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Is Fluid Flow in Paleozoic Formations of West Central Alberta Affected by the Rocky Mountain Thrust Belt?

BY

Patrick Kent Wilkinson ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Masters of Science.

DEPARTMENT OF GEOLOGY

Edmonton, Alberta
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FACULTY OF GRADUATE STUDIES AND RESEARCH

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To Mom, Dad, and Sue

Abstract

The influence that thrust belts may have on fluid flow within foreland basins is not well understood. To determine the subsurface hydraulic regime within a thrust zone, one must first identify the effect of individual faults. The influence that a single thrust fault may have on fluid flow can be grouped into four possible types: a) flow fault, b) conduit fault, c) obstruction fault, and d) barrier fault. The first and last cases represent the two end members of a spectrum, namely, complete hydraulic communication versus an impermeable barrier. A conduit fault may provide a preferential pathway for fluids through a more permeable zone. Lastly, an obstruction fault impedes flow by a partial reduction of hydraulic communication across the fault.

Geological interpretations combined with fluid pressure and chemical analyses from Paleozoic aquifers have indicated areas of preferential and restricted flow within the Alberta Foreland Basin. Within the Alberta Foreland Fold and Thrust Belt structural complexities form additional fluid barriers and conduits influencing fluid flow. Structural interpretations within the Burnt Timber region of the Alberta disturbed belt were completed prior to a hydrogeological evaluation. Both regional and local flow systems are indicated by the contrast in water chemistry between shallow meteoric sourced springs and deeper more highly saline waters. An increase in the Turner Valley Formation total dissolved solids (TDS) is observed within a Burnt Timber area below the Brazeau Thrust. The TDS values are greater than what are found in the equivalent Elkton Formation of the Alberta Foreland Basin. The obstruction of fluids across the Brazeau Thrust increases the length of flow time which causes an increase in the formation TDS. Preferential and restrictive fluid flow throughout the

study area have a significant impact on exploration due to the influence of formation waters on the migration and distribution of hydrocarbons.

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I would like to extend my thanks to all the people who have supported this thesis by providing moral support, useful technical advice, and the financial means to complete this project. First and foremost, I would like to thank my advisor Dr. József Tóth for the many cups of coffee accompanied by helpful discussions of the latest observations in my thesis. The project also benefited from Dr. Tóth's NSERC operating grant and teaching assistantships from the Department of Geology. Thanks to my advisory committee members: Dr. H.G. Machel, Dr. H.A.K. Charlesworth, and Dr. F.W. Jones.

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Chapter 1

Introduction

1.1 Statement of problem

The application of petroleum hydrogeology in exploration has become a more widely used and accepted tool. The incorporation of hydrogeology as a mainstream petroleum science is evident from numerous recent studies that have integrated hydrodynamics, fluid chemistry, isotope geology, thermodynamics, and petroleum geology (Bredehoeft *et al.*, 1994; Villegas *et al.*, 1994; Holysh & Tóth, 1994; Berg *et al.*, 1994; Rostron, 1995). These studies have expanded and added to earlier ideas by Hubbert (1953) and Tóth (1980) identifying the relationship of subsurface fluids to other geologic processes, namely, petroleum migration and accumulation.

Several regional studies have described the hydrogeology and petroleum hydrogeology in portions of the Western Canada Sedimentary Basin (WCSB) (Hitchon, 1969a; Hitchon, 1969b; Tóth, 1978; Hitchon, 1984; Rostron, 1995). The boundaries of each of these studies are within the undisturbed portion of the WCSB. Little is known about the hydrogeologic relationship at the basin's western edge. Generally, it is assumed that high fluid potentials found in the Cordillera drive formation fluids eastward away from the thrust belt resulting in various related phenomena. However, the hydraulic influence that the Rocky Mountains Thrust Belt may have on formation-fluid flow within the foreland basin has never been explicitly investigated.

A speculative hypothesis first introduced by Oliver (1986), suggested fluids are expelled from convergence zones into continental interiors. Subsequent numerical models by Ge and Garven (1994) simulate induced fluid flow from active tectonic deformation. Their calculations approximate volumes of paleo-fluids generated during orogenesis. Similarly, Deming *et al* (1990) and Burtner and Nigrini (1994) model various thermal consequences of compaction and gravity driven flow from thrusted regions. Burtner and Nigrini depicted the thermal history of the Idaho-Wyoming Thrust Belt using evidence from geothermal gradients and organic maturation. Their models suggest that gravity-driven flow transported large amounts of paleo-fluids as indicated by regions of low heat flow. However, the active geologic processes resulting in various paleo-fluid movements are not the same as the present geologic processes found today within a stable thrust belt.

Present day flow systems may or may not have similarities to modelled paleo-flow systems. Therefore, one of the general objectives of this project is to determine if it is possible to use surface and subsurface evidence to determine the influence of the disturbed belt on present flow systems. In other words, do groundwater levels within the Cordillera have a significant effect on fluid flow in the subsurface of the Foreland Basin? In essence, what is the present hydraulic nature of the thrust zone?

A thrust fault acting as either a conduit or barrier to flow has ramifications that are significant to the understanding of many large and small scale water-related processes and phenomena within the foreland area. For example, hydrocarbon migration and distribution, geothermal gradients, location and composition of springs, and source of formation fluids involved in subsurface dolomitization and surface salinization are all affected by regional water flow patterns, the origin of which is not completely understood.

1.2 Objectives

The three objectives of this project are:

- To develop an understanding of the hydrogeology within Mississippian and Devonian strata of the Disturbed Belt and adjacent Alberta Basin.
- Establish if there is any subsurface hydraulic communication between the Rocky Mountains and its Foreland regions.
- Determine if the Rocky Mountains have, or may have had, any effect on the migration and regional distribution pattern of petroleum east of the disturbed belt.

Chapter 2

Background to Study Area

2.1 Location

The study area is located in west central Alberta, approximately 70 *km* northwest of Calgary. The area is bounded by townships 29 and 36 (approximately 51°30′N to 52°10′N) on the south and north, respectively; by the fifth meridian (114°W) on the east and on the west by the eastern edge of Banff National Park and range 14w5 (116°W) (Figure 2.1, p. 5). The study area was selected to incorporate portions of both a) the Foreland Fold and Thrust Belt and b) the Alberta Foreland Basin, two structural elements within the Western Canadian Sedimentary Basin (WCSB) as defined by Wright *et al* (1994).

2.2 Geology

2.2.1 Stratigraphy

According to Mossop and Shetsen (1994), the Western Canada Sedimentary Basin can be divided into two stratigraphic sections which are indicative of differences in paleotectonic setting and sedimentation characteristics. Firstly, the cratonic platformal succession consists of predominantly carbonate Paleozoic to Jurassic rocks which were deposited adjacent to the ancient passive margin of North America. On the other hand, the generally clastic rocks of the Jurassic to Paleocene comprise the

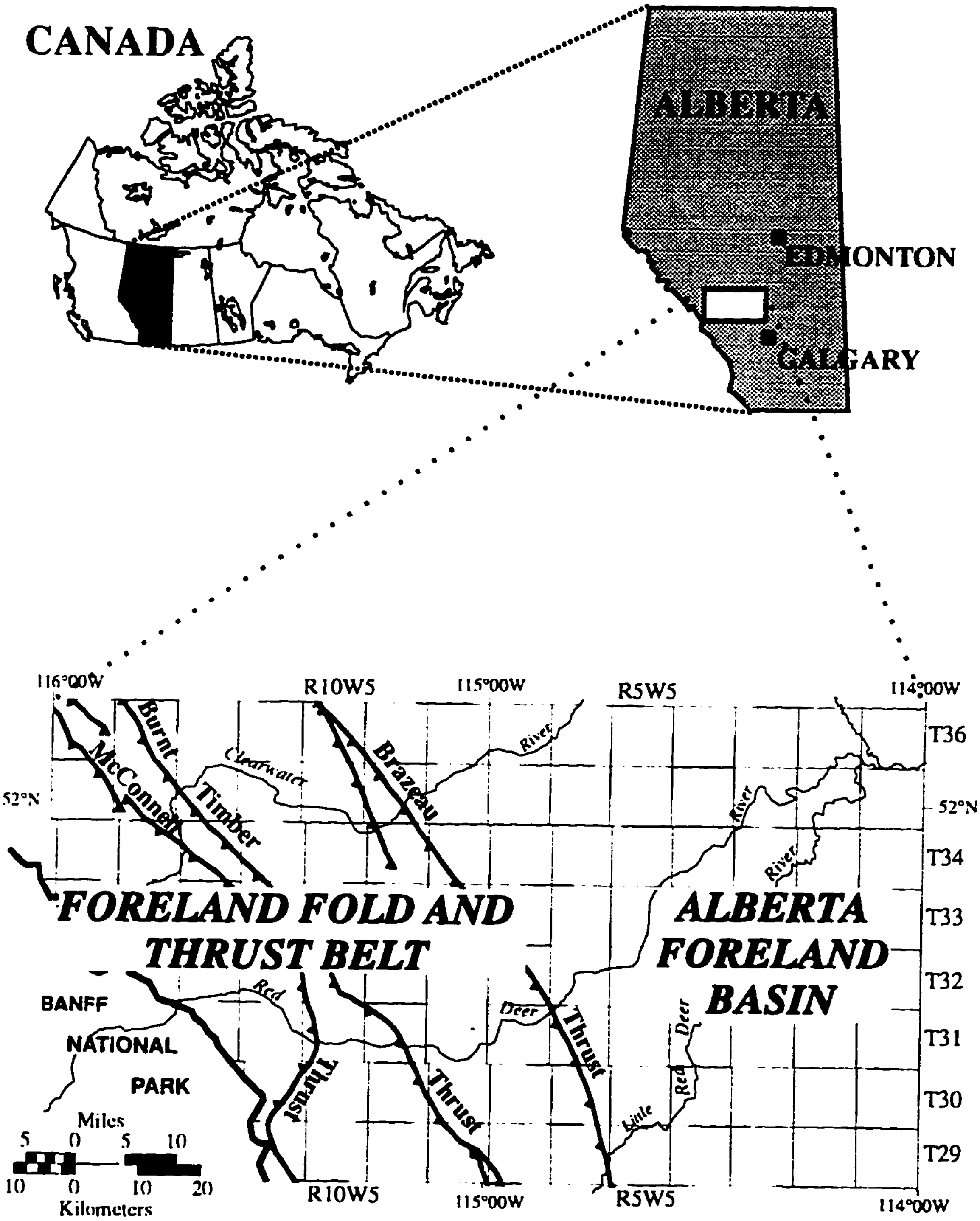


Figure 2.1: Study area location map. The Brazeau Thrust divides the Foreland Fold and Thrust Belt from the Alberta Foreland Basin (Wright, 1994).

foreland basin succession deposited bordering the active margin during orogenesis. This compressive mountain building stage lasted for approximately 120 Ma. from the Middle Jurassic to the Eocene. This study focused on the Mississippian and Devonian Formations of the platformal succession within the Alberta Basin and Foreland Fold and Thrust Belt areas.

Slight variations in stratigraphic relationships and terminology exist between the basin and disturbed belt regions. Figure 2.2 (p. 7) illustrates the basic regional stratigraphic relationships between these two regions. Within the basin, the sub-Cretaceous unconformity separates the lower platformal carbonates of the Mississippian and Devonian from the overlying foreland clastic strata. Therefore, from the western to eastern parts of the Alberta Foreland Basin, progressively older Paleozoic formations subcrop beneath the Cretaceous unconformity. Within this study area, the Elkton and Pekisko Mississippian aquifer subcrops are present (Figure 4.1, p. 43).

The rocks of Devonian age within the central plains of the Alberta Foreland Basin consist of the Elk Point, Beaverhill Lake, Woodbend, and Winterburn Groups. The Woodbend Group consists of platform and reefal carbonates found in the Cooking Lake and Leduc Formations as well as basin-filling shales in the Duvernay and Ireton Formations (Stoakes & Wendte, 1994). Switzer (1994) summarizes four significant features during the Frasnian as: a) apparent increase in rate of accumulation and preservation of sediment, b) greater amounts of basin-filling shales, c) development of regionally extensive reef complexes and source rocks resulting in, d) accumulation of large quantities of hydrocarbons. The generalized occurrence of Leduc reef complexes within the study area and surrounding regions is illustrated in Figure 2.3 (p. 9). These generalized reef edges are included on relevant maps in subsequent chapters to assist in any observations and interpretations.

The Mississippian Rundle Group is located in both the Alberta Foreland Basin and the Foreland Fold and Thrust Belt. Generally, the lithologies of the Elkton/Turner Valley and Pekisko Formations are dominantly crinoidal limestone and dolomite (Martin, 1987). The Shunda and Banff Formations can be characterized as a more

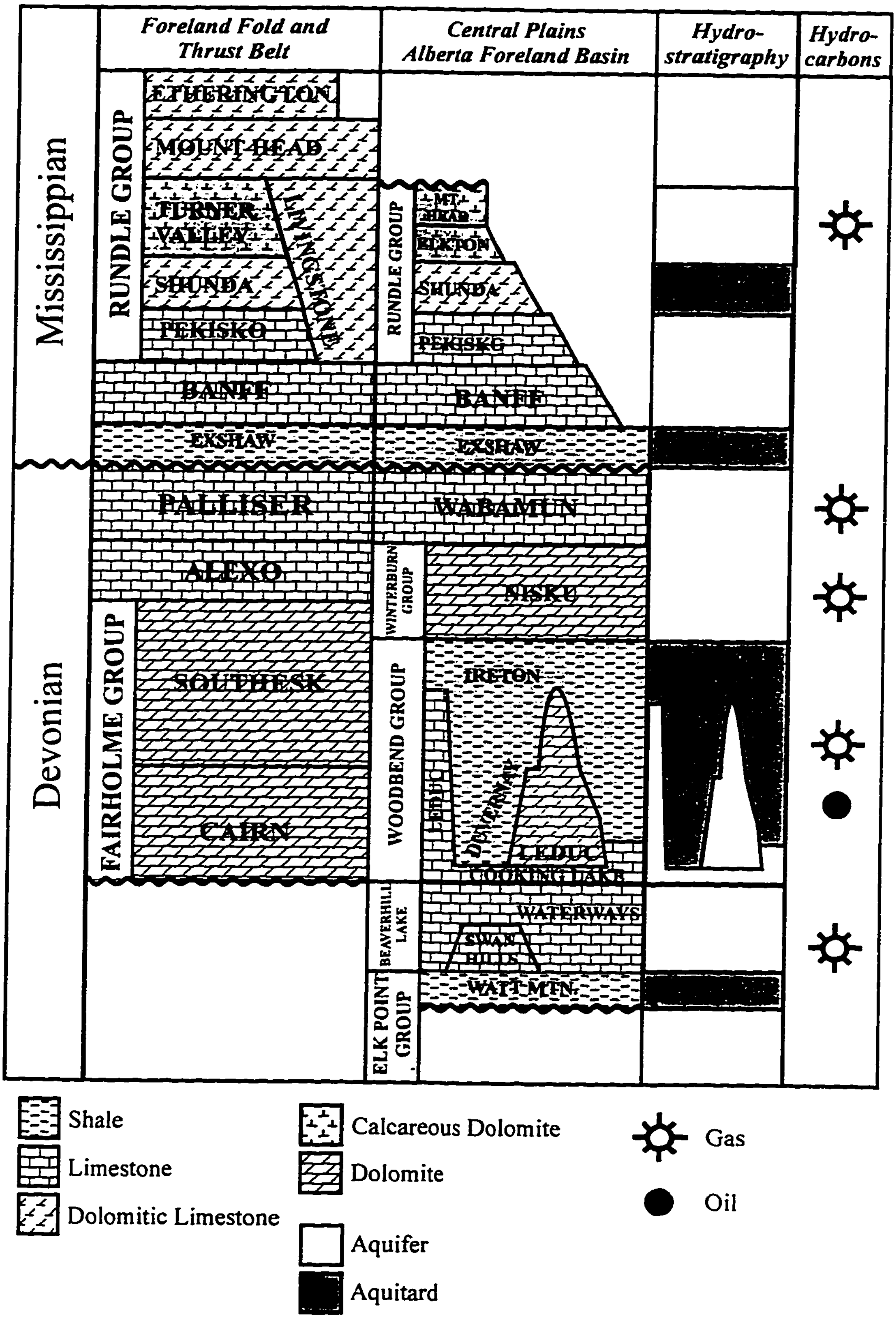


Figure 2.2: Stratigraphic and hydrostratigraphic chart including gross lithologies for the Alberta central plains and fold and thrust belt regions.

argillaceous silty dolomite. The Shunda Formation may also have a significant shale component.

2.2.2 Structural and bedrock geology

The four subprovinces of the southern Canadian Rocky Mountains are defined as the Foothills, Front Ranges, Main Ranges, and Western Ranges (Price and Mountjoy, 1970). According to Price and Mountjoy (1970), thrust faults within the Canadian Cordillera generally have the following characteristics: i) a southwest dip, ii) are concave upwards, iii) flatten with depth, and iv) gradually cut up through the stratigraphic section. Significant variations in surface and subsurface geology differentiate the Fold and Thrust Belt from the Alberta Basin within the study area. The Foreland Fold and Thrust Belt can be generally divided into three structural units underlain by the McConnell, Burnt Timber, and Brazeau Thrusts (Ollerenshaw, 1975) (Figure 2.4, p. 10).

Various fold and fault structures expose Devonian, Mississippian, Jurassic, and Cretaceous rocks west of the Brazeau Thrust. The McConnell Thrust marks the eastern edge of the Front Ranges of the Rocky Mountains where predominantly Paleozoic Formations are outcropping. The majority of the thrust faults strike trend in a northwest to southeast direction. However, the southern portion of the McConnell thrust significantly deviates from a southeast to a southwest strike around the Panther River anticlinorium. Within this structure, Mesozoic and Paleozoic Formations of the Burnt Timber Thrust sheet are strongly folded such that Mississippian carbonates crop out. Similarly, east of the Burnt Timber Thrust, Mississippian carbonates are folded and exposed within the Limestone and Marble Mountain anticlinoriums. East of the Brazeau Thrust within the Alberta basin, the Upper Cretaceous Brazeau Formation and the Paleocene Paskapoo Formation are outcropping. A basic understanding of these structural features was important before any hydrogeological data could be observed and interpreted. Additional geological observations and results are found in Section 4.1.

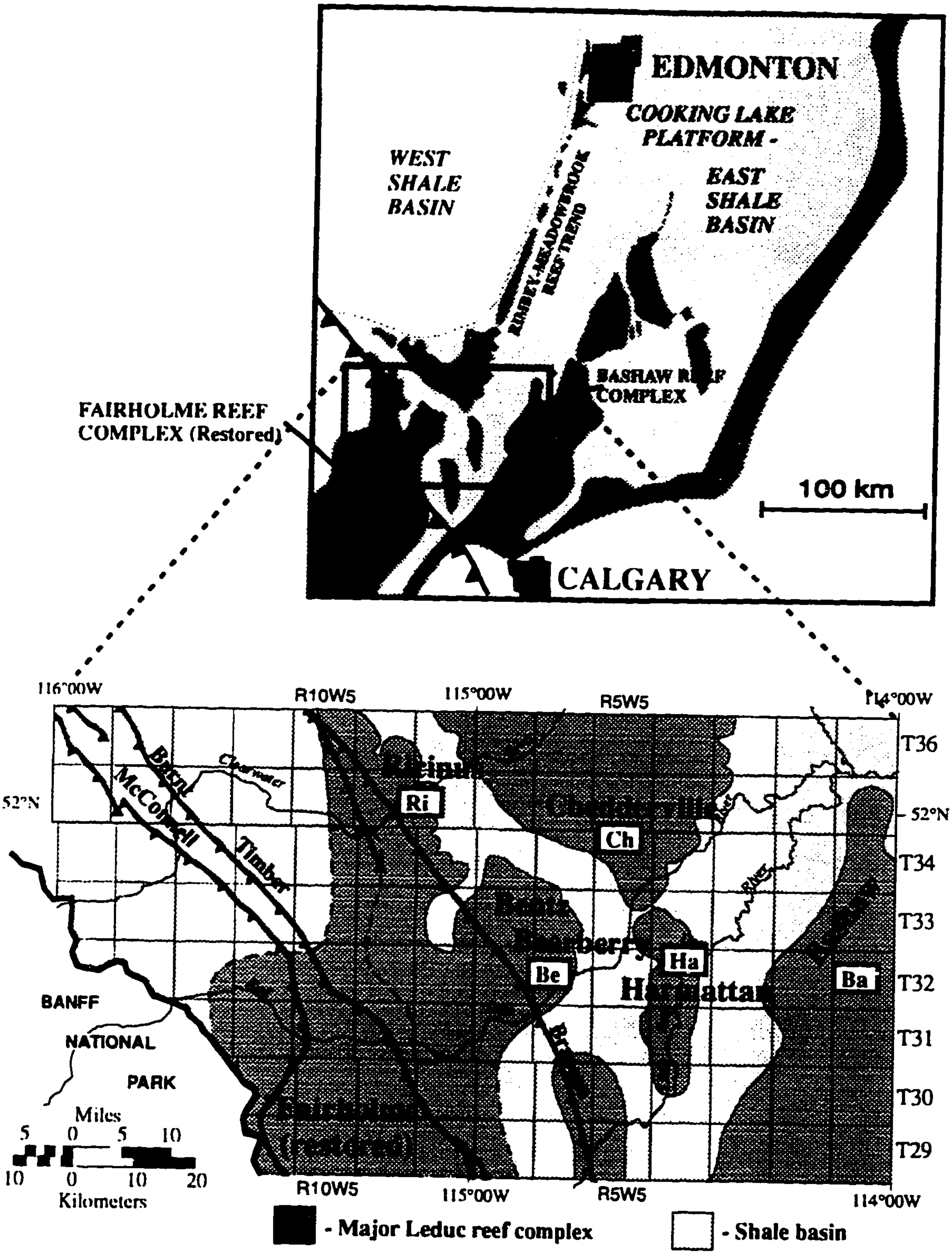


Figure 2.3: Reference map for Leduc reef complexes within the study area and surrounding regions (Modified from Switzer *et al*, 1994). Leduc reef edges from Andrews (1987).

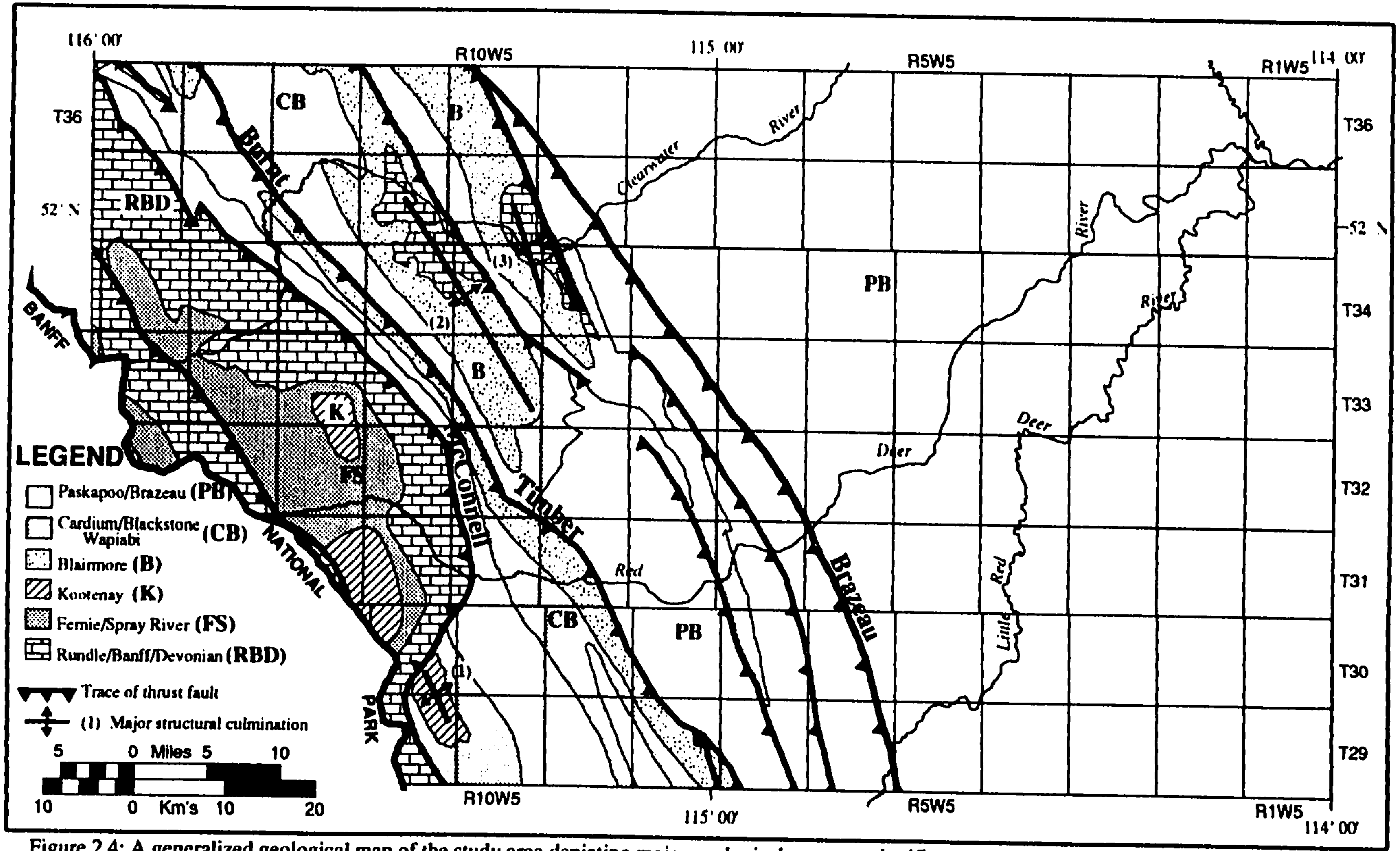


Figure 2.4: A generalized geological map of the study area depicting major geological contacts, significant thrust faults, and identification of prominent structural anticlinoriums: (1) Panther River, (2) Limestone Mountain, and (3) Marble Mountain. For clarity, only major thrust faults are shown. Formation symbols and shades do not necessarily reflect formation lithology (modified from Ollerenshaw, 1975; Wheeler and McFeely, 1991).

2.3 Hydrogeology

2.3.1 Topography

As one might expect, the topography within the study area ranges from lows within the plains of the Alberta Basin to highs within the main ranges of the Rocky Mountains (Figure 2.5, p. 12). Elevations of approximately 1000 *m.a.s.l.* (3280 *ft.*) at the eastern boundary of the study area progressively increase to values greater than 2400 *m.a.s.l.* (8000 *ft.*) at mountain peaks within the main ranges. An abrupt change in topography to values greater than 1830 *m.a.s.l.* (6000 *ft.*) occurs west of the McConnell thrust marking the eastern edge of the main ranges of the Rocky Mountains where predominantly more resistant Paleozoic carbonate rocks are outcropping. Numerous rivers are sourced within the Rocky Mountains and flow east to north-easterly through the study area. The Clearwater and Red Deer rivers originate within the main ranges forming two of the larger valleys west of the McConnell Thrust. The Little Red Deer River is a tributary of the Red Deer River flowing northerly within the eastern portion of the study area.

2.3.2 Previous hydrogeological work

The majority of the previous hydrogeological work in the Western Canada Sedimentary Basin deals with the undisturbed part of the basin east of the Brazeau Thrust. In fact, there is a limited number of references which directly discuss the disturbed belt fluids and their role on hydrocarbon migration in the basin. The following discussion is divided into five areas of research which are significant to the present study, namely, fault related fluids, paleotectonic fluids, sedimentary basin fluids, geothermal fluids, and petroleum migration.

Fault related fluids

The arrangement of permeability within a sedimentary basin may have anisotropic and heterogeneous characteristics due to formation lithology and fault distribution.

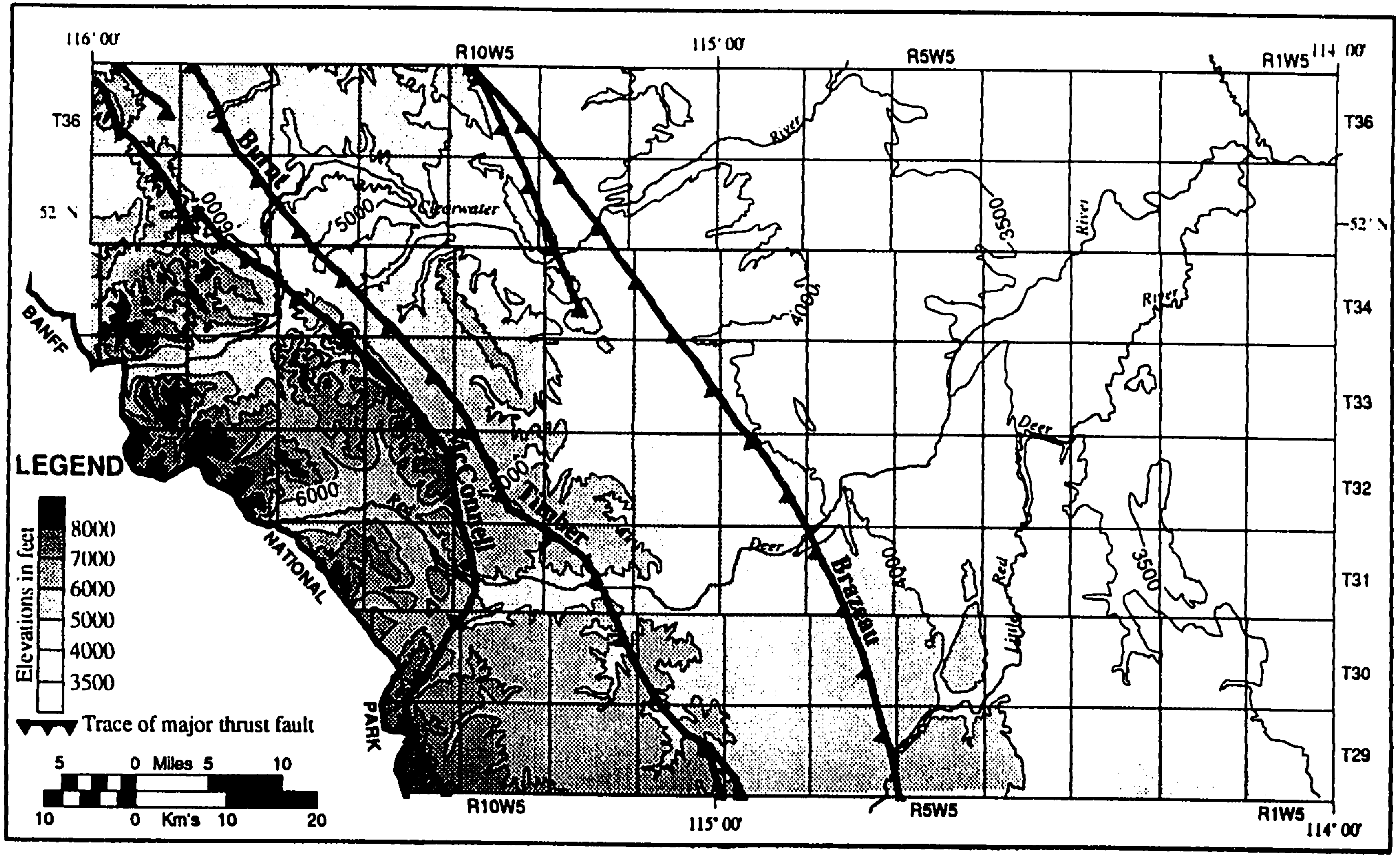


Figure 2.5: Study area topography (modified after NTS, 1960; NTS, 1964).

Individual fault properties within a stable region may influence the flow regime by either increasing or decreasing formation permeability. According to Davis and De Wiest (1966), a fault may form either a barrier or conduit to flow. A fluid barrier results due to a decrease in permeability along the fault surface which may occur in the following situations:

- Frictional sliding along the fault plane forming a layer of ground rock material known as fault gouge.
- Fault displacement laterally juxtaposing aquitards and aquifers.
- Rotation of elongated grains parallel to the fault surface.
- Deposition of minerals along the fault plane.

Otto (1992) classified possible sealing mechanisms into those related to a cap rock, fault, or hydrodynamics. A fault-related seal may result from a sealing mechanism such as fault gouge, cataclasis, and diagenesis or from the juxtaposition of a lower permeable aquitard adjacent to a higher permeable aquifer. According to Daly *et al* (1980) and Faye and Prowell (1982), in the absence of a fault gouge, the aquifer displacement along the fault is the most significant factor which influences hydraulic communication across the fault. Daly suggests increases and decreases in chemical processes such as carbonate dissolution near faulted regions are indicative of fluid movements which are either restricted or enhanced due to aquifer displacement, or lack thereof, across faults. Reduced permeabilities may result from the movements of fluids that dissolve, transport, and deposit minerals within the fault.

A fault surface may also act as a conduit for fluid flow. The location of springs (Borneuf, 1982), ore bodies (Newhouse, 1942), and oil seeps (Otto, 1992) have been associated with the movement of fluids along a fault plane. Forster and Evans (1991), studied the hydrogeology associated with thrust faults. Their field and modeling results considered the region in the vicinity of a thrust fault as a complex highly permeable zone with both conduits and barriers to flow. Furthermore, Kerrich (1986), suggested that recharging meteoric surface waters may penetrate to depths of 10 km due to the presence of highly permeable faults.

Paleotectonic fluids

The purpose of this study was to examine flow systems that develop active once faulting has ceased. Many researchers have speculated and modeled flow systems during thrusting. Oliver (1986), proposed a hypothesis where zones of convergence expel great amounts of fluids, thereby acting like a "great squeegee". This hypothesis suggested tectonic fluids have an important role associated with faulting, magma generation, hydrocarbon migration, mineral transport, metamorphism and paleomagnetism.

A series of papers by Ge and Garven (1989; 1990; 1992) modeled the paleohydrology associated with major thrust zones with applications to various types of sedimentary basins. The original paper suggested foreland basin fluids could be tectonically derived. However, tectonic compression could only create excess flow rates which were 2 to 4 orders of magnitude less than what would be expected from gravity driven flow estimated by Garven and Freeze (1984a; 1984b). According to Bradbury and Woodwell (1987), a direct association exists between the occurrence of veins and stable isotope geochemistry associated with the McConnell Thrust in the Canadian Rocky Mountains. Therefore, $\delta^{13}C$ and $\delta^{18}O$ isotopes suggest fluid-rock interactions are present within 10-15 m on either side of the thrust fault. Using this interpretation, Ge and Garven (1994) applied their earlier models to the McConnell Thrust by defining the thrust as a thin hydrostratigraphic unit which would have acted as a conduit during thrusting due to the presence of smaller fractures. Their results indicated that a low-permeability thrust fault could act as a barrier to flow.

Basinal Fluids

Within the Alberta basin, several studies have interpreted the hydrogeology within or near the boundaries of this study. Earlier work illustrating the effects of topography

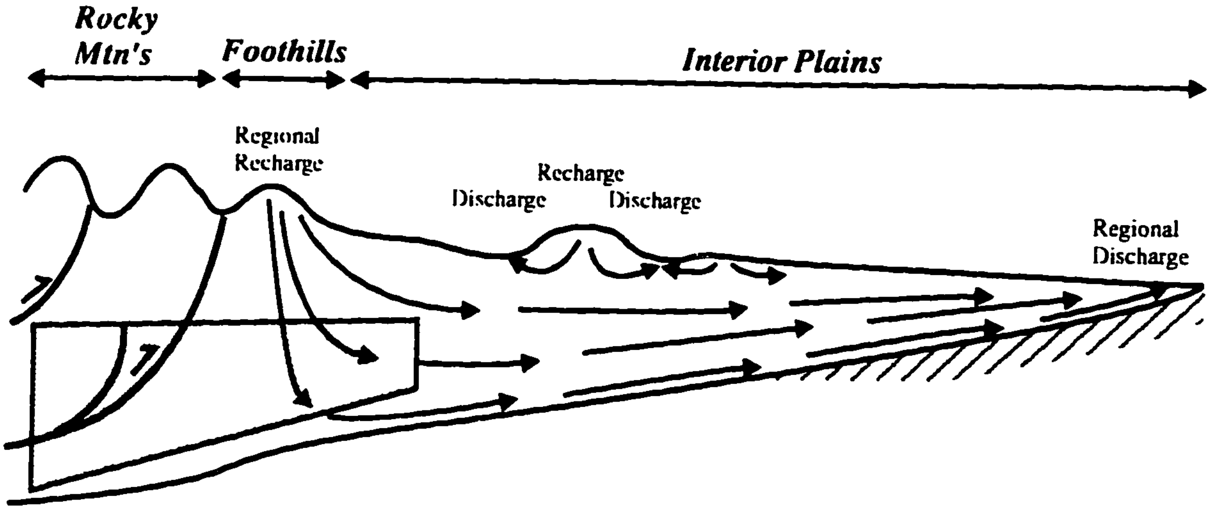


Figure 2.6: Generalized schematic flow diagram of the WCSB based on topography, temperature, and hydrodynamics (modified after Hitchon, 1984). Shaded area indicates present study area in cross section.

and geology on fluid flow within the entire WCSB was completed by Hitchon (1969a; 1969b). More recently, Hitchon (1984), suggested a generalized flow system within the Alberta basin (Figure 2.6, p. 15). Based on the hydrodynamics and temperature regimes, Hitchon suggests the principal source of fluids within the Alberta Basin is derived from the Foothills region. A more detailed study by Connolly *et al* (1990a; 1990b), studied the origin and evolution of formation waters based on the chemistry and isotope signatures. They suggested that formation waters within the Alberta Basin can be classified into three groups (Figure 2.7, p. 16). The lower group I is defined as the dominantly carbonate Devonian and Mississippian Formations as well as the Cretaceous Basal Quartz Formation. Group II waters comprise both carbonate and clastic reservoirs of the Middle Jurassic Fernie Group, Lower Cretaceous Ostracod and Viking Formations. Lastly, Group III waters are associated with the clastic Jurassic Rock Creek Formation, Cretaceous Cardium Formation and the Belly River Group. The Mississippian and Devonian Formations studied in this project roughly correspond with Connolly's lower Group I and Wright's (1994) cratonic platformal succession described in Section 2.2.1.

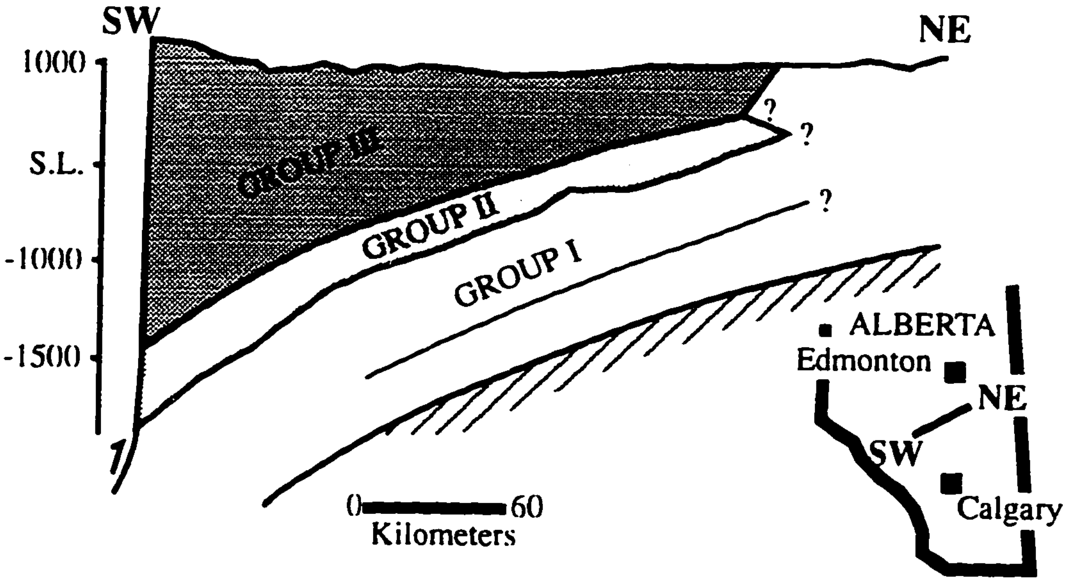


Figure 2.7: Schematic geological cross section through the Alberta basin depicting three groups of formation waters (modified after Connolly, 1990a).

According to Rostron (1995), the Phanerozoic section of north-central Alberta can be classified into the following four hydrogeologic groups: a) Paleozoic, b) Jurassic to Lower Cretaceous, c) Cretaceous and, d) shallow formations. This interpretation was based on an evaluation of cross formational fluid flow determined from fluid potentials and formation water chemistry. Rostron identifies northeast to southwest flow directions within the Cretaceous part of the section. This suggests a basinal flow pattern which deviates significantly from what was proposed by Hitchon (1984). Paul (1994) studied the hydrogeology of the Devonian Rimbey-Meadowbrook Reef trend, the base of which is present in the northern townships of this study identified as the Cheddarville Reef Complex (Figure 2.3, p. 9).

Geothermal Fluids

Convection and conduction are the two possible methods of heat transport within the Earth's crust. Within the WCSB, there is some debate over which mechanism provides the more plausible explanation for observed temperatures and geothermal gradients. The main controlling factor of heat transfer within a convection-dominated basin is the amount and direction of fluid movement whereas a conductive regime is controlled by the location of heat sources and thermal properties of the rocks. The analysis of subsurface temperature data was beyond the scope of this study. However, the following literature review provides some necessary background information which is useful in interpreting hydrogeological data within both the disturbed belt and adjacent sedimentary basin.

According to Majorowicz and Jessop (1981), Hitchon (1984), and Majorowicz *et al* (1985), the geothermal patterns in the WCSB are influenced by an interrelated geothermal gradient, hydrodynamics, and topography. Observed lower geothermal gradients in recharge areas correspond to infiltrating cooler meteoric waters at the surface. Higher geothermal gradients are found in discharge areas located in topographic lows. However, according to Bachu (1988) the hydrogeological regimes in the Swan Hills and Cold Lake regions of Alberta are too complex and formation permeabilities are too low, to allow significant convection of heat by formation waters. Bachu suggested that the heat flux could only be explained by conductive means and applied this conclusion to the remainder of the Alberta Basin based on the sedimentological and thermal conductive similarity between his study area and other parts of the Alberta Basin.

More recently, Nunn and Deming (1990; 1991) attempted to quantify fluid and heat transport using numerical models to evaluate and assess the possibility of topographically driven recharge versus overthrust compaction as mechanisms for regional fluid migration. They suggested that topographically driven recharge, which is cold at the surface, can acquire enough heat within the basin to produce observed high temperatures found within discharge zones at shallow depths. However, this would only occur in geological situations which produced very high heat flows. On the other hand, their models also do not entirely support compaction-driven flow from thrust belts as the sole mechanism to produce the observed thermal effects within the adjacent foreland basin. Therefore, they suggest spatially and temporally concentrated flow systems resulting in the observed thermal manifestations within the foreland basin.

Petroleum migration

Over the past ninety years, several major descriptions of the influence of groundwater on petroleum migration have been published. The transport of hydrocarbons by moving groundwaters within a sedimentary basin evolved from early thoughts of Munn (1909) who considered all sedimentary rocks to have some permeability providing for cross formational flow. Subsequently, Hubbert (1953) quantified the idea of petroleum entrapment under hydrodynamic conditions by describing the hydraulic, buoyant and capillary forces which are present in the subsurface. Furthermore, Hubbert illustrated the concept of different fluid potentials for gas, oil and water indicating different fluid migration directions, or in other words, sites of minimum potential energy. Lastly, Tóth (1980) formalized the *Generalized Hydraulic Theory of Petroleum Migration* based on several examples from various basins around the world. The generalized hydraulic theory is based on the following three tenets: a) mature sedimentary basins are regionally hydraulically continuous, b) topographically generated groundwater flow, and c) hydrocarbons are transported and deposited by moving groundwater. A summary of Tóth's theory is depicted in Figure 2.8 (p. 19). Hydrocarbons are thought to be trapped in areas of minimal potential energy which is associated with geological traps related to unconformities, faults, and stratigraphy.

2.3.3 Fault classification

As was introduced in Section 2.3.2, a fault surface can be considered as a barrier or conduit to flow (Davis and de Wiest, 1966). . For the purpose of this study, two additional terms will be used in addition to Davis and de Weist's terminology. Figure 2.9 (p. 21) depicts a flow fault, conduit fault, obstruction fault, and a barrier fault as four schematic simplifications of fluid flow associated with possible types of thrust faults. The development of this classification enabled the identification of possible flow scenarios and associated manifestations which would be suspected with

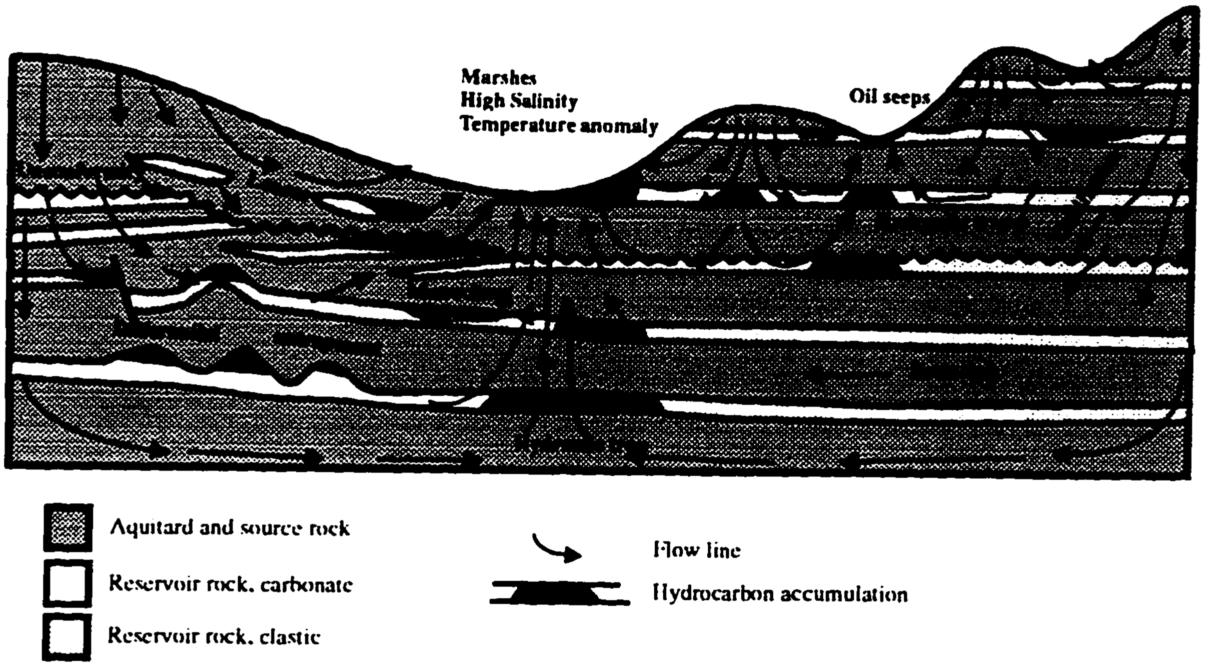


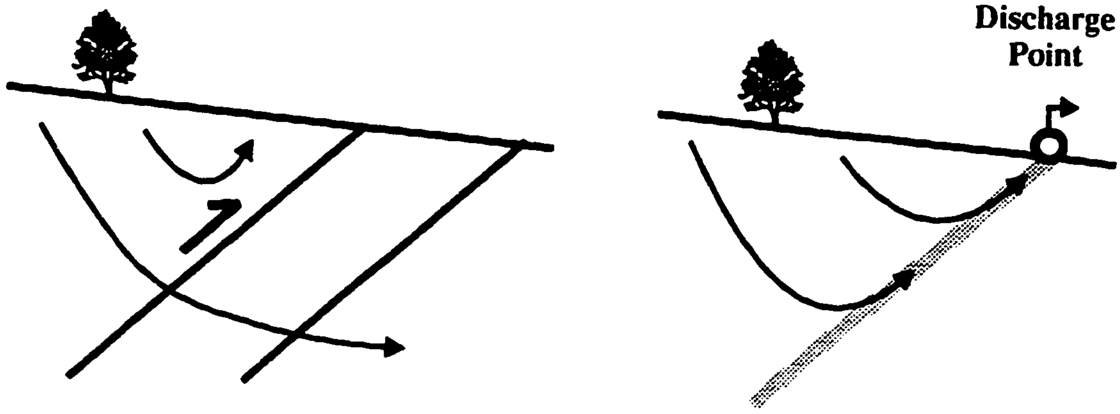
Figure 2.8: Tóth's generalized hydraulic theory of petroleum migration (modified after Tóth, 1980).

different fault characteristics. Each of these fault types are not necessarily expected to be found within the study area.

Flow and barrier faults represent two end members of a possible spectrum, namely, complete hydraulic communication versus a complete impermeable barrier (Figures 2.9A and 2.9D; p. 21). Nearly perfect communication could result across faults which either have minimal displacements or the absence of sealing mechanisms such as fault gouge. For example, a minimal disturbance in the flow system would occur across minor fault splays which originate from a major thrust fault. On the other hand, the formation of effective impermeable barriers may develop from fault gouge, juxtaposition of aquifers and aquitards, rotation of grains, and cementation (Davis and de Wiest, 1966). If the formation of an impermeable barrier is extensive, flow paths will be diverted upwards parallel to the impermeable barrier. Therefore, fluids will reach the ground surface over a zone of discharge (case D). A fault conduit (case B) provides a permeable zone of preferential flow which, in effect, focuses water along a fault trace. The formation of a fault related spring is due to focused discharge which is indicative of a subsurface fluid conduit. Lastly, a fault which impedes flow by reducing hydraulic communication, is considered an obstruction fault and may have characteristics of both flow and barrier type faults (case C). Certain regions of a thrust fault may be more permeable than others creating both fluid barriers and fluid pathways. Therefore, the overall effect of such a fault would be to impede or obstruct fluid flow.

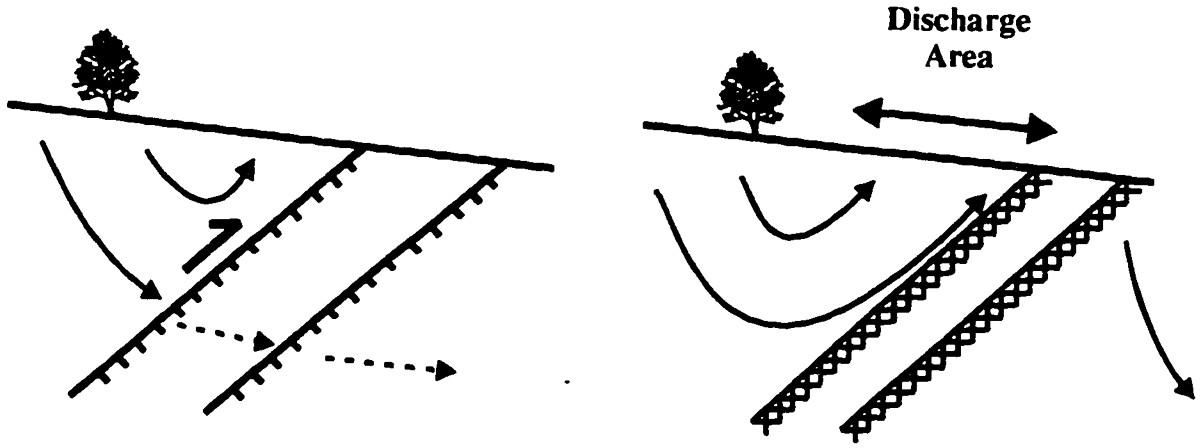
2.4 Petroleum Interest

Current hydrocarbon production within the study area can be classified into those fields associated with a) Mississippian subcrop, b) Devonian reef complexes, c) Foothills structural features, and d) Wabamun stratigraphic traps. A summary of the significant known hydrocarbon accumulations is illustrated in Figure 2.10. The largest fields are those associated with the Mississippian subcrop. Large volumes of gas are produced from the Harmattan fields in the central part of the study area. Production is also found within Wabamun stratigraphic traps in the southeast corner of the study area. Several structural fields within the disturbed belt are found in the Turner Valley and Wabamun Formations.



A - Flow Fault

B - Conduit Fault



C - Obstruction Fault

D - Barrier Fault

Figure 2.9: Possible flow scenarios associated with disturbed belt thrust faults. A - Flow fault, B - Conduit fault, C - Obstruction fault, and D - Barrier fault.

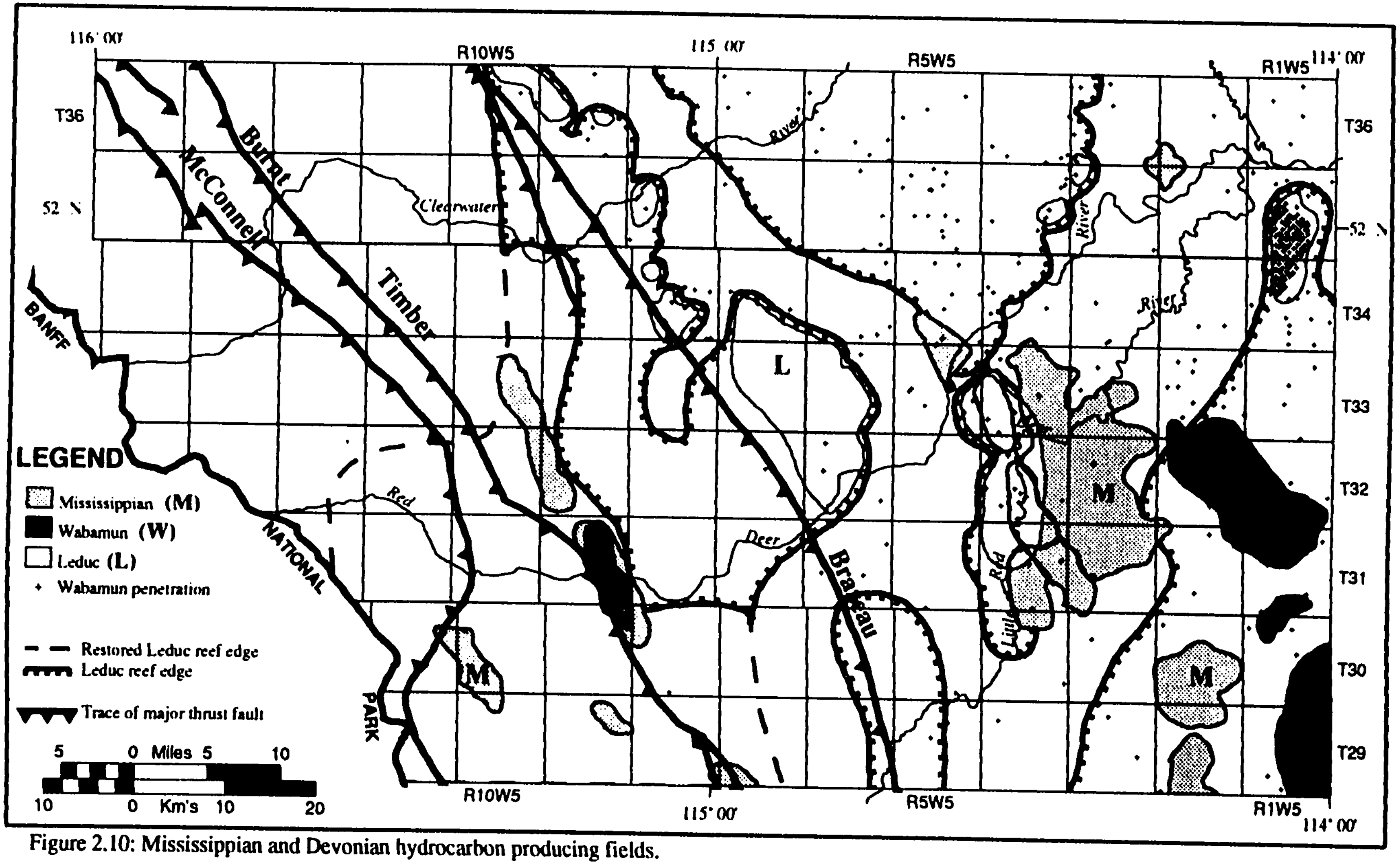


Figure 2.10: Mississippian and Devonian hydrocarbon producing fields.

Chapter 3

Methodology

The identification of the hydrogeological characteristics within the Foreland Fold and Thrust Belt and Alberta Foreland Basin involved the compilation, culling, processing and interpretation of large amounts of formation water data. A significant portion of the raw data are invalid for various reasons which will be discussed below. Final interpretations were based on the integration of geological evidence with representative formation water analyses.

3.1 Geological Determination

A prerequisite to any hydrogeological study is a comprehensive understanding of both the surface and subsurface geologic features. The geological data that were used to help interpret the hydraulic nature of the thrust belt and foreland regions included geophysical well logs, and previous foothills structural interpretations and cross sections (Ollerenshaw, 1965; Ollerenshaw, 1975).

3.1.1 Formation Tops

The identification of subsurface formations was completed by using a combination of picks from: a) re-interpreted geophysical well logs and b) Energy Resource Conservation Board (ERCB) database. The ERCB database consists of formation tops identified and submitted by the different well operators. Therefore, this process may lead to inconsistencies in formation identification. To avoid mapping potential erroneous formation tops, geophysical well logs were obtained for 120 wells distributed evenly throughout the study area. Formation tops were checked for accuracy in relation to the ERCB database obtained from CDPUBCO (1994b). The ERCB picks for the Wabamun, Shunda, Pekisko, Banff and Nisku Formations were consistent and reliable. However, a greater amount of inconsistency was identified for the Elkton, Turner Valley, Ireton, and Leduc Formation tops. Therefore, these formations were individually picked for all 120 wells that were selected. The even distribution of wells throughout the study area increased the probability of identifying significant anomalous ERCB picks. In more sensitive areas, such as within the disturbed belt, near Leduc reef edges, or close to formation subcrops, additional geophysical well logs were acquired.

3.1.2 Data contouring

All maps and well-log cross-sections in this study were produced using the Generic Mapping Tools (GMT) program developed in UNIX by Wessel and Smith (1991). The GMT gridding and contouring algorithm SURFACE (Smith and Wessel, 1990) was initially used on all contour maps. Most of these early maps were found to be non-representative. Mathematical contouring of a limited data set produced unrealistic representations of the data. Therefore, the SURFACE algorithm was only used with geological structure maps where there was adequate data control to create representative maps. As a consequence, the Ireton isopach map as well as all hydrogeological maps were contoured by hand, digitized, and plotted using the GMT mapping program. Any subsequent gradients were calculated from these final contoured maps.

3.1.3 Structural determination

The nature of the disturbed belt region within the study area required careful interpretation of geophysical well logs to assure accurate identification of formation and fault contacts. Because of the complex structural geology, the contouring of hydraulic-head and water-chemistry data were determined to be inadequate methods of representing fluid data within the disturbed belt. The placement of hydrogeologic data west of the Brazeau Thrust in plan view was only to illustrate the location and density of data. Therefore, fluid pressures and total dissolved solids (TDS) were plotted within a structural cross section which provided an improved method of relating the position of the data to the aquifer location and morphology.

Burnt Timber area

The geological structure of the Canadian Rocky Mountains and Foothills regions has been determined by Ollerenshaw (1965; 1975), Price and Mountjoy (1970), and Price (1981). Ollerenshaw's (1965) geological analysis is located within the Burnt Timber area west of the Brazeau Thrust within the disturbed belt.

A large percentage of wells drilled west of the Brazeau Thrust are within large structural culminations (i.e., Panther River, Limestone Mountain, and Marble Mountain (Figure 2.4, p. 10). The relatively high concentration of Turner Valley pressure and water chemistry data in the Burnt Timber area (i.e., east of the Panther River anticlinorium) focused the geological interpretations in that region. Unfortunately, Ollerenshaw's (1965) original interpretation was limited by two wells drilled within the cross section trace (Section 4.1.2). Since that time, additional wells have been completed in close proximity to the cross section. These newer wells were used to modify Ollerenshaw's structural cross section by projecting the wells into the original line of section (Figure 4.12; p. 56).

Well projections

The projection of oil and gas wells from relatively small distances into a cross section is a common technique in structural areas with sparse data control (Price, 1981). In complex folded terrains, the projection of a well into a cross section should be parallel to the fold axis. An accurate balanced structural section must incorporate data from outcrops, seismic, correct stratigraphic relationships, and subsurface wells. Because a more recent section along Ollerenshaw's (1965) original trace was unavailable, the schematic found in Figure 4.12 (p. 56) was constructed with four additional wells projected parallel to strike.

Ollerenshaw's (1965) *y-y'* cross section is located within the Burnt Timber area of the disturbed belt where the majority of the Turner Valley DSTs are located (Twps. 29-30, Rges. 9-11w5) (a portion of Ollerenshaw's original *y-y'* cross section is illustrated in cross section *z-z'* (Figure 4.11, p. 54)). The more recent wells in the area were projected from a maximum of 1560 *m* into the cross section trace resulting in a new schematic of Ollerenshaw's cross section (Figure 4.12, p. 56). Due to the structural complexities within the Burnt Timber area (Figure 2.4, p. 10), wells along strike from greater distances were not projected and used for structural interpretations. For the purpose of this study, it was not necessary to identify and correlate all individual formations from surface to total depth with each well log. Therefore, only the gross structural features and formation contacts were correlated and balanced following the techniques outlined by Dahlstrom (1969).

3.2 Fluid Pressure

To make quantitative evaluations of formation fluid flow, one must use reliable and representative fluid pressures which are generally obtained from drill stem tests (DSTs). A DST represents a temporary completion of the well bore allowing formation pressures to recover and fluids to be sampled. A DST measurement must represent the virgin formation pressure to be useful in hydrogeological analysis aimed at petroleum migration problems. A digital copy of the Canadian Institute of Formation Evaluation (CIFE) database was supplied by *Mobil Oil Canada* for this project. To insure that this database was valid, various methods were used to check the quality of the database.

Cife Code	Explanation	Used on Maps?
A	High Quality/stabilized pressures	Yes
B	Requires Extrapolation	Yes
C	Caution, plugging	Yes
D	Questionable readings	No
E	Low permeability, Low pressure	No
F	Low permeability, High pressure	No
G	Misrun	No

Table 3.1: Summary of the analytical CIFE codes used to evaluate DST pressures

	Elkton	Pekisko	Shunda	Wab.	Nisku	Leduc	Cook	BHL	Total
DSTs	460	83	106	218	119	202	15	15	1218
Negative	269	51	77	148	85	120	8	6	764
Positive	191	32	29	70	34	82	7	9	454
AB Oil	6	2	6	0	2	4	0	0	20
AB Gas	28	4	7	10	0	3	0	0	52
AB Water	16	2	1	11	4	23	1	3	61
C Water	22	3	3	7	5	17	1	1	59
Mapdata	72	11	17	28	11	47	2	4	192
Mud	3	4	0	3	5	6	0	1	22

Table 3.2: Summary of original CIFE pressure database. The middle section of the table is the *Mapdata* which was plotted and used on potentiometric maps

3.2.1 Evaluation of Data

The database for the project included 1218 DSTs for Mississippian and Devonian Formations. Table 3.2 summarizes the data by formation and fluid classification, the details of which will be explained below. The finalized culled pressure measurements could not be reproduced in this document.

Analytical Evaluation

The first assessment of the DSTs was completed by CIFE. For each DST, CIFE evaluated the quality of the DST and assigned a letter code (*A* through *G*) based on several qualitative and quantitative observations. A summary of the CIFE codes and their meanings are shown in Table 3.1 (p. 27).

The CIFE A test is considered to be of the highest quality where the pressure has stabilized and the measurement is mechanically sound. A B test has nearly stabilized but may have slight mechanical difficulties. The C and D tests are those which CIFE considered to have more serious problems. A C test has some mechanical difficulties which do not appear to affect the pressure measurement. The mechanical difficulties increase for a D test which may also have other problems such as a questionable recorder or interval depth.

Out of the original 1218 DSTs, 764 could be eliminated immediately because no pressure measurement was obtained, the DST was a misrun, or there was very low permeability (i.e., CIFE's E through G tests). The remaining tests were initially classified as *positive* (Table 3.2; p. 27). The *positive* tests were subsequently grouped into the CIFE A, B, C and D categories and into gas, oil, water, and mud fluid recoveries. CIFE's A and B tests were considered to be the highest quality and therefore used for building potentiometric maps. Unfortunately, when using only the top two categories, the data control became somewhat limited. Therefore, the C water, AB Oil, and AB Gas tests were also included into the *Mapdata* which were plotted on the formation potentiometric maps. These data points were flagged on the maps with unique symbols so that they could be analyzed with respect to the surrounding higher quality data. If a C water test seemed somewhat anomalous on the potentiometric surface, the test would be re-extrapolated using the Horner method (Horner, 1951).

The Horner Method

The Horner extrapolation method was used for those DSTs where the pressure build up curve failed to stabilize (Horner, 1951). The Horner method derives a pressure value representing steady state conditions by plotting the shut-in pressures P_f versus a dimensionless time function $log\frac{T+\Theta}{\Theta}$, where T is the flowing time prior to shut-in and Θ is the shut-in time. Horner plots were completed on a selected number of CIFE A, B and C tests to verify the use of the CIFE database. The difference between these new extrapolated pressures and those completed by CIFE was minimal for the A and B tests. On the other hand, differences between the C tests extrapolated pressures may have been more severe. The new extrapolated pressures for those C tests which were accepted were included on subsequent potentiometric surfaces.

Fluid recoveries

DSTs in which water was the dominant fluid recovered yielded the preferred pressures that were used to construct all potentiometric maps. Significantly higher pore pressures may occur within an oil pool than what is found in the surrounding aquifer. Elevated pressures within a hydrocarbon column are due to density differences compared with surrounding formation waters. The pressure difference increases with greater hydrocarbon column heights. Therefore, a potentiometric map including hydraulic heads calculated from samples with both water and hydrocarbon recoveries may be misleading. All potentiometric surfaces in this study represent the fluid potential of the formation water.

Production Influence

Another source of error which may influence the virgin formation pressures is hydrocarbon production or water injection in close proximity to a DST well. Inclusion of production and injection related pressures may suggest anomalously low or high pressures, respectively. Both qualitative and quantitative methods of culling production influenced pressure data were used to determine the possibility of production induced drawdown (P.I.D.).

To quantitatively evaluate production influence, a computer-aided technique was modified from Rostron (1994). A simplified production database consisting of the date of initial production or injection was obtained from (CDPUBCO, 1994a) and compared with a similar date database for drill stem tests. Rostron's initial computer program calculated the inter-well distances between DSTs and surrounding production wells. This comparison would indicate those DSTs which had production wells located in the surrounding two, five, or ten kilometer radii. However, a production well that is located relatively close may have been on production for only a very short time prior to the DST. Therefore, Rostron's computer program was modified to calculate production time prior to the DST. As a result, the computer algorithm (PRDHIST) computes the distance and time difference between those production wells which pre-date the DST. Obviously, any production wells which post-date a DST would not have influenced the formation pressure at the time of the DST. This modification follows the method used by Tóth and Corbet (1986) by calculating an interference index. Tóth and Corbet's interference index is defined by:

$$I = log_{10}\frac{t}{r^2} \tag{3.1}$$

where t is the production time (years) prior to the DST, and r is the distance separating the DST and production well (miles). Therefore, a greater production time or lower inter-well radius produces a higher interference index indicative of possible production or injection influences. A DST such as found in example B in Figure 3.1 (p. 31), would be flagged as having an increased probability of production induced drawdown.

Because the database included only the initial production date, the underlying assumption is that production continued inclusively after that point. Furthermore, the production magnitude and rate were not identified. Based only on this computer technique, possible valid data points could be eliminated. Therefore, it was felt that this quantitative method should be combined with a qualitative inspection. A qualitative assessment of the formation pressures via hydraulic head values was completed to identify any erroneous data. A combination of anomalously high or low formation pressures as well as a high interference index would result in the data point being excluded from the final potentiometric surface.

The difficulty with this method is determining at what point production induced

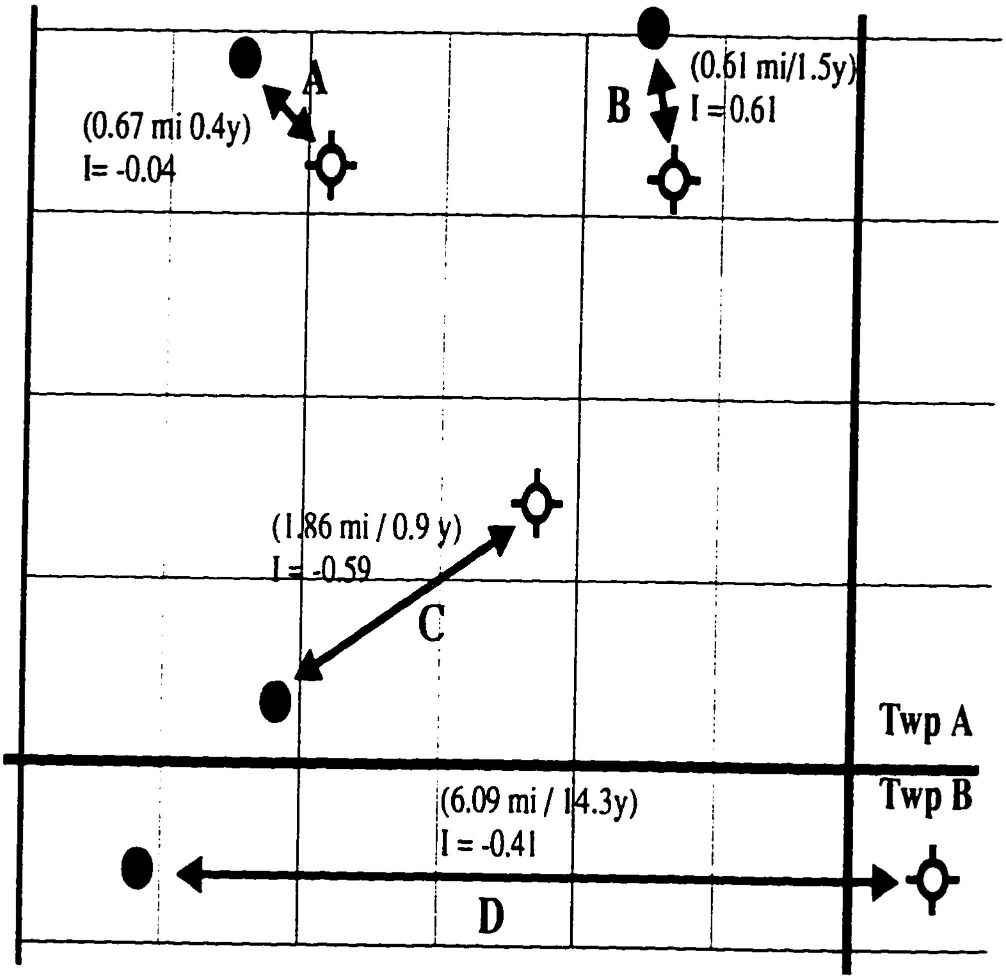


Figure 3.1: Example results of the PRDHIST program in a northern Alberta Bluesky Formation study (modified after Wilkinson, 1994). • = production well, o = DST well. Increased probability of P.I.D. in example B over example A due to increased production time and close distance. Greater length of production time in example D suggests a similar interference index as example C despite differences in distance between the DST and production well.

drawdown or injection becomes potentially significant. In a central Alberta Belly River study, Parks (1989) used only the distance as the determining factor suggesting 1.6 km as a limit of production influence on a subsequent DST. On the other hand, Tóth and Corbet (1986) proposed well distances up to 4.8 km with interferences indices greater than 0.7 as the limits of significant production influence within their southern Alberta study. More recently, Barson (1993) felt that surrounding cumulative production within the Keg River of north central Alberta would affect DSTs up to a maximum of 10 km. Barson recognized interference thresholds of $I = -0.6$ and $\Sigma I = 0.2$ for partial and total drawdowns, respectively. According to Rostron (1994; 1995), the distance is the primary factor which is indicative of production induced drawdown. Rostron suggests this minimum distance in which data may be culled ranges from 2 to 20 km. The discrepancies between each of these studies clearly suggest that production associated influences on DSTs must be dependent on the formation lithology, permeability and hydraulic conductivity within the different study areas.

3.2.2 Calculation of Fluid Potentials

Flow Equations

The quantitative evaluation of groundwater flow began with the formulation of Darcy's Law (Darcy, 1856):

$$Q = -K\frac{dh}{dl}A \tag{3.2}$$

where K [L/T] equals the *hydraulic conductivity*, $\frac{dh}{dl}$ $[L^0]$ is the *hydraulic gradient*, A $[L^2]$ is the cross sectional area of the medium normal to flow and Q $[L^3/T]$ is the volumetric discharge. The physical meaning of Darcy's Law was expressed in terms of potential energies by Hubbert (1940). Hubbert showed that the fluid potential (Φ) $[L^2/T^2]$ is a mechanical energy defined in terms of fluid pressure, density and elevation at the point of consideration:

$$\Phi = gz + \frac{P}{\rho} \tag{3.3}$$

where g is the gravitational constant $[L/T^2]$, z is the elevation point $[L]$, P is the fluid pressure $[M/LT^2]$ and ρ is the fluid density $[M/L^3]$. Furthermore, the fluid potential can be defined in terms of hydraulic head (h) as:

$$\Phi = gh \tag{3.4}$$

Therefore, hydraulic head is a measure of the potential energy of a subsurface fluid. Movement of subsurface fluids are from high to low energy, or in other words, from high to low hydraulic head. Substituting equation (3.4) into equation (3.3) gives the formulation of hydraulic head:

$$h = z + \frac{P}{\rho g} \tag{3.5}$$

The quantitative evaluation of fluid flow in the subsurface using equations (3.3) and (3.5) must be analyzed in terms of fluid impelling forces. As Figure 3.2 illustrates, the total driving force E_w on a unit mass of water is the sum of the component forces due to pressure $-\frac{\nabla P}{\rho_w}$ and gravity g.

According to Bachu (1995) who follows deMarsily (1986), the generalized form of Darcy's law which accounts for the potential driving forces can be written as:

$$q = -\frac{\mu_o}{\mu} K_{Ho}(\nabla H_o + \frac{\Delta\rho}{\rho_o}\nabla z) - K_T\nabla T - K_c\nabla C \tag{3.6}$$

where q is the specific discharge, ρ and μ are the fluid density and viscosity respectively, H_o is the hydraulic head as defined in Equation (3.5), K is the hydraulic conductivity, and T and C are the temperature and concentration of the fluid. Equation (3.6) indicates that formation fluid flow is driven by: i) potential differences (∇H_o) (i.e., pressure and topography), ii) buoyancy due to variations in fluid density $(\Delta\rho/\rho_o)\nabla z$, and iii) thermal and chemical gradients represented by $K_T\nabla T - K_c\nabla C$,

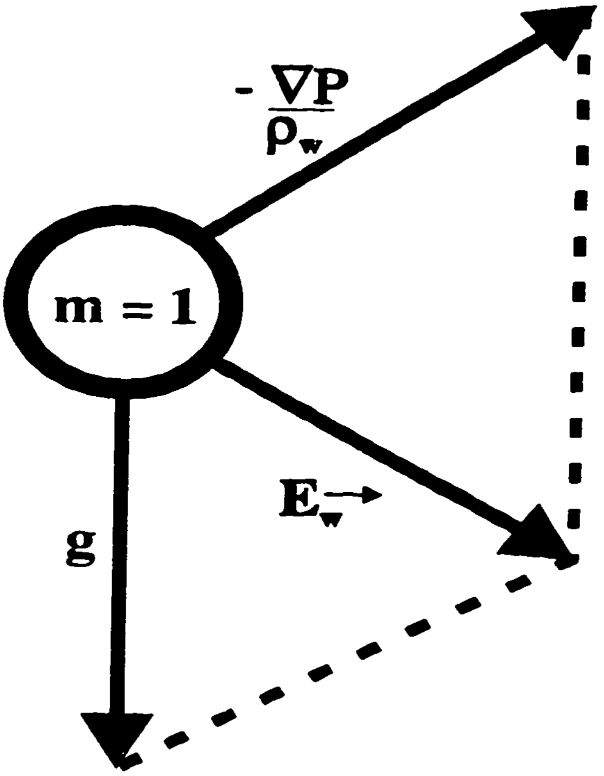


Figure 3.2: Potential forces acting on a unit mass of fluid.

respectively. Gradients resulting from pressure and density differences are the primary sources of possible forces driving formation fluid flow. Those derived from heat and chemistry are of less significance and will not be considered any further.

Fluid Density

Variations in subsurface fluid density generally result because of changes in salinity, temperature, pressure and lithology. Often, the fluid density increases with depth due to elevated temperatures, pressures, and salinities. Depending on which intervals and associated depths are being studied, one may have to account for a buoyant force due to the increase in fluid density. By definition, the calculation of hydraulic head in equation (3.5; p. 33) assumes a uniform reference fluid density for the formation in question. Given the fact that fluid densities may vary both vertically and laterally, the question arises as to which reference fluid density should be used in the calculation. Several methods for estimating subsurface fluid densities have been used. Firstly, according to Lusczynski (1961), buoyancy effects can be accounted for by using the calculation of environmental head. This method calculates the height of a variable density fluid column above the point of measurement. The densities within the overlying fluid column should correspond to the formation fluid density found at the equivalent depth. Secondly, the point source method calculates hydraulic head by using the formation water density at the point of measurement as a reference. Thirdly, the reference density can be estimated from the average formation water density. Lastly, a freshwater reference density is a convenient method which uses a standard between all hydrogeological horizons. In all cases, the real formation density (ρ_r) will vary from the estimated formation density (ρ_e) by some ($\Delta\rho$). In this study, a fresh water density of $1000 kg/m^3$ was used to calculate all values of head.

The underlying assumption in calculating freshwater hydraulic heads is that flow is horizontal. As a consequence, the buoyant effects due to variations in fluid density are minimal and can therefore be ignored. However, according to Davies (1987), the density related term ($\frac{P}{\rho g}$) (Equation 3.5) should be evaluated using a driving force ratio to determine the relative importance of the buoyant forces. The driving force ratio (DFR) is defined as a ratio of the density-related and hydraulic head-related terms:

$$DFR = (\rho_w - 1)\frac{\nabla E}{\nabla H_f} \tag{3.7}$$

where ρ_w is the density of the formation water, ∇E is the aquifer slope, and ∇H_f is the freshwater hydraulic head gradient. The DFR analysis indicates that the density-related term depends on the relative magnitude of the head gradient. Increasing DFR values indicate flow systems with more significant buoyant forces. Davies considers a $DFR = 0.5$ as an upper boundary of insignificant density related terms. A summary of the DFR values which were calculated for individual aquifers is listed in Table 3.3 (p. 36). Structure contour maps of the respective formations (Figure 4.2, p. 44; Figure 4.4, p. 46) illustrate the locations of the gradient estimations. In each case, the regional DFR calculations are well below Davies 0.5 threshold suggesting that

Formation	ρ_w	∇H_f	∇E	DFR
Elkton1	1.055	0.017	0.014	0.046
Elkton2	1.055	0.008	0.020	0.138
Wabamun	1.084	0.009	0.017	0.164
Leduc	1.139	0.006	0.017	0.382

Table 3.3: Summary of Driving Force Ratio calculations (DFR).

the buoyancy effects are negligible.

3.3 Fluid Chemistry

Mineral matter may be dissolved, transported, and deposited by subsurface waters. Therefore, by observing the relationship between the chemical trends and fluid potentials in the subsurface, one may be able to a) evaluate patterns of groundwater flow, and b) reconstruct suspected chemical conditions from a known flow field (Tóth, 1984). The major factors that influence the chemical composition of groundwaters can be summarized as follows (randomly excerpted and modified from Tóth (1984)):

1. **Host Rock**
    (a) Lithology and surface area
    (b) Solubility and prior water chemistry
2. **Flow system**
    (a) Contact time and length of flow path
    (b) Depth (i.e., Temperature and Pressure)
3. **Climate**
    (a) Precipitation, evaporation, and temperature
4. **Element mobility**

According to Chebotarev (1955), the anionic evolution of formation water proceeds in the following sequence:

$$HCO_3^- \Rightarrow HCO_3^- + SO_4^= \Rightarrow SO_4^= + HCO_3^- \Rightarrow SO_4^= + Cl^- \Rightarrow Cl^-$$

In ideal geologic and subsurface hydraulic conditions, this sequence can be correlated with local, intermediate and regional flow systems in both a lateral and vertical sense. Therefore, local shallow flow systems tend to be enriched in HCO_3^- and $SO_4^=$, intermediate systems with $SO_4^=$, HCO_3^- and Cl^- , and regional systems with $SO_4^=$ and Cl^-. The TDS may be suspected to increase along a flow path as well as with increasing depth. To identify these possible trends, TDS maps, Piper diagrams (Piper, 1944) and the Sulin's (1946) formation water classification were used.

3.3.1 Subsurface Data

A compiled digital version of all fluid chemical analyses within the study area were supplied by *Mobil Oil Canada*. A total of 814 water analyses are available for the formations of Mississippian and Devonian age (Table 3.4; p. 38). Similar to formation pressure data, fluid chemistries must also be screened to ensure high quality data representing original formation conditions. The sources of contamination within fluid chemical samples are generally either acids or muds introduced during drilling and completion procedures. Therefore, various techniques may be used which suggest possible anomalies which would not be suspected under normal reservoir conditions. These erroneous data points accounted for a majority (564 tests) of the initial analyses.

Culling Techniques

Data points were eliminated in stages based on the confidence in the culling variables. Initial culling removed a large number of data points due to incomplete or duplicate analyses. The Na/Cl ratio, TDS, pH, fluid recoveries, and ionic balance were variables used to identify contaminated values within the remaining data. A fluid sample which

	Elkton	T.V.	Pekisko	Shunda	Wab.	Nisku	Leduc	BHL	Total
Analyses	177	21	61	30	163	55	240	67	814
Positive	35	17	6	11	30	22	115	14	250
Negative	142	4	55	19	133	33	125	53	564
Map data	20	6	4	3	13	13	54	3	116
?? data	11	9	2	5	0	4	29	6	66
extra	4	2	0	3	17	5	32	5	68

Table 3.4: Summary of original water chemical analyses

appeared to have anomalous values (i.e., non-formation waters, Table 3.5) for all these variables was eliminated first. On the other hand, a sample with one anomalous value was screened more carefully. For example, a data point with an apparent anomalously low pH may have resulted due to laboratory or sampling techniques and therefore should not be eliminated. Generally, if there was minor question as to a data point's validity (?? data in Table 3.4), the value would be highlighted and plotted along with the better quality data. The method in detecting analytical errors in chemical water analyses is completed by calculating the condition of electroneutrality. In other words, the sum of the major cations and anions should balance. According to Freeze and Cherry (1979), the charge-balance error can be calculated as follows:

$$IBE(\%) = \frac{\Sigma zm_c - \Sigma zm_a}{\Sigma zm_c + \Sigma zm_a} x100 \qquad (3.8)$$

where z is the ionic valence and m_c and m_a are the molalities of the cations and anions, respectively. This technique can only be used on those solutions which have a complete analysis. Because Na was calculated by difference on most analyses prior to 1980, the condition of electroneutrality will be achieved artificially. In those cases, the charge-balance error test is irrelevant.

Formation water samples which have been contaminated with foreign fluids (i.e., acids or muds) can be identified using the values of pH, total dissolved solids (TDS), Na/Cl ratio, presence of CO_3, and poor fluid recoveries. A summary of these values and interpretations is listed in Table 3.5, as well as from Hitchon and Brulotte (1994).

Culling Value	value	Interpretation
TDS	low	mud water
Na/Cl	> 1.0 $1.0 - 0.5$ < 0.5	mud water formation water acid waters
pH	> 9.0 $5.0 - 9.0$ < 5.0	mud waters formation water acid waters
CO_3	present	drilling mud
Recovery	*high*	better test

Table 3.5: Culling parameters used to determine chemical contamination of formation waters.

Ideally, a mud sample may be identified by a high Na/Cl ratio due to the increased Na content in drilling muds, a relatively low TDS due to the addition of fresher drilling fluids, mud fluid recoveries, and a relatively high pH.

3.3.2 Foothills Springs

According to Davis and De Wiest (1966), a spring is defined as any natural surface discharge large enough to form a small rivulet. The formation and size of a spring is dependent on: a) aquifer permeability, b) aquifer recharge area, and c) amount of recharge. Generally, there is an increase in permeability resulting in the localization of a spring. The two most common types of springs are those located at formation and faults contacts. Contact springs generally form at the surface where a highly permeable formation is juxtaposed against a lower permeable formation resulting in a concentration of fluids within the more permeable formation. Similarly, an increase in permeability along a fault or joint surface will focus flow of waters.

Spring data were used to complement subsurface fluid data in identifying flow systems within the disturbed belt. The water chemical analysis from 39 springs were obtained from *Alberta Environmental Protection* and from Borneuf (1982). The majority of the springs were sampled in the late-1960's to mid-1970's by the Alberta

Research Council. The spring database consisted of flow rates, temperatures, total dissolved solids, pH and composition of the major cations and anions. Unfortunately, all these variables were not necessarily obtained for every spring. For example, flow rates and temperatures were quite often not sampled.

Chapter 4

Observations and Results

One of the primary objectives of this study was to determine whether or not hydraulic communication exists between the disturbed belt region and the adjacent foreland basin. In other words, does the elevated topography of the disturbed belt effect fluid flow hundreds of kilometers into the Foreland Basin? In attempting to answer these questions, observations were categorized into two distinct geomorphologic areas, namely, a) The Foreland Fold and Thrust Belt and b) Alberta Foreland Basin. It was found that the water chemistry and pressure data within these areas had differing distributions. Furthermore, there are significant geological variations within each region. Obviously the structural characteristics of the disturbed belt create additional complexities which are not encountered within the basin. The fluid dynamic parameters were observed within each of these areas in an attempt to discern the large scale hydraulic nature of the thrust belt and associated effects on petroleum migration and accumulation. The following chapter is therefore subdivided into *Geology*, *Alberta Foreland Basin waters*, and *Foreland Fold and Thrust Belt waters* sections.

4.1 Geology

The geology of the foreland basin and disturbed belt regions was observed through the use of geophysical well logs and previously constructed structural cross sections. This task became increasing more difficult within the disturbed belt where data control was sparse. Significant geological features within the study area which most likely have some influence on fluid flow will be discussed in the following section. Figure 4.1 (p. 43) shows the location of cross sections A-A' through G-G'. A larger scale reference map for the Burnt Timber area (Figure 4.10; p. 53) illustrates Ollerenshaw's (1965) G.S.C. study area and original cross section trace that were used for reference in this project.

4.1.1 Alberta Foreland Basin

Devonian

The Wabamun Formation was used to estimate the regional structural orientation of the Devonian formations because of a high data density and relatively consistent geophysical well log identification. The Wabamun Formation is dipping at 17.1 m/km or 0.98° (Figure 4.2, p. 44).

Within the Alberta basin, the Ireton Formation comprises both Upper and Lower Members (Switzer *et al.*, 1994). The Nisku and Leduc aquifers within the study area are separated by the Lower Member of the Ireton Formation which consists of both argillaceous carbonate and shale units. Four Devonian structural cross sections (Figures 4.4 through 4.7; p. 47 to p. 50) illustrate that the Lower Ireton Member is predominantly shale and therefore forms a significant aquitard located between the Leduc and Nisku aquifers. The morphology of any significant aquitard within a basin may have important implications for fluid flow.

As Figure 4.3 (p. 46) illustrates, variations from 0 to 120 m in the Ireton aquitard isopach corresponds to the presence or absence of the underlying Leduc Formation, respectively. The Ireton isopach exceeds 120 m between the Ricinus and Cheddarville reef trends. On the other hand, a relatively large area is present where the Ireton shale thins to less than 5 m within the Cheddarville complex (Twps. 34-35, Rges. 4-5w5). Furthermore, the Ireton is absent in several wells allowing the Leduc Formation to be

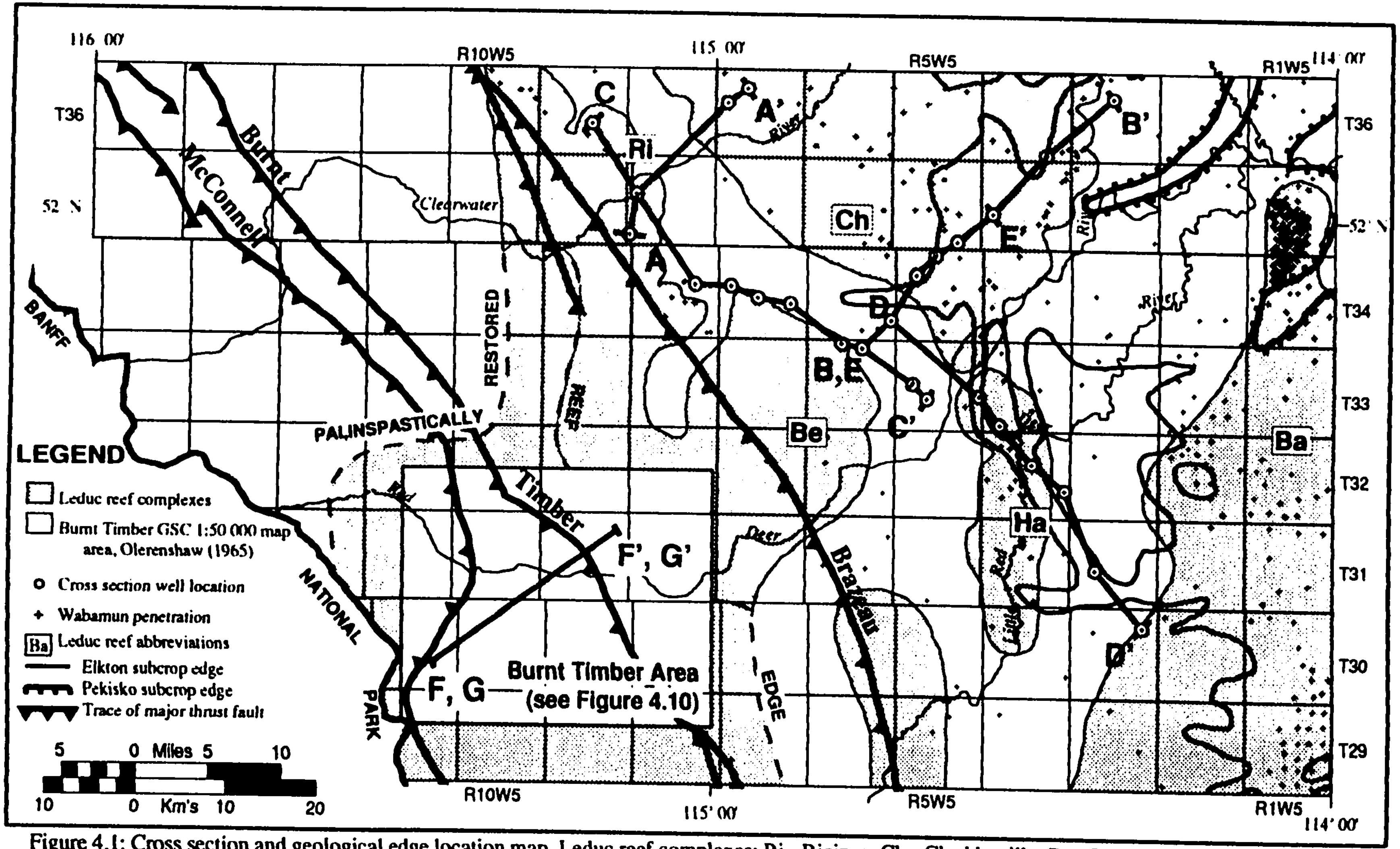


Figure 4.1: Cross section and geological edge location map. Leduc reef complexes: Ri - Ricinus, Ch - Cheddarville, Be - Bearberry, Ha - Harmattan, and Ba - Bashaw.

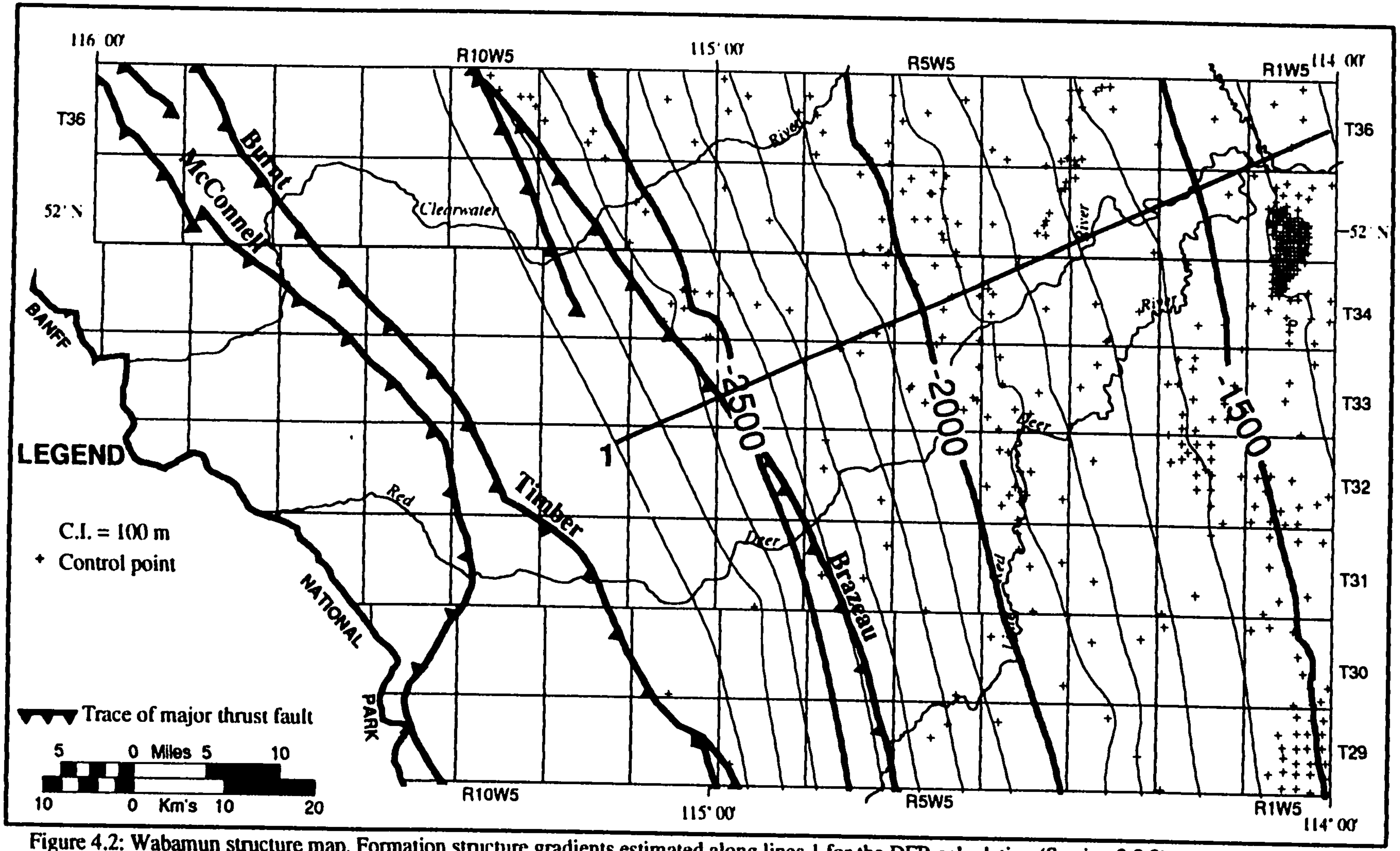


Figure 4.2: Wabamun structure map. Formation structure gradients estimated along lines 1 for the DFR calculation (Section 3.2.2).

in direct contact with the overlying Nisku Formation. Similar Lower Ireton Member thins also occur within the central part of the Bearberry and southern Bashaw reef complexes. Examples of the changing Ireton morphology are best illustrated in cross sections B-B' and C-C' (Figures 4.5 and 4.6; p. 48 and p. 49). Cross section C-C' extends through the area of maximum Ireton thickness while section B-B' illustrates the lack of Ireton shale in the Cheddarville reef complex.

Mississippian

The Mississippian strata within the study area are unconformably overlain by Jurassic and Cretaceous rocks. According to Martin (1987), the thickness of the Mississippian rocks in central Alberta varies from approximately 65m to 300m. Figure 4.8, p. 51 illustrates the southwestward dipping Elkton Formation with its updip erosional edge shaded in grey. The dip of the Elkton in this part of the basin was measured at 1.1° or $19.5 m/km$ (see line of measurement: Figure 4.8, p. 51). Cross section E-E' (Figure 4.9, p. 52) is a dip section of the Mississippian formations near the erosional edge (line of section: Figure 4.1, p. 43). The Paleozoic formations subcrop beneath the overlying sub-Cretaceous unconformity across the WCSB. Within this study area, erosional edges for the Elkton and Pekisko Formations are present.

4.1.2 Foreland Fold and Thrust Belt

Geological observations within the disturbed belt were primarily based on two Geological Association of Canada map sheets compiled by Ollerenshaw (1965; 1975). Ollerenshaw completed several structural cross sections through various parts of the disturbed belt region of the study area which were used for structural and geological interpretations. The section that was studied in more detail for this project due to the proximity to hydrogeological data west of the Brazeau Thrust, is identified as *y-y'* (Figure 4.10, p. 53). The central part of Ollerenshaw's original *y-y'* section has been reproduced as section *z-z'* (Figure 4.11, p. 54).

Geophysical well logs from more recent wells indicate that speculative formation

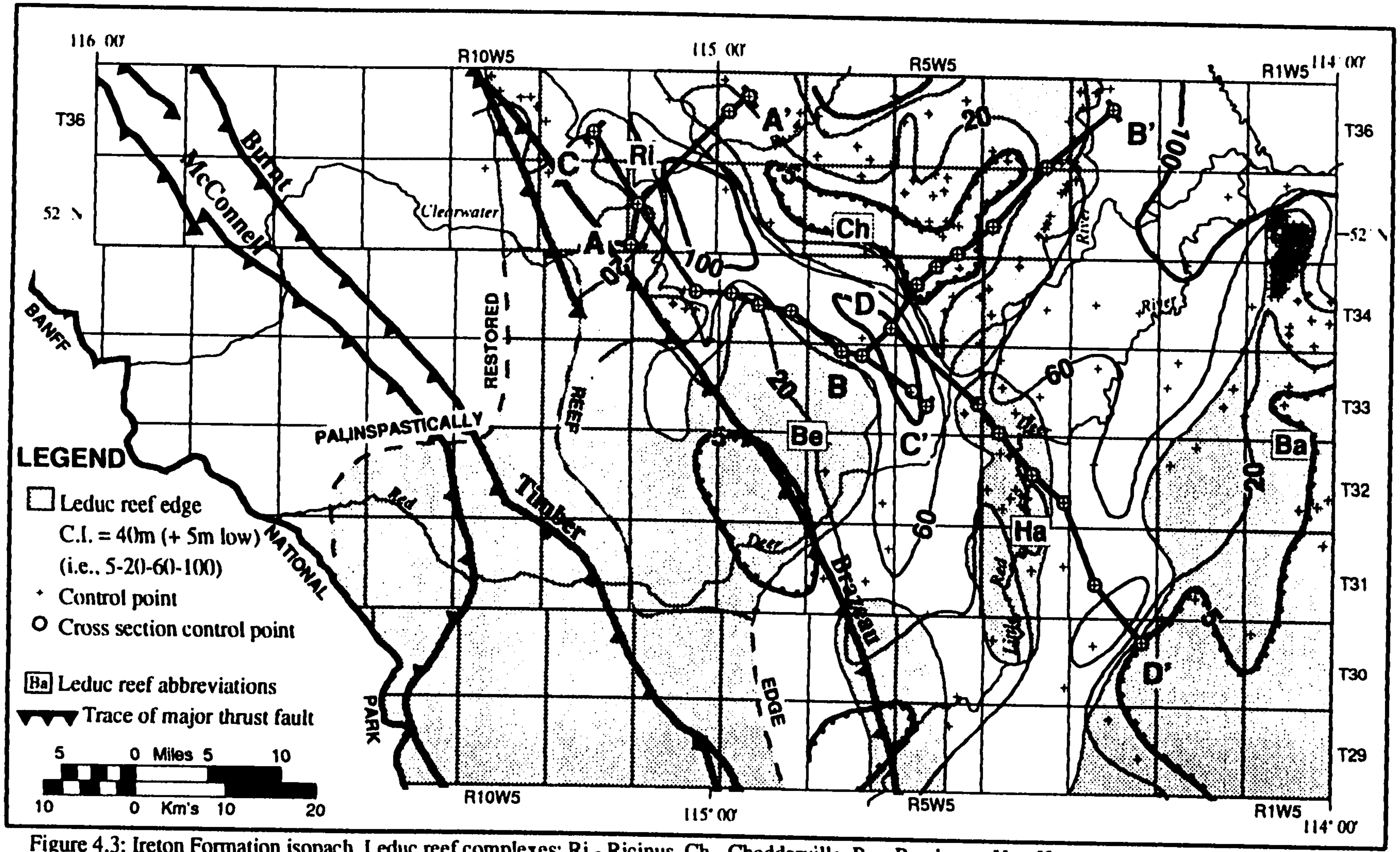


Figure 4.3: Ireton Formation isopach. Leduc reef complexes: Ri - Ricinus, Ch - Cheddarville, Be - Bearberry, Ha - Harmattan, Ba - Bashaw.

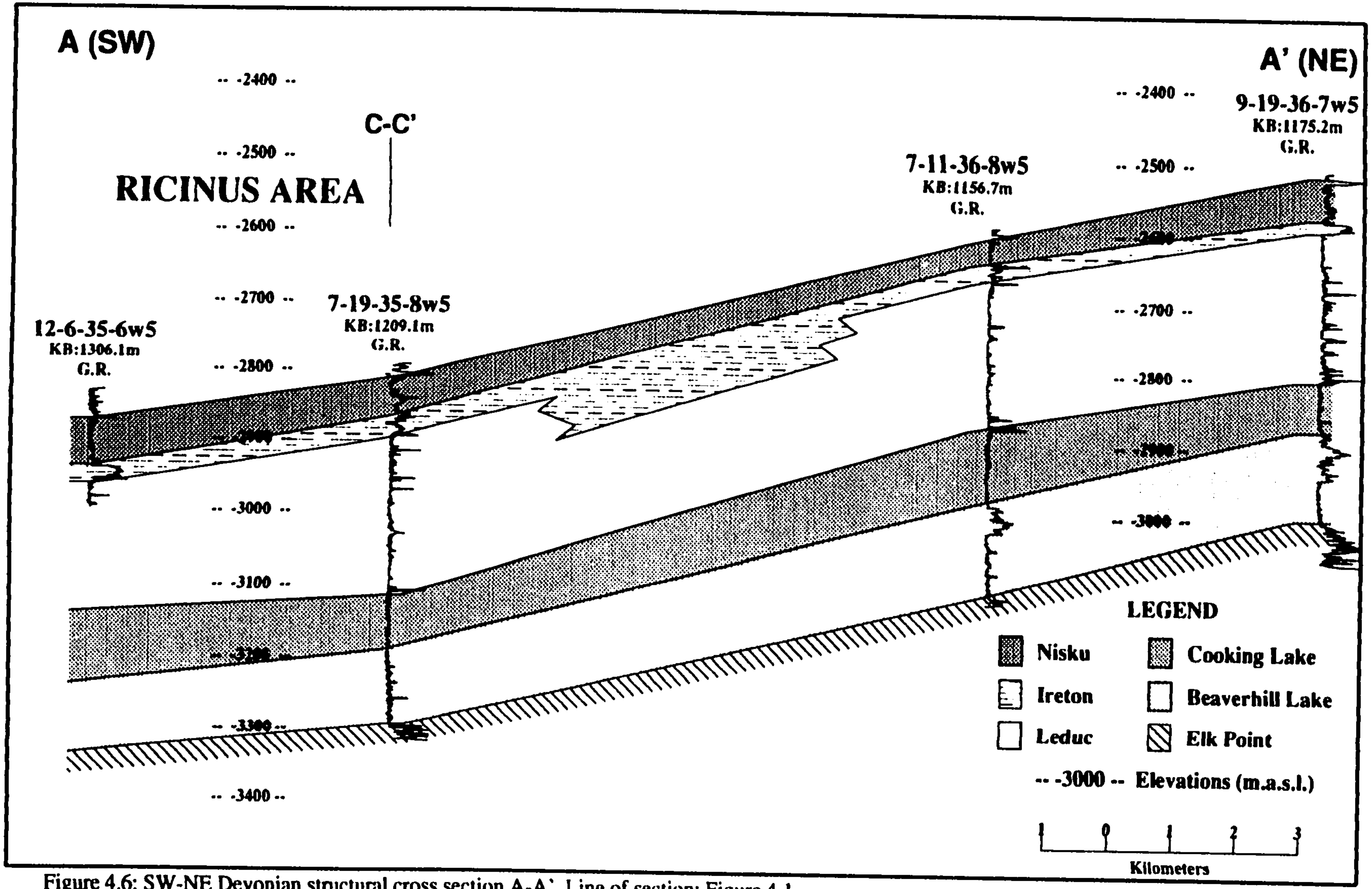


Figure 4.6: SW-NE Devonian structural cross section A-A'. Line of section: Figure 4.1.

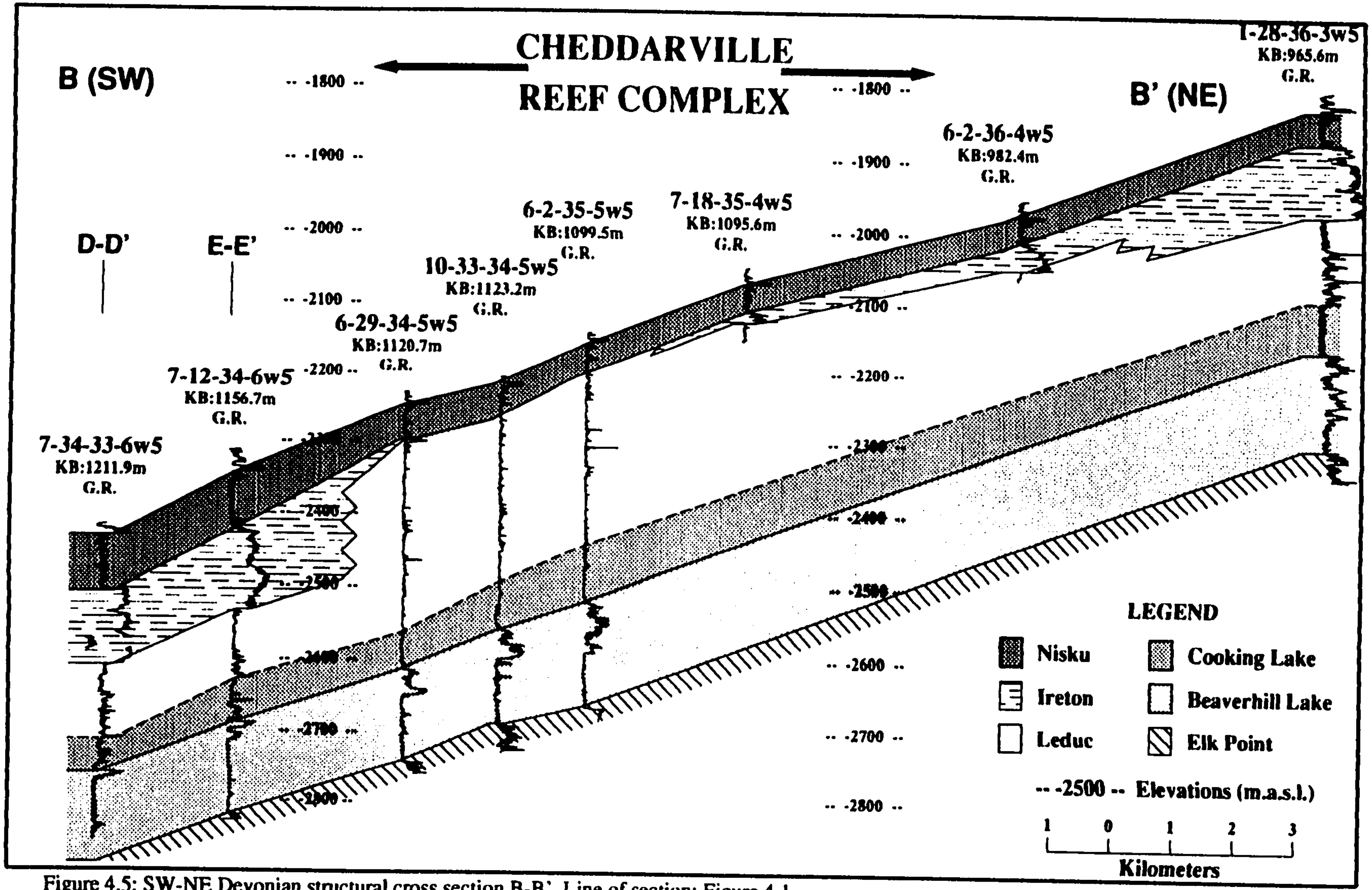


Figure 4.5: SW-NE Devonian structural cross section B-B'. Line of section: Figure 4.1.

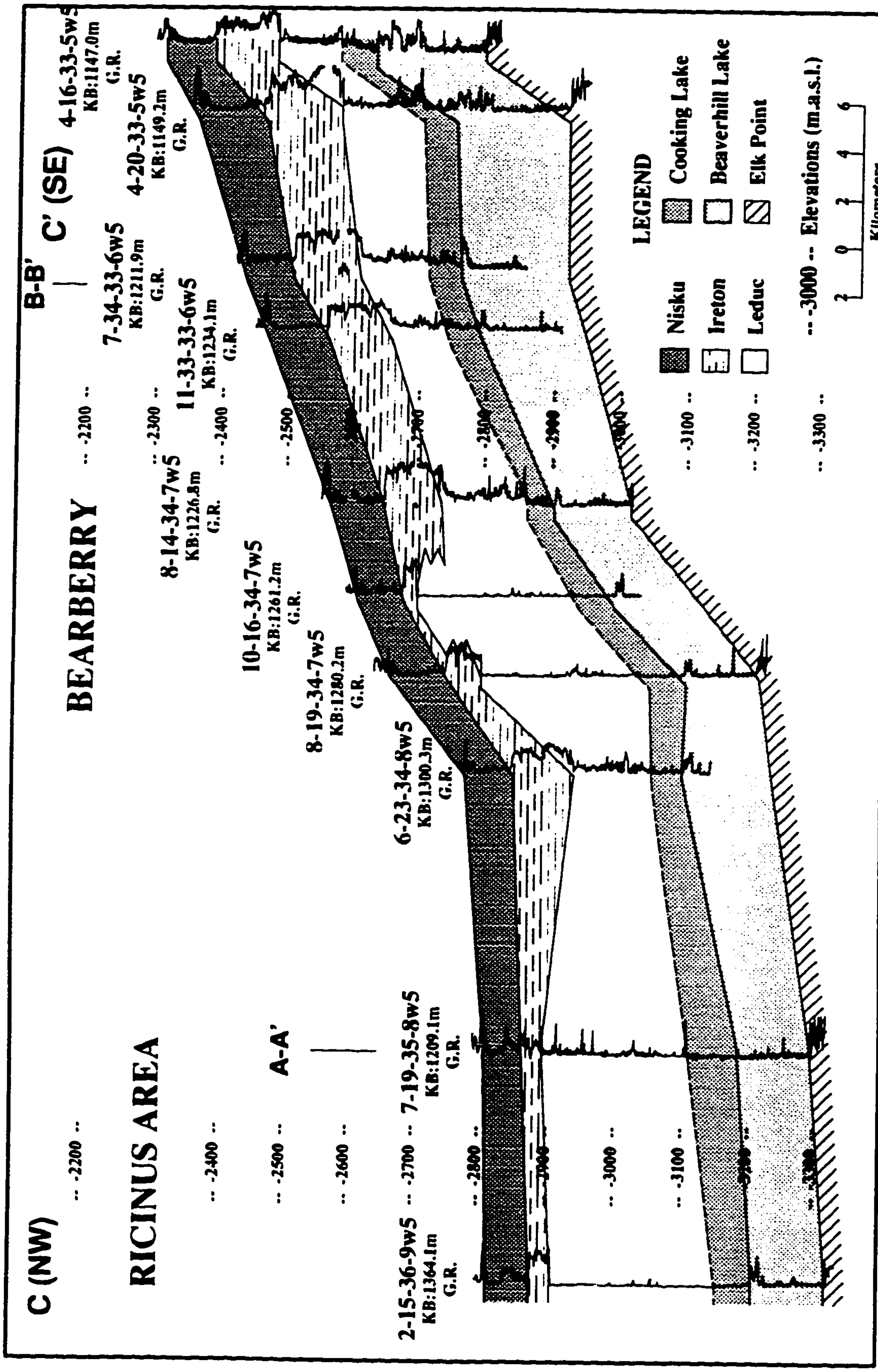


Figure 4.6: NW-SE Devonian structural cross section C-C'. Line of section: Figure 4.1.

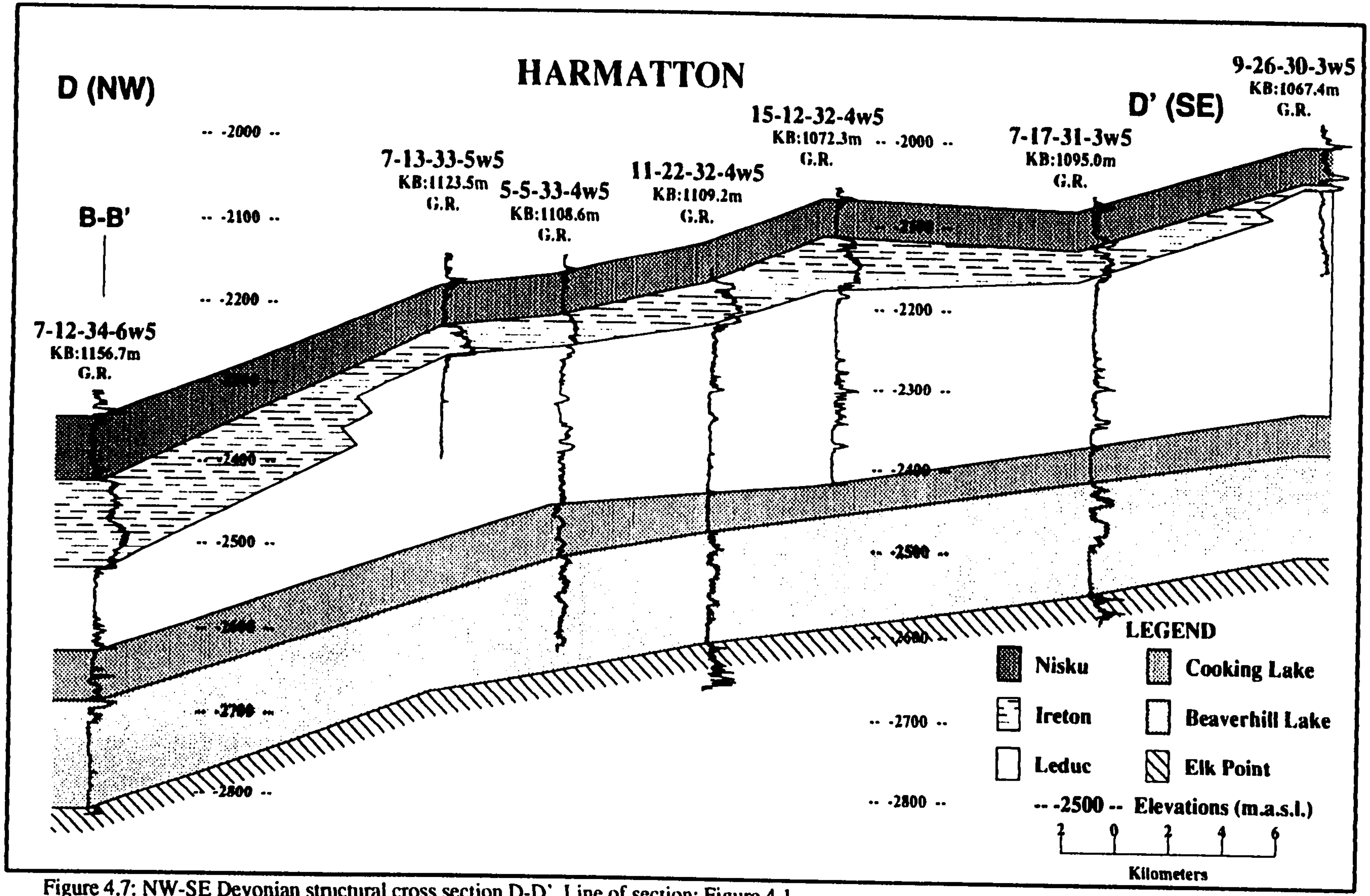


Figure 4.7: NW-SE Devonian structural cross section D-D'. Line of section: Figure 4.1.

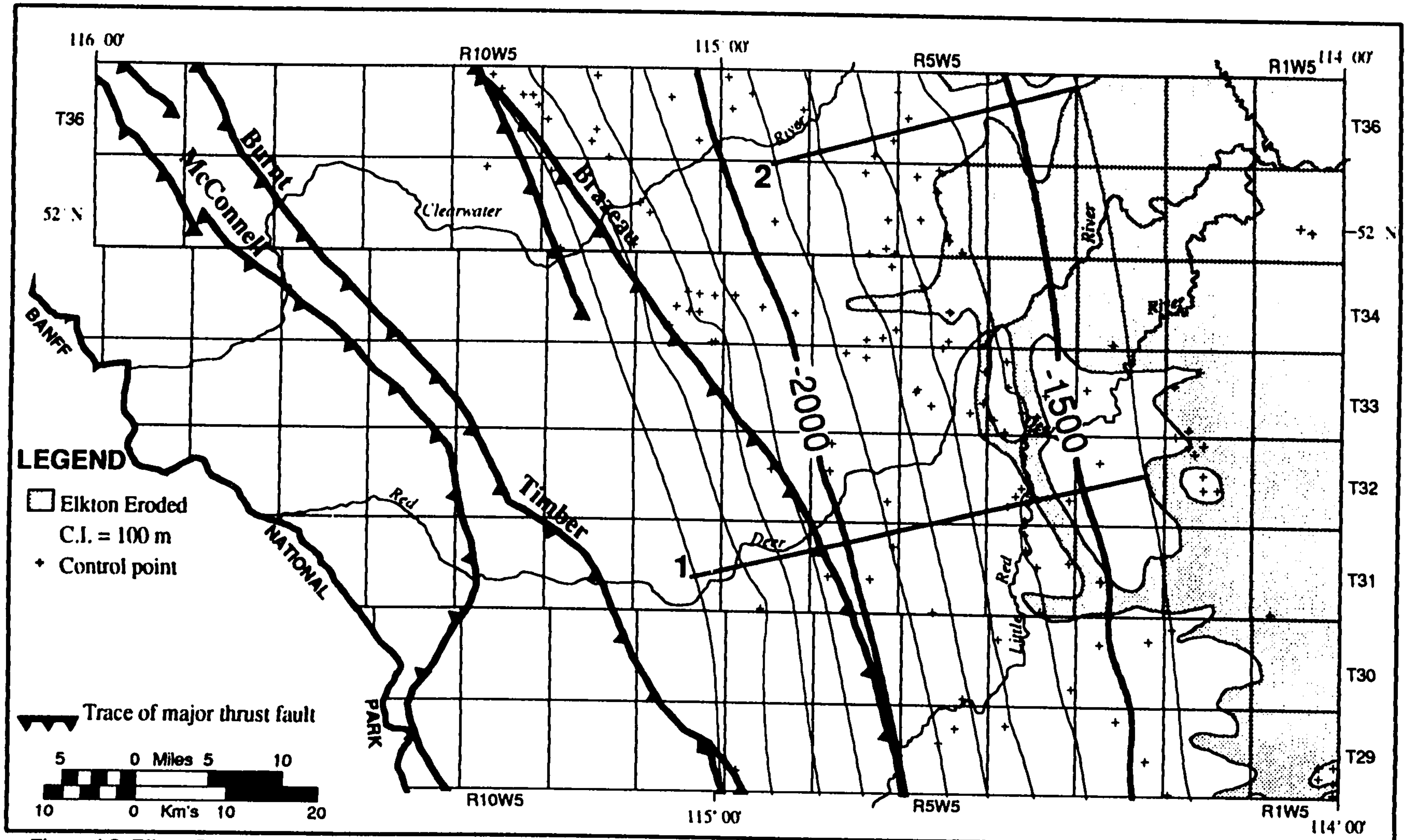


Figure 4.8: Elkton Formation structure map. Formation structure gradients estimated along lines 1 and 2 for the DFR calculations (Section 3.2.2).

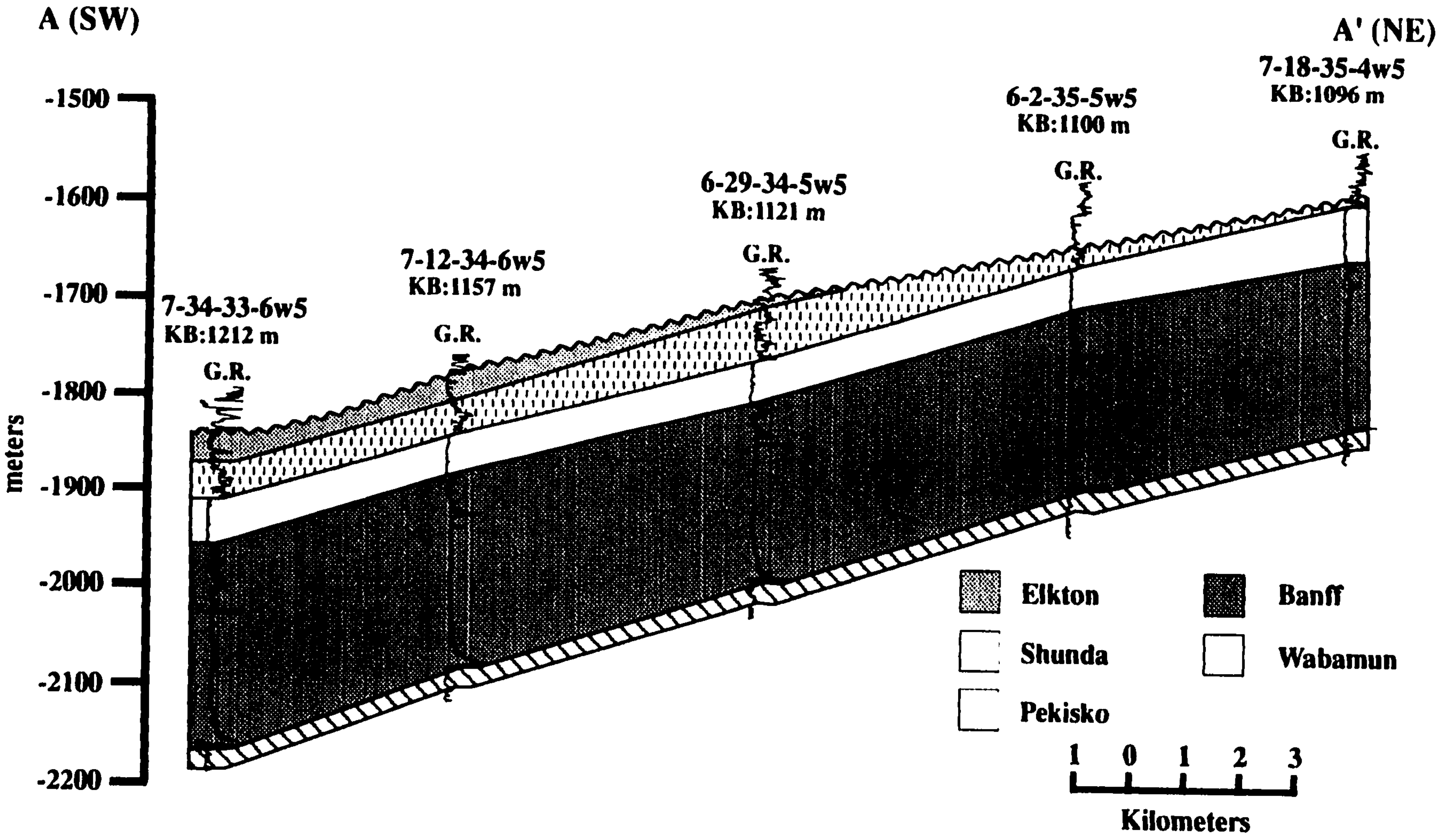


Figure 4.9: Mississippian structure cross section A-A'. Line of section: Figure 4.1.

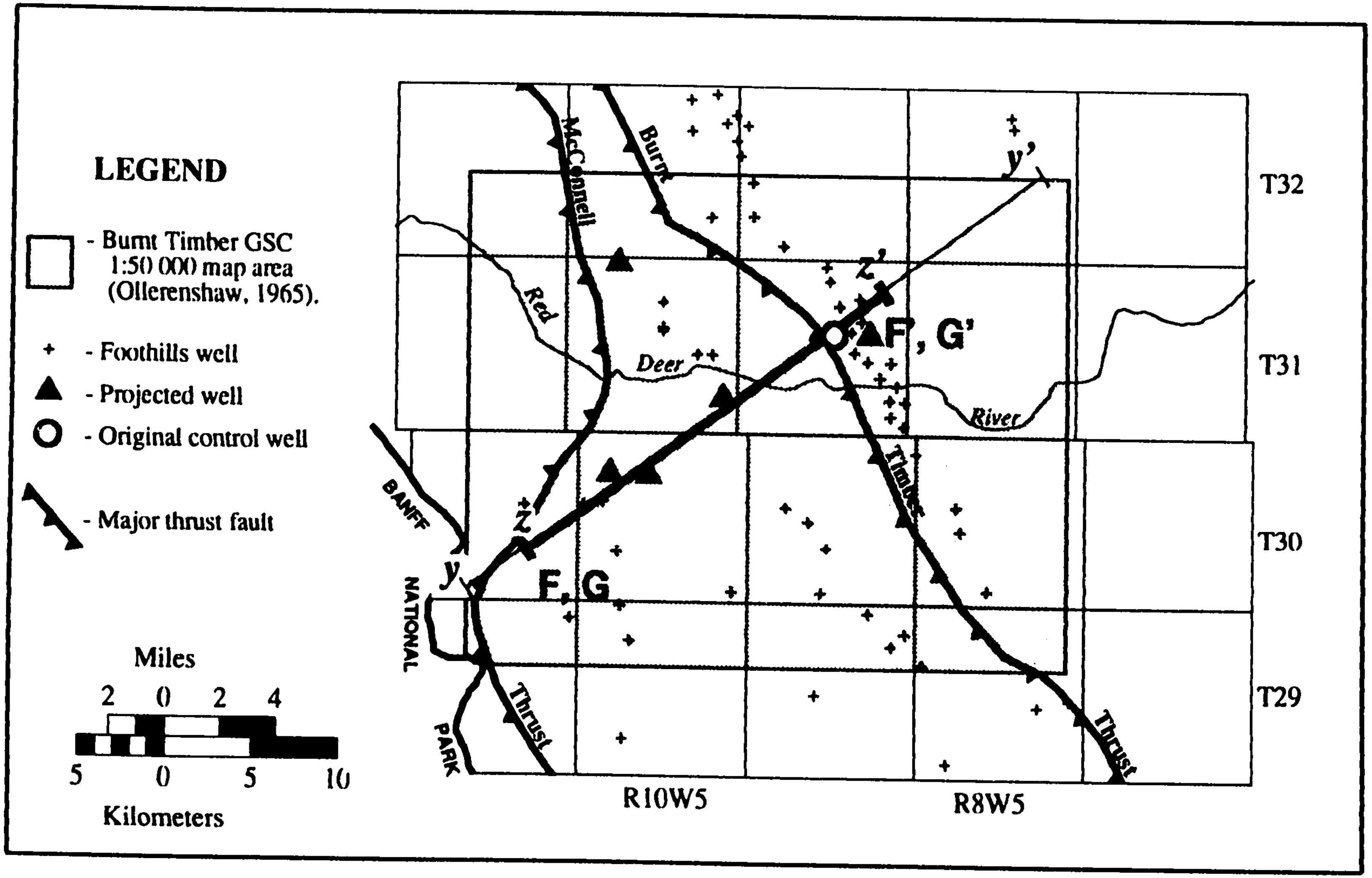


Figure 4.10: Burnt Timber area cross section location map. y-y' - Ollerenshaw's (1965) original line of section; z-z' - Portion of Ollerenshaw's original section illustrated in Figure 4.11; F-F' - Reinterpreted structural section; G-G' - Modified structural section including hydrogeological data.

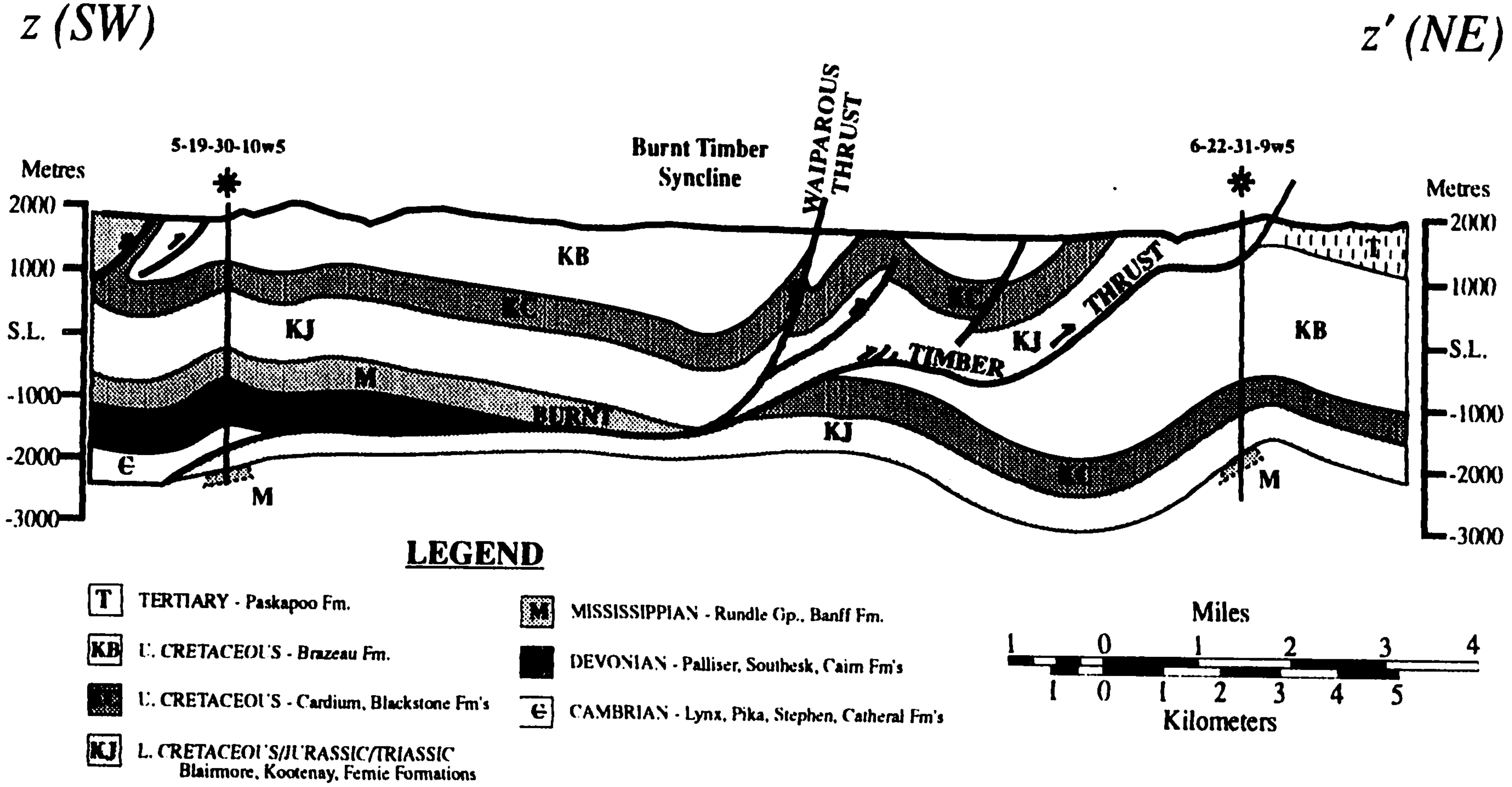


Figure 4.11: Cross section z-z'. The cross section represents a portion of the original y-y' cross section through the Burnt Timber area (modified after Ollerenshaw, 1965).

contacts on Ollerenshaw's Burnt Timber cross section are inaccurate. Therefore, Figure 4.12 (p. 56) illustrates a modified version of Ollerenshaw's cross section based on several newer wells located near his cross section trace. This cross section is a modified schematic of Ollerenshaw's original section and is therefore not intended to represent a rigorous structural interpretation of the area. Price (1981) illustrates a well established empirical rule that thrust faults produce repetitions in the stratigraphic sequence by transporting older rocks over younger. A thrust fault cuts up through the stratigraphic package in the direction of relative displacement. This allochthonous nature can be identified in geophysical well logs along Ollerenshaw's Burnt Timber cross section trace. Repetition and thickening of various strata suggest locations of additional major and minor thrust faults.

To identify and interpret various formations within the Burnt Timber area, cross section F-F' is subdivided into four nappes (Figure 4.12, p. 56). This classification is for descriptive purposes and not intended to imply timing of thrust sheet emplacement. Generally, because of the nature of thrust sheet emplacement, formations may be repeated within a vertical bore hole. This formation repetition may lead to confusion in mapping hydrogeological data if the structural relationships are not well understood. Two significant modifications illustrated in Figure 4.12 (p. 56) were made to Ollerenshaw's (1965) original cross section, namely, a) adjustment of the Brazeau and Burnt Timber Thrusts and b) addition of several smaller thrust splays within the McCue Creek anticline.

Brazeau and Burnt Thrusts

Ollerenshaw identified a major thrust surface (Unamed) in 5-19-30-10w5 at an elevation of approximately -1830m where Cambrian strata (Unit C) is underlain by Cretaceous strata (Unit KJ). A similar contact can be located in younger wells further to the northeast. The Mannville Group is present below Cambrian Formations in 5-29-30-10w5 and 6-28-30-10w5 and underlying Devonian carbonates in 2-12-31-10w5 and 7-23-31-9w5. Based on extrapolations from the Wabamun and Elkton structure

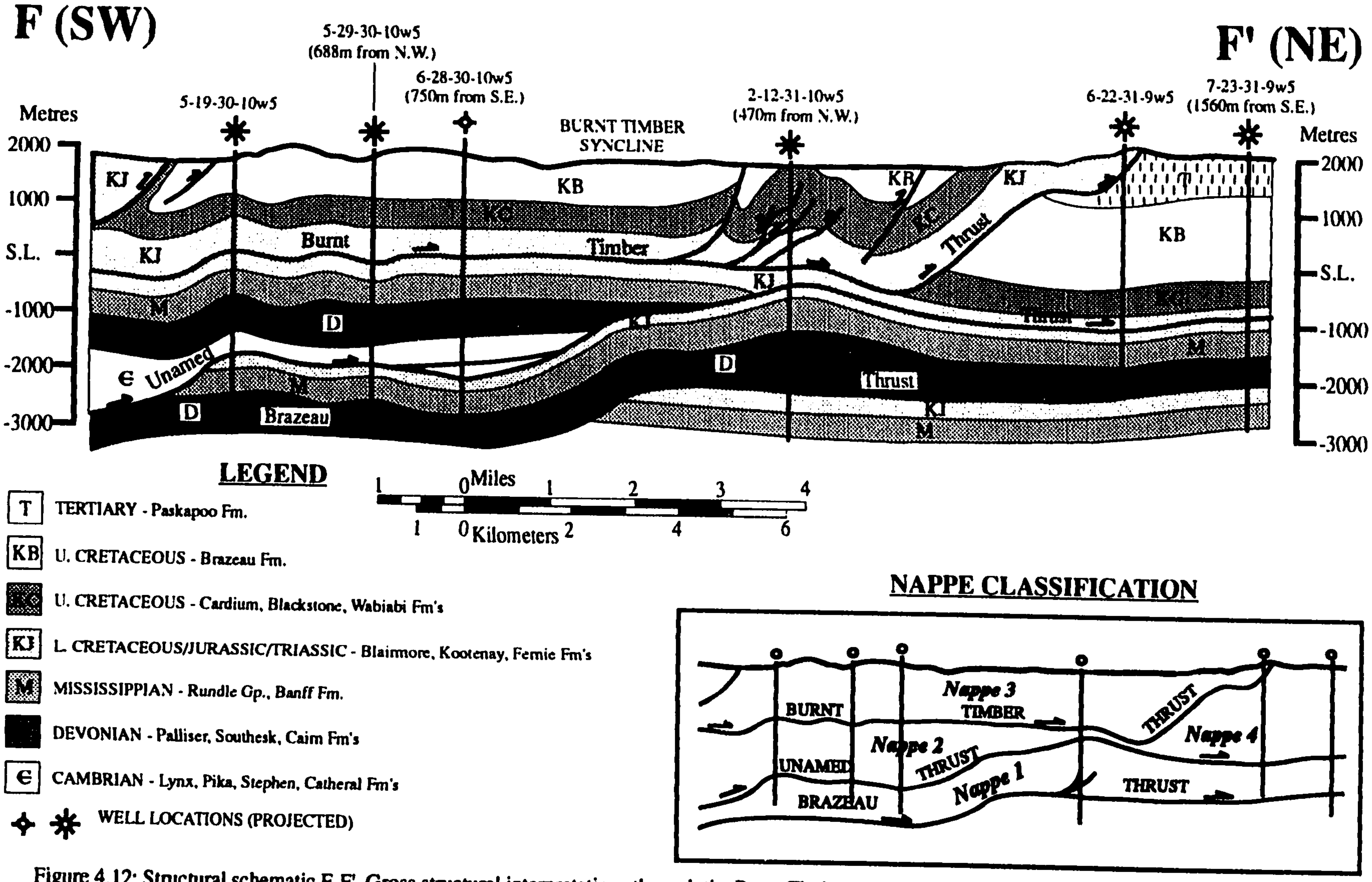


Figure 4.12: Structural schematic F-F'. Gross structural interpretations through the Burnt Timber area were modified after Ollerenshaw (1965; 1975) and newer geophysical well logs. Figure inset identifies a descriptive nappe classification.

contour maps (Figures 4.2 and 4.8, p 44 and 51), the strata below the Brazeau Thrust in the 2-12-31-10w5 and 7-23-31-9w5 wells are autochthonous. The Brazeau Thrust is drawn at greater depths below the extent of Ollerenshaw's (1965) interpretations in the 5-19-30-10w5, 5-29-30-10w5, and 6-28-30-10w5 wells. The subsurface trace of the Burnt Timber Thrust extends through the lower part of the KJ unit and outcrops east of 6-22-31-9w5. The formation contacts within nappe 2 have been shifted to higher elevations matching formation contacts in the respective geophysical well logs. Furthermore, Cambrian Formations are identified within 5-29-30-10w5 and 6-28-30-10w5 extending Ollerenshaw's upper Cambrian contact approximately 6 *km* to the northeast near the Burnt Timber syncline.

McCue Creek Anticline

The 2-12-31-10w5 well was drilled within the McCue Creek anticline. The subsurface formation contacts within this well were difficult to interpret due to a combination of clastic lithologies and several smaller thrust splays originating from the Burnt Timber Thrust. As a result, only the gross Cretaceous lithologies are depicted in Figure 4.12 (p. 56). The thickness of Cretaceous strata within the 2-12 well is greater than the surrounding wells due to repetition of portions of the formations. Based on Ollerenshaw's (1965) geological map, the Burnt Timber thrust splays appear to terminate in the subsurface within the Cretaceous sediments. Identification of further structural details within nappe 3 of the McCue Creek anticline were determined to be irrelevant for this study. However, the thickness of the Devonian formations in nappe 1 also appear to increase due to smaller fault splays. The fault surfaces were much easier to identify based on the more resistant carbonate lithologies of the Paleozoic formations.

4.2 Alberta Foreland Basin waters

4.2.1 Devonian Aquifers

The Wabamun, Nisku, Leduc, Cooking Lake, and Beaverhill Lake Formations all form significant regionally extensive aquifers within the study area. The Ireton Formation is a major aquitard which separates the Leduc from the overlying Nisku Formation (Section 4.1.1). The greatest number of quality DSTs that were used for potentiometric mapping were found within the Leduc Formation followed by the Wabamun and Nisku Formations. The Cooking Lake and Beaverhill Lake Formations have sparse data control. Any data points that were located within the Cooking Lake Formation were grouped together with the Leduc Formation.

Water potential

The freshwater hydraulic heads in the Leduc Formation are contoured in Figure 4.13, (p. 59). The highest values of hydraulic head are located in wells adjacent to the Brazeau Thrust while the lowest values are found in the central part of the Cheddarville reef trend. The potentiometric surface has two significant features indicating a distribution of fluid potentials which deviate from what was observed in the overlying Wabamun Formation. Firstly, a steep hydraulic gradient exists which separates the Ricinus/Bearberry reef complexes from the Cheddarville reef trend (Twps. 34-36; Rges. 7-9w5). Freshwater hydraulic heads exceed 1100 m within the Ricinus/Bearberry trends and decrease in the northeast direction to less than 700 m at the western edge of the Cheddarville trend. The hydraulic gradient between the Cheddarville and Ricinus/Bearberry areas was calculated to be approximately 34.8 m/km.

Pressure-depth and pressure-elevation plots of the Leduc Formation are illustrated in Figure 4.16 (p. 63). The Leduc pressure data were grouped into their respective reef trend areas so that each reef complex could be compared and distinguished. Both the pressure-depth and pressure-elevation plots for the Leduc Formation indicate that

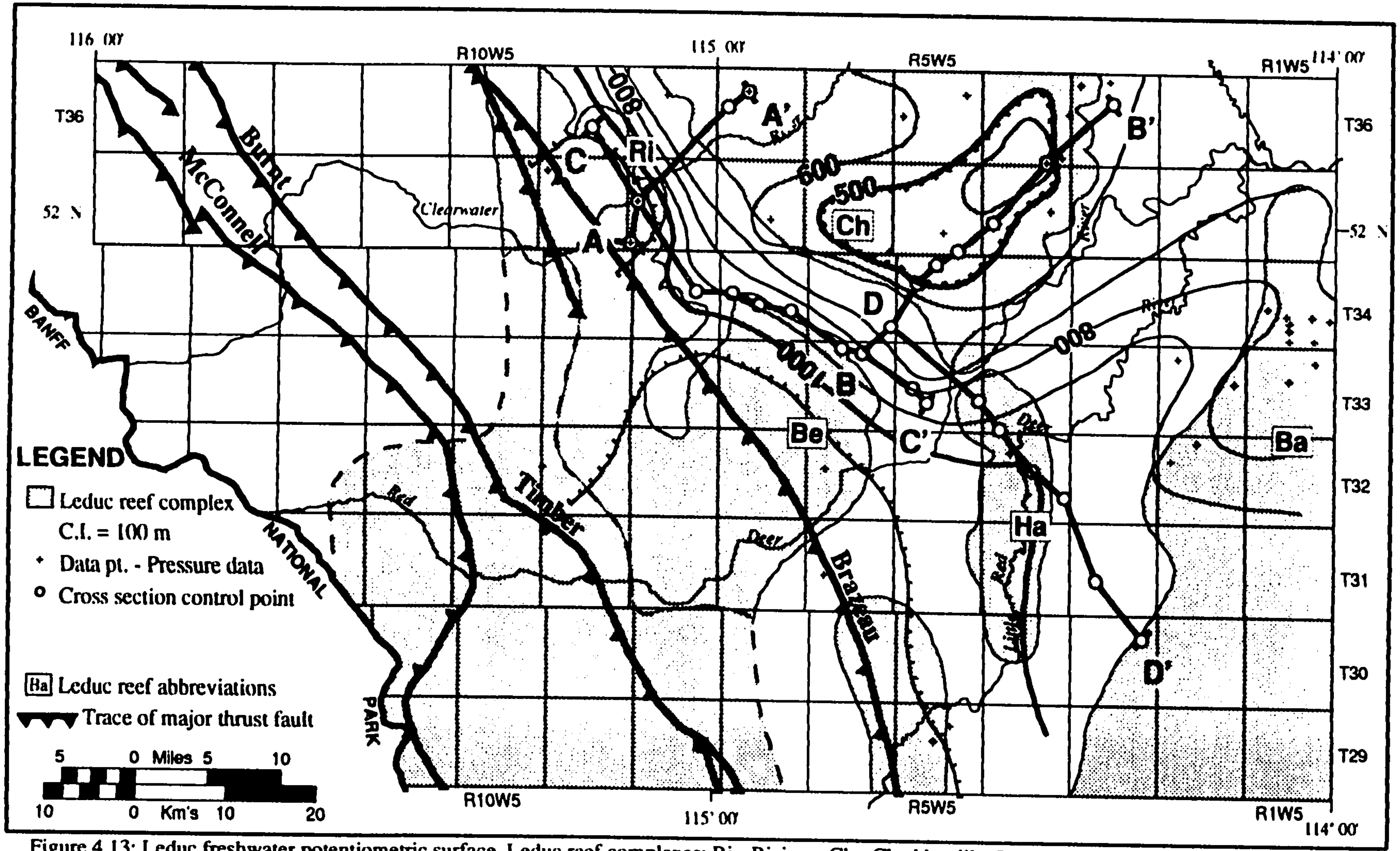


Figure 4.13: Leduc freshwater potentiometric surface. Leduc reef complexes: Ri - Ricinus, Ch - Cheddarville, Be - Bearberry, Ha - Harmattan, Ba - Bashaw.

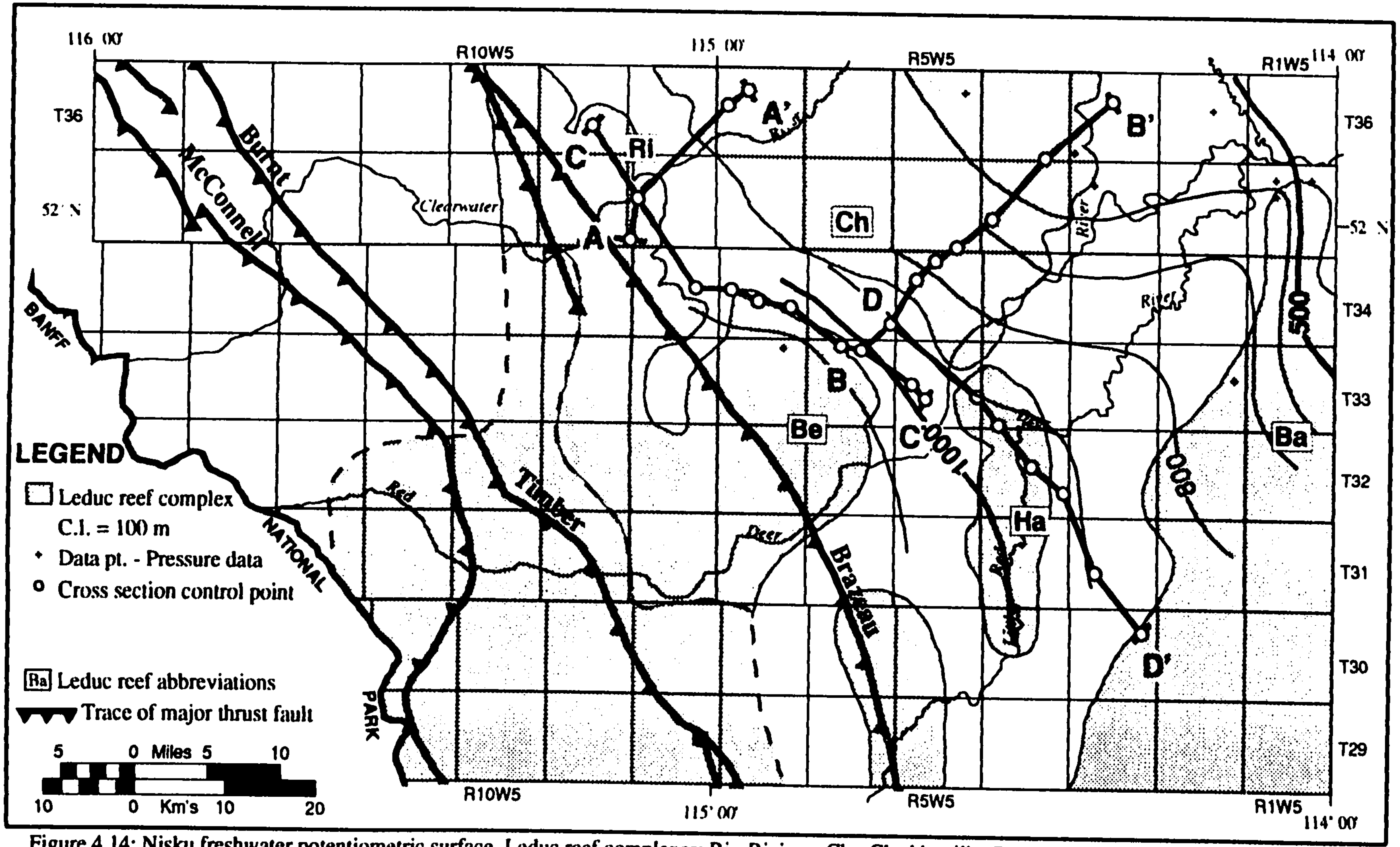


Figure 4.14: Nisku freshwater potentiometric surface. Leduc reef complexes: Ri - Ricinus, Ch - Cheddarville, Be - Bearberry, Ha - Harmattan, Ba - Bashaw.

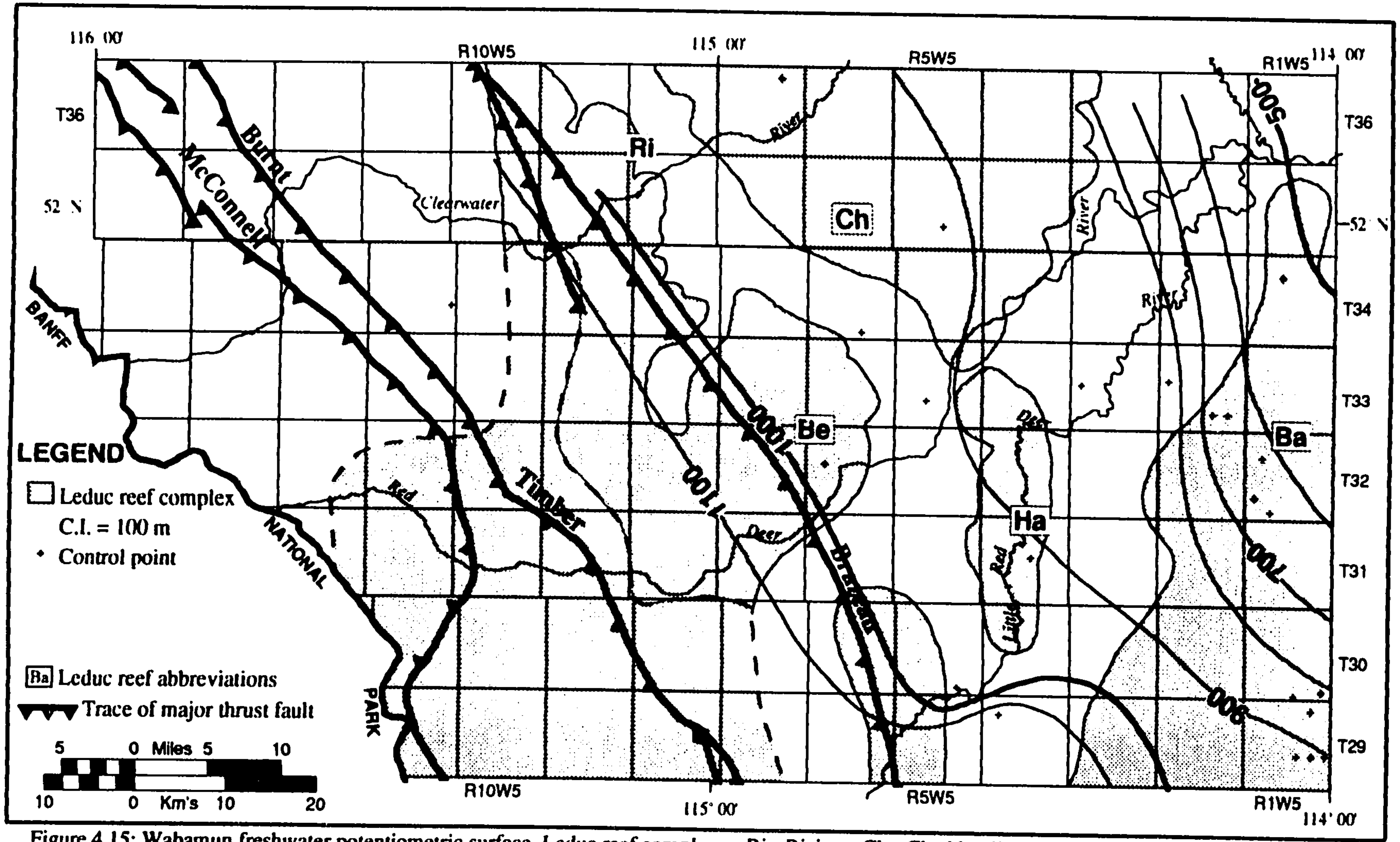


Figure 4.15: Wabamun freshwater potentiometric surface. Leduc reef complexes: Ri - Ricinus, Ch - Cheddarville, Be - Bearberry, Ha - Harmattan, Ba - Bashaw.

the Cheddarville reef trend is more underpressured than all other reef trends within the study area.

A second significant feature of the Leduc potentiometric surface (Figure 4.13, p. 59) is the occurrence of a potentiometric low which is situated in the central portion of the Cheddarville reef complex (Twps. 34-35; Rges. 4-6w5). Hydraulic head values in this region decrease to less than 500 *m*. The potentiometric low coincides with a thinning of the overlying Lower Ireton Member aquitard (Figure 4.3, p. 46); Section 4.1.1). The SW-NE C-C' cross section (Figure 4.5, p. 48) illustrates several wells where the Ireton Formation has thinned or is not present. Similar relationships between the Leduc, Ireton, and Nisku Formations were observed by Rostron (1995) in a central Alberta hydrogeologic study incorporating the Clive and Bashaw reef complexes.

The data control in the overlying Nisku Formation potentiometric surface is quite sparse (Figure 4.14, p. 60). Unfortunately, only a handful of finalized culled pressure data points are present in the northern half of the study area. However, the Nisku fresh-water head values appear to have a similar magnitude to those found in the underlying Leduc Formation. Values of hydraulic head vary from greater than 1100 *m* east of the Brazeau Thrust overlying the Leduc Bearberry reef complex to less than 500 *m* in the northeast corner of the study area. A potentiometric low similar to what was observed in the central part of the Leduc Cheddarville reef was not found in the overlying Nisku Formation. A pressure-depth plot combining data points from both the Nisku and Leduc Formations within a smaller local area is shown in Figure 4.17 (p. 65). The pressure-depth plot indicates that the water pressure data within the Leduc and Nisku Formations near the Leduc potentiometric low have a similar gradient with respect to the hydrostatic rate of pressure change.

The potentiometric surface for the Wabamun Formation is illustrated in Figure 4.15 (p. 61). The highest hydraulic head values, which exceeded 1000 *m*, are located in wells drilled near the surface expression of the Brazeau Thrust. Hydraulic heads decrease to approximately 500 *m* in the north-east corner of the study area.

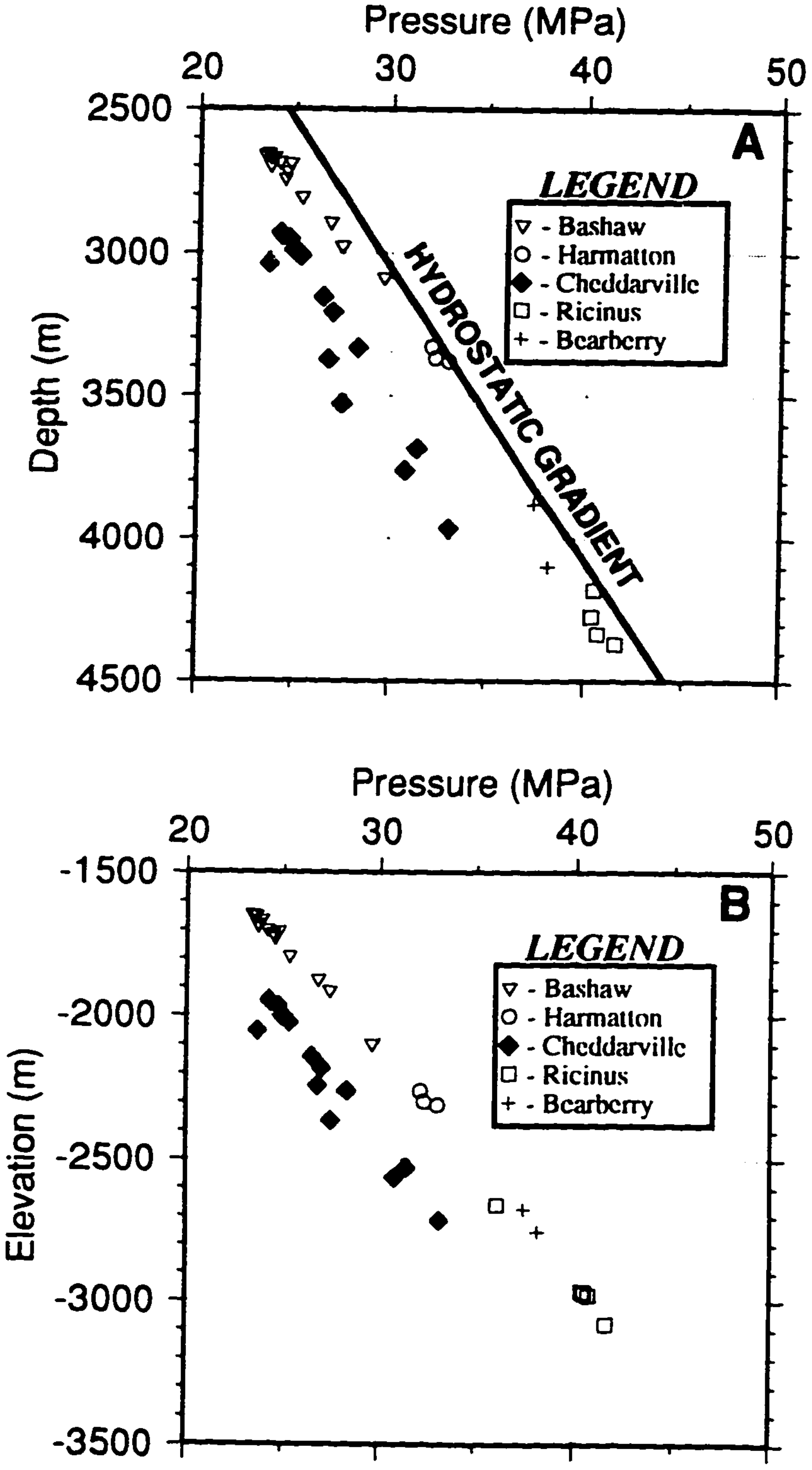


Figure 4.16: Leduc pressure relationships. A - Pressure-depth plot. B - Pressure - elevation plot. Data is grouped into six Leduc reef trend areas (for reference see Figure 2.3).

The hydraulic head contours indicate a potentiometric surface which has a relatively constant hydraulic gradient. A slight separation of the contours exists in the central part of the study area over the underlying Cheddarville and Harmattan Leduc reef complexes. The greatest fluid potential in the Wabamun Formation is located adjacent to the disturbed belt and decreases in the north-east direction perpendicular to strike.

Fluid Chemistry

Figures 4.18 through 4.20 (p. 66 to p. 68) illustrate the distribution of finalized culled formation water data points and TDS magnitudes within Devonian formations. A statistical summary of TDS, pH, and Na/Cl ratios are listed in Table 4.1 (p. 69). The formation waters within the Leduc appear to have the highest salinity with values ranging from approximately 140 g/l to greater than 240 g/l. The majority of the highly saline waters are found in the Bashaw complex surrounding the Innisfail field (Twps. 34-35, Rge. 1w5: Figure 4.18, p. 66). The overlying Nisku Formation waters have a similar chemical composition as the Leduc Formation in terms of TDS, pH, and Na/Cl ratio. On the other hand, there is an approximate 100 g/l average decrease in the TDS within the Wabamun Formation waters. Therefore, the TDS in Devonian Formation waters appear generally to increase with depth. Differences in the Wabamun, Nisku, and Leduc Formation water compositions are illustrated on Piper diagrams (Figures 4.22 and 4.21; p. 70 and p. 69). The relative enrichment of Na and Cl ions in the Nisku and Leduc Formation waters appears to be similar. However, the Wabamun Formation has a relative increase in the amounts of Ca and Mg found in the water samples. According to Sulin's classification (Sulin, 1946), the majority of all Devonian Formation waters are of the $Na - Cl$ type.

4.2.2 Mississippian Aquifers

Mississippian aquifers within the study area are the Elkton/Turner Valley, Shunda and Pekisko Formations. The majority of the fluid data within these aquifers pertains

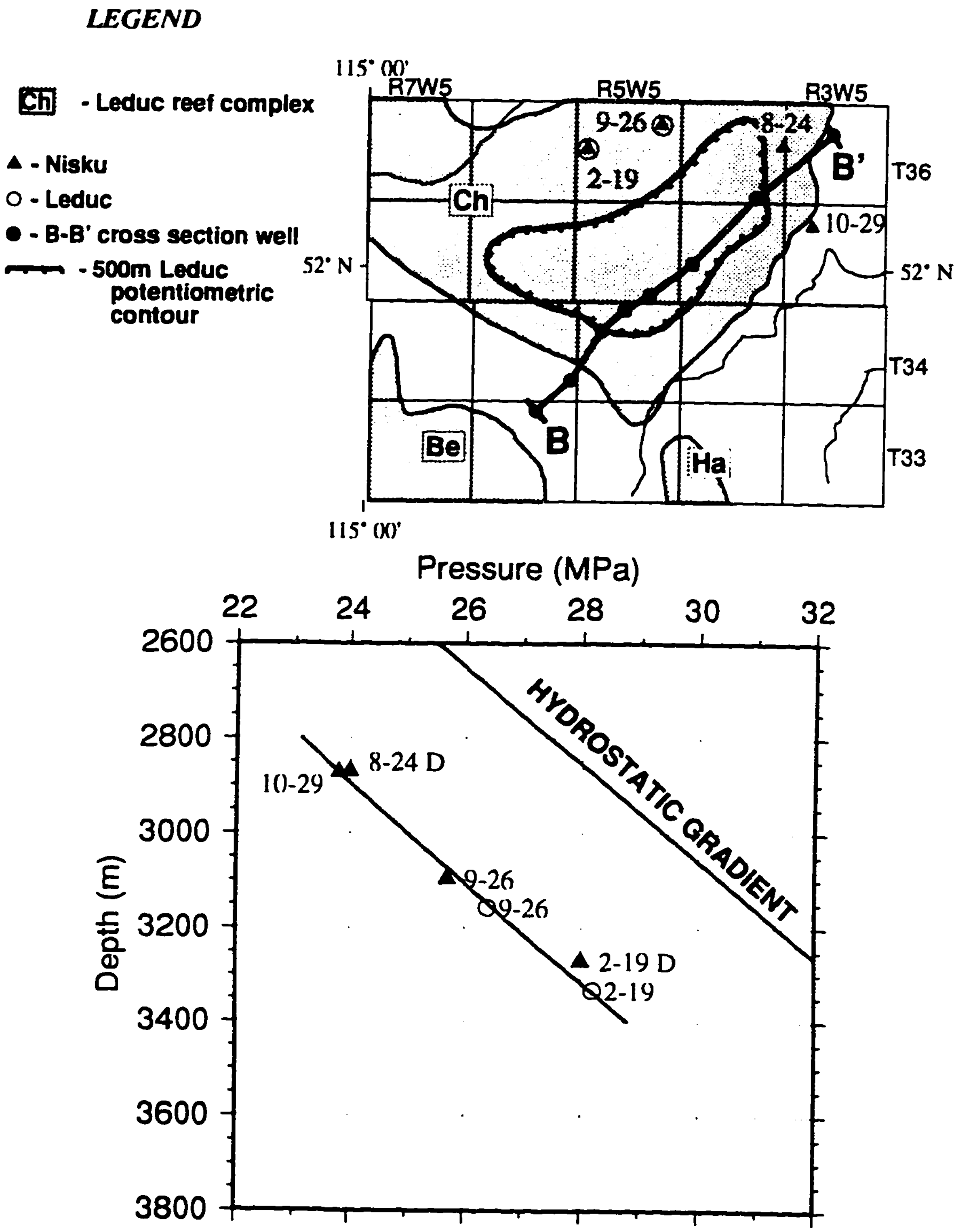


Figure 4.17: Pressure-depth relationship in the Leduc and Nisku Formations within the Cheddarville reef complex. A "D" appended to the well label indicates a D CIFE quality test.

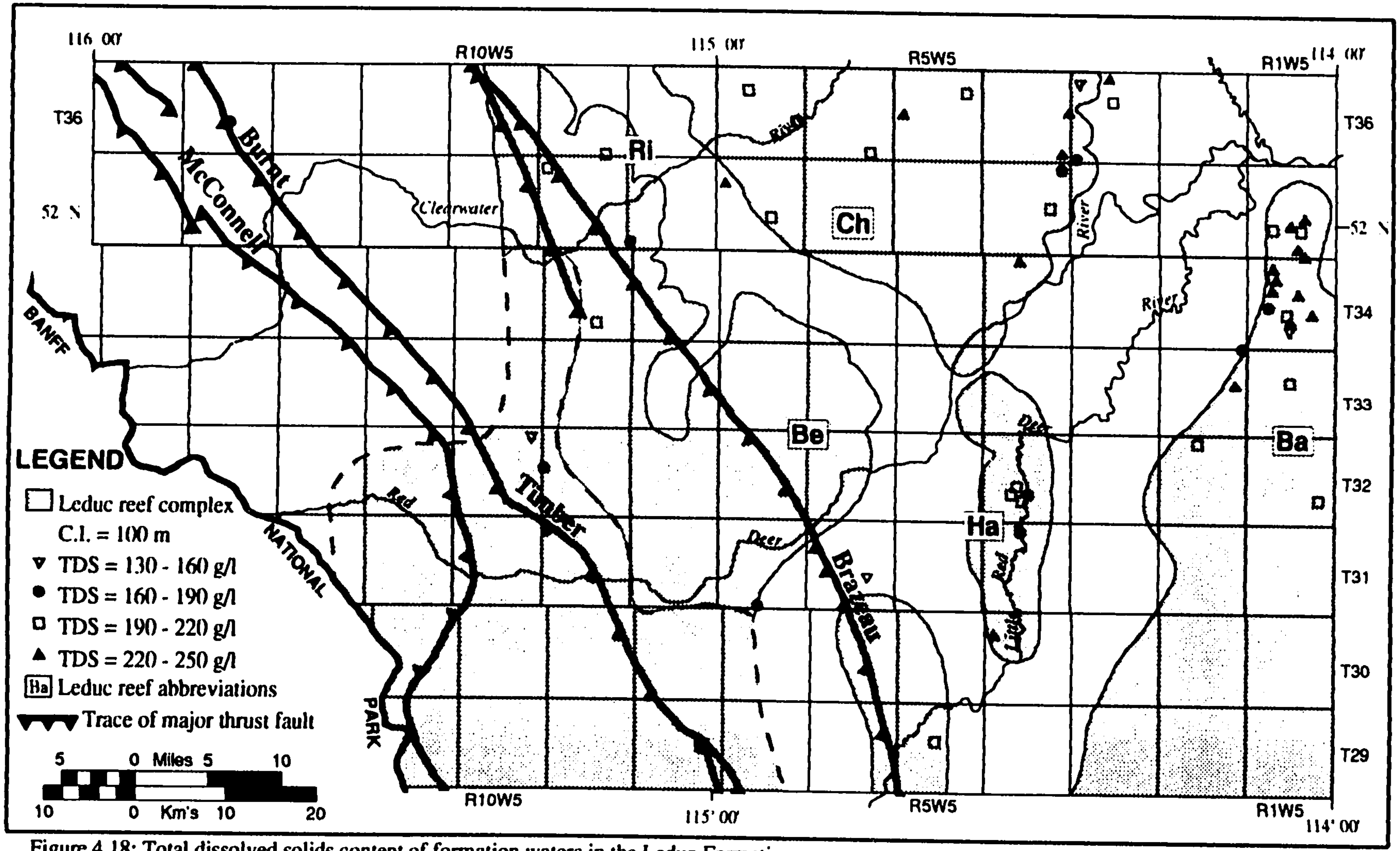


Figure 4.18: Total dissolved solids content of formation waters in the Leduc Formation.
Leduc reef complexes: Ri - Ricinus, Ch - Cheddarville, Be - Bearberry, Ha - Harmattan, Ba - Bashaw.

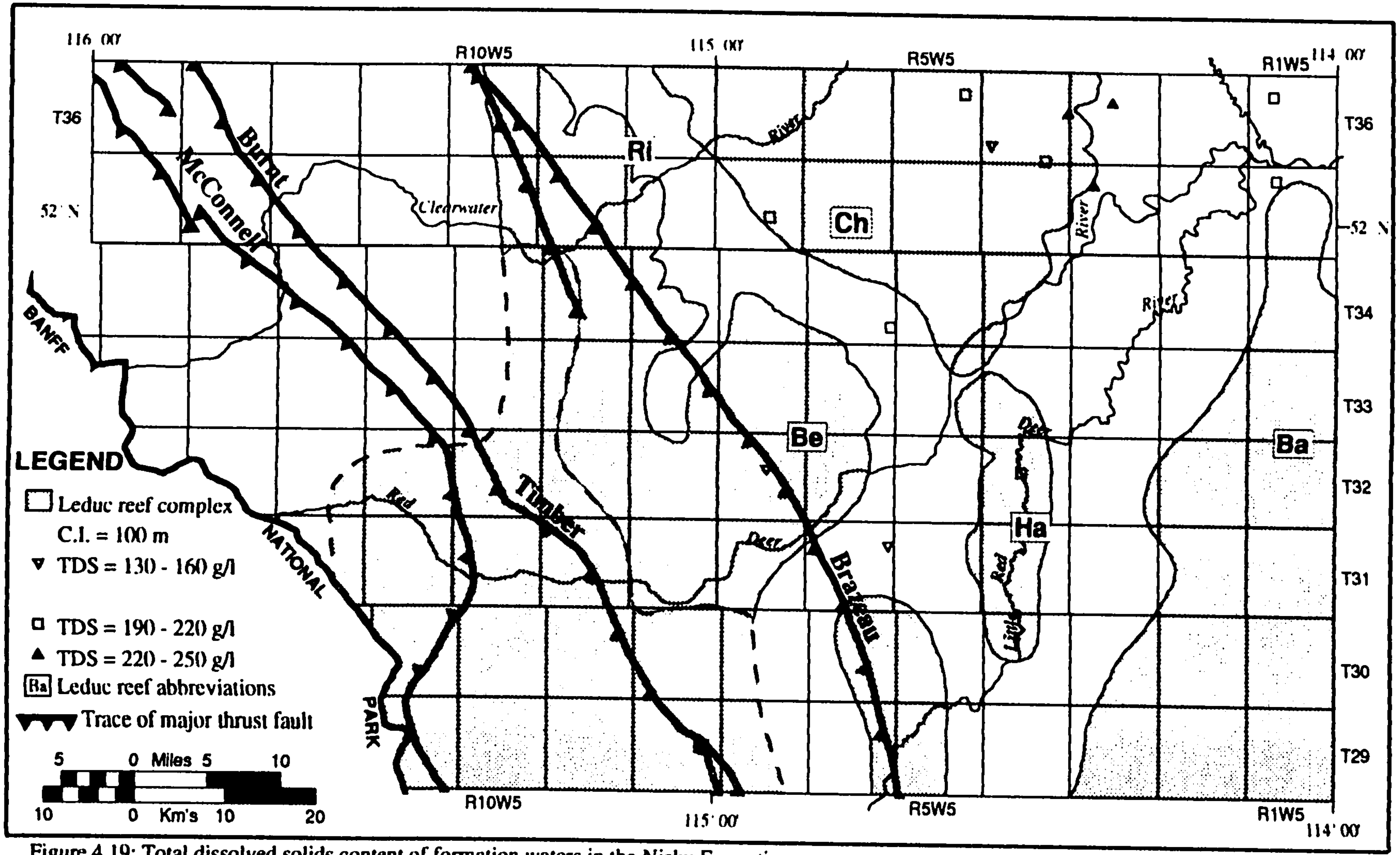


Figure 4.19: Total dissolved solids content of formation waters in the Nisku Formation.
Leduc reef complexes: Ri - Ricinus, Ch - Cheddarville, Be - Bearberry, Ha - Harmattan, Ba - Bashaw.

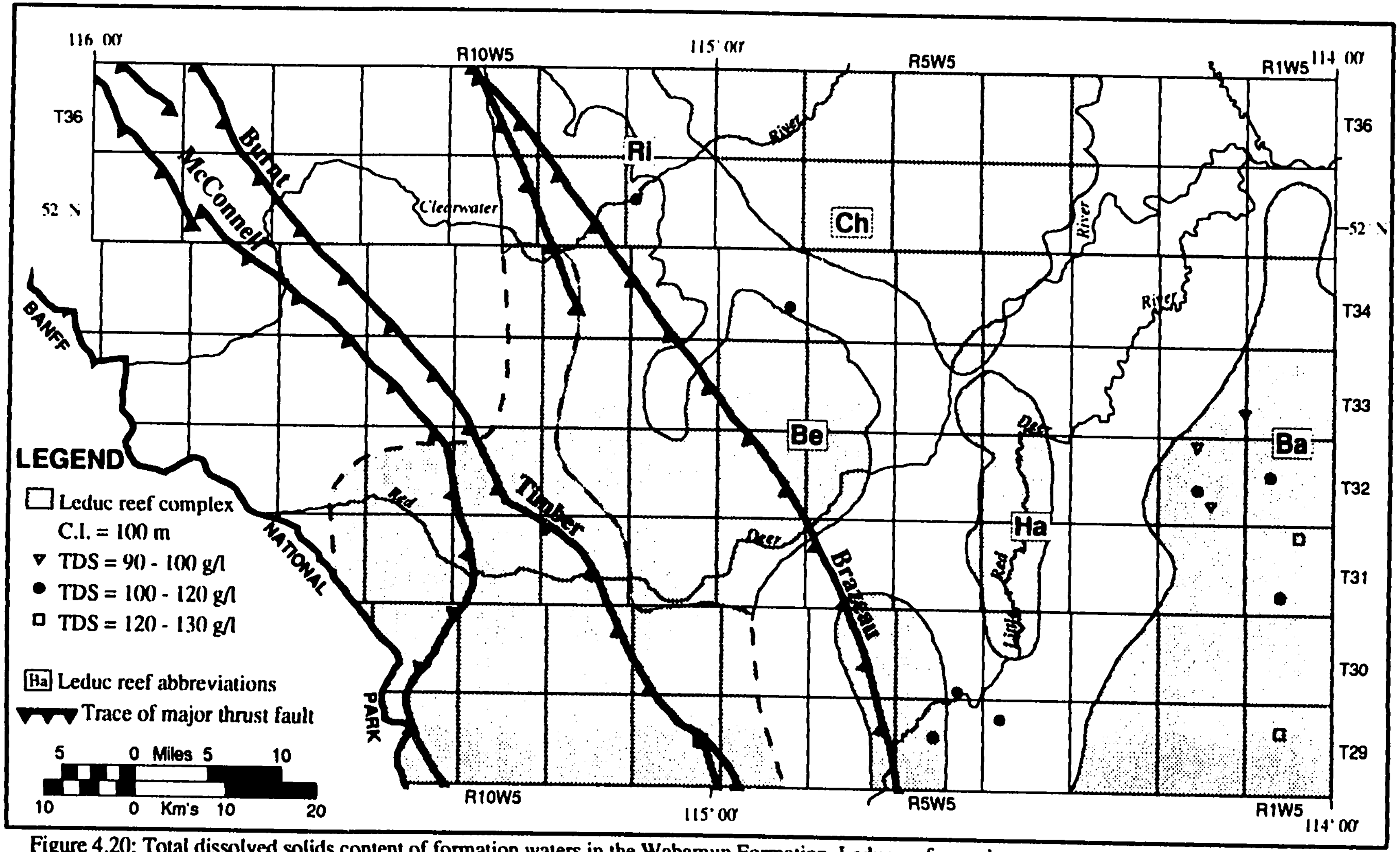


Figure 4.20: Total dissolved solids content of formation waters in the Wabamun Formation. Leduc reef complexes: Ri - Ricinus, Ch - Cheddarville, Be - Bearberry, Ha - Harmattan, Ba - Bashaw.

	Wabamun	Nisku	Leduc
Max.TDS(g/l)	125	240	242
Min.TDS(g/l)	91	130	141
Avg.TDS(g/l)	107	195	204
Max.pH	7.5	8.3	8.2
Min.pH	4.3	6.1	5.9
Avg.pH	6.8	7.1	6.9
Max.Na/Cl	1.006	0.777	0.829
Min.Na/Cl	0.539	0.626	0.422
Avg.Na/Cl	0.771	0.699	0.633
TotalCount	30	22	115
+Count	13	13	54

Table 4.1: Summary of Devonian Formation water chemical analyses. The calculated values are for those positive culled tests (+ Count).

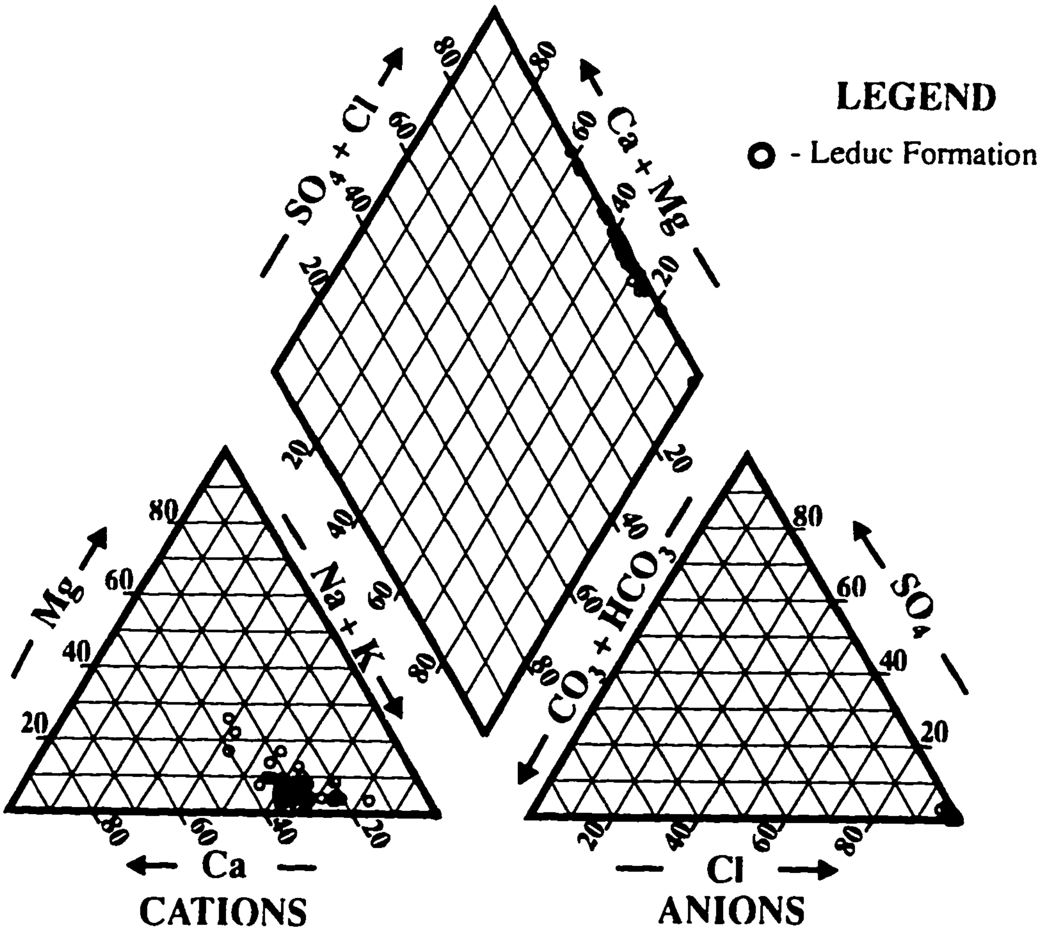


Figure 4.21: Piper diagram for the Leduc chemical formation water analyses.

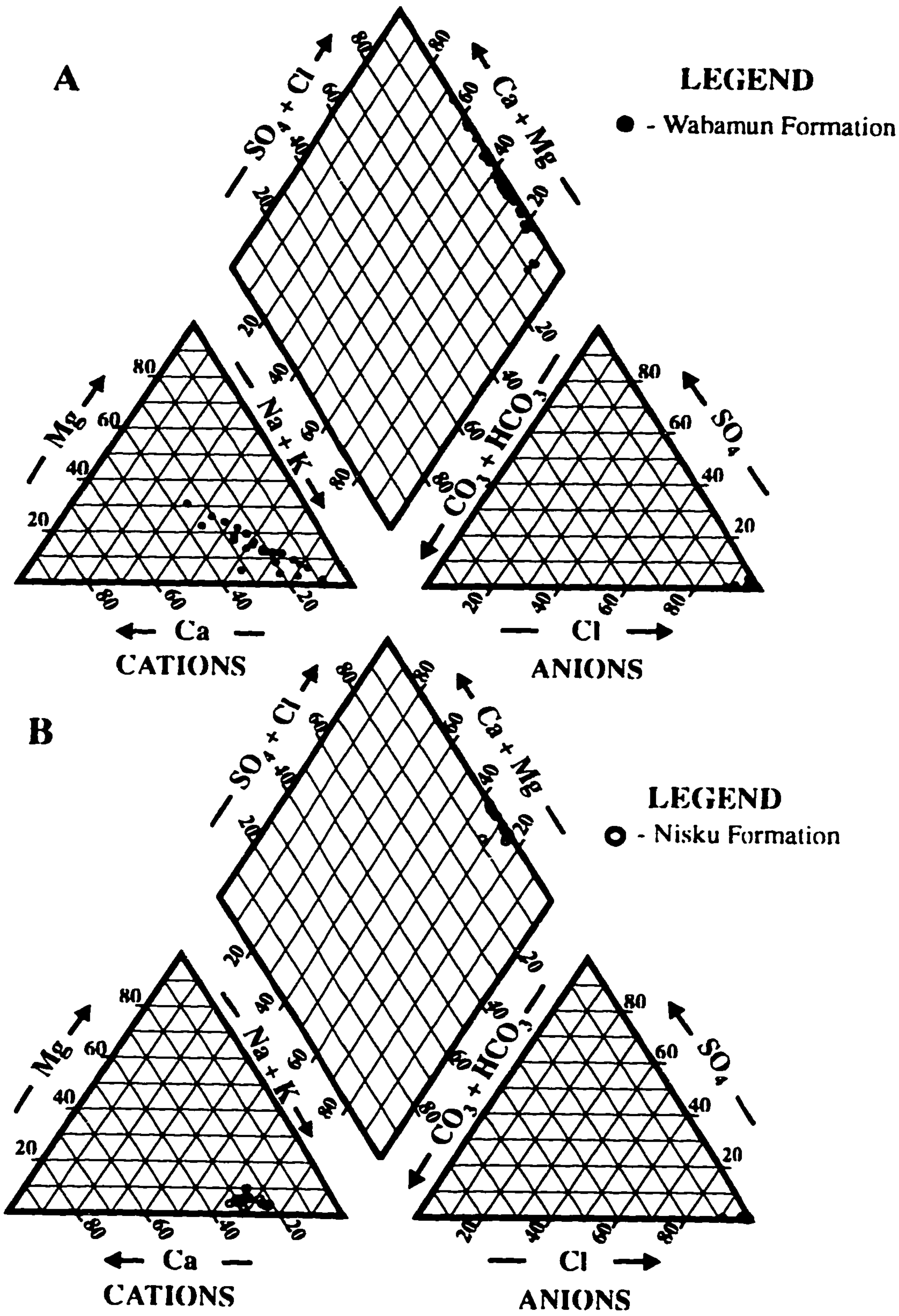


Figure 4.22: Piper diagram for the Wabamun (a) and Nisku (b) chemical formations water analyses.

to the Elkton and equivalent disturbed belt Turner Valley Formation. The distribution of the Mississippian formations may be limited to the east by their erosional edge underlying the pre-Cretaceous unconformity. The eastern limits of the Elkton and Pekisko aquifers are illustrated in Figure 4.1 (p. 43).

Water potential

The Elkton potentiometric surface includes those data points found east of the Brazeau Thrust (Figure 4.23, p. 72). The Turner Valley Formation data west of the Brazeau Thrust have been omitted from the potentiometric surface. In structurally complex areas, hydraulic head values must be interpreted within a vertical structural cross section (Section 4.3). The relatively even distribution of Elkton Formation hydraulic head values in close proximity to its erosional edge are indicative of the significance of the erosional edge on hydrocarbon accumulations.

The values of hydraulic head within the Elkton Formation generally decrease in the northeast direction. The maximum values exceed 900 *m* towards the surface expression of the Brazeau Thrust as well as within the Harmattan erosional outlier (Twps.31-33, Rges. 3-4w5). A relatively steep hydraulic gradient exists at the northern boundary of the study (Twp. 36, Rges. 4-5w5). Hydraulic head values decrease from greater than 900 *m* to 400 *m* over a distance of approximately 20 *km*. This gradient coincides with an erosional restriction in the Elkton Formation in both a lateral and vertical direction. Therefore, the vertical distance between the lower boundary of the Elkton Formation and the overlying Cretaceous strata is reduced.

Water chemistry

The majority of the water chemical analyses in Mississippian aquifers were within the Elkton Formation. Table 4.2 (p. 73) summarizes the distribution and upper and lower limits of the various chemical parameters. Generally, the TDS of Mississippian formation waters are less than 100 *g/l*. The average TDS decreases from approximately 74 *g/l* in the Elkton to 40 *g/l* and 59 *g/l* within the underlying Shunda and

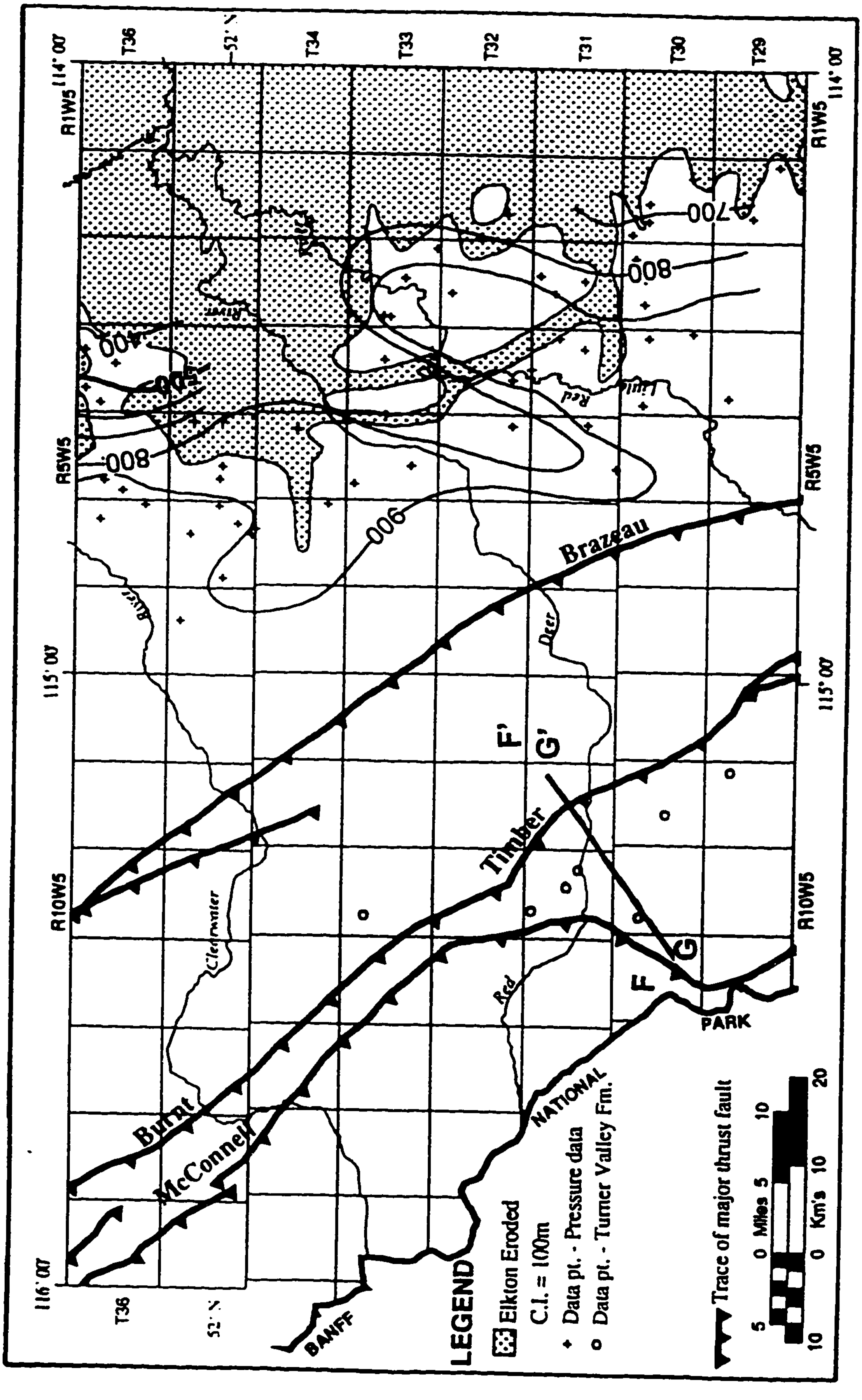


Figure 4.23: Elkton freshwater potentiometric surface.

	Elkton	Turner Valley	Shunda	Pekisko
$Max.TDS(g/l)$	132	158	51	72
$Min.TDS(g/l)$	51	69	32	32
$Avg.TDS(g/l)$	74	114	40	59
$Max.pH$	8.2	7.3	7.8	7.7
$Min.pH$	6.1	6.6	6.6	6.3
$Avg.pH$	7.0	7.0	7.3	6.9
$Max.Na/Cl$	1.00	0.88	0.97	1.00
$Min.Na/Cl$	0.63	0.53	0.69	0.41
$Avg.Na/Cl$	0.90	0.71	0.88	0.73
$TotalCount$	35	17	11	6
$+Count$	20	6	3	4

Table 4.2: Summary of finalized culled Mississippian Formation water chemical analyses. + *count* indicates the number of finalized data points.

Pekisko Formations, respectively. This suggests an apparent reversal in a general trend of increasing TDS with depth. However, the limited number of data points in the latter two formations may skew the calculated average. Locally within the Elkton, the TDS appears to generally decrease in the northeast direction towards the erosional edge (Figure 4.24, p. 74). This is best observed in the northern part the study (Twps. 35-36, Rges. 7w5-4w5).

The ionic composition of the Elkton Formation water is illustrated graphically by plotting the finalized culled data on a Piper diagram (Figure 4.25, p. 75). The location of the cluster of data points indicates that the formation waters are enriched with Cl and Ca. This is corroborated using the Sulin classification which identifies all Elkton Formation waters as Cl-Ca type waters. Similarly, Sulin's method classifies the waters within the Pekisko and Shunda Formations as Cl-Ca type.

4.3 Foreland Fold and Thrust Belt waters

The analysis of the formation waters within the disturbed-belt incorporated subsurface fluid pressures, water chemical analyses for both subsurface formations and

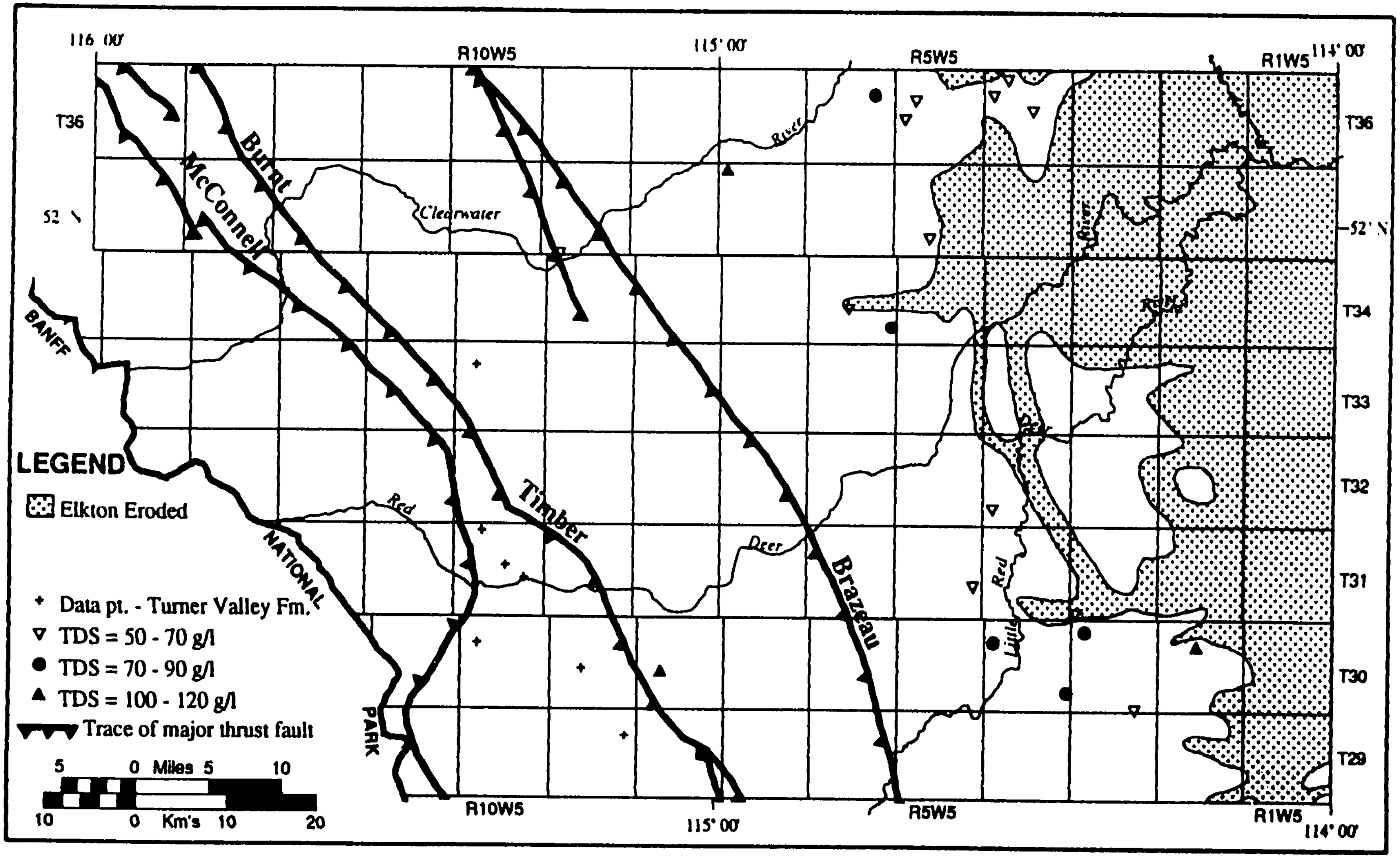


Figure 4.24: Total dissolved solids content of the formation waters in the Elkton Formation.

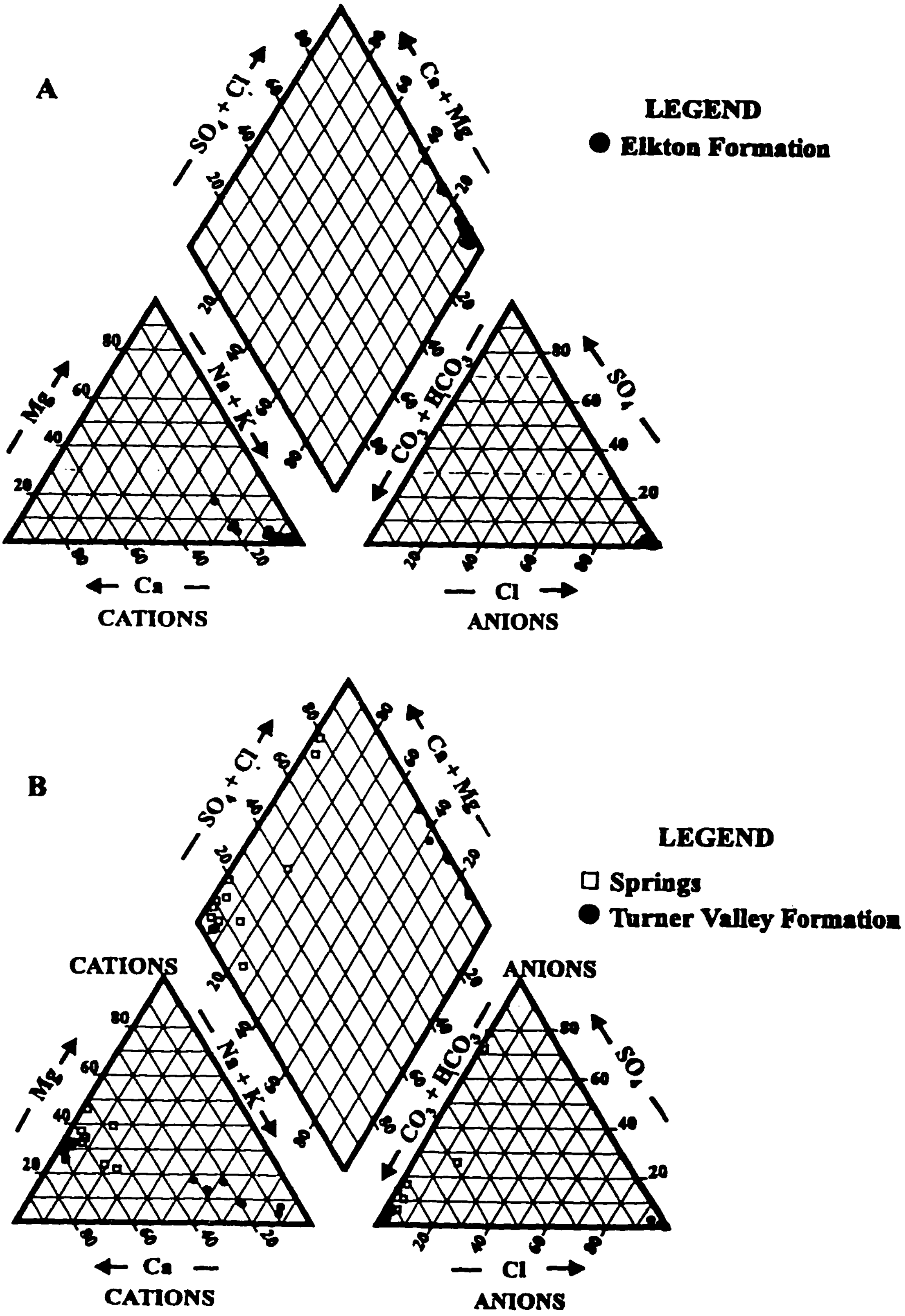


Figure 4.25: Piper diagrams for the Mississippian Formations. A-Elkton, B-Turner Valley Formations and surface springs.

Formation	Total Data Points	
	TDS	Pressures
Turner Valley	8	7
Shunda	0	1
Wabamun	1	1
Nisku	1	0
Leduc	7	3
Beaverhill Lake	1	0

Table 4.3: Summary of subsurface fluid pressure and chemistry data west of the Brazeau Thrust.

surface springs, and spring discharge rates. A summary of the occurrence and type of subsurface water data located west of the Brazeau Thrust is found in Table 4.3 (p. 76). The relatively greater numbers of Turner Valley Formation data points were located within nine townships in the southwest part of the study area. This concentration of data resulted in greater emphasis on the geological interpretation in that vicinity. The geology section of this chapter (Section 4.1, p. 41) discusses various subsurface geological features which were identified and re-interpreted along Ollerenshaw's (1965) cross section through the Burnt Timber area. This analysis identified vertical repetitions of formations due to thrust sheet emplacement, added and adjusted locations of major and minor thrust faults, and re-interpreted geological formation contacts. These observations were an important precursor for the understanding and interpretation of hydrogeological data within a complex structural area. The source of hydrogeological observations made in the Burnt Timber area were either from subsurface water pressure and chemistry data or from surface spring discharge rates and chemical analyses.

4.3.1 Subsurface Data

The subsurface fluid data within the Burnt Timber area were interpreted using a modified structural cross section classified into four nappes (Figure 4.12, p. 56). This section was re-interpreted from Ollerenshaw's (1965) cross section (Cross section *z*-

z', Figure 4.11, p. 54). The fluid data within the area were subsequently plotted on this modified schematic cross section (Figure 4.26, p. 79). Direct and indirect indicators of flow directions were inferred from calculated freshwater hydraulic heads and formation water chemistry, respectively.

Generally, hydraulic heads measured in the Turner Valley Formation west of the Brazeau Thrust are greater than those values within the Elkton Formation east of the Brazeau Thrust. However, the structural interpretations discussed earlier in this chapter indicate that at least one major thrust fault separates Turner Valley and Elkton Formation DSTs. Furthermore, the Turner Valley Formation within the study area west of the Brazeau Thrust is located at different elevations within each nappe. Unfortunately, the Turner Valley Formation DSTs and water chemical analyses were not evenly distributed between the four Burnt Timber nappes. The DSTs were located within nappes 1 and 2 while the water chemical analyses were measured in nappe 1 and the autochthone.

Turner Valley Formation hydraulic heads of nappe 2 have similar magnitudes as the overlying topographic surface (Figure 2.5, p. 12) and indicate a general trend of decreasing freshwater hydraulic heads with depth (Figure 4.26, p. 79). In a lateral sense, hydraulic heads within nappes 1 and 2 decrease in the northeast direction towards the Alberta Foreland Basin. Several Turner Valley water chemical analyses are located at the southwest margin of nappe 1 as well as in the autochthone below the Brazeau Thrust. There is a significant TDS increase in the northeast direction from 85 g/l in nappe 1 to approximately 150 g/l in the autochthone. A Piper diagram (Figure 4.25, p. 75) and Sulin classification of the Turner Valley waters both indicate $Na - Cl$ type waters. The Piper diagram illustrates a relative increase in the amount of Ca^{++} and Mg^{++} compared with those water samples measured in the Elkton Formation. The TDS values within the Elkton Formation of the Foreland Basin (Figure 4.24, p. 74) are lower by approximately 50-70 g/l than the Turner Valley Formation values found at the eastern edge of the Burnt Timber area. Therefore, the Mississippian Elkton Formation appears to have a zone of increased TDS at the southwestern edge of the autochthone below the Brazeau Thrust (Figure 4.26, p. 79).

4.3.2 Spring Data

Surface spring data were added to complement the subsurface formation water data illustrated on Figure 4.26 (p. 79). The spring discharge rates and chemical characteristics were interpreted from two sources: a) springs summarized by Borneuf (1982), and b) additional *Alberta Research Council* spring samples. A statistical summary of these data, including spring flow rates, temperatures, TDS, and pH are found in Table 4.4 (p. 80).

The location and discharge rates for the springs within the study area are illustrated in Figure 4.27 (p. 81). A greater number of springs are found west of the Brazeau Thrust suggesting an association with the local structural features. According to Borneuf (1982), the formation of disturbed belt springs in Alberta may result due to karst features, formation contacts, and faults. Several springs are located in close proximity to both major and minor fault traces located at the ground surface (Figure 4.27, p. 81). A comparison to the gross geological features of the area (Figure 2.4, p. 10) suggests there is no preferred location of springs within a particular geological formation or zone.

According to Borneuf (1982), spring flow rates may change with time and location. Flow rates may vary by several orders of magnitude over the course of a year due to seasonal precipitation changes, melt-thaw cycles or other unknown causes. It is also possible for springs which are in close proximity to have two to three orders of magnitude difference in their respective discharge rate. Within the study area, the spring flow rates range over four orders of magnitude. The maximum flow rate of 265 l/s found at the Raven Spring Fish Hatchery is the only spring of that magnitude (Twp. 36, Rge. 5w5).

The discharging spring waters were found to be relatively fresh as indicated by the total dissolved solids (Figure 4.28, p. 82). All springs within the study area have TDS

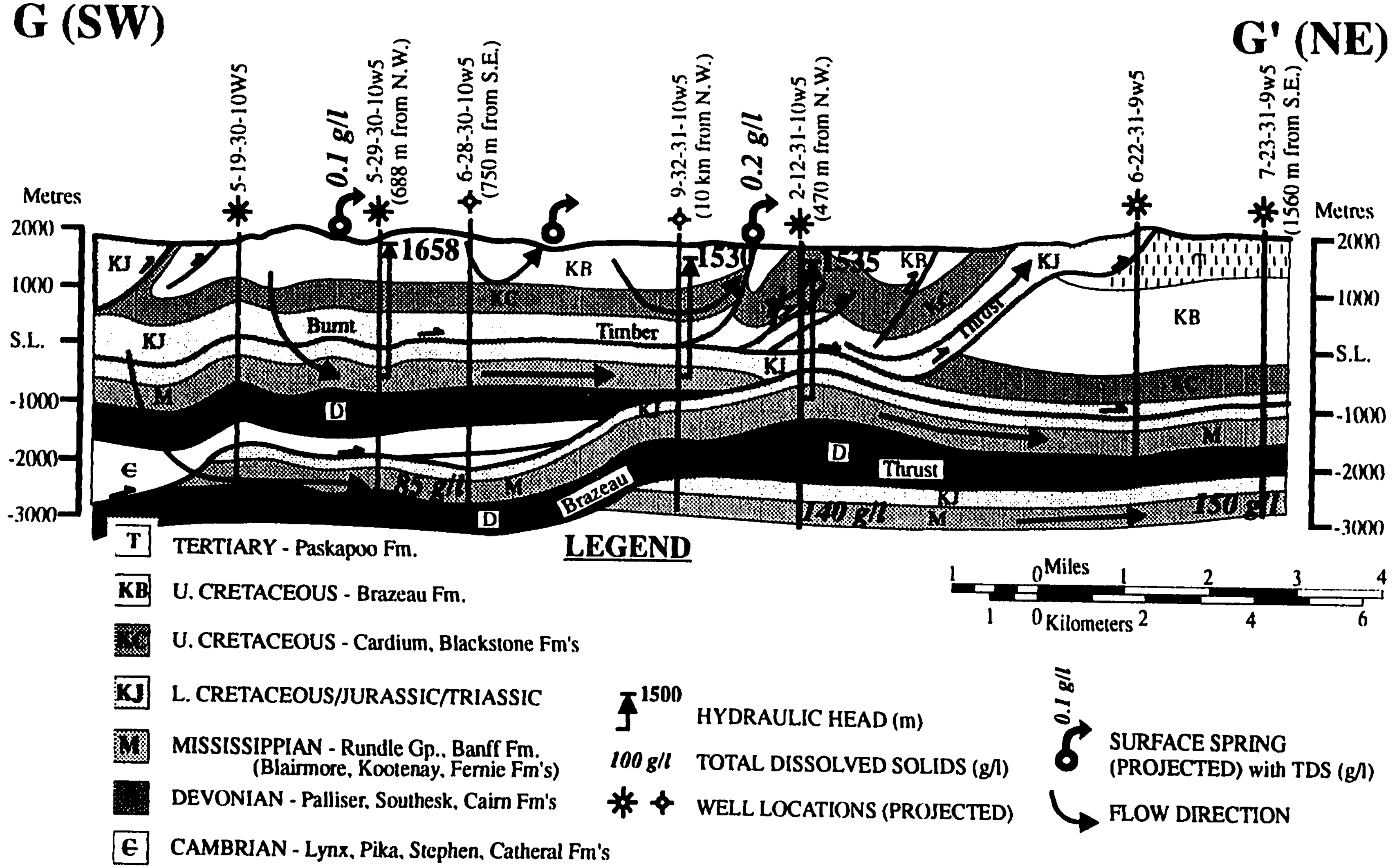


Figure 4.26: Burnt Timber hydrogeological schematic G-G'. A modified structural cross section illustrating known hydraulic heads, chemical analyses, and surface springs within the Burnt Timber area of the Foreland Fold and Thrust Belt (geology modified after Ollerenshaw (1965)).

	Flow (l/s)	Temp.(C^o)	TDS (mg/l)	pH
Maximum	265.0	10.0	1190	8.6
Minimum	0.4	1.5	53	6.5
Average	19.2	4.4	285.2	7.7
Std.Dev.	48.5	1.86	260.1	0.41
Count	31	27	36	38

Table 4.4: Summary of foothills spring data from Borneuf (1982) and Alberta Research Council files.

values less than 500 mg/l. The TDS does not appear to have any obvious correlation with the flow rates, pH or temperatures. However, the low TDS is reflected in the spring chemical composition. The relative spring ionic chemistry was plotted with the Elkton and Turner Valley Formation data on a piper diagram (Figure 4.25, p. 75). As would be expected, the low TDS spring waters are enriched in HCO_3, Ca, and Mg as compared with the subsurface formation waters. Sulin's classification indicates that the springs are $SO_4 - Na$ and $HCO_3 - Na$ type waters.

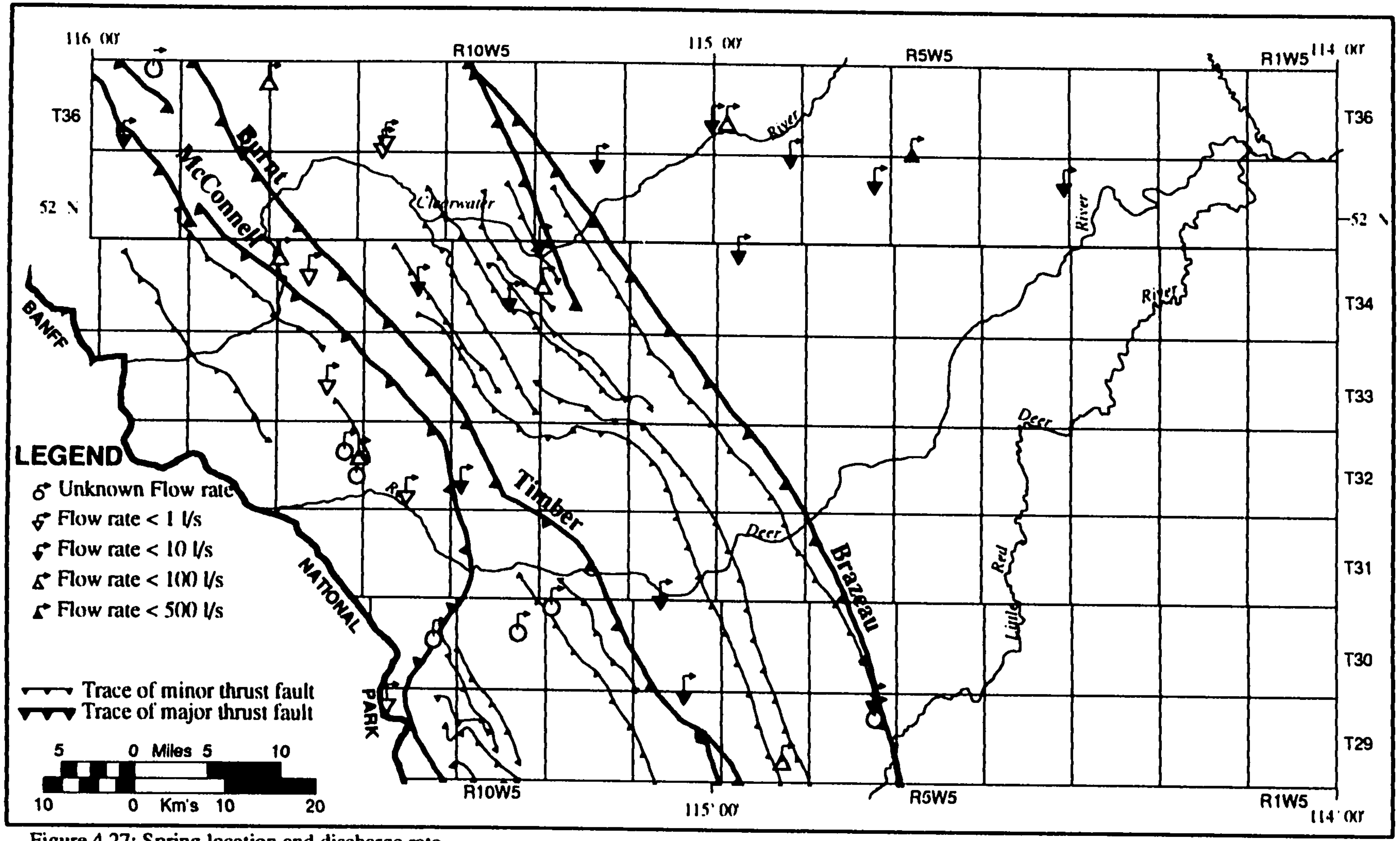


Figure 4.27: Spring location and discharge rate.

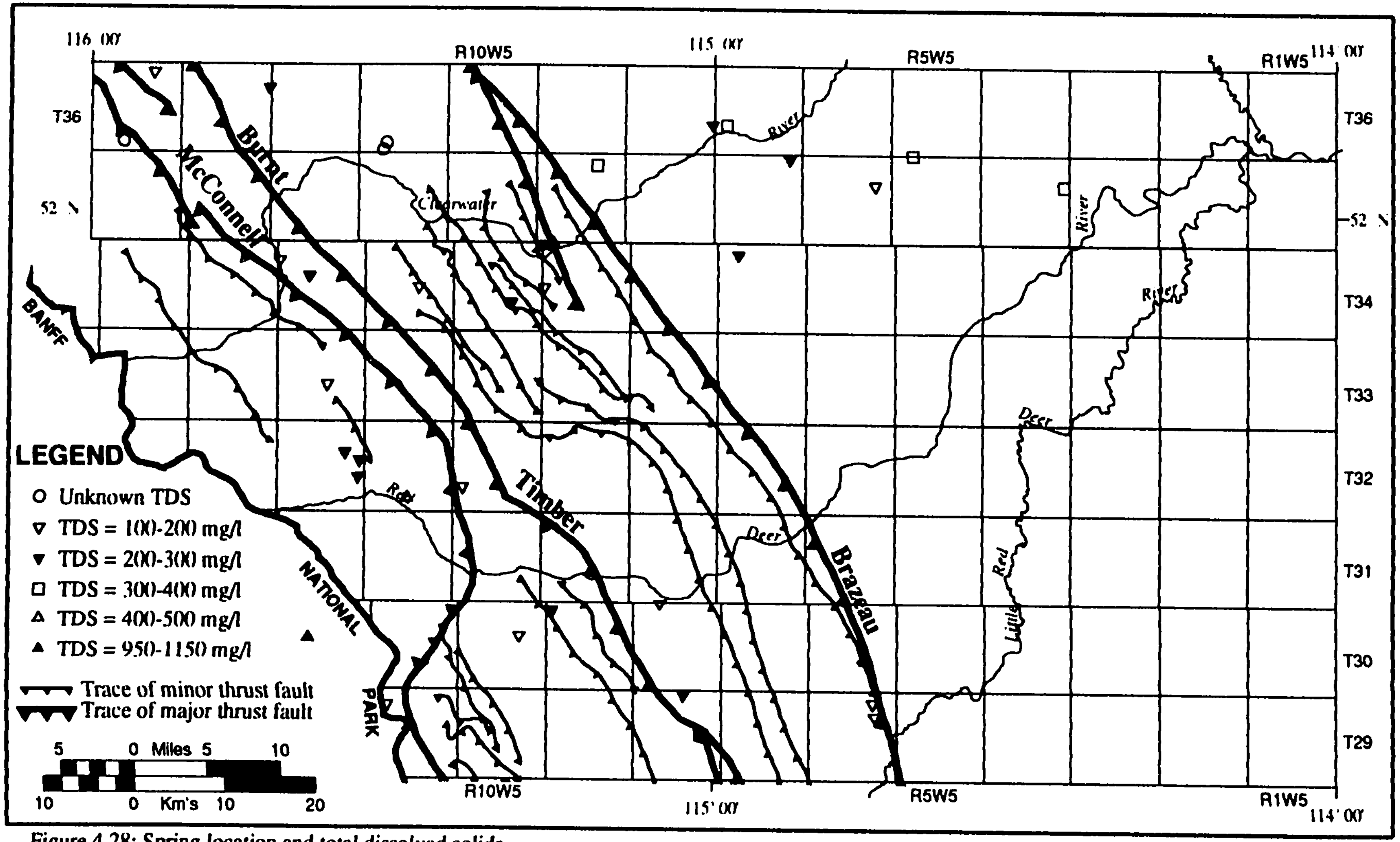


Figure 4.28: Spring location and total dissolved solids.

	Max.	Min.	Avg.	Count
$Flow(l/s)$	—	—	—	—
$TDS(mg/l)$	266	148	203	7
pH	8.1	7.7	8.0	7
$Flow(l/s)$	0.76	0.38	0.5	7
$Temp.(C)$	5.5	1.5	3.3	4
$TDS(mg/l)$	1111	93	387	5
pH	8.6	7.4	8.0	6
$Flow(l/s)$	7.6	1.51	5.3	17
$Temp.(C)$	7.6	2.5	4.4	17
$TDS(mg/l)$	1190	100	336	16
pH	8.4	7.1	7.7	17
$Flow(l/s)$	75.8	11.7	32.1	5
$Temp.(C)$	6	2	4	4
$TDS(mg/l)$	352	100	84	5
pH	8.3	7.1	7.9	5

Table 4.5: Summary of foothills spring data grouped into flow rates. Each section increases by one order of magnitude.

Chapter 5

Discussion

The observations and results in this study were discussed in the context of two geomorphological areas: a) Alberta Foreland Basin and b) Foreland Fold and Thrust Belt. Each of these areas have specific geologic features and related hydrogeologic phenomena which were identified in the previous chapters. The objectives of this study (Section 1.2, p. 2) were: firstly to understand the hydrogeology within each of these geomorphological regions, secondly, determine the effects of the Cordillera on subsurface fluid movement in the Alberta Foreland Basin, and lastly, to develop an understanding of the previous objectives in terms of the regional distribution pattern of petroleum. The following discussion integrates the two geomorphological areas mentioned above into two main lines of thought, namely, a) hydraulic communication and b) hydrocarbon migration and accumulation. An understanding of both of these conditions, within this or any disturbed belt and associated foreland basin, is essential in developing effective strategies of petroleum exploration in these types of areas.

5.1 Hydraulic Communication

5.1.1 Basinal related fluid flow

Observations from geological mapping, potentiometric surface analysis, pressure-depth and pressure-elevation plots, and water chemical analysis within the subsurface characterize the movement of formation waters. Each of the potentiometric surfaces completed within the Mississippian and Devonian formations in this study suggests a general direction of fluid flow from southwest to northeast perpendicular to strike. However, there is evidence to suggest some local flow patterns which do not correspond to a uniform northeast flow direction. Several flow features within the Elkton and Leduc Formations reflect areas of preferential and restricted fluid flow.

Preferential flow

Areas of significant preferential flow have been identified within the Leduc Formation. An example of an upward fluid conduit allowing fluids to migrate between the Leduc and Nisku Formations is located within the central part of the Cheddarville reef complex. This fluid pathway connecting the two formations is identified by a Leduc potentiometric low (Figure 4.18, p. 67) and a corresponding absence and thinning of the intervening Ireton Formation shale (Figures 4.5 and 4.7, p. 48 and p. 50). The physical connection and associated potentiometric relationship is supported by other hydrogeological evidence. TDS maps (Figures 4.22 and Figure 4.23, p. 72 and p. 73) and Piper diagrams (Figures 4.24 and 4.25, p. 74 and p. 75) of both the Nisku and Leduc Formations indicate similar highly saline Na-Cl enriched formation waters. Furthermore, a common pressure-depth gradient within the Nisku and Leduc Formations near the fluid conduit suggests communication between the formation waters (Figure 4.20, p. 70). Rostron (1995) also identified significant regions within the Clive and Bashaw reef areas (Twps. 38-42, Rges. 22-26) (Figure 2.3, page 9) where Leduc and Nisku Formation waters are identified to be in complete hydraulic communication. These observations were based on similar Leduc and Nisku Formation water characteristics and Ireton Formation isopach thins.

The combination of those features identified by Rostron (1995) as well as the Cheddarville fluid conduit identified in this study, suggests there is a pervasive regional communication of fluids between the Leduc and Nisku Formations in west-central Alberta. Therefore, other vertical fluid conduits are suspected in the central portion of the Bearberry and southern Bashaw reef complexes even though there is an absence of supporting evidence from formation water DSTs and chemical analyses due to the lack of well control. The greater control in determining the thickness of the Ireton Formation indicates aquitard thinning similar to the Cheddarville example (i.e., $< 5m$) in the Bearberry and Bashaw reef areas. This minimal physical distance separating the Nisku and Leduc Formations suggests a potential for other locations of preferential flow between the two formations.

Restricted flow

Geological and hydrogeological evidence in the study area suggests areas of restrictive fluid flow. Similar to areas of preferential flow, fluids which are restricted by geological boundaries are reflected in the formation potentiometric surface. An increased hydraulic gradient near the northern Elkton erosional edge (Twps. 35-36, Rges. 4w5-5w5) coincides with a restriction in the areal extent of the Elkton Formation as well as an overlying erosional boundary with Cretaceous strata (Figures 4.3 and 4.13, p. 45 and p. 59). Therefore, fluids are focused through a narrowed Elkton aquifer and pass upward into the overlying formations.

A similar potentiometric feature is present in the Leduc Formation. A steep Leduc hydraulic gradient between the Cheddarville reef trend and Bearberry and Ricinus reef areas coincides with an increased thickness in the Ireton Formation as well as a more argillaceous off reef equivalent Leduc lithology (Figures 4.8 and 4.18, p. 51 and p. 67). In addition, both the Leduc pressure-depth and pressure-elevation plots suggest unique Cheddarville pressure conditions compared with surrounding Leduc reef complexes implying Cheddarville fluids which are not in total hydraulic communication (Figure 4.19, p. 68). In this case, fluid flow is restricted in a vertical sense where the thickness of the effective Leduc aquifer is decreased.

5.1.2 Fault zone related fluid flow

Fluid communication across a thrust zone will be influenced by the combined effect of individual thrust faults. However, it is possible, if not probable, that a particular thrust fault may not have the same effect as the overall combined influence of the thrust zone. This study analyzed the small scale hydrogeological features associated with a thrust zone and adjacent foreland basin. The data distribution did not allow a large scale analysis of a single thrust fault. However, one may speculate on possible scenarios of fluid movement along a fault assuming certain properties. As was introduced in Sections 2.3.2 and 2.3.3, the possible effects of a fault surface on fluid flow can be classified as one of four types: a) flow fault, b) conduit fault, c) obstruction fault, and d) barrier fault. The purpose of this classification was to define guidelines which can be used to help interpret hydrogeological data within a disturbed belt region. The disturbed belt region which was analyzed in this study was the Burnt Timber area west of the surface expression of the Burnt Timber thrust (Figure 4.10, p. 53).

Indications of fault related fluid movement should be represented by trends or anomalies in hydrogeological data such as fluid pressures, water chemical analyses and surface springs. Evidence within this study area indicates conduit and obstruction type faults are present. Figure 4.26 (p. 79) includes hydrogeological data along a structural cross section through the Burnt Timber area. This schematic will be explained in the remaining part of this discussion.

Disturbed belt springs

The seasonally fluctuating discharge rates and low TDS found in disturbed belt springs suggests waters of a recent meteoric origin. The location of some of these springs at a surface fault boundary is indicative of a conduit fault where the subsurface waters are focused along the fault boundary. However, the depth that the fault conduit may extend remains unclear. If the fault conduit reaches deeper more highly saline Mississippian formation waters (i.e., $> 60g/l$), one might expect to see greater values of TDS in waters discharging at the surface. Because all the springs have TDS less than $0.5g/l$, there is no indication that the spring waters are sourced from deeper saline formation waters. Therefore, the springs are part of a shallow local flow system.

Subsurface waters

The more highly saline waters in the Mississippian subsurface are indicative of a deeper regional flow system. The similar magnitude of topography and hydraulic heads within the Burnt Timber nappe 2 suggests the present day ground surface is influencing subsurface fluid flow to a depth of at least 2200 m (Figure 4.26, p. 79). The decreasing hydraulic heads within this nappe imply fluid flow from the southwest to northeast along the cross section. A similar flow direction can be inferred by the increase of TDS content from 140 g/l to 150 g/l in the north east direction within the Turner Valley Formation beneath the Brazeau Thrust. Figure 4.14 (p. 61) indicates that the majority of the TDS values found within the Elkton Formation near the subcrop edge ranges from 50-90 g/l. Therefore, the Brazeau Thrust which separates the Turner Valley Formation of nappe 1 and the Elkton Formation of the Alberta Foreland Basin may have an important influence on hydraulic communication across a section of the disturbed belt between the Cordillera and Foreland regions of the Rocky Mountains. This example is used to meet the second objective listed in Section 1.2 (p. 2) and will be explained below.

Explanation of formation water TDS

The difference in TDS between the Turner Valley and Elkton Formations likely results due to the influence from subsurface thrust faults. The most plausible explanation for the values of TDS in the Elkton and Turner Valley Formations would be that the Brazeau Fault is acting as an obstruction to fluid flow. Therefore, unlike the conduit nature of some thrust faults near the surface, there does not appear to be a continuous flow path across the Brazeau Thrust at depth in the Burnt Timber area. As was explained in Section 2.3.3, it is likely that obstruction thrust faults will have portions which are acting as barriers while other parts allow the passage of fluids. The Turner Valley Formation waters within nappe 1 in the hanging wall of the

Brazeau Thrust are less saline than the equivalent footwall Turner Valley Formation waters. The very steep chemical gradient across the Brazeau Thrust from 85 g/l to 140 g/l suggests two flow systems, one on either side of the Brazeau Thrust. The highly saline waters in the autochthone are part of a stagnant flow zone created in the shadow of the overlying Brazeau Thrust Fault. Therefore, because the thrust fault is impeding fluid flow, there is an increase in the length of flow time which is reflected in greater values of TDS measured in the formation waters in the shelter of the thrust surface.

The decrease in TDS from the highly saline waters in the Turner Valley Formation in the Burnt Timber area to the waters in the Elkton Formation near the erosional edge also suggests a lack of communication. In this case, the lower saline waters of the Elkton Formation may have a secondary source of fluids other than those found within the disturbed belt Turner Valley Formation. The origin of these fluids were not determined in this study as the sediments overlying Mississippian Formations was not included in the study area.

5.2 Hydrocarbon migration and accumulation

The flow direction and source of fluids which influence hydrocarbon migration are important considerations to understand known and potential locations of hydrocarbon accumulations. The obstruction of fluids within the disturbed belt indicates that the migration and regional distribution of petroleum in the Mississippian and Devonian strata of the Alberta Basin have been effected by a more complex flow pattern than initial observations may suggest.

Present producing Leduc fields within the study area and surrounding regions are associated with a significant thickness ($> 20m$) of the overlying Ireton shale. A lack of Ireton shale in the Cheddarville reef area (Figure 4.5, p. 48) corresponds to an absence in Leduc hydrocarbon accumulations (Figure 2.10, p. 22). This association suggests that a vertical fluid conduit, identified by a Leduc potentiometric low as well as other hydrogeological data (Figure 4.18, p. 67), provided a vertical flow pathway. This conduit allowed the migration of hydrocarbons into the overlying Nisku Formation. This suggests a possible migration pathway for many updip Nisku hydrocarbon accumulations found north and northeast of the study area. Similarly, hydrocarbons which migrated through the Elkton Formation could likely be found in the overlying Cretaceous strata. Figure 4.13 (p. 59) indicates southwest to northeast flow directions towards the Elkton subcrop. These fluid potentials combined with the unconformity increases the potential of hydrocarbon migration between the Mississippian and Cretaceous formations.

The exploration for hydrocarbons within the disturbed belt region may be influenced by similar lithological barriers and restrictions to fluid flow as is found in the foreland basin. However, structural complexities create possible additional fluid barriers and conduits which may influence hydrocarbon migration and accumulation. A structural or stratigraphic trap will be enhanced by fluid flow which opposes the force of buoyancy. Similarly, obstruction of fluid flow may increase the potential for hydrocarbon entrapment by not removing or transporting hydrocarbons to other locations. Therefore, the stagnant flow zone indicated by the increase in TDS in the autochthonous Turner Valley/Elkton Formation underlying the Brazeau Thrust (Figures 4.26, p. 79), suggests a potential regional area for hydrocarbon accumulations.

Chapter 6

Conclusions

This petroleum hydrogeological study within the Foreland Fold and Thrust Belt and associated Alberta Foreland Basin has made several conclusions. The following concluding statements are subdivided into those which are general, specific to the Foreland Fold and Thrust Belt, relating to the hydraulic communication of subsurface formation waters, and important to petroleum migration and accumulation in the WCSB.

1. **General**
    (a) An understanding of the local geological features is a prerequisite for any hydrogeological observations and interpretations. Specifically, the structural re-interpretation within the Burnt Timber area of the disturbed belt was essential to subsequent interpretations.

    (b) Generally, the direction of fluid flow in Paleozoic formations within the Alberta Foreland Basin is from the southwest to northeast, perpendicular to strike.

    (c) The fluid chemistries from surface springs and within the Mississippian subsurface suggest both local and regional flow systems are present within the disturbed belt.

2. **Foreland Fold and Thrust Belt**

   (a) Fault surfaces can be classified into four hydraulic types based on the relationship to subsurface fluid flow: a) flow fault, b) conduit fault, c) obstruction fault, or d) barrier fault.

   (b) Disturbed belt surface and subsurface observations indicate a stagnant flow zone beneath the Brazeau Thrust within the Burnt Timber area of the study. Movement of formation waters are impeded by thrust faults which are classified as obstruction faults.

3. **Hydraulic communication**

   (a) Lateral restrictions in fluid flow can be detected from potentiometric surfaces and pressure-depth relationships. A steep hydraulic head gradient and unique pressure-depth plot within the Leduc Formation correspond with changes in local geology indicative of aquifer restrictions.

   (b) Hydraulic communication exists between the Leduc and Nisku Formations in locations where the intervening Ireton shale thins to less than 5 meters.

   (c) A stagnant flow zone within the Turner Valley Formation suggests that there is a lack of hydraulic communication across the Brazeau Thrust into the autochthonous formations of the Alberta Basin.

4. **Petroleum migration**

   (a) Migration of hydrocarbons from the Leduc Formation into the overlying Nisku Formation was possible through a vertical fluid pathway identified by a Leduc potentiometric low and corresponding absence and thinning of the Ireton Formation shale.

   (b) An increased probability of hydrocarbon accumulations was identified by a stagnant flow zone found in the Turner Valley Formation within the Burnt Timber area of the study. An increase in the total dissolved solids in the Turner Valley Formation within the shelter of the Brazeau Thrust suggests a stagnation of formation waters increasing the potential of hydrocarbon accumulation.

References

Andrews, G.D. 1987. Devonian Leduc outcrop reef-edge models and their potential seismic expression. *Pages 427–450 of:* McMillan, N.M., Embry, A.F., and Glass, D.J. (eds), *Devonian of the World, Proceedings of the Second International Symposium on the Devonian System.* Canadian Society of Petroleum Geologists. Memoir 14, v. II.

Bachu, S. 1988. Analysis of Heat Transfer Processes and Geothermal Pattern in the Alberta Basin, Canada. *Journal of Geophysical Research*, **93**, p. 7767–7781.

Bachu, S. 1995. Flow of Variable-Density Formation Water in Deep Sloping Aquifers: Review of Methods of Representation with Case Studies. *Journal of Hydrology*, **164**, p. 19–51.

Barson, D. 1993. *The Hydrogeological Characterization of Oil Fields in North-Central Alberta for Exploration Purposes.* Ph.D. thesis, University of Alberta, Edmonton, Alberta, Canada.

Berg, R.R., DeMis, W.D., and Mitsdarffer, A.R. 1994. Hydrodynamic Effects on Mission Canyon (Mississippian) Oil Accumulations, Billings Nose Area, North Dakota. *AAPG Bulletin*, **78**, p. 501–518.

Borneuf, D. 1982. *Springs of Alberta.* Tech. rept. Alberta Research Council. Earth Sciences Report 82-3.

Bradbury, H.J., and Woodwell, G.R. 1987. Ancient fluid flow within foreland terrains. *Pages 87–102 of:* Goff, J.C., and Williams, B.P.J. (eds), *Fluid Flow in*

Sedimentary Basins and Aquifers. Special Publication No. 34. Geological Society of London.

Bredehoeft, J.D., Wesley, J.B., and Fouch, T.D. 1994. Simulations of the Origin of Fluid Pressure, Fracture Generation, and the Movement of Fluids in the Uinta Basin, Utah. *AAPG Bulletin*, **78**, p. 1729–1747.

Burtner, R.L., and Nigrini, A. 1994. Thermochronology of the Idaho-Wyoming Thrust Belt During the Sevier Orogeny: A New, Calibrated, Multiprocess Thrermal Model. *AAPG Bulletin*, **78**, p. 1586–1612.

CDPUBCO. 1994a. *Alberta Production History*. Tech. rept. CD Pubco Inc. Geobase.

CDPUBCO. 1994b. *Alberta Well File*. Tech. rept. CD Pubco Inc. Geobase.

Chebotarev, I.I. 1955. Metamorphism of natural waters in the crust of weathering, Part 1-3. *Geochimica et Cosmochimica*, **8**, p. 22–48,137–170,198–212.

Connolly, C.A., Walter, L.M., Baadsgaard, H., and Longstaffe, F.J. 1990a. Origin and evolution of formation waters, Alberta Basin, Western Canada Sedimentary Basin. I. Chemistry. *Applied Geochemistry*, **5**, p. 375–395.

Connolly, C.A., Walter, L.M., Baadsgaard, H., and Longstaffe, F.J. 1990b. Origin and evolution of formation waters, Alberta Basin, Western Canada Sedimentary Basin. I. Isotope systematics and water mixing. *Applied Geochemistry*, **5**, p. 397–413.

Dahlstrom, C.D.A. 1969. Balanced cross sections. *Canadian Journal of Earth Sciences*, **6**, p. 743–757.

Daly, D., Lloyd, J.W., Misstear, B.D.R., and Daly, E.D. 1980. Fault control of groundwater flow and hydrochemistry in the aquifer system of the Castlecomer Plateau, Ireland. *Quaterly Journal of Engineering Geology*, **13**, p. 167–175.

Darcy, H. 1856. Determination of the laws of the flow of water through sand. *Pages 14–19 of:* Freeze, R.A., and Back, W. (eds), *Physical Hydrogeology.* Benchmark Papers in Geology 72. New York: Hutchinson Ross.

Davies, P.B. 1987. Modeling Areal, Variable-Density, Ground-Water Flow using Equivalent Freshwater Head - Analysis of Potentially Significant Errors. *Pages 888–903 of: Solving Ground Water Problems With Models Conference.* IGWMC/NWWA, Denver, Colorado.

Davis, S.N., and DeWiest, R.J.M. 1966. *Hydrogeology.* New York: John Wiley and Sons Inc.

DeMarsily. 1986. *Quantitative Hydrogeology.* San Diego: Academic Press.

Deming, D., Nunn, J.A., and Evans, D.G. 1990. Thermal Effects of Compaction-Driven Groundwater Flow From Overthrust Belts. *Journal of Geophysical Research*, **95**, p. 6669–6683.

Faye, R.E., and Prowell, D.C. 1982. *Effects of Late Cretaceous and Cenozoic Faulting on the Geology and Hydrogeology of the Coastal Plain near the Savannah River, Georgia and South Carolina.* Tech. rept. United States Geological Survey. Open-File Report 82-156.

Forster, C.B., and Evans, J.P. 1991. Hydrogeology of Thrust Faults and Crystalline Thrust Sheets: Results of Combined Field and Modeling Studies. *Geophysical Research Letters*, **18**, p. 979–982.

Freeze, R. A., and Cherry, J. A. 1979. *Groundwater.* Englewood Cliffs, New Jersey, USA: Prentice-Hall, Inc.

Garven, G., and Freeze, R.A. 1984a. Theoretical analysis of the role of groundwater flow in the genesis of strata-bound ore deposits: 1. Mathematical and numerical model. *American Journal of Science*, **284**, p. 1085–1124.

Garven, G., and Freeze, R.A. 1984b. Theoretical analysis of the role of groundwater flow in the genesis of strata-bound ore deposits: 2. Quantitative results. *American Journal of Science*, **284**, p. 1125–1174.

Ge, S., and Garven, G. 1989. Tectonically Induced Transient Groundwater Flow in Foreland Basin. *Pages 145–157 of:* Price, R.A. (ed), *Origin and Evolution of Sedimentary Basins and their Energy and Mineral Resources*. Geophysical Monograph 48. AGU.

Ge, S., and Garven, G. 1990. A Theoretical Model for Deep Groundwater Expulsion from Tectonic Belts. *Journal of Geophysical Research*, **95**, preprint.

Ge, S., and Garven, G. 1992. Hydromechanical Modeling of Tectonically Driven Groundwater Flow With Application to the Arkoma Foreland Basin. *Journal of Geophysical Research*, 97, p. 9199–9144.

Ge, S., and Garven, G. 1994. A Theoretical Model for thrust-induced deep groundwater explusion with application to the Canadian Rocky Mountains. *Journal of Geophysical Research*, 99, p. 13 851–13 868.

Hitchon, B. 1969a. Fluid Flow in the Western Canada Sedimentary Basin 1. Effect of Topography. *Water Resources Research*, **5**, p. 186–195.

Hitchon, B. 1969b. Fluid Flow in the Western Canada Sedimentary Basin 2. Effect of Geology. *Water Resources Research*, **5**, p. 460–469.

Hitchon, B. 1984. Geothermal Gradients, Hydrodynamics, and Hydrocarbon Occurrences, Alberta, Canada. *AAPG Bulletin*, **68**, p. 713–743.

Hitchon, B., and Brulotte, M. 1994. Culling creteria for "standard" formation water analyses. *Applied Geochemistry*, **9**, p. 637–645.

Holysh, S., and Tóth, J. 1994. Flow of Formation Waters - A Likely Cause for Poor Definition of Soil-Gas Anomalies over Oil Fields in East-Central Alberta, Canada. *In:* Schumacher, D., and Abrams, M. (eds), *Near Surface Expressions of Hydrocarbon Migration.* Hedberg Conference. AAPG.

Horner, D.R. 1951. Pressure build-up in wells. *Third World Petroleum Conference Proceedings, Section II.*, p. 503–521.

Hubbert, M. King. 1940. The theory of groundwater motion. *Journal of Geology*, **48**, p. 785–944.

Hubbert, M. King. 1953. Entrapment of petroleum under hydrodynamic conditions. *AAPG Bulletin*, **37**, p. 1954–2026.

Kerrich, R. 1986. Fluid Infiltration into Fault Zones: Chemical, Isotopic, and Mechanical Effects. *Pure and Applied Geophysics*, **124**, p. 225–268.

Lusczynski, N.J. 1961. Head and Flow of Ground Water of Variable Density. *Journal of Geophysical Research*, 66(12), p. 4247–4256.

Majorowicz, J.A., and Jessop, A.M. 1981. Regional heat flow patterns in the Western Canada Sedimentary Basin. *Tectonophysics*, **74**, p. 209–238.

Majorowicz, J.A., Rahman, M., Jones, F.W., and McMillan, N.J. 1985. The Paleogeothemal and Present Thermal Regimes of the Alberta Basin and Their Significance for Petroleum Occurrences. *Bulletin of Canadian Petroleum Geology*, **33**, p. 12–21.

Martin, H.L. 1987. *Mississippian Subsurface Geology, Rocky Mountain House Area, Alberta.* Tech. rept. Geological Survey of Canada. Paper 65-27.

Mossop, G.D., and Shetsen, I. 1994. Introduction to the Geological Atlas of the Western Canada Sedimentary Basin. *Pages 1–12 of:* Mossop, G.D., and Shetsen, I. (eds), *Geological Atlas of the Western Canada Sedimentary Basin.* Canadian Society of Petroleum Geologists and Alberta Research Council, Calgary.

Munn, M.J. 1909. The anticlinal and hydraulic theories of oil and gas accumulation. *Economic Geology*, **4**, p. 509–529.

Newhouse, W.H. 1942. *Ore deposits as related to structural features.* Princeton, N.J.: Princeton University Press.

NTS. 1960. *Rocky Mountain House.* Tech. rept. Department of Mines and Technical Surveys. 83-B, Edition 1 ASE, Series A 502.

NTS. 1964. *Calgary.* Tech. rept. Department of Mines and Technical Surveys. 82-O, Edition 2 ASE, Series A 502.

Nunn, J.A., and Deming, D. 1991. Thermal Constraints on Basin-Scale Flow Systems. *Geophysical Research Letters*, **18**, p. 967–970.

Oliver, J. 1986. Fluids expelled tectonically from orogenic belts: Their role in hydrocarbon migration and other geologic phenomena. *Geology*, **14**, p. 99–102.

Ollerenshaw, N.C. 1965. *Geology Burnt Timber Creek.* Tech. rept. Geological Survey of Canada. Map 11-1965.

Ollerenshaw, N.C. 1975. *Geology, Calgary, Alberta-British Columbia.* Tech. rept. Geological Survey of Canada. Map 1457A.

Otto, C.J. 1992. *Petroleum Hydrogeology of the Pechelbronn-Soultz Basin in the Upper Rhine Graben, France: Ramifications for Exploration in Intermontane Basins.* Ph.D. thesis, University of Alberta, Edmonton, Alberta, Canada.

Parks, K.P. 1989. *Groundwater Flow, Pore-Pressure Anomalies and Petroleum Entrapment, Belly River Formation, West-Central Alberta.* M.Sc. thesis (unplublished), University of Alberta, Edmonton, Alberta, Canada.

Paul, D. 1994. *Hydrogeology of the Devonian Rimbey-Meadowbrook Reef Trend of Central Alberta, Canada.* M.Sc. thesis (unplublished), University of Alberta, Edmonton, Alberta, Canada.

Piper, A.M. 1944. A graphic procedure in the geochemical interpretation of water analyses. *Trans. American Geophysical Union*, **25**, p. 914–923.

Price, R.A. 1981. The Cordilleran foreland thrust and fold belt in the southern Canadian Rocky Mountains. *Pages 427–448 of:* McClay, K.R., and Price, N.J. (eds), *Thrust and Nappe Tectonics*. Special Publication No. 9. Geological Society of London.

Price, R.A., and Mountjoy, E.W. 1970. Geologic Structure of the Canadian Rocky Mountains Between Bow and Athabasca Rivers - A Progress Report. *Pages 7–25 of:* Wheeler, J.O. (ed), *Structure of the Southern Canadian Cordillera*. Special Publication No. 6. Geological Association of Canada.

Rostron, B. 1994. A New Method for Culling Pressure Data used in Hydrodynamic Studies. *AAPG Annual Convention Abstract Volume*, p. 247.

Rostron, B. 1995. *Cross-formational Fluid Flow in Upper Devonian to Lower Cretaceous Strata, West-Central Alberta, Canada*. Ph.D. thesis, University of Alberta, Edmonton, Alberta, Canada.

Smith, W.H.F., and Wessel, P. 1990. Gridding with continuous curvature splines in tension. *Geophysics*, p. 293–305.

Stoakes, F.A., and Wendte, J.C. 1994. The Woodbend Group. *Pages 153–170 of:* Krause, FF., and Burrowes, O.G. (eds), *Devonian Lithofacies and Reservoir styles in Alberta*. Canadian Society of Petroleum Geologists, Calgary.

Sulin, V.A. 1946. Waters of Petroleum Formations in the System of Natural Waters. *Gostoptekhizdat*, p. 35–96.

Switzer, S.B., Holland, W.G., Christie, D.S., Graf, G.C., Hedinger, A.S., McAuley, R.J., Wierzbicki, R.A., and Packard, J.J. 1994. Devonian Woodbend-Winterburn Strata of the Western Canada Sedimentary Basin. *Pages 165–202 of:* Mossop, G., and Shetsen, I. (eds), *Geological Atlas of the Western Canada Sedimentary*

Basin. Canadian Society of Petroleum Geologists and Alberta Research Council, Calgary.

Tóth, J. 1978. Gravity-Induced Cross-Formational Flow of Formation Fluids, Red Earth Region, Alberta, Canada: Analysis, Patterns, and Evolution. *Water Resources Research*, **14**, p. 805–843.

Tóth, J. 1980. Cross-Formational Gravity-Flow of Groundwater: A Mechanism of the Transport and Accumulation of Petroleum (The Generalized Hydraulic Theory of Petroleum Migration. *Pages 121–169 of:* III, W.H. Roberts, and Cordell, R.J. (eds), *Problems of Petroleum Migration.* AAPG Studies in Geology No. 10. American Association of Petroleum Geologists.

Tóth, J. 1984. The Role of Regional Gravity Flow in the Chemical and Thermal Evolution of Ground Water. *Pages 3–39 of:* Hitchon, Brian, and Wallick, E.I. (eds), *Proceedings First Canadian/American Conference on Hydrogeology, Practical Applications of Ground Water Geochemistry.* National Water Well Association, Worthington, Ohio.

Tóth, J., and Corbert, T. 1986. Post-Paleocene evolution of regional groundwater flow-systems and their relation to petroleum accumulations, Taber area, southern Alberta, Canada. *Bulletin of Canadian Petroleum Geology*, **34**, p. 339–363.

Villegas, M.E., Bachu, S., Ramon, J.C., and Underschultz, J.R. 1994. Flow of Formation Waters in the Cretaceous-Miocene Succession of the Llanos Basin, Colombia. *AAPG Bulletin*, **78**, p. 1843–1862.

Wessel, P., and Smith, W.H.F. 1991. Free software helps map and display data. *EOS Trans. Amer. Geophys. U.*, p. 445–446.

Wheeler, J.O., and McFeely, P. 1991. *Tectonic Assemblage Map of the Canadian Cordillera and adjacent parts of the United States of America.* Tech. rept. Geological Survey of Canada. Map 1712A.

Wilkinson, P.K. 1994. A Hydrogeological Evaluation of the Bluesky and Wabamun Formations, Northwestern Alberta. *Husky Oil internal report*, 49 p.

Wright, G.N., McMechan, M.E., and Potter, D.E.G. 1994. Structure and Architecture of the Western Canada Sedimentary Basin. *Pages 25–40 of:* Mossop, G., and Shetsen, I. (eds), *Geological Atlas of the Western Canada Sedimentary Basin*. Canadian Society of Petroleum Geologists and Alberta Research Council, Calgary.