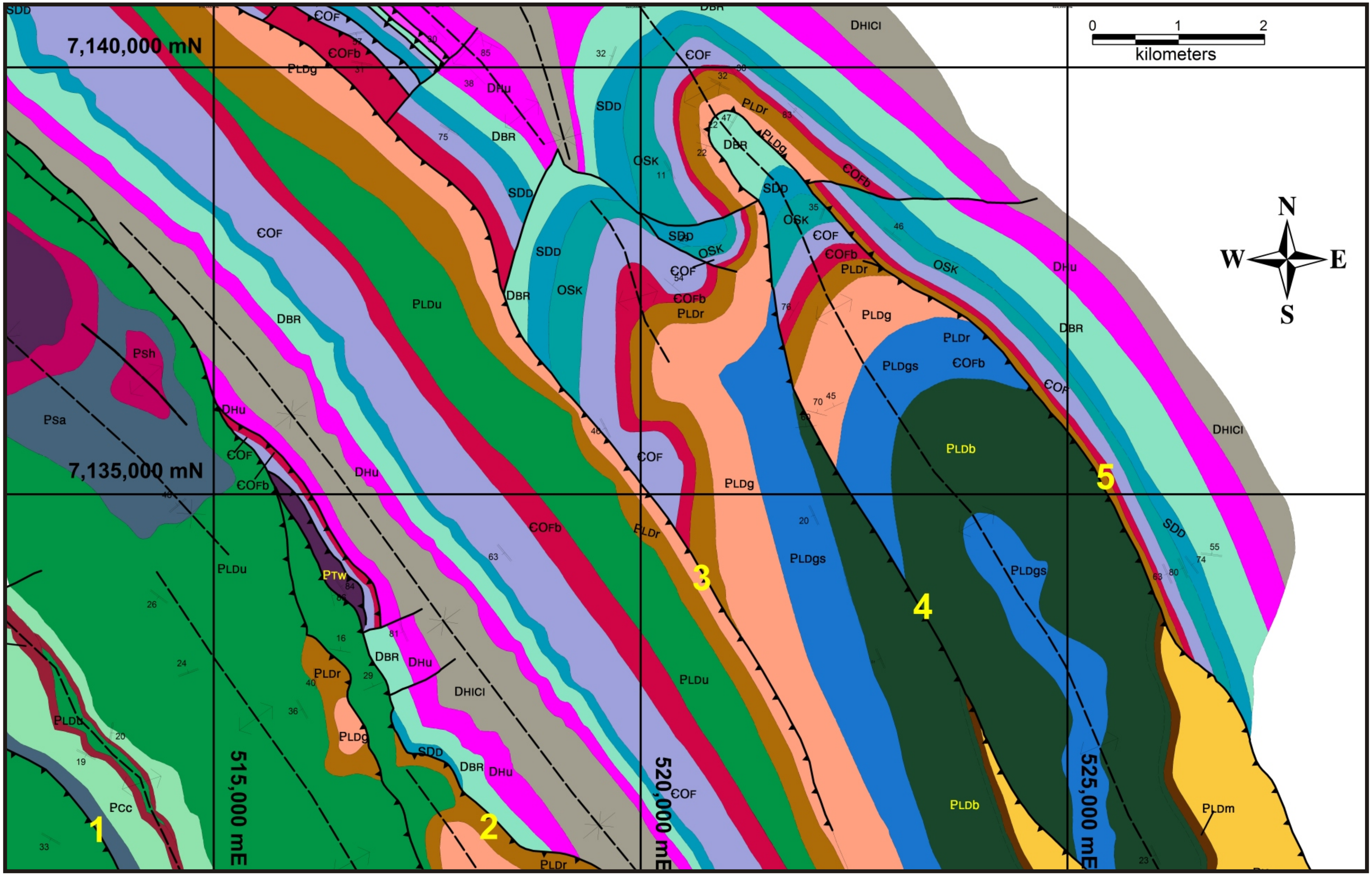

Figure 3.6: Simplified geologic map of the Cache Lake Fold with numbers 1-5 in yellow defining the thrust faults from southwest to northeast. See Figure 1.6a,b for map legend. 1:50 000 scale map located in pocket.

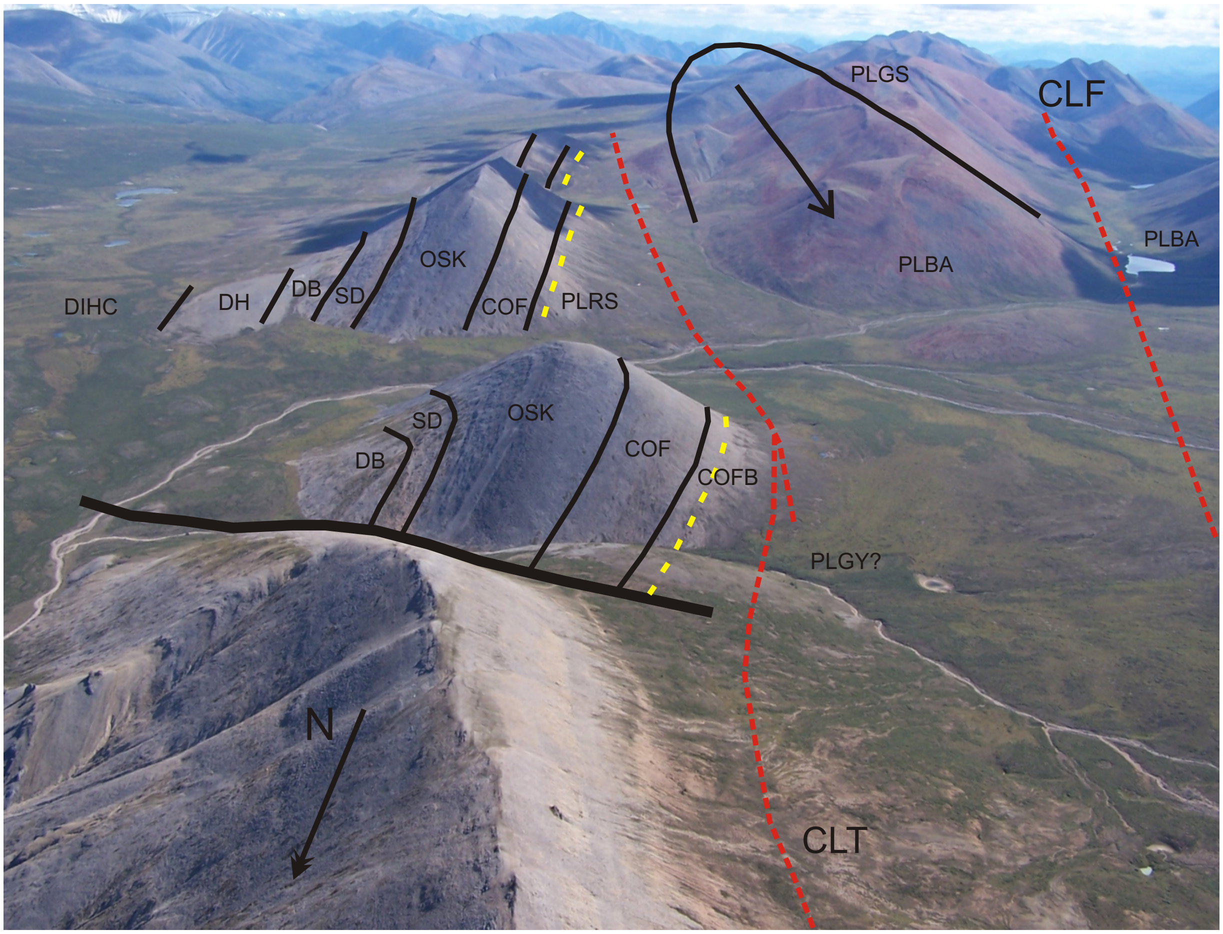

Figure 3.7: Aerial photo of northeast limb and core of the Cache Lake Fold. Black solid lines define contacts between individual formations as well as tear fault (thick black line), red dashed lines represent position of Cache Lake Thrust (thrust 4 on above diagram) and fault 5 which truncates fault 4. Yellow dashed line represents unconformity between overlying Franklin Mountain basal red beds and underlying Little Dal Rusty Shale formation. Abbreviations as in Figure 1.6a,b.

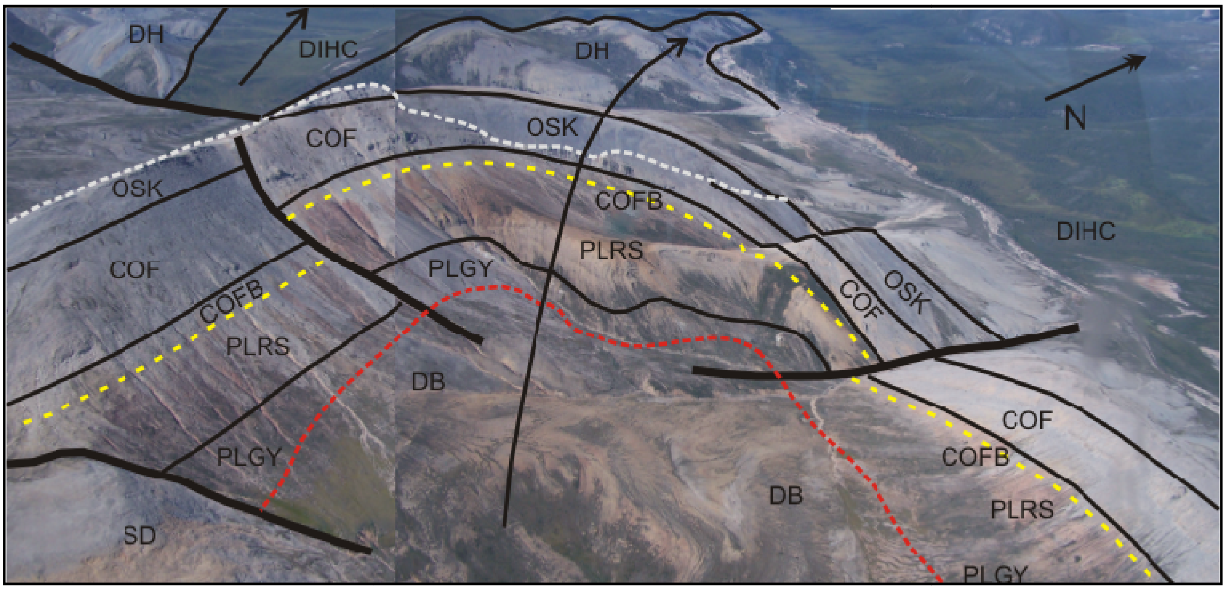

Figure 3.8: Aerial photo of Cache Lake fold nose. Black solid lines represent unit contacts as well as tear faults (thick black lines). White dashed line defines top of ridge in the foreground, red dashed line represents fault 4 (Cache Lake Fault), yellow line represents unconformity between overlying Paleozoic Franklin Mountain basal red beds and underlying Proterozoic Little Dal Rusty Shale formation. Abbreviations as in Figure 1.6a,b.

With further shortening, a later fault such as fault 5 may have developed to form a structural scenario akin to what is interpreted in the Cache Lake Anticline area. The Cache Lake Fold is discussed later in Chapter three with the help of a series of balanced and schematic cross-sections through the area.

3.2.2.3 Plateau Fault

In addition to the faults described above, there are numerous other thrust faults as well as normal faults and back-thrust faults of varying importance, perhaps the most important of these faults is the Plateau Fault.

The southwest side of the TSRSC is as mentioned above, is bounded by a large structure known as the Plateau Fault or the Plateau Thrust (Aitken et al., 1982). Throughout the 2006-2008 mapping project, Fallas et al. (2008) mapped along the thrust from the Wrigley Lake map sheet (95M) northwest to the Eduni Map sheet (106A) where the thrust is locally, well exposed. On the southwest side of the Eduni map, or hangingwall of the Plateau Fault, the strata generally shallowly dip to the southwest and contains several Laramide aged structures as well as numerous Proterozoic high-angle normal faults that generally dip north to northwest (Personal Communication Gordey, 2008). These faults locally have dramatic effects on the stratigraphy, by varying the thickness of the Proterozoic units by hundreds of meters over a short (several hundred meters) distance which makes for complicated map patterns and structural sections.

The Plateau Fault itself behaves differently along its >250 km strike length, most notably between the Wrigley Lake map sheet and the Eduni Map sheet (Fallas et al., 2008). The fault is defined by its consistent detachment level in the Little Dal Gypsum formation. The gypsum is commonly squeezed out along the fault surface resulting in the immediate hangingwall of the fault being at the stratigraphic level of the Rusty Shale formation rather than the Gypsum formation, or the thrust has cut up through the Gypsum formation and remains at the contact with the overlying Rusty Shale formation. The footwall of the fault often varies based on fault splays and folding leading to intense footwall deformation; however it is usually at the level of the Devonian clastic rocks of the Hare Indian, Canol and Imperial formations. The detachment surface at this level is commonly accepted as one of the major detachment levels in the Mackenzie Mountains and is evident while mapping along the Plateau Fault and in several locations to the northeast of the fault in the northwestern part of the TSRSC.

In the central Wrigley Lake map and to the southeast along strike, the Plateau Fault is interpreted to be a relatively high angle fault with complicated splays in the footwall Paleozoic rocks (MacNaughton et al., 2008). Previous researchers have postulated as much as 55 kilometers of northeast transport on the fault in the northeast corner of the Sekwi Mountain map area, with potential for Paleozoic rocks to be buried at depth in the footwall thus creating an environment suitable for hydrocarbon trap formation (Aitken et al., 1982; Cecile and Cook, 1981). Farther to the northwest, there is evidence for a low-angle structure, which although appearing listric near the surface, actually has a ramp angle of ~25° and a minimum displacement of 20 kilometers. This work is based on interpretation by field mapping where the exposed thrust is observed to cut through strata in the hangingwall due to its slightly oblique ramp geometry in this particular area (Figure 3.9). A cross-section drawn across the fault is presented later in Chapter three.

To date there have been three published cross-sections drawn through the Mackenzie Mountains, these were completed by Gordey (1981); Cecile and Cook (1981) and MacNaughton et al. (2008) in different locations. The Gordey (1981) section is drawn through the south-central Mackenzie Mountains (Figure 3.10) whereas the Cecile and Cook section is drawn, as mentioned above, through the northeast corner of 105 P Sekwi Mountain map sheet (Figure 3.11). The sections portray the Plateau Fault very differently, Gordey depicts it as a high angle listric fault in the southeast (just northwest of where the Plateau Fault dies out on the map) whereas Cecile and Cook (1981) depict it as a low angle thrust sheet farther to the northwest with a significant displacement and a 20 kilometer panel of Paleozoic rocks buried in the footwall.

The MacNaughton et al. (2008) sections (Figure 3.12a and b) present two different interpretations for the Plateau Fault, depending on the amount of Proterozoic strata present in the hangingwall. The first of the sections, Figure 3.12a, shows a footwall flat to match the hangingwall flat, modeled purposely after the Cecile and Cook (1981) section, which eventually cuts down-section in the transport direction, breaking a fundamental rule in Cordilleran Foreland geometry (Dalhstrom, 1969; MacNaughton et al., 2008). This first section was an attempt to display that Paleozoic strata would be very difficult, if not impossible, to be present under the hangingwall flat, and obey all the rules of geometry in cross-section construction. The Plateau Fault in this section shows a consistent detachment level at the Rusty Shale/Gypsum formation for some ~45 kilometers, indicating an offset of at least 50 kilometers. The second section (Figure 3.12b), shows a much thicker Proterozoic footwall with a steeper fault trajectory, which cuts up-section through the hangingwall, eventually remaining at the level of the Little Dal Rusty Shale formation for a few kilometers before being exposed at surface. In this section, the Plateau Fault is actually rooted in the Tsezotene detachment, and this section produces an offset of approximately 20 kilometers, with no Paleozoic rocks preserved under the fault in the footwall.

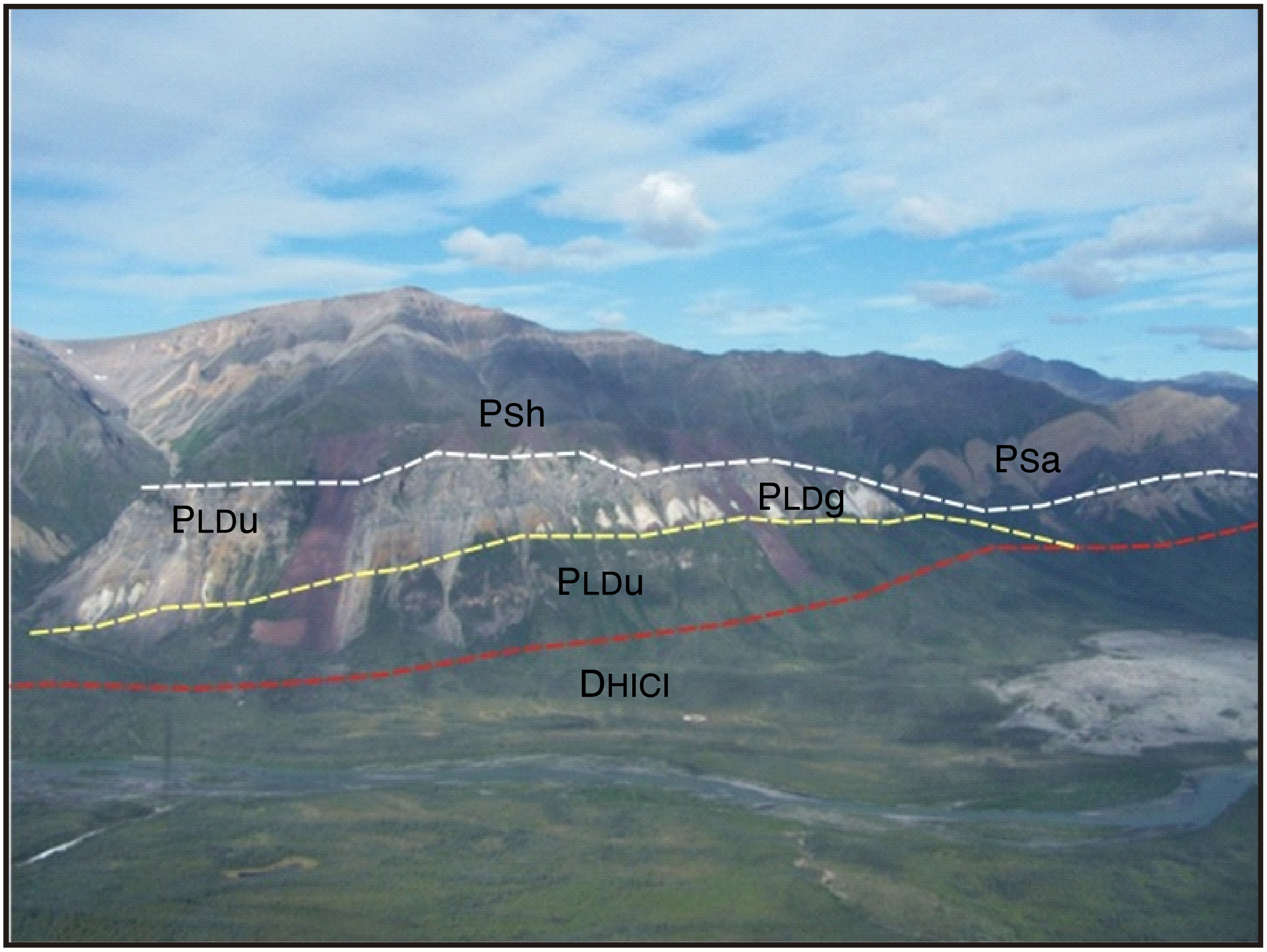

Figure 3.9: Photo looking west at Plateau Fault with Proterozoic strata in the hangingwall and Devonian strata in the footwall. Red line represents the Plateau Fault, yellow line defines the thrust repeat of the Little Dal Upper Carbonate (PLDu)formation with the white gypsum of the Little Dal Gypsum formation (PLDg) in the hangingwall (notice how it is squeezed into two separate pods) overlain by Upper Carbonate formation (PLDu). The white line defines the unconformable contact between the Underlying Little Dal Upper Carbonate formation (PLDu) and the overlying Sayuni and Shezal formations (PSa, PSh) in the hangingwall. DHICI represents the Devonian aged Hare Indian, Canol and Imperial formations, which are grouped and referred to as the Devonian clastic rocks.

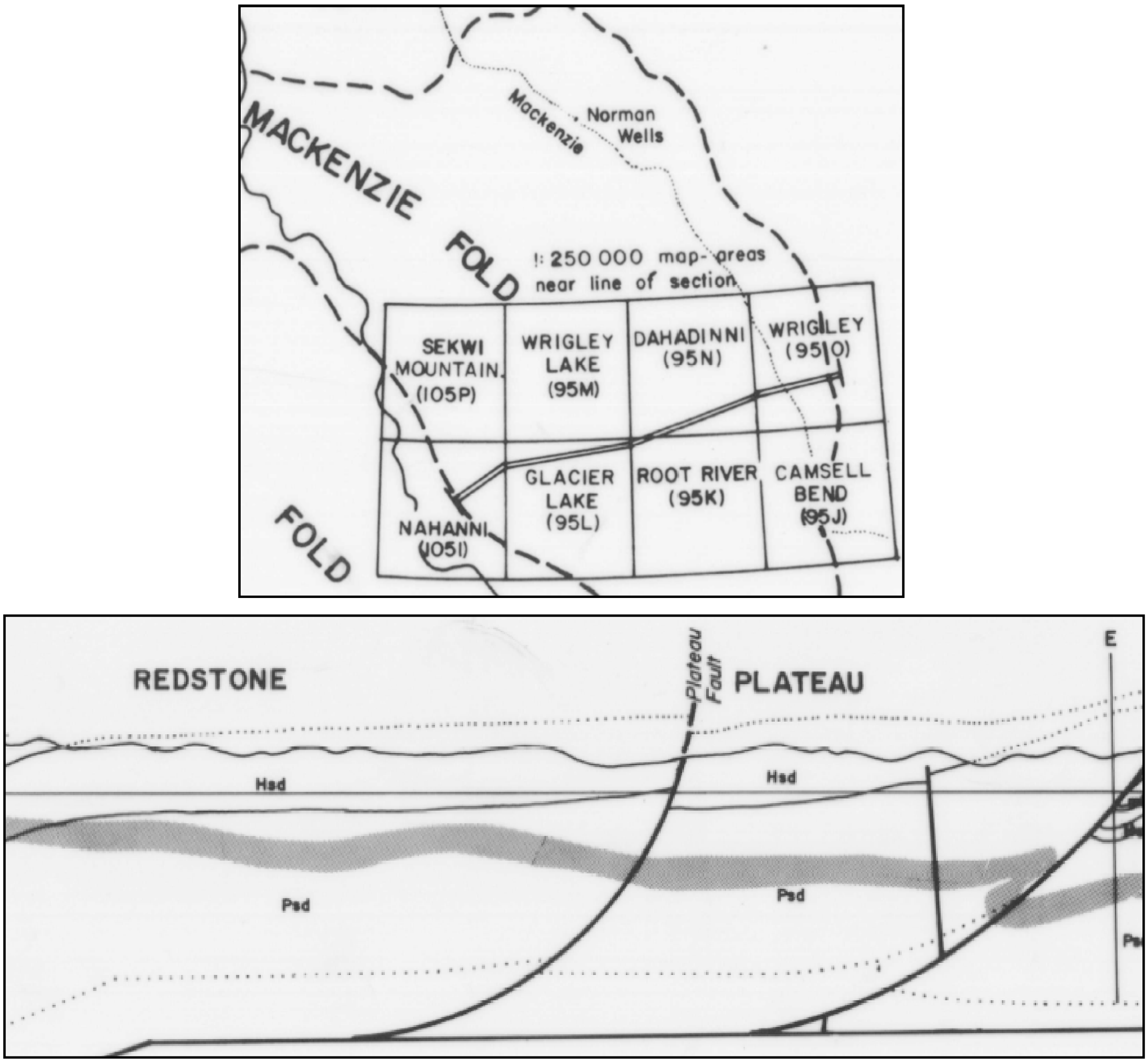

Figure 3.10: Part of regional cross-section and location map by Gordey (1981) through the southcentral Mackenzie Mountains with the Plateau Fault depicted as a high-angle listric fault with very little displacement.

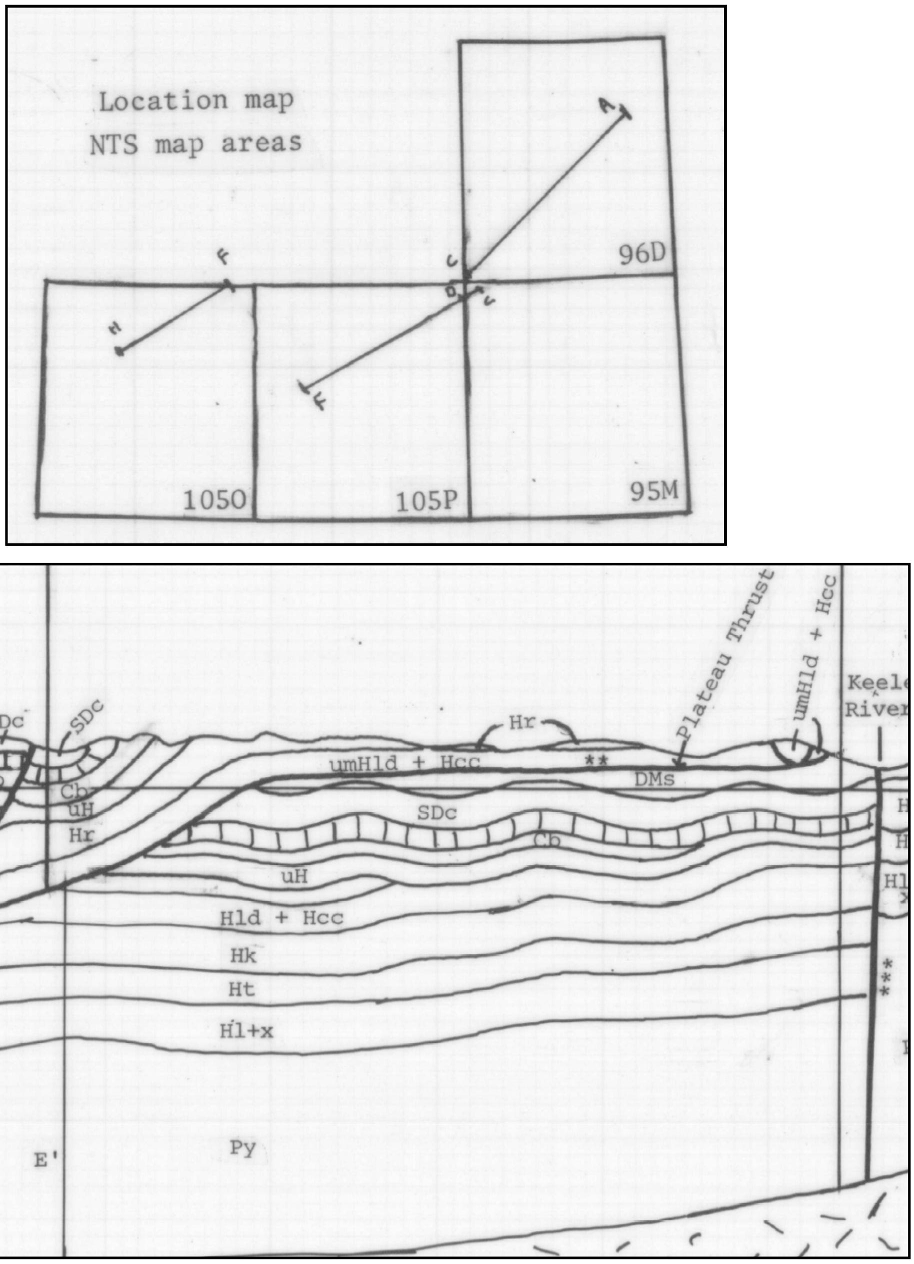

Figure 3.11: Part of regional cross-section through central Mackenzie Mountains by Cecile and Cook (1981) with the Plateau Fault depicted as a low-angle, far traveled thrust fault covering a significant package of Paleozoic stratigraphy.

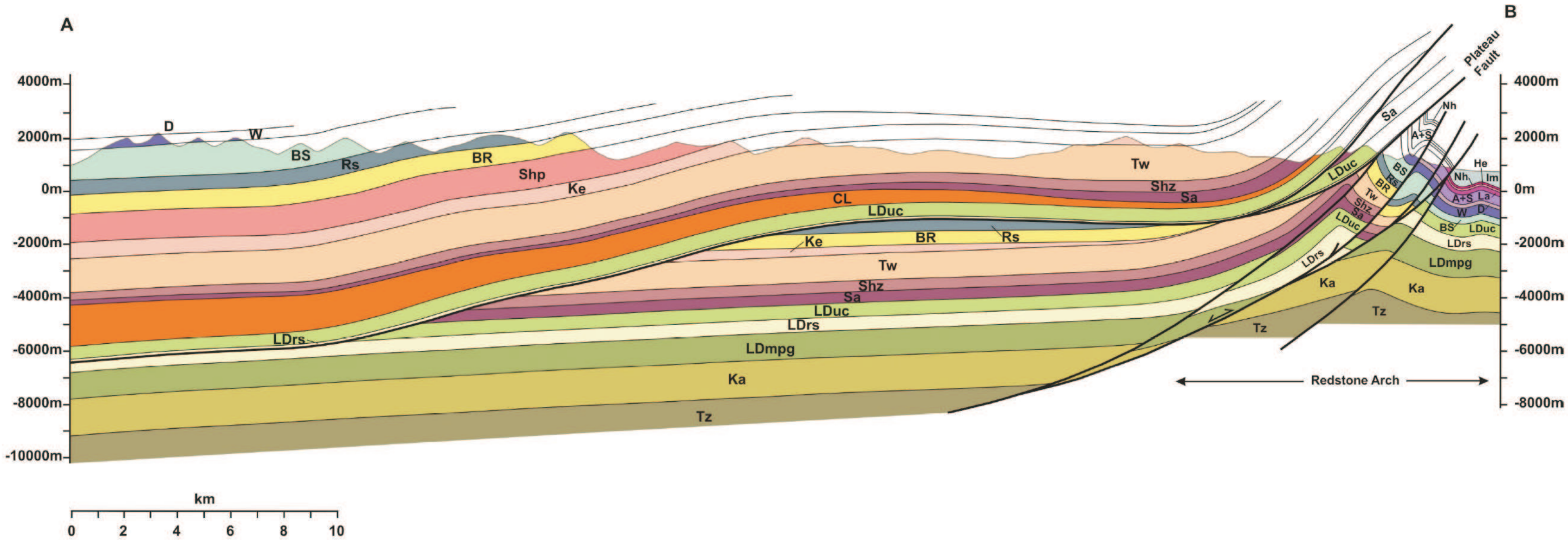

Figure 3.12a: Unbalanced cross-section by MacNaughton et al., (2008) through central Wrigley Lake map area (NTS 95M) with the Plateau Fault rooted in the Little Dal Rusty Shale/Gypsum detachment with deformed Paleozoic rocks in the footwall.

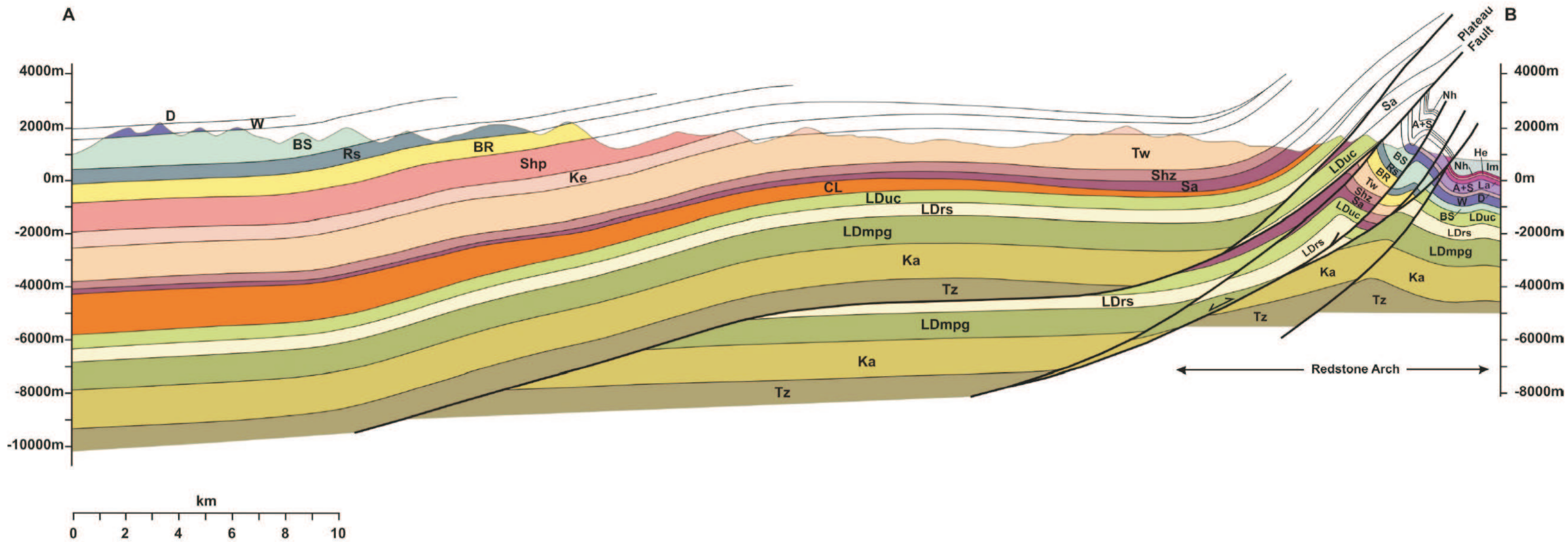

Figure 3.12b: Unbalanced alternative cross-section through same area as Figure 3.12a, this time with the Plateau Fault rooted at the level of the Tsezotene detachment. Section by MacNaughton et al.,(2008).

It is important to note that the Plateau Fault is a ~250 kilometer long fault through the entirety of the Mackenzie Mountains and the geometry of this fault may very well change numerous times along the strike of the fault. The first attempt at a regional scale cross-section through the Mount Eduni map sheet is presented later in this chapter, with a 50 kilometer southwest-northeast balanced section that includes the Plateau Fault as well as several other important structures such as the above-mentioned Cache Lake Fold and the large box shaped Shattered Range Anticline.

3.2.2.4 Other Fault Structures

In addition to the Plateau Fault, there are a number of interpreted thrust faults that run northwest-southeast in the TSRSC, many of which may be connected along strike but have varying ramp geometries. Very few of the thrust faults have bedding parallel ramps, leading to map patterns where units are cut off either upsection or downsection along the strike of the exposed fault in the hangingwall and the footwall. Depending on how oblique the ramp is, the units may be cut off over several tens of kilometers or they may be cut rapidly over a few kilometers (Figure 3.13a&b). It is important to remember when looking for patterns on the map related to ramp geometry that the numerous unconformities mentioned in Chapter 2 can result in a similar pattern thus it is important to be aware of the rapid changes in stratigraphy along strike of the structures (Figure 3.13c).

As mentioned above, the majority of the dip-slip northeast vergent faults in the TSRSC are believed to have been manifested at the level of the Tsezotene detachment, below the oldest rocks exposed in the Mount Eduni map sheet. The main evidence for a detachment at this level is the outcrops of Tsezotene formation mentioned above and the exposed Katherine Group rocks in the hanging wall of many thrust faults, particularly those in the southeast portion of the study area. This places the detachment at a level either somewhere in the Tsezotene formation or below it at the base of the H1 Unit.

The Shattered Range Anticline, a large box fold to the northeast of the study area, has symmetrical limbs and a well exposed core consisting of Katherine Group rocks with Paleozoic carbonate rocks exposed on the limbs. Due to the large scale of this fold, and the fact that there are large synclines on its southwest and northeast sides, the fold was used to calculate the “depth to detachment” with the excess area method. By treating the center of the synclines as a datum where the thickness is thought to be representative of the true thickness of the strata at that particular location (i.e. little to no structural thickening so the syncline cores are at the same elevation) the area within the fold can be calculated to determine a reasonable idea of where the detachment responsible for that fold is located at depth. This calculation and explanation is discussed later in this chapter.

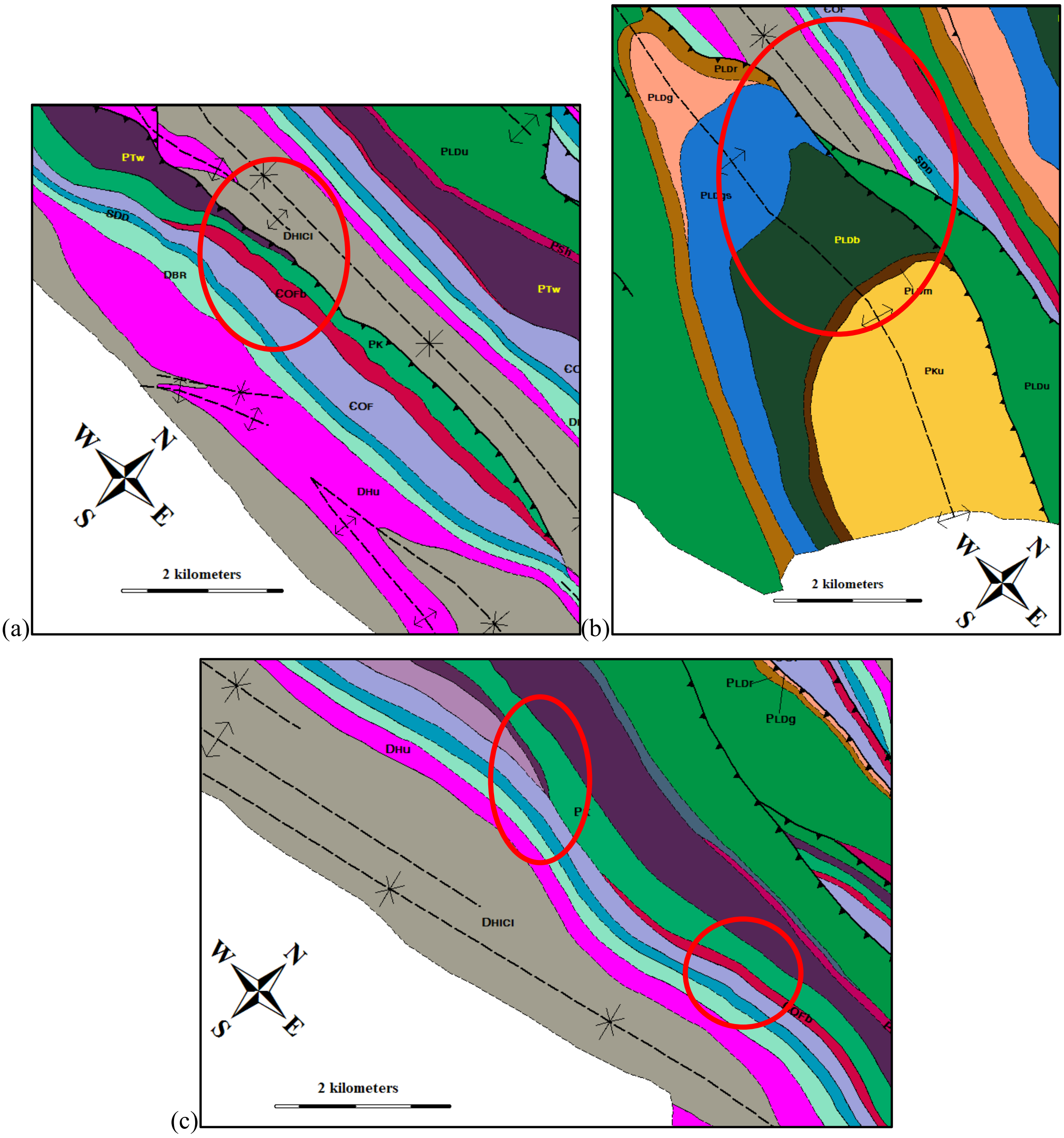

Figure 3.13a, 3.13b, and 3.13c: Map (a) shows an example of a gradual cutoff in the hangingwall of a thrust where the thrust cuts upsection from the purple (Twitya fm.) to the light blue (Franklin Mountain fm.). Map (b) shows an oblique ramp geometry where the thrust cuts upsection in the hangingwall from the Katherine Grp. (yellow) to the Little Dal Rusty Shale fm. (brown) over only a few kilometers. Map (c) is an example of an unconformity at the base of the Franklin Mountain fm. (light blue) where the map pattern suggests the units pinch out along strike. See Figure 1.6a,b for legend.

3.3 Cross-sections

3.3.1 Introduction

The nature of the structures in a fold-and-thrust belt is such that they are best portrayed in a cross-section that is drawn deep enough in the crust to show any detachments and how the faults behave geometrically enroute to the surface. Cross-sections can range in complexity from simple schematics drawn in a field notebook to area-balanced and accurately restored regional sections that require very tedious measurements and constant changing of geometry during construction.

In a fold-and-thrust belt such as the Mackenzie Mountains, the surficial data is collected by the mapping geologist and the interpretations are almost always made on the outcrop during mapping. Thus it is important to understand that because they rely on an interpretation, no cross-section is ever “perfect” or “right” but some are more “correct” than others, and any section that cannot be restored is definitely not correct. The surficial geology, structural measurements and basic principles of geology are all that are needed to construct an accurate section.

Due to the unique size and shape of the study area, a number of cross-sections were constructed against the structural grain, along the strike of the map. Of the nine sections that were constructed, only one, the regional section, is balanced and has its beds restored to their original length and geometry.

3.3.2 Regional Cross-section

The construction of a “balanced” cross-section requires a sufficient length of section so that the geometry of structures in the subsurface (e.g., 8 km depth) can be accurately represented. The regional section that was constructed across the southeast portion of NTS sheet 106A is approximately 50 kilometers in length and incorporates data collected by the author in the study area as well as the regional mapping completed during the SEKWI Mountain Project. Figure 3.14 shows which areas of the section rely on data from the SEKWI Project versus the data acquired during this study in the TSRSC.

The location for the regional cross-section was strategically chosen to incorporate a variety of important geological features identified on the Mount Eduni map. First and foremost, the section had to transect the Cache Lake Fold, to gain some idea of the amount of shortening across the most intensely deformed part of the study area. Other features that were important to include in a regional section were the Plateau Fault, which is located to the southwest of, and forms the boundary of the TSRSC, and the Shattered Range Anticline to the northeast of the study area for its unique geometry. The Shattered Range

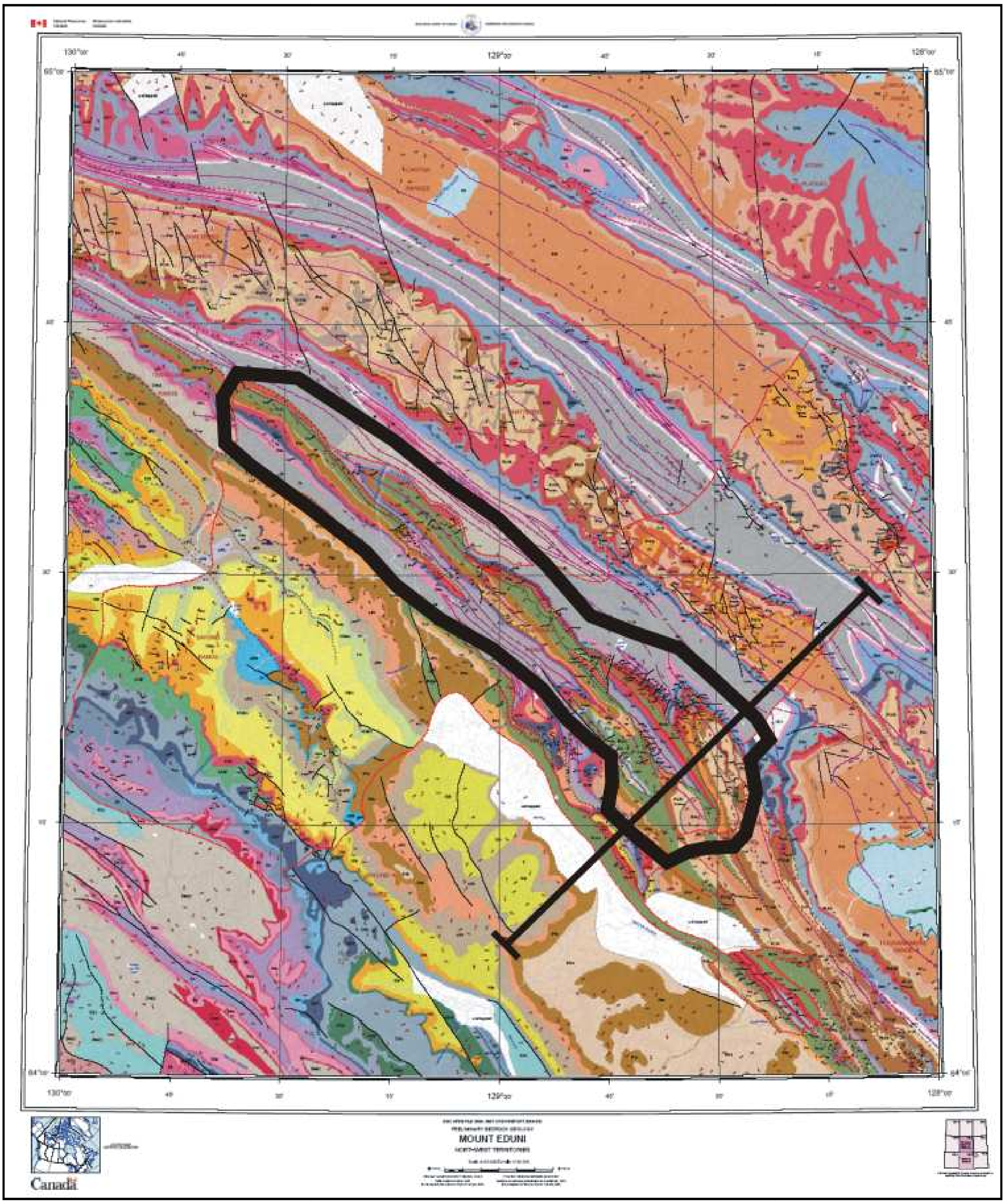

Figure 3.14: NTS Sheet 106A (Mount Eduni) preliminary geological map with study area outlined (black polygon) and trace of balanced cross-section represented by black line. Geology outside the black polygon is by Gordey et al. (2008), Blusson (1974) and Aitken and Cook (1974).

Anticline has a similar geometry to a box fold with limbs of relatively equal proportion making it a favorable choice for calculating the "depth to detachment" in the regional cross-section. The above criteria are all well represented in the regional cross-section (Figure 3.15), and help to increase the accuracy of the restoration. To discuss the regional cross-section, Figure 3.15 has been labeled with letters A-E for each area of interest which will be referred to in the text.

Area A: This area is the most southwesterly end of the section and has several important features including the detachment level of the Plateau Fault as well as the regional dip of the section which in turn dictates the dip of the lowermost detachment, the Tzezotene Detachment. The Plateau Fault is depicted here as a shallow, southwest dipping fault with a thrust geometry that begins to steepen when it approaches the surface where it takes on the appearance of a steep reverse fault rather than a thrust fault. The panel above the Plateau Fault is shallowly dipping to the southwest providing evidence that the fault itself is also shallow dipping. Due to the panel having been transported from the southwest into the section, it is unknown how much displacement is on the Plateau Fault at this location and where it ramps up through the (structurally) underlying Little Dal Upper Carbonate formation. Given the angle of the thrust in the section it is likely that this cutoff occurs several kilometers laterally to the southwest and at a low angle resulting in an estimation of minimum 20 kilometers displacement as mentioned above. In addition to this, it is important to note that the detachment level is somewhere below the -2000 m level as this is where the Gypsum Detachment is shown in the section and it is cutting through the Little Dal Upper Carbonate which would increase the structural elevation by at least 100 - 500 m. Thus a reasonable estimate for the actual level of the gypsum detachment is -2500 - -3500 m.

Area B: This area is located directly in the footwall of the Plateau Fault and has been deformed by small northeast verging faults. Faulting of this geometry and frequency is commonly observed in the footwall of the Plateau Fault and along the margins of the TSRSC where deeper seated structures related to the Tsezotene Detachment surface. It is important to note that there is little or no overlap of the Paleozoic strata by the hangingwall of the fault, thus ruling out any possibility for hydrocarbon trap formation in this particular area. Another important feature in area B is the stratigraphic "pinch-out" of the Backbone Ranges formation in the footwall of the splay, thus providing evidence for one of the many unconformities in the study area. The Twitya formation is observed in area B to be half the thickness that it is in area A. This is either due to an unconformity or a syn-depositional fault which would have thickened the Twitya formation on the southwest more than on the northeast side. It is impossible to know which of the two is responsible, or if it is a combination of both at play in this case. Similarly, underlying

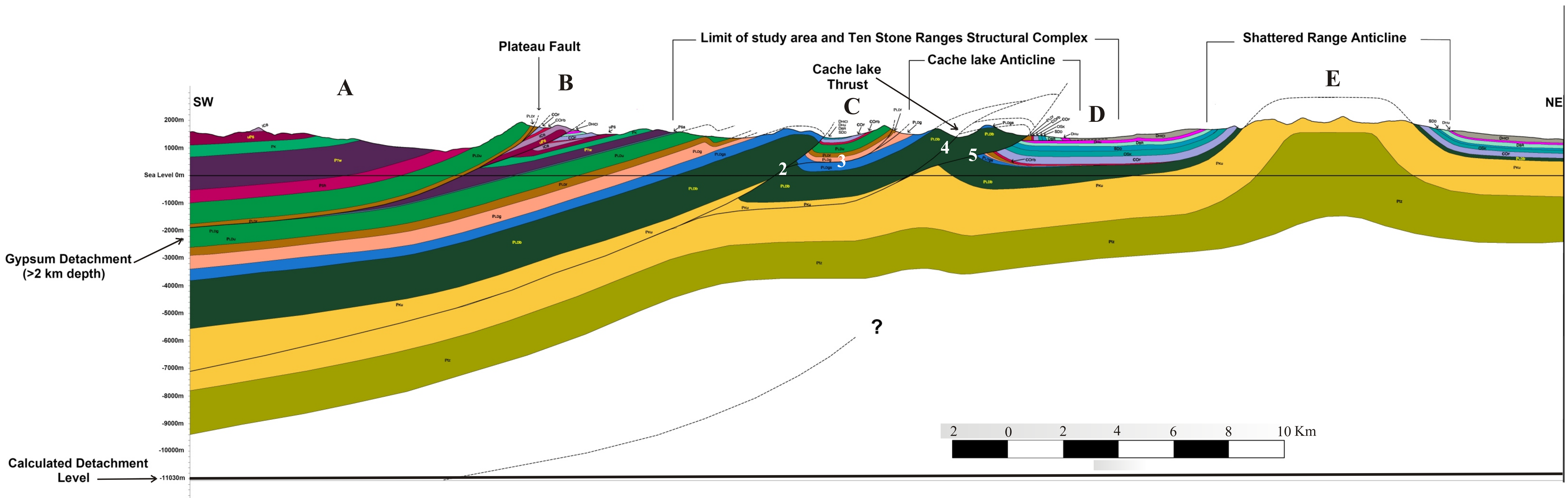

Figure 3.15: Regional cross-section X-X' through the southeast portion of Mount Eduni map sheet. The section is approximately 50 kilometers and is based on data from this study as well as previous work by Blusson (1974), Aitken (1974), and Gordey et al. (2008). See Figure 1.6a,b for legend. Refer to 1:50 000 scale section in pocket.

the Twitya formation in the hangingwall is the Shezal formation, whereas in the footwall it is underlain by the Sayuni formation, so the pinching-out of these units is commonplace in the map area.

Area C: This area contains the remainder of the faults in the regional section which are labeled 2-5 from southwest to northeast. Fault 2 appears to have a relatively small displacement with only 1100 m of offset, a broad anticline in the hangingwall and a corresponding syncline in the footwall. Fault 3 has very little offset in this section, with only tens of meters of displacement, and dies out some 100 meters southeast of the section line. Fault 4 has been named the Cache Lake Fault above, and is explained in detail in the Cache Lake Fold section. Fault 4 is a lower-angle fault with thrust geometry, ranging from 5-35 degrees in dip, is folded nearest the Cache Lake Anticline and later truncated by fault 5. Fault 5 initiates as a fault propagation fold and later breaks through the anticline truncating fault 4. All of these faults aside from fault 3 initiate from the same detachment level, that of the Tsezotene Detachment, due to the fact that they all expose units older in age than the Little Dal Gypsum formation in their hangingwall(s). Fault 3 is the only fault that is rooted in the Gypsum detachment.

Area D: This area is in the footwall of the Cache Lake Thrust and is significant in that it is a footwall syncline where a number of units pinch out due to an unconformity at the base of the Cambrian Franklin Mountain formation. The Little Dal Grainstone, Gypsum and Rusty Shale formations all pinch out in the area between the northeast limb of the Cache Lake Anticline and the southwest limb of the Shattered Range Anticline where they are no longer exposed. In addition to these units, the Franklin Mountain formation basal red beds pinch out as well resulting in Franklin Mountain formation overlying Little Dal Basinal Assemblage on the southwest limb of the Shattered Range Anticline.

Area E: This large scale anticline, known as the Shattered Range Anticline, has geometry similar to a box fold and provides a unique opportunity to calculate the "depth to detachment" as was shown above (Aitken and Cook, 1974). In the southeast corner of the Mount Eduni map sheet, the Tsezotene formation is exposed in the core of this same fold, and is the oldest exposed outcrop in the map area. Measured sections of the Tsezotene suggest it is a minimum of 1000 m and may be upwards of 2000 m thick in the Eduni Map area, thus this was the thickness used in construction of the regional cross-section and the unit is open at depth due to lack of thickness constraint. Outside the line of section, to the northeast, there is another anticline of almost exact proportion and geometry as the Shattered Range Anticline, and it occurs at the same structural elevation. Given that the two are so much alike in all aspects, and that they appear to be harmonic, conjugate folds of a parallel style, it is likely that they are formed above the same detachment surface. If there was to be a step in the detachment surface below, this geometry would not be the result and the folds would be either non-existent or at different structural elevations.

The regional cross-section has one other very interesting feature that was first recognized in this area by Gordey (1981) when drawing the structure section through the southcentral Mackenzie Mountains. The "structural elevation" of the Devonian clastic rocks, which always occur in the core of synclines in this area, are all approximately equal. It has been postulated that in these areas of preserved Devonian clastic rocks, there has been little to no crustal thickening, however there may have been detachments actively sliding beneath these synclines (Gordey (Personal Communication), 2009). This relationship is true when examining the section however there may be several areas that have very minor thickening which is shown by their increased elevation relative to the cores of other adjacent synclines. This is further evidence for a single, flat lying basal detachment in the Mackenzie Mountains.

3.3.3 Schematic Cross-sections

In addition to the regional cross-section that was described above, a series of smaller schematic sections were constructed to aid in the understanding of the map pattern, the attitude and geometry of structures in the TSRSC and to demonstrate the presence of a "Transfer Zone" in the southeast portion of the study area. Dahlstrom (1969) defines a "transfer zone" as the "compensatory mechanism for thrusts where a kind of lap joint exists wherein the fault whose displacement is diminishing is replaced by an echelon fault whose displacement is increasing". It is important to realize that a "transfer zone" could not exist unless all faults are rooted in a common sole fault (décollement) (Dahlstrom, 1969). It has been suggested that along a mountain trend the shortening is relatively consistent; it is just dispersed over many structures that are all undoubtedly linked at a basal décollement surface above the crystalline basement (Dahlstrom, 1969). This is likely true for the Mackenzie Mountains as well however it is difficult to determine the exact shortening because the calculation will only ever be hypothetical as there is no detailed seismic imagery or deep well data within the heart of the Mackenzie Foreland Belt, nor are the thicknesses of major stratigraphic units such as the Tsezotene or H1 known. In addition to this, there are no definite constraints on the actual depth of crystalline basement in the Mackenzie Mountains so it is currently impossible to be sure what depth the basement is below the surface.

The location of the structural sections are all dictated by either interesting map patterns that need further understanding or the necessity to see the development of structures, particularly thrust faults, along strike of an anomalous map pattern. Figure 3.16 shows the position of all eight schematic sections as well as the position of the regional cross-section.

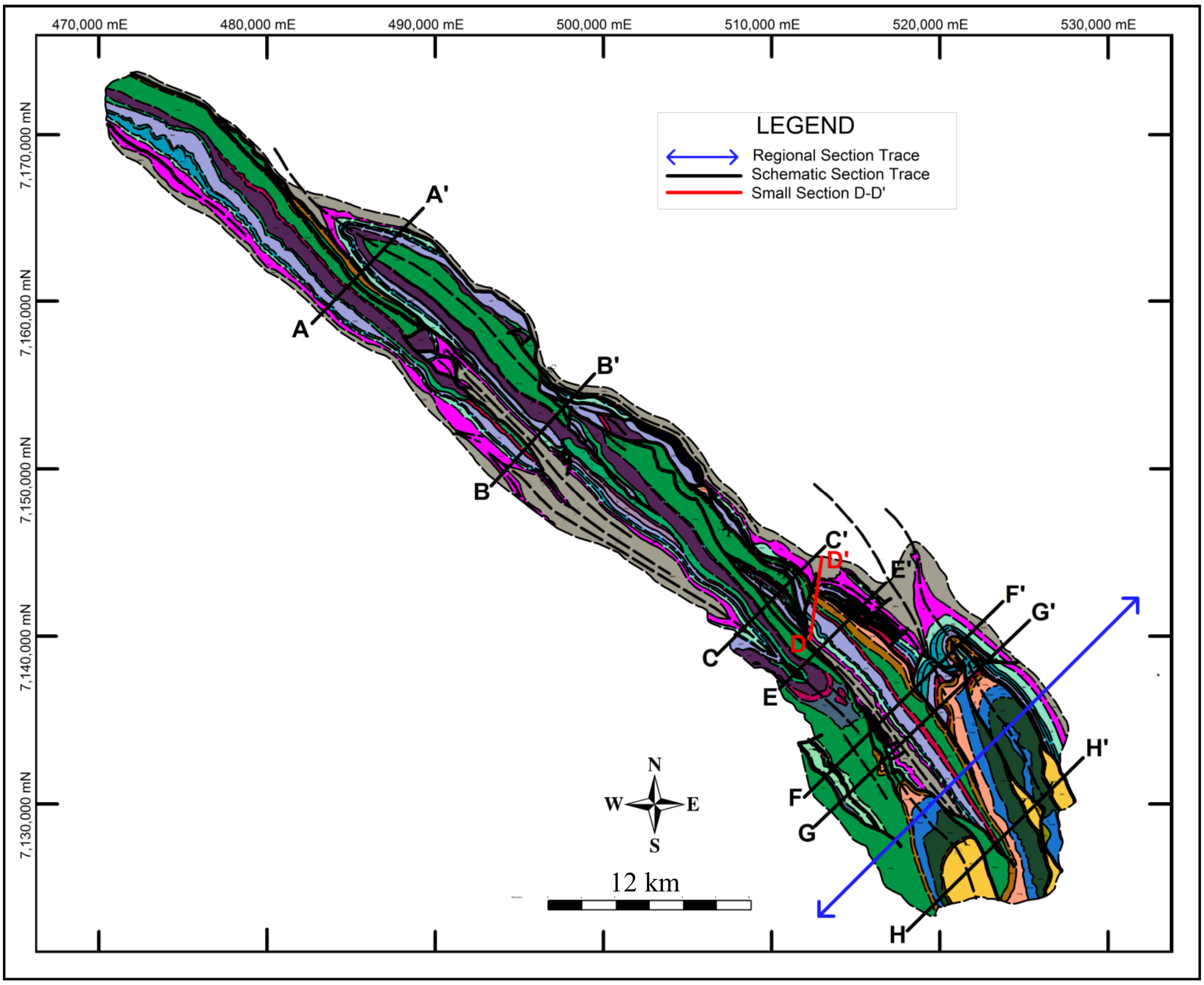

Figure 3.16: Simplified geologic map of study area within the *TSRSC*. Lines represent traces of structural cross-sections (black) and the trace for the regional cross-section (blue). See Figure 1.6a,b for legend; 1:50 000 scale geologic map located in pocket.

There are a series of 8 schematic cross-sections, starting with section A-A' and ending with section H-H'. These sections are all constructed at 1:50 000 scale and are not balanced however they are intended to be geometrically possible and representative of the structures in the subsurface and rely solely on surface data collected by the author during the course of this study.

Section A-A': This cross-section (Figure 3.17) is located in the northwest portion of the study area and was constructed to attempt to determine the geometry of the Mountain River Fold at depth. There are two areas of interest in this section. Area 1 contains two faults; the southwestern one is a repeat of the earlier, deeper seated fault to the northeast. This fault geometry is determined by the bedding in the hangingwall which is indicative of the ramp angle near the surface as well as the repetition of the Little Dal Upper Carbonate and Rusty Shale formations. By inspection of the cut-offs it is likely that there is at least 3 kilometers of throw on this fault which is reasonable considering there is Proterozoic Little Dal Gypsum formation juxtaposed against Devonian Clastic rocks in the immediate footwall indicating the fault ramped up through at least 1200-1500 meters of stratigraphy in this particular case.

From the map pattern, the development of a blind thrust is apparent in this section as the thrust surfaces just tens of meters southeast of the section trace whereby the Mountain River Anticline develops into a fault-bend-fold and is thrust atop the Devonian clastic rocks in the adjacent valley. This fault is most likely rooted at the Gypsum detachment, thus is drawn on the cross section in this manner. From a stratigraphic standpoint, there are three interesting features in this schematic cross section: (1) the thickness changes in the Twitya formation from the hangingwall to the footwall (in this case the Mountain River fold) where the unit is several tens of meters thicker in the hangingwall, (2) the absence of the Mount Kindle formation in the hangingwall, (3) the absence of the Keele and Shezal formations on either side of the Twitya formation in the footwall. Note that when examining the accompanying geologic map, the Keele and Shezal formations do re-occur farther to the southeast, thus they are just missing nearest the nose of the fold. Perhaps the most important of the above mentioned features is the dramatic thickness change in the Twitya formation; this demonstrates the abrupt changes that are encountered when attempting to draw a geometrically possible section through any part of this study area.

Section B-B': There are two places of interest in this cross-section (Figure 3.18), the first involves a relatively low displacement fault to the southwest in area 1, which is likely rooted at the Little Dal Gypsum formation detachment, to the southwest of the section. This fault is interesting as it cuts up section through the hangingwall exposing a number of units along the strike of the fault which is indicative of an oblique ramp geometry, not a bedding parallel thrust fault.

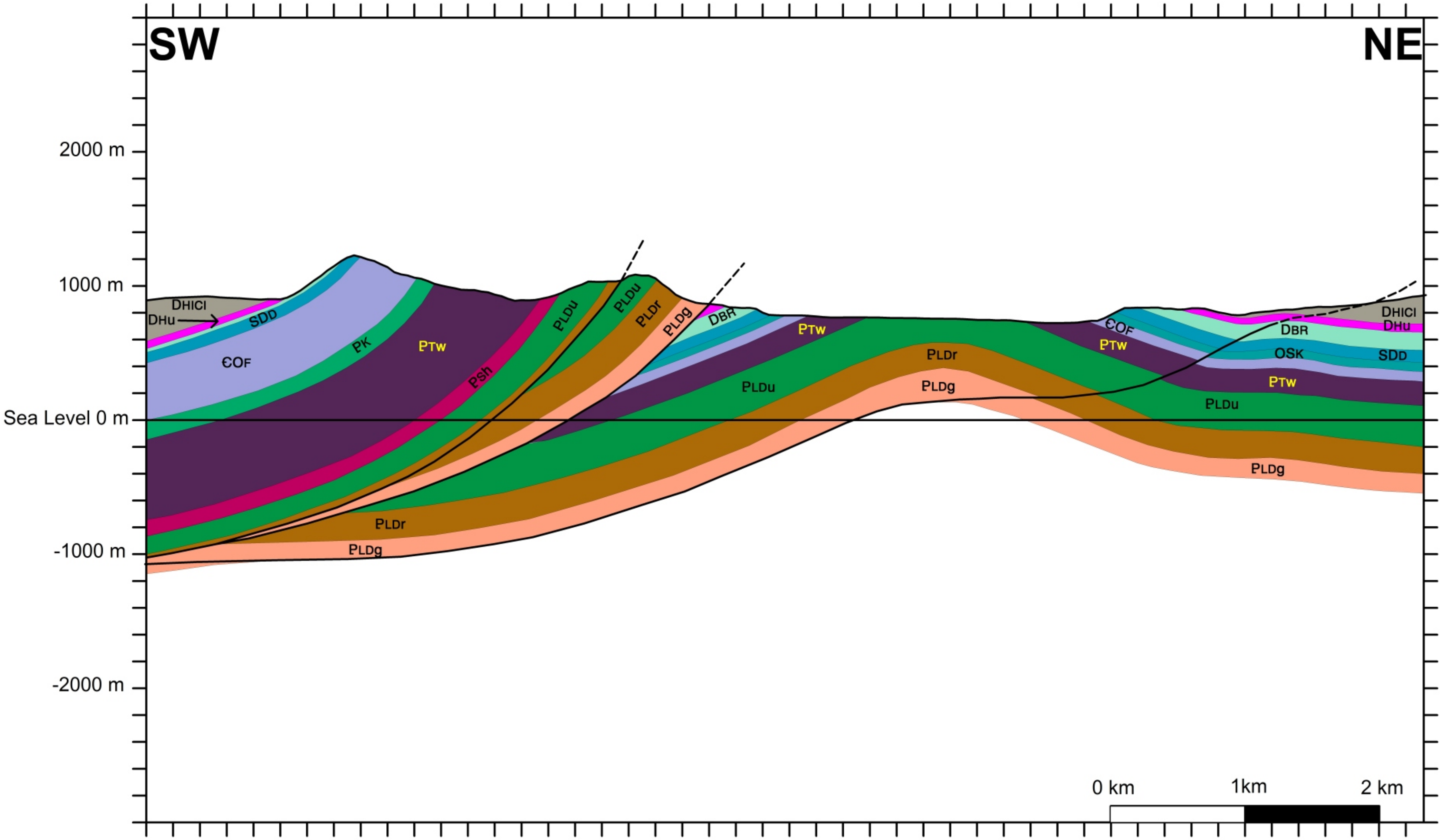

Figure 3.17: Cross-section A-A’ showing geometry of Mountain River Fold and associated faults. Refer to Figure 1.6a,b for legend.

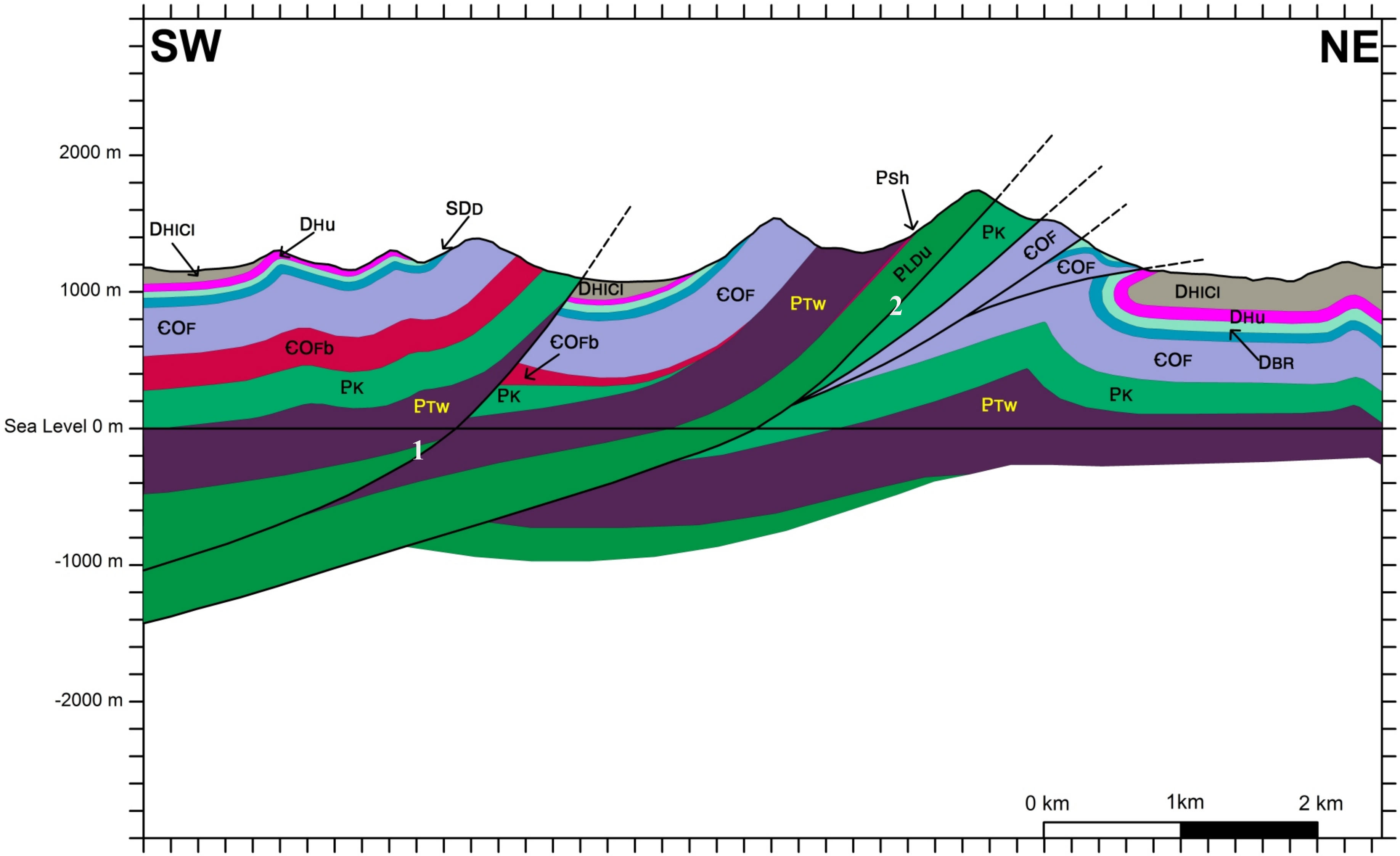

Figure 3.18: Cross-section B-B' showing the "out of syncline" fault (number 1) to the southwest and another fault rooted at the level of the Gypsum detachment in the center of the section with associated footwall splays that complicate the Paleozoic footwall strata. Numbers 1 and 2 refer to faults described in the text. Refer to Figure 1.6a,b for legend.

By examining the occurrence of progressively older units to the northwest along the strike of the fault, it is likely that the fault plane is dipping slightly to the west rather than southwest.

Area 2 contains one large displacement fault with at least six kilometers of throw and several small footwall splays that complicate the Proterozoic Keele formation and “decapitate” a footwall anticline by slicing up the Cambrian Franklin Mountain formation resulting in an overturned southwest limb in the immediate footwall. There is a stratigraphic “pinch out” of the Little Dal Upper carbonate formation and the Franklin Mountain Basal formation whereby they are likely truncated by an unconformity. There is also a “pinch-out” and reappearance of the Keele formation in this section, again, likely due to an unconformity or topographic highs/lows during deposition.

Section C-C’: This section (Figure 3.19) was constructed to better understand the complicated map pattern in an area that contains some four thrust faults over a six kilometer distance. In this section, the Little Dal Upper Carbonate formation is repeated four times and varies in thickness each time due to structural and stratigraphic thinning. All of the faults appear to be rooted at the Little Dal Gypsum formation detachment level and the section suggests that there is a good deal of “flow” or ductile deformation in the Little Dal Gypsum formation. The shortening in this area is distributed amongst a series of smaller offset thrust faults rather than one or two large offset faults and the ramps appear to be relatively parallel as units tend to be preserved along the trace of the fault rather than be cut out. The fault with the most displacement in this section is the most southwest “out of syncline” fault that forms a large hangingwall syncline. Just above the detachment, again in the southwest side of the section, the rehologically incompetent Little Dal Gypsum formation is squeezed into the core of the anticline and may be the location of a “blind thrust” at the core of a “fault bend fold”.

Section D-D’: This cross-section (Figure 3.20) was constructed to show the folding style in the footwall of the fault in this area. The overturned stratigraphy in the footwall is the southwest limb of a footwall syncline, the best exposed example of this in the study area. The Paleozoic stratigraphy is often intensely deformed but usually by a combination of smaller fault splays and folding rather than just by folding. The Little Dal Upper Carbonate formation must “pinch-out” somewhere in the hangingwall or is dramatically thinned by a Proterozoic normal fault as it is not present anywhere in the footwall along the entire strike length of this fault. In terms of displacement on this structure it is unknown exactly how much there is but given its relationship to the sections adjacent to this one, it is likely > 5 kilometers. By examining Figure 3.16, one can see that section D-D’ to section G-G’ all show this particular thrust fault and how it varies in attitude and geometry along strike. This fault will be named the “Boundary Thrust” as it continuously truncates the southwest limb of the Cache Lake Anticline.

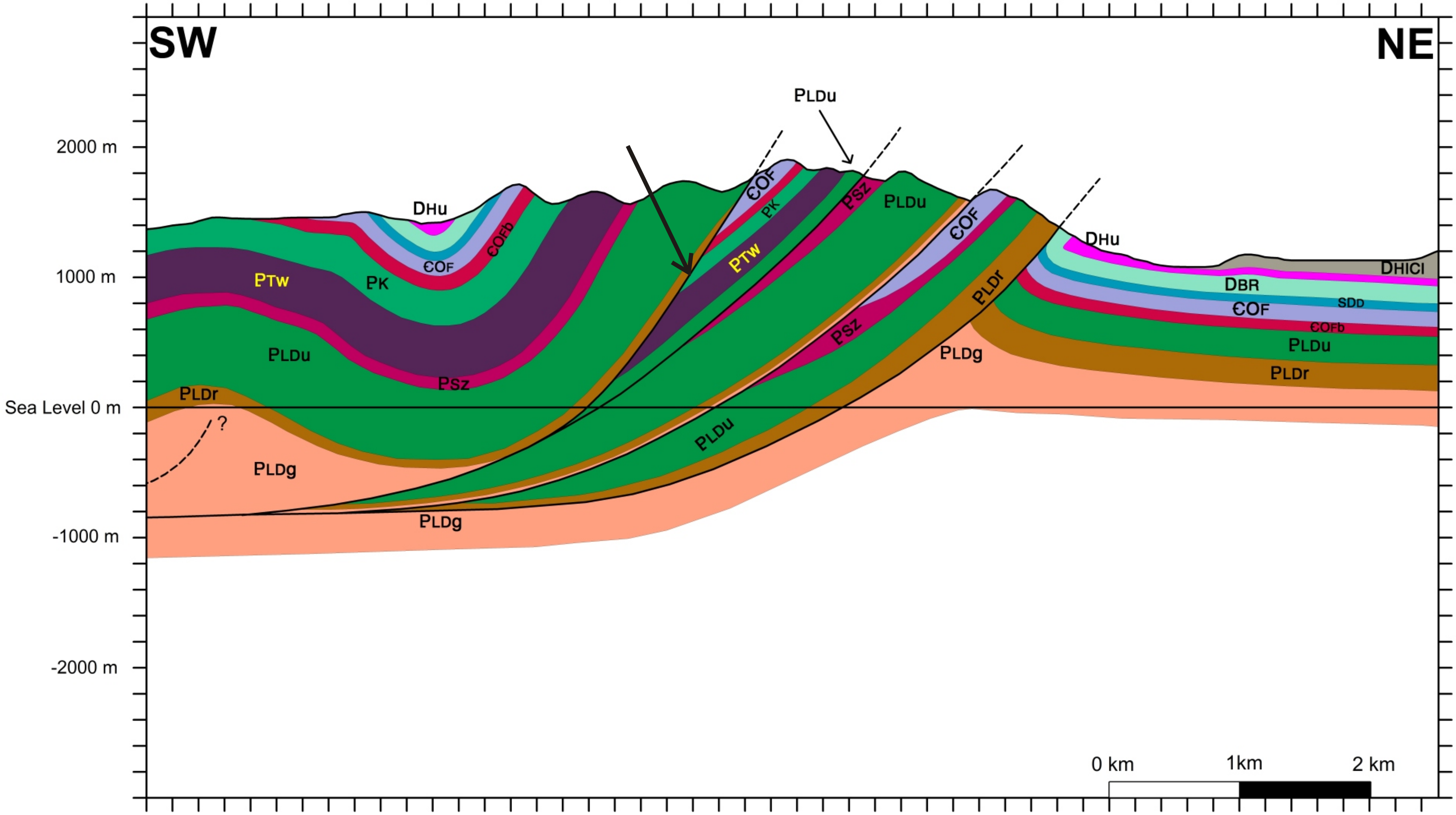

Figure 3.19: Cross-section C-C' shows the "out of syncline" fault (arrow) to the southwest as well as several other faults that form an imbricate stack in this area. Refer to Figure 1.6a,b for legend.

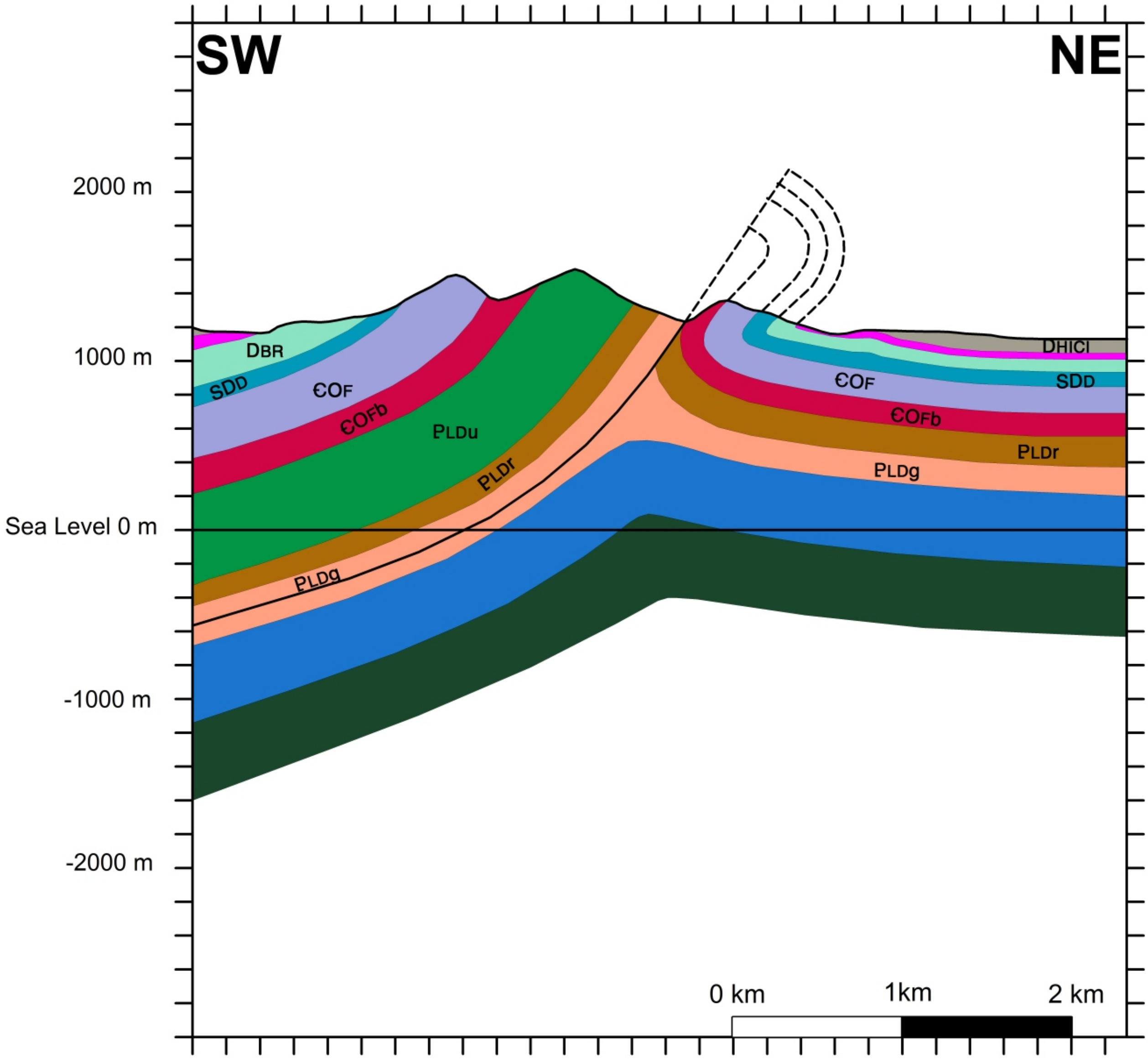

Figure 3.20: Cross-section D-D' shows the fold geometry in the footwall Paleozoic rocks.

As one follows this fault along strike it is apparent that the fault is rooted in the Gypsum detachment as there is little structural thickening in the hangingwall syncline as the Devonian Clastic rocks are only slightly elevated compared to the regional level of the syncline cores. Also, the Gypsum formation is continuously exposed in the hangingwall along the strike of the fault indicating the structure is likely a bedding parallel ramp rather than an oblique one.

Section E-E’: In this section (Figure 3.21), there are three main faults and several smaller splays. The most southwesterly fault is a continuation of the “out of syncline” fault in section C-C’ however in this section it is no longer at the level of the Gypsum detachment but is indeed rooted much deeper in the Tsezotene detachment due to its moderate dip and presence of Little Dal Grainstone formation in the hangingwall. The second fault in this section is the Boundary Fault that truncates the southwest limb of the Cache Lake Anticline. Here this fault is also shown to be rooted at a continuous level of the Gypsum detachment, which is again indicated by the Devonian clastic rocks in the syncline cores in the section remaining at a very similar elevation. The middle panel that is bound by the above faults is a syncline that runs through a prominent valley on the map and is present in cross-sections E-E’ through G-G’, as well as in the regional section. This syncline is progressively truncated on its southwest limb along the strike of the “out of syncline” fault toward the northwest. The third fault of interest in this section is a west-south-west verging “out of syncline” fault that shows only minor offset and is believed to be rooted at the level of the Gypsum detachment. In the hangingwall of this fault, the Paleozoic strata is sometimes tightly folded along strike of the fault and the structure dissects the northeast limb of a small anticline in the footwall of the larger “boundary fault” to the southwest. It is unknown how much offset there is on the “boundary fault”, but it is likely >2 kilometers in this particular section taking into account the thickness of the Little Dal Gypsum formation and the good control on the dips of the strata in the hangingwall of the fault which are the only controls on cut-offs in the subsurface.

From a stratigraphic standpoint, a number of the Proterozoic units pinch out between the first two (southwest) structural panels in the section as they do not occur in the second fault bound syncline but are present in the most southwest syncline. The Little Dal Upper Carbonate formation also pinches out toward the northeast as it does not outcrop in the footwall of the “boundary fault” or anywhere northeast of this in the study area. The last area of interest in this section is again, the immediate footwall of the “boundary fault” where there is a minor fault that repeats the Franklin Mountain formation in the southwest limb of the small footwall anticline further complicating the Paleozoic strata in this area.

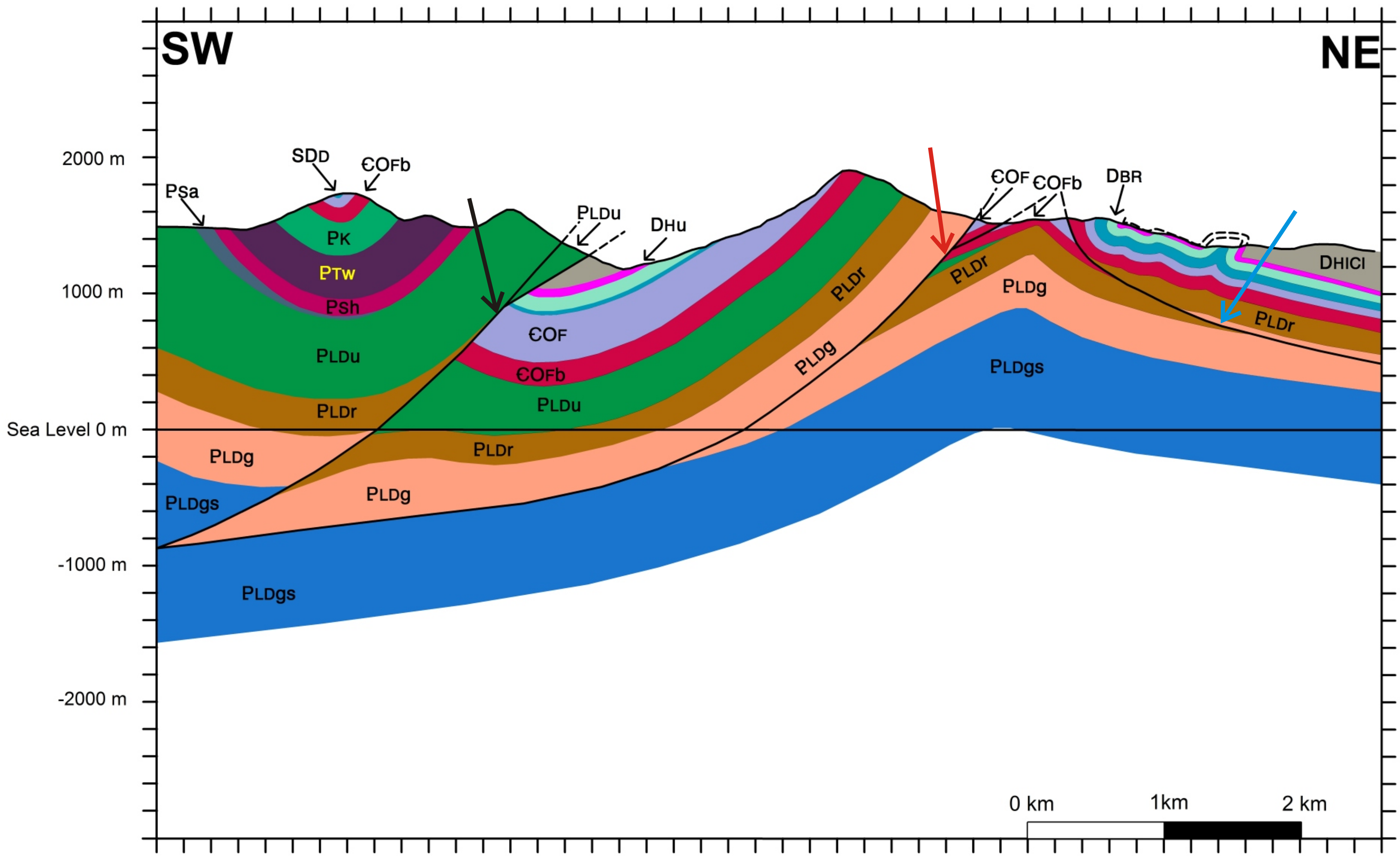

Figure 3.21: Cross-section E-E' with three major faults, the most southwesterly is the "out of syncline" fault (black arrow) which is rooted in the Tsezotene detachment level, the middle (red arrow) is the "boundary fault" which is a splay off of the "out of syncline" fault and remains at the level of the Gypsum detachment while the third fault is a southwest verging "out of syncline" fault (blue arrow) with minor displacement. Refer to figure 1.6a,b for legend.

Section F-F’: This cross-section (Figure 3.22) is constructed across the most complicated region in the study area, the Cache Lake Anticline (Figure 3.6). The section contains a number of faults that were present in the previous sections D-D’ and E-E’ (labeled faults 2 and 3), as well as several other faults, one of which is labeled 1 on the most southwesterly end of the section.The other two faults are labeled 4 and 5, where number 4 has been called the Cache Lake Fault and number 5 is a splay off of the Cache Lake Fault which is represented by a dashed line in this section because it does not surface but is present in the regional section to the southeast.

Fault 1 is shown to repeat the Little Dal Upper Carbonate in this section, and it is unknown if the fault is rooted at the Gypsum or Tsezotene detachment level. Fault 2 is the southwesterly extension of the “out of syncline” faults from sections E-E’ and C-C’ above, and in this section it no longer has a large syncline in its hangingwall but a rather gentle fold. The ramp geometry has changed substantially as it now has a shallower more consistent dip and is not as “listric” toward the surface as it is in the previous two sections. There are a number of splays associated with this fault in the footwall which complicate the Proterozoic and Paleozoic strata nearest the southwest limb of the valley syncline in the middle of the section. Fault 3 is also known as the Boundary Fault and is very steep in this section with a listric geometry, progressively steepening toward the syn-orogenic erosional level. This fault is rooted at the Gypsum detachment and remains at this level to the surface. Fault 4, also known as the Cache Lake Fault, is a very unique structure as there are no other known faults with this geometry in the study area or in the entirety of the Mackenzie Mountains.

By examining the map pattern alone is it is difficult to understand the complexity of this area thus a series of structural sections, one of which is balanced (regional section) were constructed across this fold to further investigate the attitude and geometry of the fault/fold system and to link the sections along strike to explain the cut-off of units and later truncation of the Cache Lake Fault/Fold by fault 5. In this section, the fault is rooted at the level of the Tsezotene detachment and is thrust up over the footwall such that the fault cuts up-section through all the units in the hangingwall until it eventually dies out in the Devonian clastic rocks in the valley to the northeast of the study area. It is believed that the displacement on the fault at its leading edge is completely absorbed by folding and minor shearing in these Devonian Clastic rocks rather than having an exposed structure for which there is absolutely no evidence in this area.

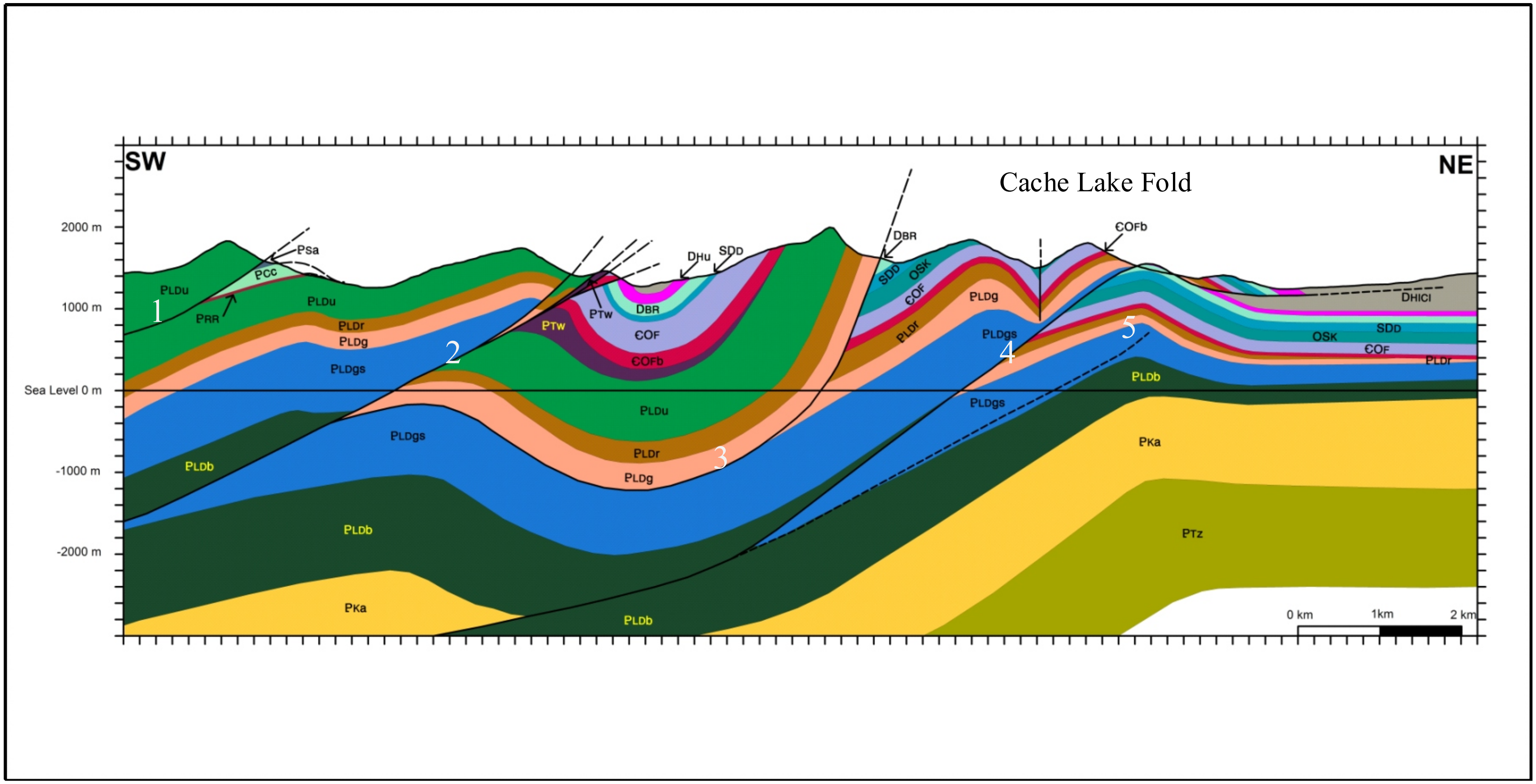

Figure 3.22 Cross-section F-F' shows the geometry of five faults, labeled 1-5 from southwest to northeast. This is the first of four sections that are drawn across the Cache Lake Fold, shown on the northeast side of the section.

Another unique feature of this area is that while this thrust is active, a splay develops in the footwall and takes on the form of a blind thrust, contemporaneously folding the footwall into an anticline while the Cache lake Fault is still actively passing over the footwall strata, slicing them at a low angle as they are being folded such that the map pattern eventually displays each unit of the footwall from the Proterozoic Little Dal Basinal Assemblage at the southeast area of the Anticline up to the Devonian Bear Rock formation in the northwest core of the Anticline, all of which is covered by Proterozoic strata of the hangingwall. To further complicate the map pattern, the above mentioned Proterozoic strata of the hangingwall is cut up-section from the Katherine Group right up to the level of the Little Dal Rusty Shale formation, exposing these units along the interior of the hangingwall fold limbs. As mentioned above, this fault eventually cuts up past the Little Dal Rusty Shale formation up to the Devonian Clastic rocks of the Canol, Hare Indian and Imperial formations. The amount of off-set on this fault is approximately 2-3 kilometers in this particular cross-section.

The next section (the regional section) to the southeast shows the result of fault 5 cutting through the footwall anticline and truncating the above hangingwall anticline and Cache Lake Fault. Fault 5 is only dashed in to show an approximation of its blind geometry. In the southwest limb on the Cache Lake Anticline, there is a relict “z” asymmetry parasitic fold that has been later dissected by a small northwest-southeast trending tear fault above the Little Dal Gypsum formation. The effect this parasitic fold has on the overall map pattern is to eventually cut out all of the Paleozoic units along the “boundary fault” in a much shorter distance that if there was no parasitic fold here.

Also in this section, there are a number of units that pinch out toward the northeast such as the Proterozoic Little Dal Upper Carbonate, Redstone River, Copper Cap, Shezal, and Twitya formations, and later more northeasterly in the section the Little Dal Grainstone, Gypsum, and Rusty Shale formations. Also, the Paleozoic Mount Kindle formation pinches out toward the southwest as it does not occur in the valley syncline in the middle of the section.

Section G-G’: Due to the close proximity of this section (Figure 3.23) trace to that of section F-F’, the faults that were in section F-F’ are the same as in this section with only minor variations in ramp geometry and cut-off depths etc. The faults are again labeled 1-5 from southwest to northeast. Fault 1 has less displacement than in the previous section, largely due to the fact that this fault dies out to the southeast and is not at all present in the regional section, some 3 kilometers to the southeast. Fault 2 is similar in geometry to the previous section aside from a small change in the splay associated with the footwall which in this section is much larger than in section F-F’.

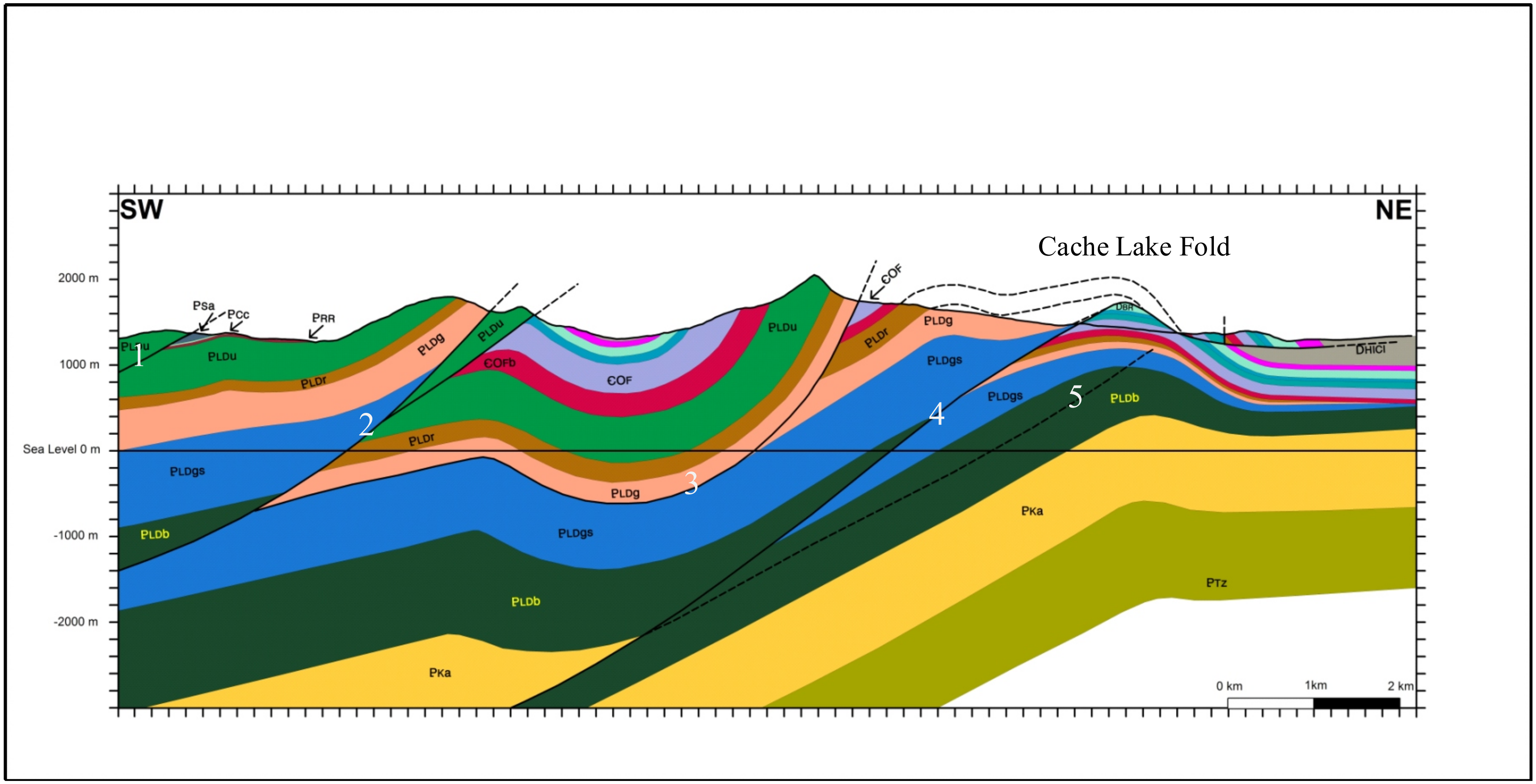

Figure 3.23: Cross-section G-G' shows the geometry of faults 1-5 as well as the Cache Lake Fold.

Fault 3 is unchanged while fault 4 has changed slightly, with a footwall anticline exposing older strata in its core and the hangingwall southwest limb of the Cache Lake anticline now is comprised primarily of Proterozoic strata rather than Paleozoic that has been folded. The displacement on all five of the faults is thought to be relatively similar as the sections are only 1.5 kilometers apart and there is little evidence for any change in displacement in the ramp geometries.

From a stratigraphic standpoint, this section is the same as section F-F' aside from the Twitya formation is not exposed at all along the trace of the section so was therefore left out of the construction.
Section H-H': This section (Figure 3.24) was constructed to show the geometry of the structures southeast of the regional section where the faulting involves many deeper structures as is indicated by the large presence of the Katherine Group rocks. There are 3 faults in this section, all of which are also present in the regional section as well as sections F-F' and G-G'. The first fault to the southwest is a continuation of the "out of syncline" fault in the previous sections except that the ramp has changed significantly in angle, allowing for Katherine Group rocks to be exposed as a fault bend anticline in the hangingwall. This fault has a small splay in its footwall which repeats the Little Dal Upper Carbonate formation. The second fault is a continuation of the Cache Lake Fault from the previous sections, and here it is observed to be cutting up-section (as described previously) through the Katherine Group. The third fault is a splay off of the Cache Lake Fault which repeats the Katherine Group and Little Dal Basinal Assemblage and faults them atop the Devonian units in the footwall. At this point in the study area the Cache Lake Anticline is no longer, and the deeper rooted Tsezotene detachment structures are better exposed than anywhere else in the study area. There are several changes in the stratigraphy in this section, for one the Little Dal Grainstone is much thinner here, only tens of meters compared to the hundreds of meters in the sections to the northwest. In addition to this, the Paleozoic rocks are cut off against a fault and are overall much less abundant in this area where the section transects. The structures that were much deeper in the crust to the northwest are at a much higher structural elevation in this part of the map area, likely due to an increased thickness of Proterozoic strata, particularly the Katherine Group and Tsezotene formation.

3.4 Cross-section Restoration and Depth to Detachment

3.4.1 Regional Cross-section Restoration

The regional section was drawn based on surface data only, without the help of seismic imagery or well data so all predictions in the section are based on structural measurements, unit thicknesses from measured sections and stratigraphic relationships seen elsewhere in the Mount Eduni map sheet.

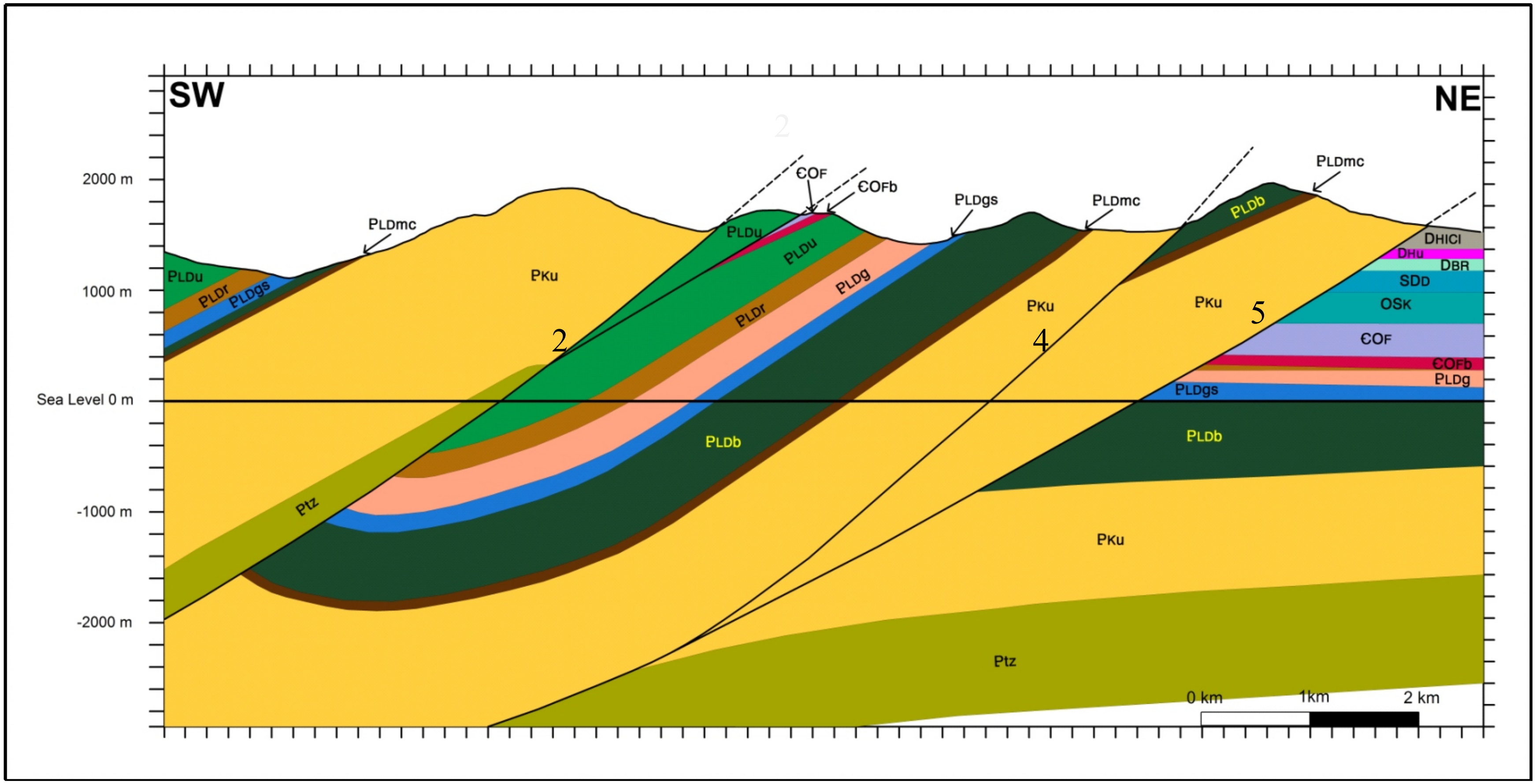

Figure 3.24: Cross-section H-H' shows the geometry of faults 2, 4 and 5 from the previous sections.

Construction of the regional section revealed that only one unit was continuously present across the entirety of the 50 kilometer section, the Little Dal Basinal Assemblage. As mentioned above, the other Proterozoic units that would normally be good candidates for “marker beds” have all been eroded and are truncated by the Sub-Franklin unconformity. In addition to this, the Paleozoic units such as the Franklin Mountain formation, do not continue across the entire section, and die out or fade into their basinal equivalents. Much of the Paleozoic strata have either been eroded due to their high structural elevation, or they have been intensely deformed by small splays of the larger structures making the “key bed” method almost impossible without major speculation and extrapolation of fault cut-offs above the current erosion level. The well exposed Little Dal Basinal Assemblage allowed for thickness and dips to be measured in all of the thrust panels providing the necessary data to reconstruct the bed along the line of section accounting for any thickness changes that occurred toward the basin. By examining this unit on the section it is obvious that it changes in thickness from just a few tens of meters in the northeast to upwards of a 1000 m in the southwest, likely due to the effects of the Sub-Cambrian unconformity at the base of the Franklin Mountain formation and possibly topographic constraints during deposition allowing for greater sediment accumulation toward the basin.

The restored section (Figure 3.25) displays evidence for the “Mackenzie Arch” proposed by Cook and Mclean (1991), whereby the Proterozoic units thicken toward the southwest and have a steepening dip toward the southwest, while they are almost all truncated by the Sub-Cambrian unconformity.
The restoration of the regional section depends heavily on the thickness changes observed in the Proterozoic units along the line of section, especially the Little Dal Group rocks. Due to the well constrained thickness and attitude of the Little Dal Basinal Assemblage, the ‘Equal-Area and Key-Bed Balancing” technique was used to reconstruct the section to the way it would have appeared before Early Cretaceous deformation structurally thickened and compressed the rocks in the region (Mitra et al., 1989). This technique requires each segment of the Little Dal Basinal Assemblage to be independently measured for both thickness and area. This data is then plugged into the equation la = Ax/t whereby la is the length of the undeformed segment, Ax is the area of the deformed segment (WXYZ) and t is the thickness of the bed that remains constant in the deformed and undeformed section (Figure 3.26). The new polygon W’X’Y’Z’ has the same area (Ax), and bed thickness (t) but the length of the polygon is now what it was before compression. All of these measurements assume plane strain and restoration must be done sequentially from the foreland to the hinterland (Mitra et al., 1989).

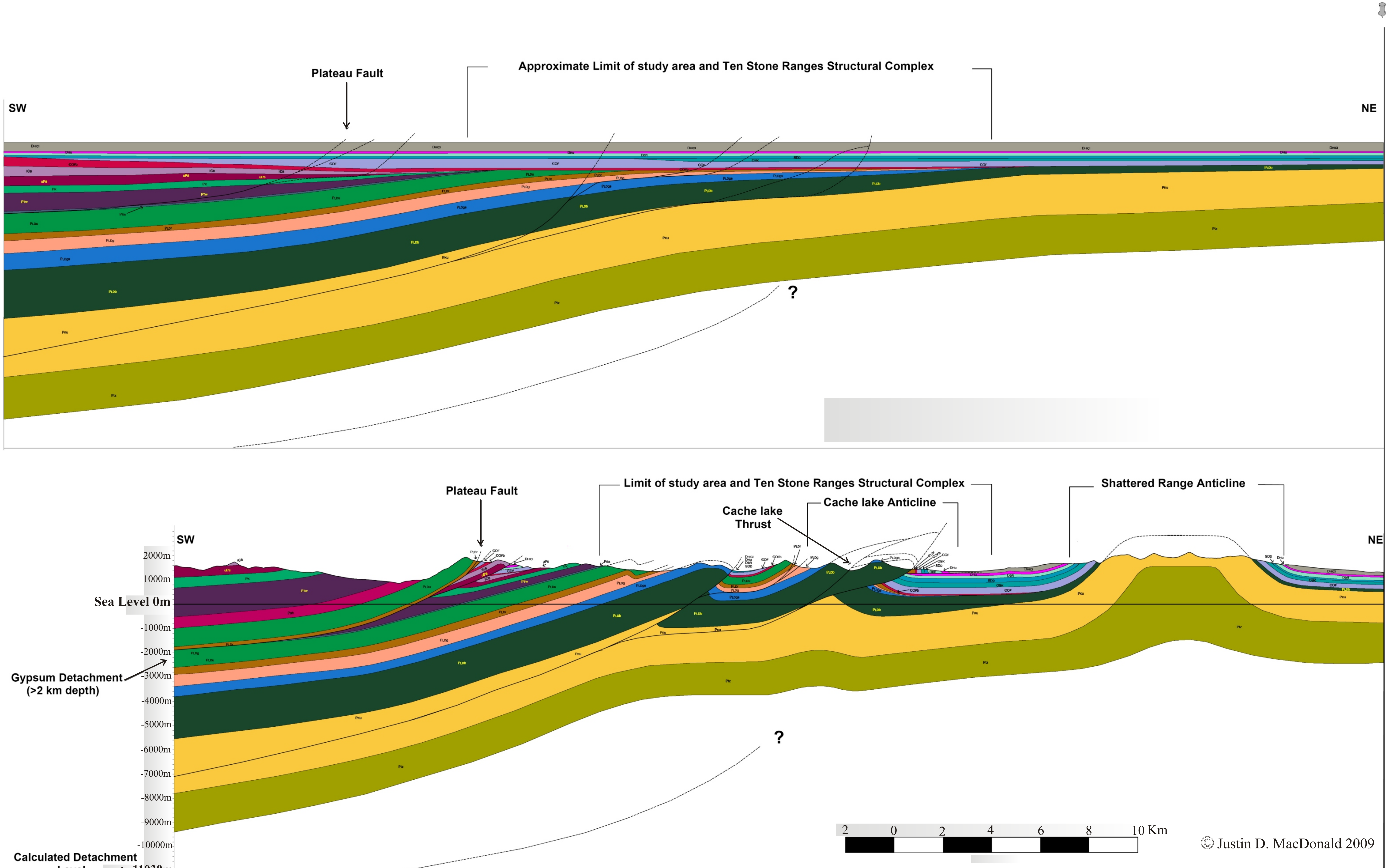

Figure 3.25: Regional cross-section X-X' that has been restored to original state before deformation that was constructed using a combination of "equal-area" and "key-bed" balancing techniques (Mitra et al., 1989). Fault trajectories are dashed beyond the current erosional level. Refer to figure 1.6a,b for legend. Refer to 1:50 000 scale regional cross-section in pocket.

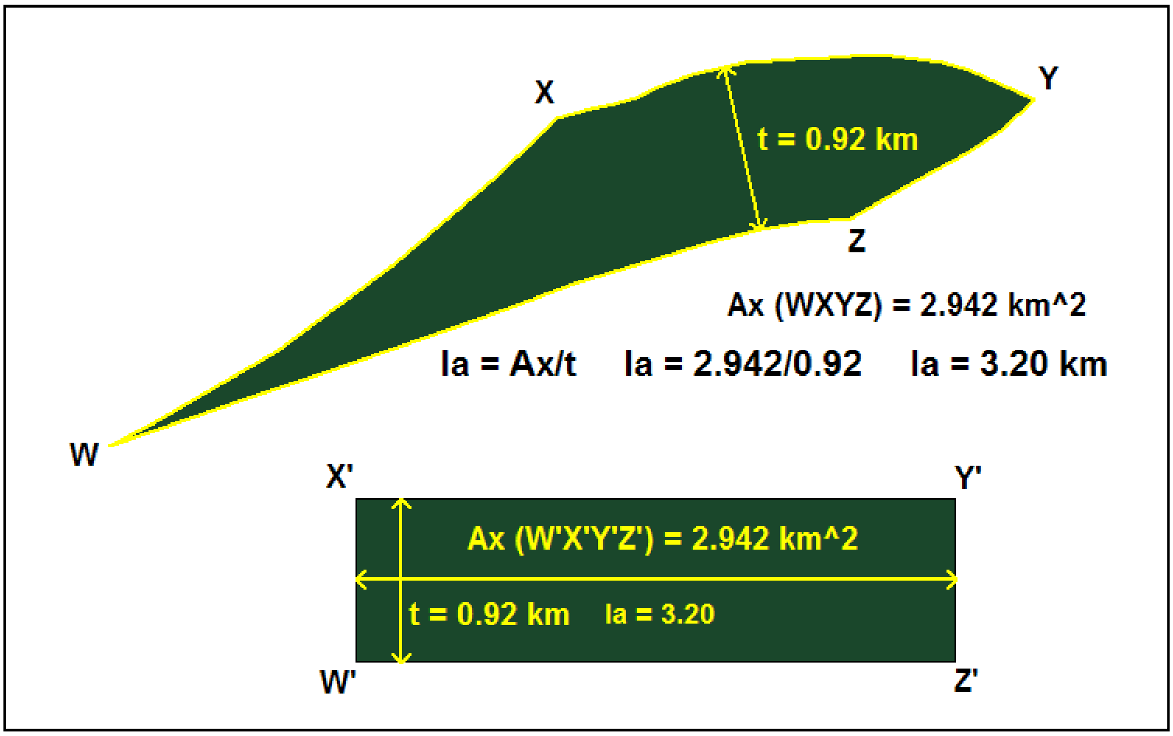

Figure 3.26: Sample polygon WXYZ from regional cross-section showing a section of Little Dal Basinal Assemblage that was thrust bounded on both sides (W-X and Z-Y) and used as an example to calculate the undeformed length la by using the Equal-Area equation la = Ax/t. Assuming plane strain conditions bedding thickness (t) is constant and following the "Law of conservation of volume" area (Ax) is equal in both undeformed and deformed states (Dahlstrom, 1969).

This Equal-Area method does preserve the area of the bed or panel however it does not always accurately portray where the fault cut-offs are or the exact ramp geometries thus the "Key-Bed" measurement helps to correctly predict the ramp geometries.The Key-Bed balancing involved measuring the original undeformed line length of the Key-Bed (l^o) and the length of the deformed regional section (l') and using the formula Shortening (S) = l^o – l' which for the Little Dal Basinal Assemblage was S = 57.04 – 49.69 = 7.35 kilometers of shortening or 14.79 %.

By measuring the line-length and of every segment of the Little Dal Basinal Assemblage, the "Key-Bed" in the regional section, and coupling this with the Equal-Area calculation, the restored bed was reconstructed with the appropriate thicknesses, area and length and fault geometries could be accurately portrayed. Each of the units in the regional section was measured, from foreland to hinterland, and transferred to the restored section sequentially from youngest to oldest, with the base of the Middle Devonian Hume formation as the horizontal datum across the top of the section. The reason this was chosen as the horizontal datum is due to the Middle to late Devonian marking the end of majority of the sedimentation in the Mackenzie Mountains, aside from younger Cretaceous rocks that are present in NTS sheet 105P. By Late Devonian, the Mackenzie Arch was formed and the later deposition of the Hume formation and overlying clastic rocks are thought to have happened in a relatively stable environment (Roots et al., 2008).

Once all units were measured and areas calculated and transferred to the restored section, the Katherine Group and Tsezotene formation were added to allow for fault trajectories to be placed on the restored section. Faults were measured from the regional section with each structural panel was checked for bed-length intersection points and area, and were then added to the restored section with their original trajectories determined and panel areas preserved.

3.4.2 Depth to Detachment Calculation

The "excess area" method was first used by Chamberlain (1910, 1919) in the central Appalachians and the Colorado Rockies and has since been used by numerous researchers around the world (Mitra et al., 1989). The theory involves the assumption of an originally rectangular stratigraphic sequence WXYZ that is bounded by two vertical pin lines XY and WZ that are situated in this case in the cores of the valley synclines on either side of the Shattered Range Anticline (Figure 3.27). Once deformed, the rectangle is shortened to the geometry of WX'Y'Z where the area lost in the deformation is equal to that "excess area" (A) above the datum line (Figure 2.28). The depth to detachment (Z) in its simplest case is then given by Z=A/(l^o – l'), where l^o is the original bed length, l' is the length of the deformed section from pin line to pin line and their difference is the shortening (Δl) (Mitra et al., 1989). In the case of the Shattered Range Anticline all of the parameters are measurable with a cross section so the access area (A) can be calculated with the above formulae. There is one assumption required for this method, which is that the vertical lines are in fact pin lines. In order for this to be true it must satisfy two criteria: (1) there is no transfer of slip into or out of the section (such as with a fault bend fold), and (2) there is no interbed shear (Mitra et al., 1989). The only unit that shows obvious signs of interbed shear is the Little Dal Gypsum formation which is not present in the fold limbs due to an unconformity so this has been ruled out as a possible source of error.

To determine the depth to detachment for the Shattered Range Anticline, a cross section was first drawn at 1:50,000 scale across the anticline from the mapping data. From this cross section, a datum was chosen at the base of the synclines on either side of the fold and a base line was drawn above which everything is considered "excess". The area of the polygon above the datum line was calculated by determining the area of a series of triangles and rectangles that were used to fill the polygon (Figure 3.27). This area (A) was transferred to the side of the diagram in Figure 3.27 where the width of the rectangle was determined from the change in line length ($l^o - l'$) to be 1.8 kilometers and then using the formula above the depth was calculated to be 12.7 kilometers below the datum line or 11.3 kilometers below sea level. Figure 3.27 also shows both the detachment level that was predicted from the cross section (black line) and the level that was calculated (red line) and there is only a few tens of meters difference in the two. This suggests that the detachment level is acceptable as it has met the criteria for both the calculation and the geometry of the section.

3.4.3 Sources of Error

Due to the high degree of interpretation and the sometimes qualitative nature of field mapping it is possible to have a number of errors associated with a project of this scope. Several of the more important sources of error are mentioned in this section.

3.4.3.1 Map and Cross-section Construction

The process of geologic mapping involves long days in often extreme weather conditions at high elevation, as is the case in the Mackenzie Mountains. As some areas are not traversable or are too dangerous to visit, interpretations must sometimes be made by using an aerial photograph or standing on the other side of a valley and making interpretations with binoculars.

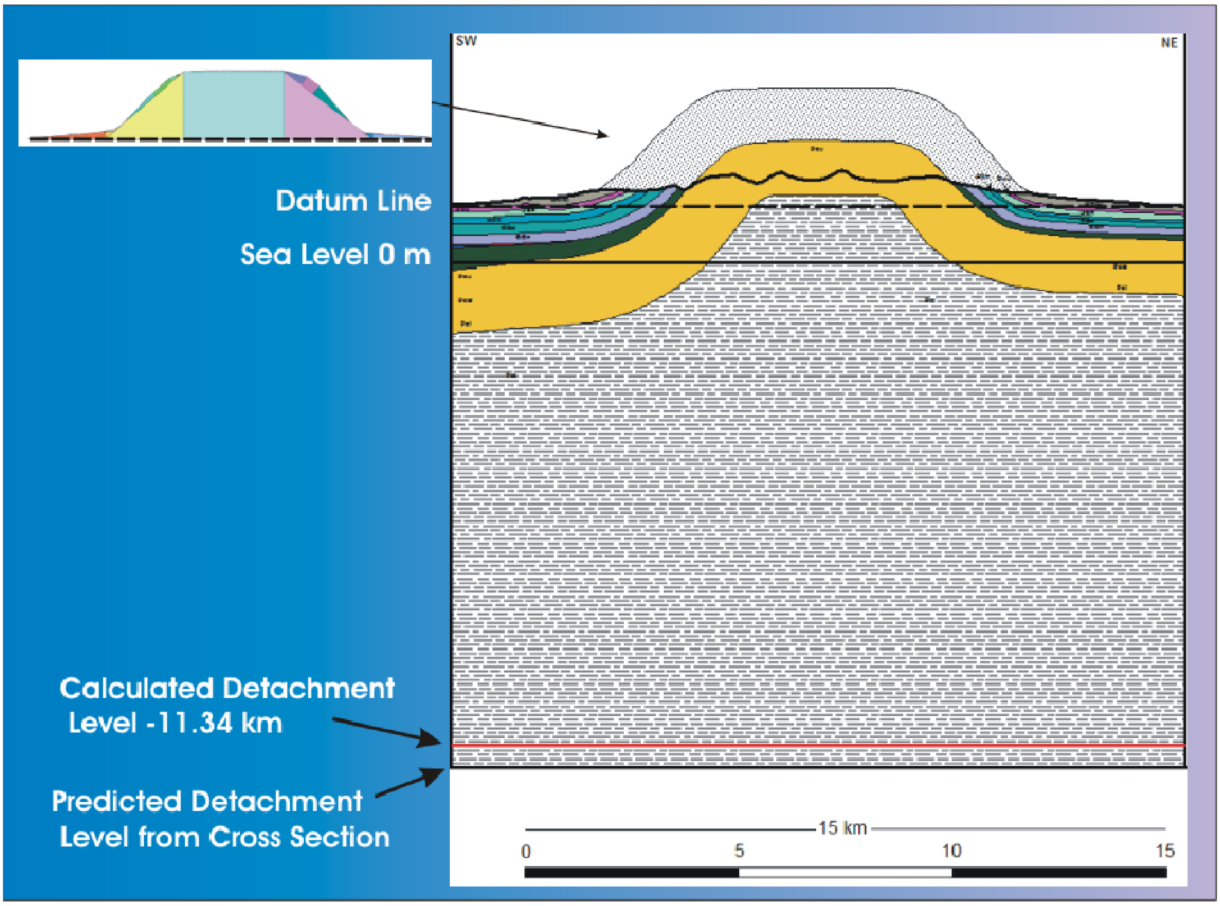

Figure 3.27: Schematic diagram showing the Shattered Range Anticline cross section with the position of the datum line (black dashed), sea level line (black solid), the calculated detachment level (red solid) and the detachment level predicted from the regional cross section (black solid bottom). Note also the polygon to the left showing the "excess area" with the colored rectangles and triangles inside used to calculate the area.

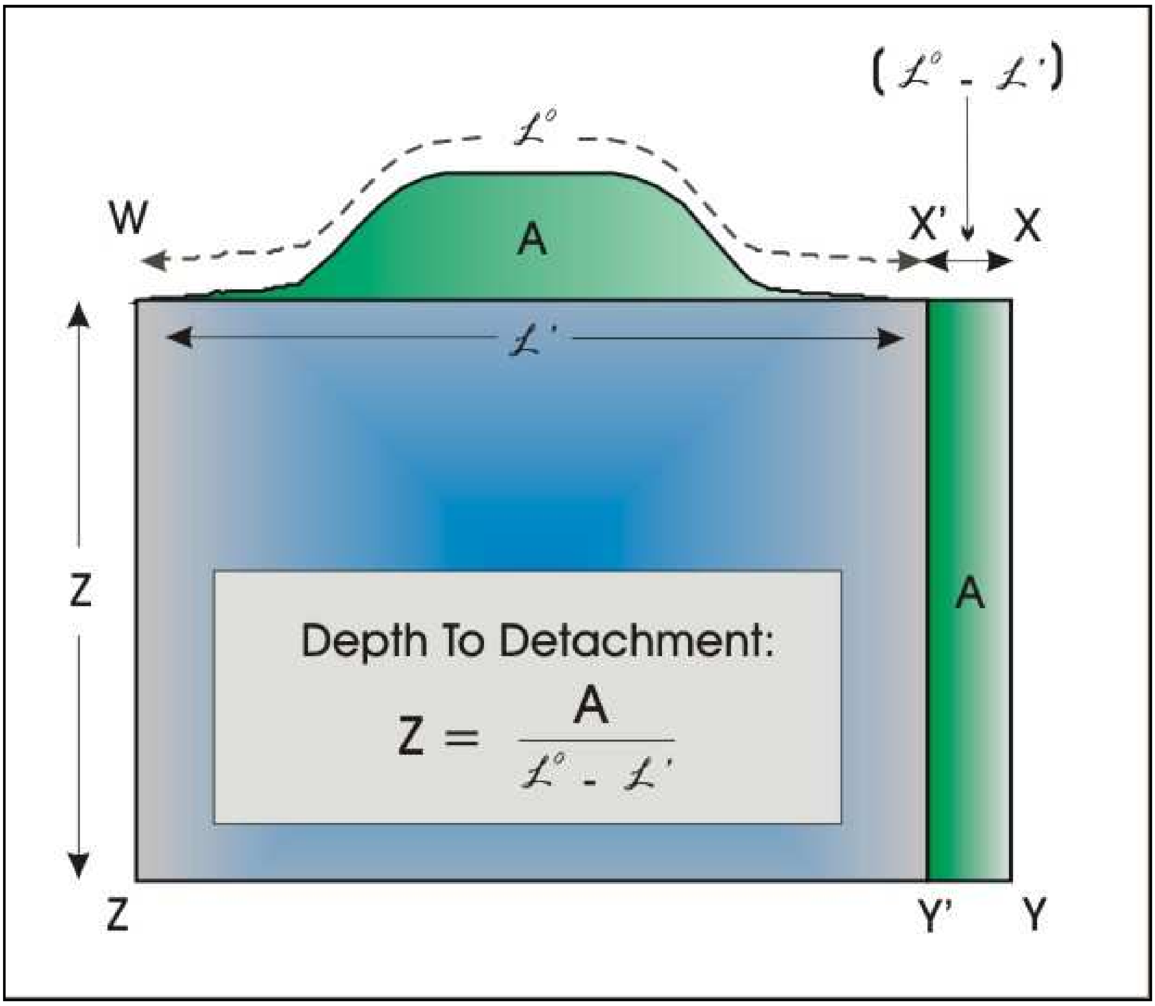

Figure 3.28: Schematic diagram showing the parameters involved in calculation of the depth to detachment for the Shattered Range Anticline where l^o is the original length of the reference bed, l' is the length of the deformed section and the area shown in green (A) is the excess area that has been transferred during deformation. The result (Z) is the depth to detachment (after Mitra et al., 1989).

In addition to this, valleys offer poor exposure and are often where large-scale faults are located as fault zones are more easily eroded than a competent outcrop.
Many of the structures are interpreted solely on stratigraphic position and repetition of units and the actual faults are often not measureable, so trajectories must be obtained by using strike/dip data on adjacent units in the hangingwall and footwall.

When constructing a geologic map, some contacts are assumed or inferred as they must occur but there is no outcrop in that particular area, thus an interpretation is shown on the map with a dashed line rather than a solid one. Some workers may re-map an area at a larger scale and improve on or update older work, maybe even come up with a new interpretation when newer data is available. This does not necessarily mean the older work was wrong, but rather it was not as accurate as the newer interpretation.

When constructing cross-sections in an area that has no control points in the subsurface such as with this project, there could be any number of possibilities for geometries of structures as everything below the surface is interpretation. However, there are numerous rules that must be followed ranging from the basic principles of geology to the more complex rules of balanced cross-section construction, but in the final product, the interpretations must be geometrically possible.

3.4.3.2 Restoration Error

Perhaps the largest source of error in restoring a cross-section is the construction of the cross-section in the first place. The section must be conservatively constructed, then "pulled back" or restored to see if the geometry of the individual units, folds and faults all make sense. For instance, in an environment such as the Mackenzie Mountains, thrust or reverse faults must always (aside from some very special circumstances) place older over younger strata, and units must not be below their regional structural level. This means that a Paleozoic unit will not likely occur two thousand meters below the regional datum for that unit unless there are special circumstances such as normal faults at play to lower it.

Undoubtedly the largest source of error in this project is in the cross-section construction for the schematic sections. The regional section has been restored and in doing so almost every aspect of the original section was revised, sometimes several times. This was done to ensure all geometries in the section are possible. The schematic sections were constructed so they are geometrically possible at that scale, however because they were not restored there may be unforeseen complications.

It is assumed that plane-strain deformation is the main deformation mechanism in this environment and internal or grain-scale deformation is negligible. In addition to this, because volume is conserved and folding is concentric, bedding thickness does not change (structurally) with deformation in a two-dimensional cross-section (Dahlstrom, 1969). There may be slight variations to the above rules in the case of the Little Dal Gypsum formation where bedding thickness is observed to change and the gypsum can be “squeezed” and acts in a ductile manner in certain circumstances. Overall, the effect on the cross-sections by the ductile nature of the Gypsum formation is likely insignificant, but should be mentioned as a potential source of error.

3.4.3.3 Depth to Detachment Error

The depth to detachment calculation above involved an assumption that there was no net material added or subtracted from the system (no change in cross-sectional area) during growth of the anticline (Jones, 1987). Jones (1987) suggests that this is not the case and there is material added and removed as it is not a closed system. It has been shown that results from a calculation such as this often show a detachment level that is too deep; this is known from reversing the calculation when a detachment level is known through drilling and/or seismic data. However, in the case of the Mackenzie Mountains, as previously mentioned, there are no such data to rely on so rough calculations of the detachment depth are a good indication of detachment depth. In addition to this, the depth to detachment was calculated after the regional section was drawn, and it lies just below the minimum depth of the Tsezotene formation, indicating that it is a reasonable result (see Figure 3.25) for this cross-section.

3.5 Structure Summary

There is little doubt that the most structurally complex part of the Mount Eduni map sheet is the central thrust-and-fold belt which makes up the TSRSC. This area contains structures typical of a fold-and-thrust belt such as thrust faults, décollement folds, tear faults, fault bend folds and all scales of parasitic folds. Within the TSRSC, the Cache Lake Fold displays a complex map pattern, and is best described with the use of serial cross-sections to demonstrate the variability of individual structures along their strike lengths.

The use of a balanced cross-section to determine a reasonable estimate for the shortening in this area (7.35 kilometers or 14.9%) was essential, as it would be very difficult if not impossible to derive an accurate estimate of shortening by using the serial sections drawn across the TSRSC. The shortening in this area is much less than has been determined for the southern Rocky Mountains, and the underlying detachment is the glide plane above which all of the Laramide age structures in this area formed. This detachment has been both calculated and determined from the balanced cross-section construction and has an estimated minimum depth of 12.68 kilometers below the surface. The reader must keep in mind that all of these results are based entirely on geologic surface data and no seismic or drill data were available for the Mount Eduni area when this study was completed.

Chapter 4
Discussion and Conclusions

4.1 Introduction

The Mackenzie Mountains are a great example of a thin-skinned tectonic regime and are the northern extension of the Rocky Mountains in the Cordillera. The mountains form a foreland fold-and-thrust belt, where Laramide-aged southwest to northeast compression resulted in a dominantly décollement folded terrain with listric thrust faults. These mountains span a cross-section from Paleozoic platformal rocks in the northeast to basinal graptolitic equivalents to the southwest, nearest the Selwyn Basin of the eastern Yukon. These Paleozoic rocks are underlain by a thick package of Neo-Proterozoic strata that have undergone extension in the late Proterozoic as well as Laramide compression. These supracrustal rocks are all deformed above a number of detachment or décollement surfaces that are located in the Proterozoic stratigraphy overlying the crystalline basement, of which the depth is uncertain in the Mackenzie Mountains. Several balanced cross-sections exist across parts of the central and south-central Mackenzie Mountains, with estimated shortening of 53 kilometers, similar to the 55 kilometers proposed by Gabrielse and Talyor for the northern Rocky Mountains (Gordey, 1981).

4.2 Regional Detachment Levels

Perhaps the best studied and best understood of the detachments in the Mackenzie's is that of the Gypsum detachment associated with the previously discussed Plateau Fault. From examining the regional section, and comparing the detachment depth on this section to the sections constructed by Gordey (1981), Cecile and Cook (1981), Roots (2008) and MacNaughton et al. (2008) it is apparent that along the fault the average level of the detachment is quite variable depending on how the above authors construct their sections. The Gypsum detachment has been presented in these sections at elevations between -12 kilometers to +1 kilometer, so the depth to this detachment is dependent on where the author chose to draw the section and how they depicted the Plateau Fault and Gypsum detachment at depth. The Gypsum detachment level is not as significant as the level of the Tsezotene detachment, as this is the level that any fault in the Gypsum detachment would have to been rooted at initially.

There are many locations in the Mackenzie Mountains where strata older than the Little Dal Gypsum formation are exhumed in the hangingwall of various faults. For this reason these faults are undoubtedly rooted at a detachment level below the Little Dal Gypsum formation. Where exactly in the crust the detachment is located is not certain; it could be at the base of the Katherine Group, or in lower stratigraphy such as the Tsezotene formation or H1 Unit. Given that the oldest exposed strata in the Mount Eduni map area is the Tsezotene formation, and that little is known about the rocks below this level, it is safe to assume that the detachment is either in the Tsezotene or below it, thus this was the name chosen for the detachment.

While constructing the structural section through the central Mackenzie Mountains, Gordey (1981) was interested by a regional trend involving the elevation of the Devonian clastic rocks of the Hare Indian, Canol and Imperial formations. It has been proposed that the cores of regional synclines in a thin-skinned environment represent an area of little tectonic thickening; however detachments can pass below and operate without raising the structural elevation of the rocks in the syncline cores (Dahlstrom, 1969). This is likely a similar situation to what was happening in the Mackenzie's when it was observed that a straight edge placed on the section from syncline core to syncline core showed the same elevation. This was applied in the sections constructed for this project as well, and with similar results. Every syncline where Devonian clastic rocks were preserved had a similar elevation, thus this is evidence that there is very little tectonic thickening below the synclines.

In the TSRSC, these synclines are often bound on the southwest side by a northeast vergent fault, stepping up from the regional detachment below. This position of the synclines in the footwall of major faults is indicative that the syncline will allow the detachment to pass under for some time until the next fault ramps up through the stratigraphy and breaks through, thickening the strata northeast of the syncline. It is for this reason that the detachment level is believed to be flat under the Mackenzie's rather than stepped (Gordey (Personal Communication), 2009). If the detachment had a major step, let's say caused by a topographic high in the crystalline basement, then everything northeast of the step would be at a higher structural elevation. Due to the phenomenon stated above with the Devonian rocks in the syncline cores, there is likely no step or ramp in the underlying Tsezotene detachment. Thus the regional section presented in chapter three has a flat detachment at its base, and the area above this that is uncolored is likely a thick package of Proterozoic strata whose thickness is unknown as mentioned in chapter two.

4.3 The Plateau Fault

There has been much interest over the years in determining the exact geometry of the Plateau Fault, which is intimately associated with the Gypsum detachment, the glide plane for the fault. In the 1970's the Plateau Fault was first mapped at a reconnaissance scale of 1:250 000 and was hypothesized to be a potential hydrocarbon play. The Plateau Fault was thought of as the most significant structure in the mountains and was a large scale structure with an approximate strike length of 250 kilometers, that had the potential to cover significant quantities of Paleozoic, particularly Devonian aged stratigraphy that were already proven to be excellent source and reservoir rocks in the Mackenzie Planes, near Norman Wells. It became quite obvious that the Gypsum formation of the Little Dal Group was the likely detachment surface and due to its rheology, it would act as a potential seal for a reservoir.

This potential hydrocarbon play drove the need to understand the structure of the Plateau Fault as well as its Gypsum detachment by further studies. Fallas et al. (2008) of the Geological Survey of Canada spent three summers mapping along the Plateau Fault from 2006-2008, from Wrigley Lake (NTS 95M), northwest to Mount Eduni (NTS 106A) in which time a number of cross-sections and a much better understanding of the fault was developed. The main questions involving the fault were: (1) what is the overall geometry of the fault? and (2) is there evidence for or potential for significant Paleozoic strata to be buried in the footwall of the fault? In addition to these questions, MacNaughton et al. (2008), also of the Geological Survey of Canada, did a thorough investigation of the stratigraphy along the fault, investigating the potential source and reservoir rocks to see if conditions were favorable for hydrocarbon generation and accumulation.

After investigating the fault and analyzing previous sections by Gordey, (1981) and Cecile and Cook, (1981), MacNaughton et al. (2008) concluded that the Plateau Fault was not a suitable structure, mainly because of the geometry, the absence of evidence for large volumes of Paleozoic rocks in the footwall and also due to insufficient hydrocarbon source rocks. As was discussed in chapter 3, the geometry along the fault was found to be insufficient to cover any significant amount of Paleozoic strata, and in most areas the fault is more of a steep reverse fault rather than a far-traveled thrust sheet. In the regional section constructed for this project, it is evident that the fault has > 20 kilometers of displacement; however it has listric geometry nearest the surface where the Paleozoic rocks are located in the footwall. This geometry is unfavorable for hydrocarbon trap formation, and it appears to be prominent along the entirety of the structure.

4.4 The Ten Stone Ranges Structural Complex

The TSRSC is undoubtedly the most intensely deformed zone in the Mount Eduni map area, with a high-density of faults and many interesting fold structures (Figures 3.4, 3.6). This area has been described in chapter three as a transfer zone where many of the large structures surface, and interesting map patterns are exposed such as the Cache Lake and the Mountain River Folds. The exact location of this central thrust-and-fold belt is intriguing and can best be explained by examining the regional cross section (Figure 3.25). The restored section shows a change from the northeast to the southwest whereby the strata, particularly the Tsezotene formation and Katherine Group; change from almost horizontal to moderately southwest dipping. This change is fairly abrupt, and occurs directly under the TSRSC as can be seen by the superimposed fault geometry on the restored section. In addition to this, the "Mackenzie Arch" model that was discussed in chapter 2 is evident in this section whereby the Little Dal Group is truncated (aside from the Basinal assemblage) across the area that is now occupied by the TSRSC. When taking these observations into consideration, it is evident that the location of the TSRSC transfer zone is likely influenced by the change in dip of the stratigraphy, as well as the increase in thickness of the Little Dal Group to the southwest.

The restored section which runs through the most intensely shortened area of the TSRSC had an estimated shortening of 7.35 kilometers, majority of which happened within the TSRSC. This value is difficult to compare to the above mentioned shortening value (53 kilometers) by Gordey (1981) as that cross-section spanned the entirety of the Mackenzie Mountains, as well as the Franklin Mountains and the Interior Plains to the northeast. It is however very useful for a number of reasons: (1) any future structural studies (such as ongoing construction by Gordey (2009) of a balanced cross-section through northwest Mount Eduni map sheet) with shortening values can be compared to the value attained from the regional section, (2) this value would be important to other researchers in the area who are undertaking stratigraphic studies and would need to know the approximate distance over which particular formations thin or thicken between platform and basin, and (3) perhaps the most important use of this data would be for future petroleum or mineral exploration companies that would require an estimate of the amount of compression in the Mount Eduni map area.

4.5 Conclusions

4.5.1 Synopsis of completed work

From 1:50 000 mapping in the study area, some 500+ square kilometers of the Ten Stone Ranges were mapped by the author for the purpose of documenting and determining the nature of the structures present in this area. The TSRSC contains numerous structures of varying complexity from 1:250 000 scale folds like those of the Cache Lake and Mountain River, to the smallest of structures such as cm scale ductile drag folds in the Little Dal Gypsum formation. The structures in this area have been well documented, and are aided by a number of strategically placed cross-sections displaying individual faults and how they change geometry along strike. The main advantage of serial cross-sections is that they allow the reader to follow any one fault in the transfer zone across several sections along strike of the structural grain, aiding in visualization and understanding of this complex system of structures.

In addition to the above mentioned cross-sections, this project involved the construction of a regional balanced cross-section which was used to determine the amount of shortening in the area, as well as for the calculation of the depth to detachment for the regional décollement surface underlying the mountains. The result of the depth to detachment calculation supported what previous authors predicted for the basal detachment, but, without detailed seismic imagery, it is likely to never be confirmed. The above data, along with the 1:50 000 scale map of the TSRSC, have resulted in an increased understanding of the structural geometry of the area, as well as the geometry of the Plateau Fault in the Mount Eduni map sheet.

Overall, the Mount Eduni 1:250 000 map sheet now has a detailed map of the central thrust-and-fold belt (the TSRSC), a series of schematic cross-sections from southeast to northwest and a 50 kilometer balanced cross-section through the southeast portion of the map which will be available for future scientists and industry working in this area.

4.5.2 Concluding Remarks

From the above work, a number of conclusions have been made:

1) The most significant detachment level in the central Mackenzie Mountains is likely located within the Tsezotene formation and has been calculated to be 12.68 kilometers below the current erosional level. Due to the geometry of the Shattered Range and Stony Range Anticlines, there is a high probability that the detachment surface is flat and does not step up in the central Mackenzie Mountains.
2) The Plateau Fault has a thrust fault geometry in the Mount Eduni map area with a minimum of 20 kilometers lateral displacement and is rooted at the level of the Gypsum detachment, which in this area is estimated to be -2500 - -3500 meters below the current erosional level. Due to the listric geometry that the fault has where it surfaces, there is little to no possibility of significant Paleozoic strata being buried in the footwall; thus the probability of hydrocarbon trap formation is low.
3) The Cache Lake Fold system is complex, and is best classified as a fault-bend-fold whereby the footwall is also folded to mimic the hangingwall geometry. This system is very unique in that it involves folding of an earlier thrust fault (the Cache Lake Fault) and is the only fold of this complexity in the Mount Eduni map area, and likely the Mackenzie Mountains.

4) The TSRSC is a unique area that provides a window to view both detachment levels as well as the relationship of the Plateau Fault to the area. It is evident that the Plateau Fault had a very minor role in the formation of the structures in the TSRSC; these structures, including the regional Anticlines to the northeast, are a result of the interaction of the Tsezotene detachment on the significant change of dip and thickness of the underlying Neo-Proterozoic stratigraphy (i.e. the Mackenzie Arch) in the area of the TSRSC. Thus, in conclusion, it is evident that the TSRSC is an artifact of a complex combination of stratigraphic thickness change and structural geometry of the basal detachment.

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