EUB/AGS Special Report 62

Development, Stratigraphy and Summary Diagenetic History of the Athabasca Basin, Early Proterozoic of Alberta and Its Relation to Uranium Potential

Alberta Energy and Utilities Board
Alberta Geological Survey

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Paul Ramaekers[1]

[1]Under contract to the Alberta Geological Survey

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Author address:
Paul Ramaekers
832 Parkwood Drive S.E.
Calgary, AB T2J 3W7
(403) 278-9423
E-mail: paulramaekers@shaw.ca

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Alberta Energy and Utilities Board
Alberta Geological Survey
4th Floor, Twin Atria Building
4999 – 98th Avenue
Edmonton, Alberta
T6B 2X3
Canada

Tel: (780) 422-3767 (Information Sales)
Fax: (780) 422-1918
E-mail: EUB.AGS-Infosales@gov.ab.ca

Web Site: www.ags.gov.ab.ca

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Acknowledgments

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Abstract

The Athabasca Group in Alberta was deposited between 1730 Ma and 1600 Ma in four sequences, separated by unconformities, and largely deposited in separate sub-basins, in a tectonic environment dominated by regional compressive stress. Reorganization of basin architecture, major changes in grain size and changes in drainage directions distinguish the sequences. During sequence 1 and 2, the locus of deposition shifted from west to east in response to the after effects of the Trans-Hudson Orogen and coeval orogens. Sequence 1 is largely restricted to the Jackfish Basin in the northwestern quarter of the Athabasca Basin. Sequence 2 is developed most prominently in the Cree Basin in Saskatchewan. Sequences 3 and 4 appear related to more distant compressional forces along the margins of the continent and were deposited in the more central Mirror Basin, partitioned by later faulting into a number of troughs. Sediments deposited during later deepening of the basin have been removed by erosion and are likely to have been deposited under conditions of regional tensile stress.

Uranium mineralization in and near Alberta is related to repeated, but minor, reactivation of major shear zones bordering the Athabasca Basin and its sub-basins, and is usually found where two major fault systems intersect. Disruption of the basal unconformity by faulting, accompanying the later stages of basin growth or deformation, facilitated the development of the hydrothermal systems that emplaced the uranium.

1 Introduction

This study reviewed and analyzed available data on the stratigraphy of the Alberta part of the Athabasca Basin, placed this in its regional tectonic and diagenetic context, and related that to the uranium potential of the area. Thus, it concentrated on the regional distribution of the various units of the Athabasca Group. The broad scope of the discussion was appropriate because the regional structural history, stratigraphy and diagenesis of the area were all major factors in the development of the unconformity uranium deposits of the Athabasca Basin. These provide about 30 per cent of the world's uranium supply. Known uranium mineralization will be mentioned where appropriate, but this work is not intended as a review of the known uranium mineralization. The core logs, lithological and basic stratigraphic data, on which this study is based, are reported in EUB/AGS Special Report 61 (Ramaekers, 2003). This is supplemented by reference to diagenetic and stratigraphic work in the literature of the Alberta and Saskatchewan portions of the Athabasca Basin (Ramaekers, 1978, 1979, 1980, 1981, 1990; Wilson, 1985, 1986).

2 Stratigraphy of the Athabasca Group

The basic core data on which the Alberta maps of this study are based may be found in Alberta Geological Survey Special Report 61 (Ramaekers, 2003). Most holes used in this study were relogged in detail, with the notable exception of two drillholes in the deepest part of the basin, FC68 and FC69, which were lost in a forest fire. For these the original company logs were used, which were adequate to establish the main stratigraphic divisions. The following lithological descriptions are summarized from Special Report 61 and focus on the criteria for distinguishing the formations and informally described members. The subcrop distribution of the Athabasca Group formations and the cross-sections used in this study are shown on Figure 1. Distribution of sequences, stratigraphic units, facies, depositional environments and lithology are shown on Tables 1 and 2. General structural elements (sub-basins, major faults) of the Athabasca Basin are shown on Figure 2 and in more detail for the Alberta part on Figure 3.

Four sequences are recognized in the Athabasca Group (Figures 4-7), separated by unconformities. The unconformities are generally difficult to recognize in core, as the lithologies of the different units are nearly all quartz-rich sandstones, and soil development in the Proterozoic was minimal, especially in fluvial depositional systems. Abrupt changes in paleocurrent directions caused by regional changes in basin slope (Figures 4-7) helped distinguish regional unconformities from the minor local discontinuities in deposition that are characteristic of fluvial sedimentation.

The regional extent and thickness variation of the stratigraphic units of the western side of the Athabasca Basin are illustrated in isopachs maps (Figures 8-25) and cross-sections (Figures 26-35).

The isopachs were generated using linear interpolation between drillholes. Surface geological data (Wilson, 1985; Ramaekers, 1990) were used as a guide where available, especially in the northwestern quarter of the basin. The uneven distribution of the drillholes should be kept in mind, especially in the central part of the study area where there are few drillholes, and even fewer that reach basement (cf. Ramaekers, 2003). This has resulted in contours that average the differences in thickness between widely separated drillholes and, therefore, are likely to give a poor idea of sub-basin margins that may occur in the central part of the study area. The isopach maps ignore the effects of the Ordovician Carswell structure where data are available from both sides of the Carswell structure for all formations, except the Locker Lake and Otherside formations. Other tectonic events and the present erosional level in the Carswell area also affect the thicknesses of the latter two units.

The distribution of major sedimentary facies is shown for Sections I-I' and J-J', two roughly orthogonal cross-sections along the axes of the Athabasca Basin sub-basins. These intersect all of the Proterozoic strata of the Athabasca Group seen in Alberta (Figure 36).

Table 1. Facies, depositional environment and lithology of the Athabasca Group.

Facies	Depositional Environment	Lithology
Facies 12	Playa lakes, sheetflow, braided streams; eolian influenced	Well-sorted, fine and medium sandstones, with rounded, small, hard intraclasts, mudstones 0-200 cm thick, volcanic ash pseudomorphed by apatite cement
Facies 11	Braided streams, sheetflow, minor playa lakes, eolian influenced	Well-sorted, fine and medium sandstones, mudstones 0-50 cm thick
Facies 10	Braided streams, sheetflow	Coarse to fine sandstones, more common mudstones 0-20 cm thick, rare 1 layer thick pebble horizons
Facies 9	Braided streams, low paleoslope	Medium to fine sandstones, abundant large angular clay intraclasts, 1 layer thick pebble beds (Moosonees drainage only)
Facies 8	Braided streams	Coarse to fine sandstones, rare thin mudstones
Facies 7	Braided streams	Coarse to fine sandstones, pebbly sandstones, 1 layer thick pebble beds, minor clay intraclasts, rare thin mudstones (more common in Moosonees drainage)
Facies 6	Braided streams, sheetflow gravel, higher paleoslope	Coarse to medium sandstones, pebbly sandstones, conglomerates
Facies 5	Braided streams, sheetflow, hyperconcentrated flow	Coarse to medium sandstones, pebbly sandstones
Facies 4	Braided streams, hyperconcentrated flow, sheetflow	Pebbly sandstones, coarse to medium sandstones, thin conglomerates
Facies 3	Hyperconcentrated flow, braided streams, sheetflow, debris flows?	Pebbly sandstones, 1 layer thick pebble beds, granule to medium sandstones
Facies 2	Hyperconcentrated flow, sheetflow, debris flows, braided streams	Pebbly to cobbly sandstones, thin conglomerate beds, minor mudstones
Facies 1	Hyperconcentrated flow, debris flows, braided streams	Cobbly and pebbly conglomerates, minor granule to coarse sandstone, minor mudstones
Facies 0	(intermittently present at base of FP, MF; mappable locally) Sheetflow, braided streams, small playa lakes	Pebbly sandstones, sandstones, mudstones

Table 2. Sequences, lithostratigraphic units, facies, distance to source area and depositional lithology of the Athabasca Group.

Sequences	Stratigraphic Units	Facies	Distance to source	Dominant lithology at time of deposition
Sequence 4	Carswell Formation (CF) Douglas Formation (DF) Otherside Formation (OF) OFb OFa Locker Lake Formation (LL) LLc LLb LLa	dolomites 11 8 7 5 4 5	authigenic far	 carbonates Qtz arenite, minor sublithic arenite, subarkose, arkose Qtz arenite and sublithic arenite
Sequence 3	Wolverine Point Fm (WP) WPc WPb WPb3 WPb2 WPb1 WPa WPa2 WPa1 Lazenby Lake (LzL)	11 12 11 12 7, 8 10 5 (coarse at base only)	far far	Bimodal: largely arkose with minor qtz arenite Qtz arenite to minor arkose Qtz arenite, minor subarkose
Sequence 2	Manitou Falls Formation (MF) MFd MFc MFb MFa MFa2 MFa1	 9 7, 8 6 3 0	more distal proximal proximal proximal	Qtz arenite, minor sublithic arenite Sublitharenite Sublitharenite
Sequence 1	Fair Point Formation (FP) FPc FPb FPb2 FPb1 FPa FPa2 FPa1	 3 2 1 3 0	proximal proximal very close to source	Arkose to subarkose

The stratigraphic nomenclature for the Athabasca Group is in a state of flux. Not enough data are available about the areal extent and lithological variation of many of the subunits for them to be described as formal members or submembers with reasonable expectation of stability. For this reason, the informal designations using letter and number suffixes used in the past have been retained.

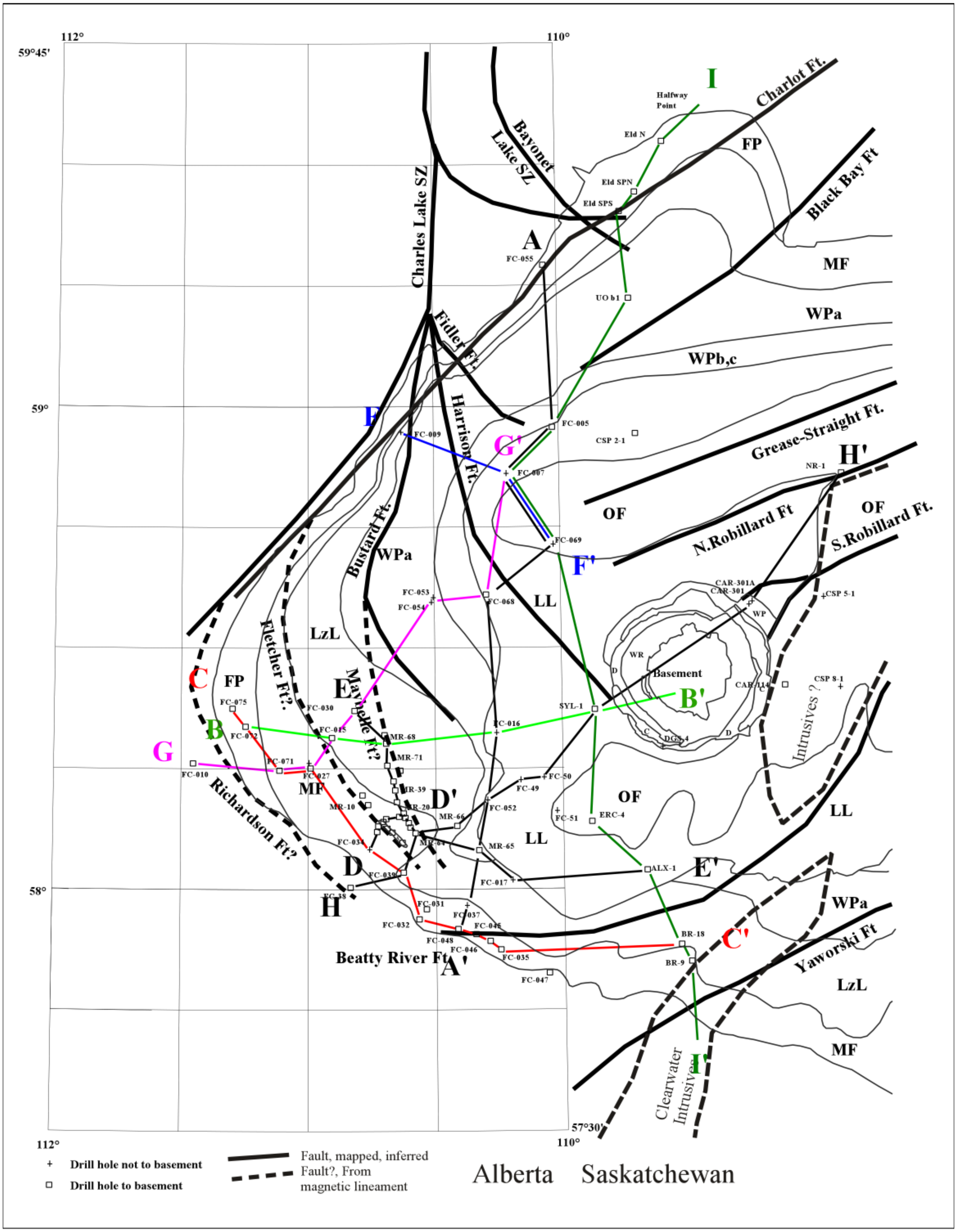


Figure 1. Subcrop map of formations of the Athabasca Group in Alberta and location of cross-sections AA' to II'. Abbreviations of stratigraphic names on Table 2.

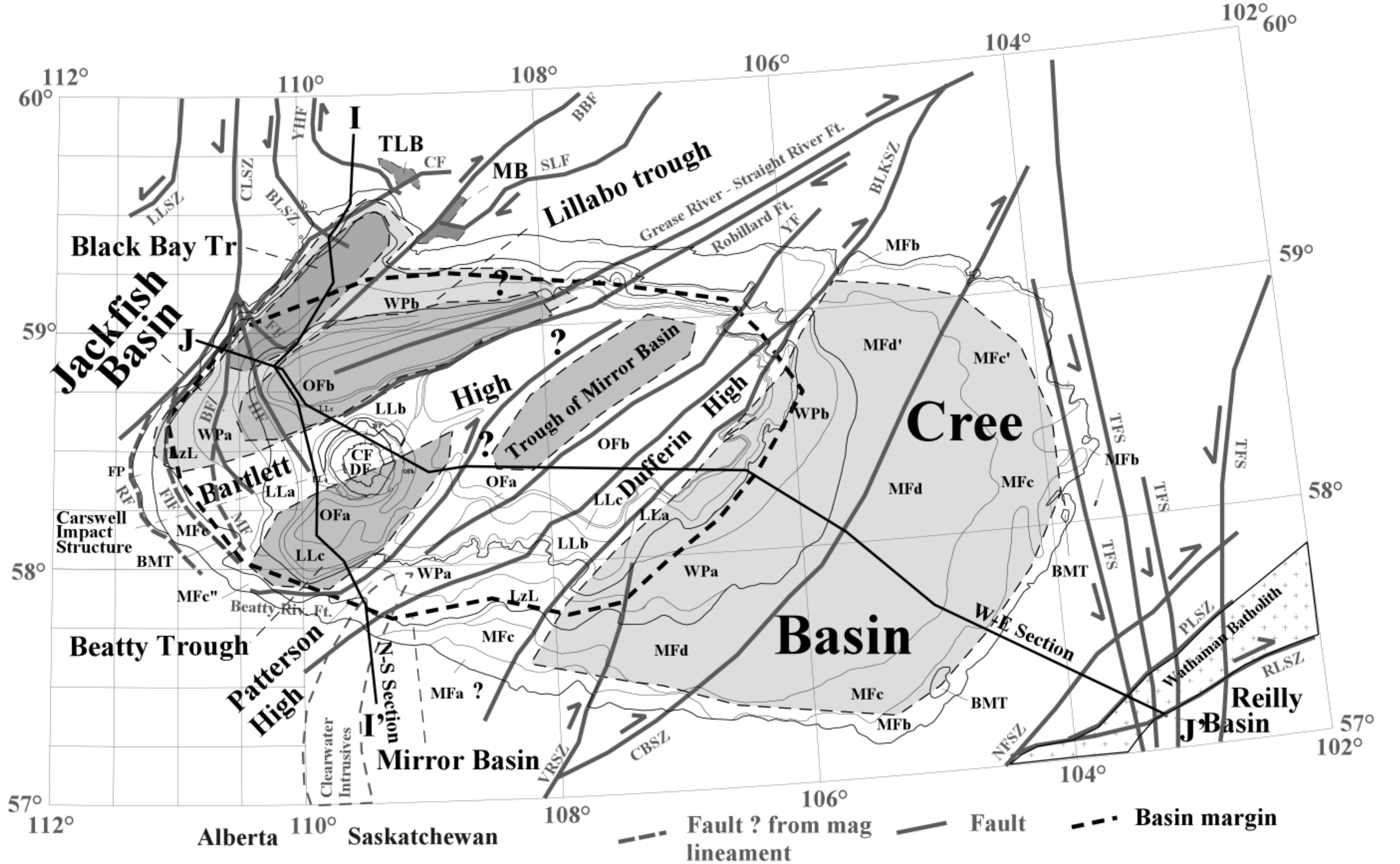


Figure 2. Major structural elements of the Athabasca Basin in Alberta and Saskatchewan. SHEAR ZONES (SZ): BLSZ, Bayonet Lake; BLKSZ, Black Lake; CBSZ, Cable Bay; CLSZ, Charles Lake; LLSZ, Leland Lake; NFSZ, Needle Falls; PLSZ, Parker Lake; RLSZ, Reilly Lake; VRSZ, Virgin River; FAULTS (F): BF, Bustard; BBF, Black Bay; CF, Charlot; FF, Fidler; FIF, Fletcher; HF, Harrison; MF, Maybelle; RF, Richardson; SLF, St.Louis; TFS, Tabbernor fault system; YHF, Yatsore-Hill Island; SUBBASINS (B): MB, Martin; TLB, Thluicho Lake. Location of cross-sections II' and JJ'. Abbreviations of stratigraphic names on Table 2.

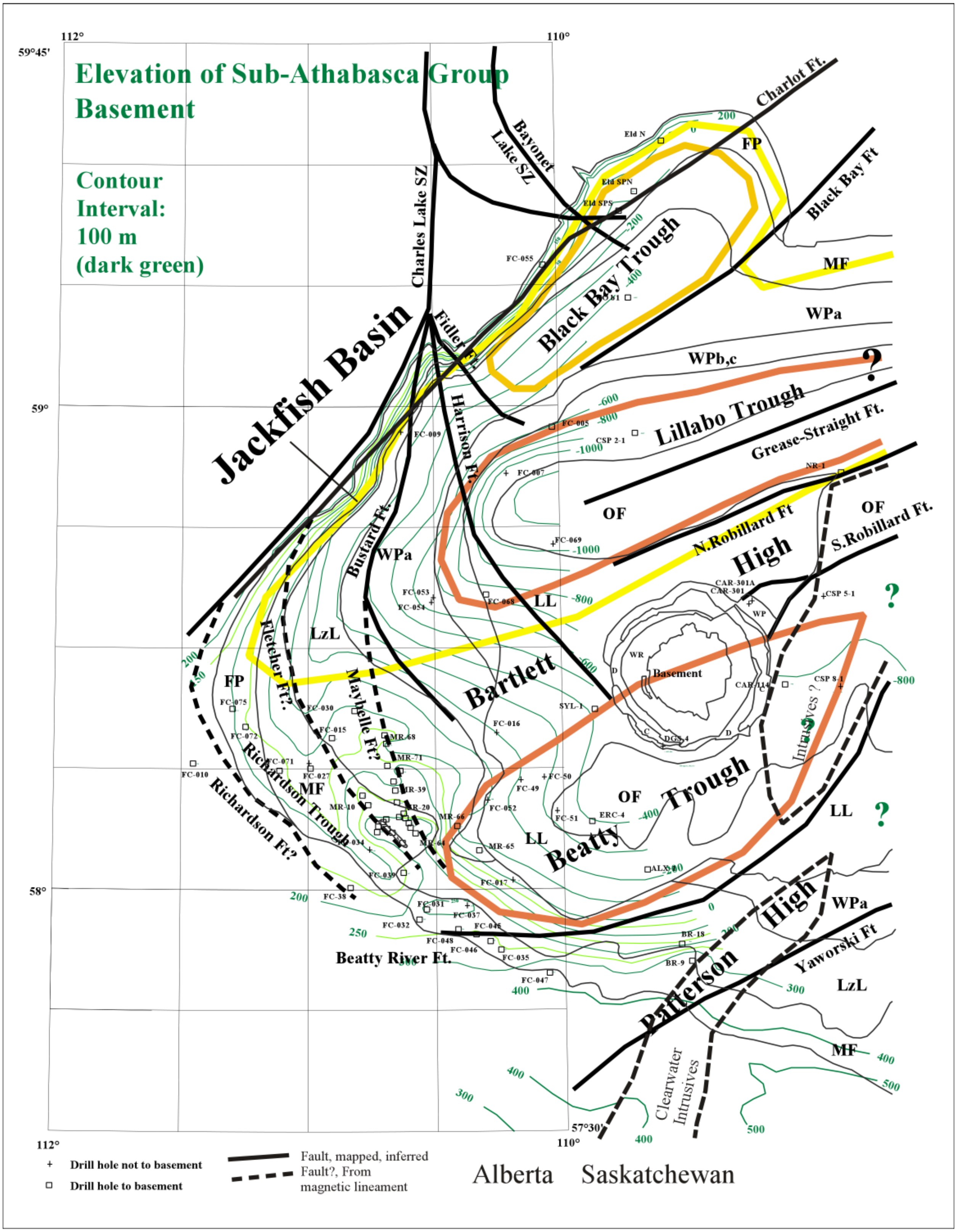


Figure 3. Structural elements of the Athabasca Basin in Alberta and elevation of basement in m. Abbreviations of stratigraphic names on Table 2.

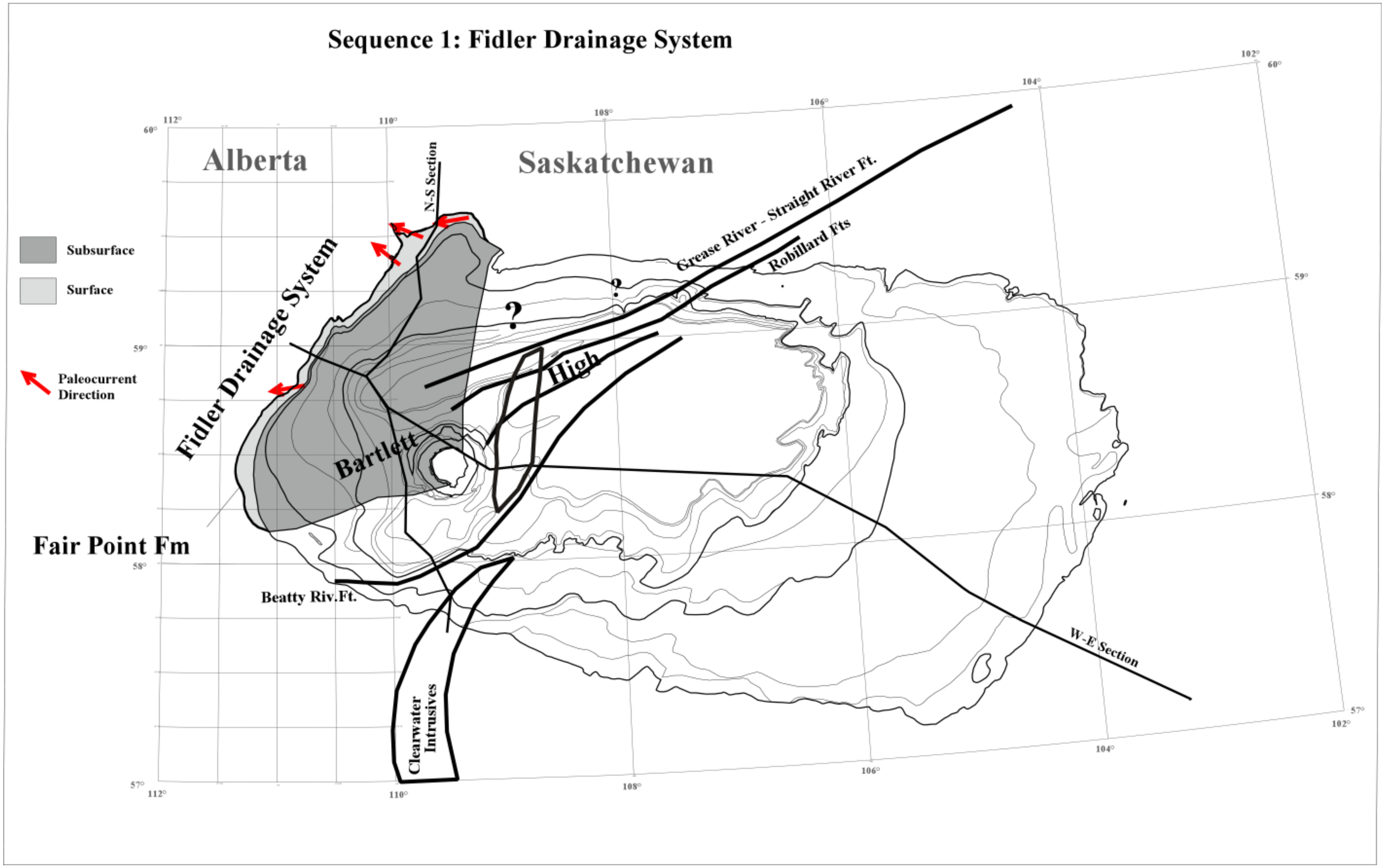


Figure 4. Sequence 1 of the Athabasca Group. Surface and subsurface extent; paleocurrent directions.

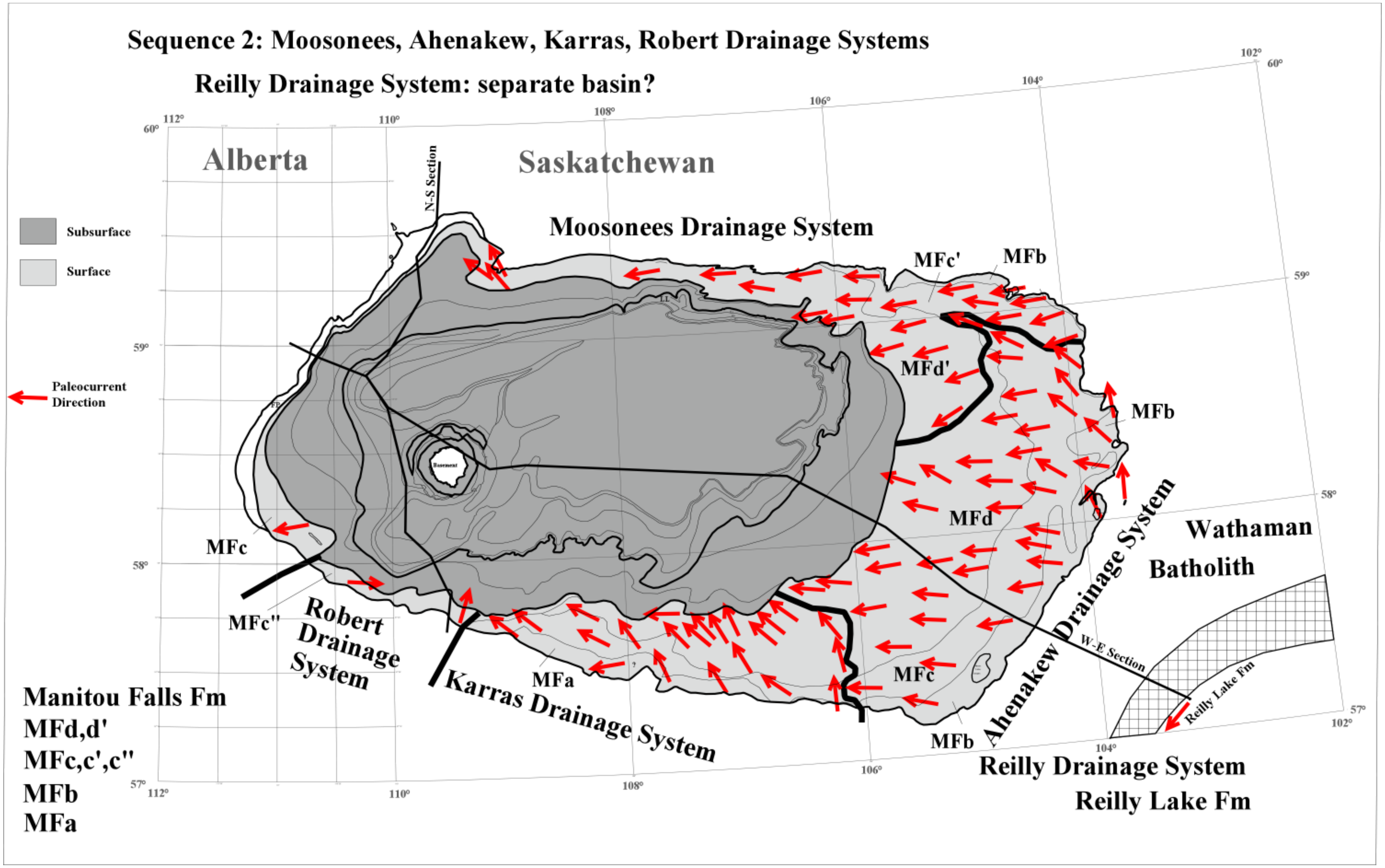


Figure 5. Sequence 2 of the Athabasca Group. Surface and subsurface extent; paleocurrent directions.

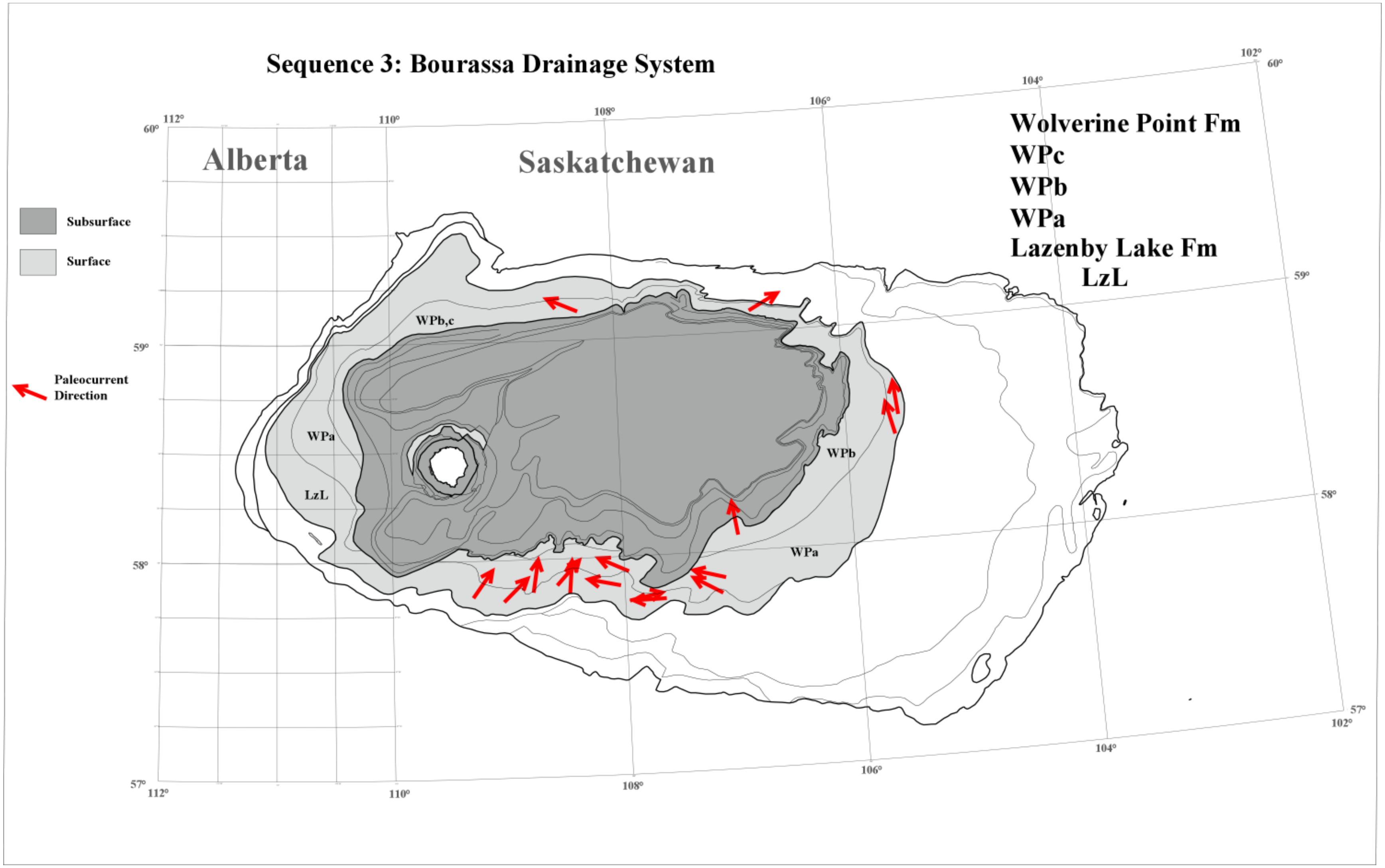


Figure 6. Sequence 3 of the Athabasca Group. Surface and subsurface extent; paleocurrent directions.

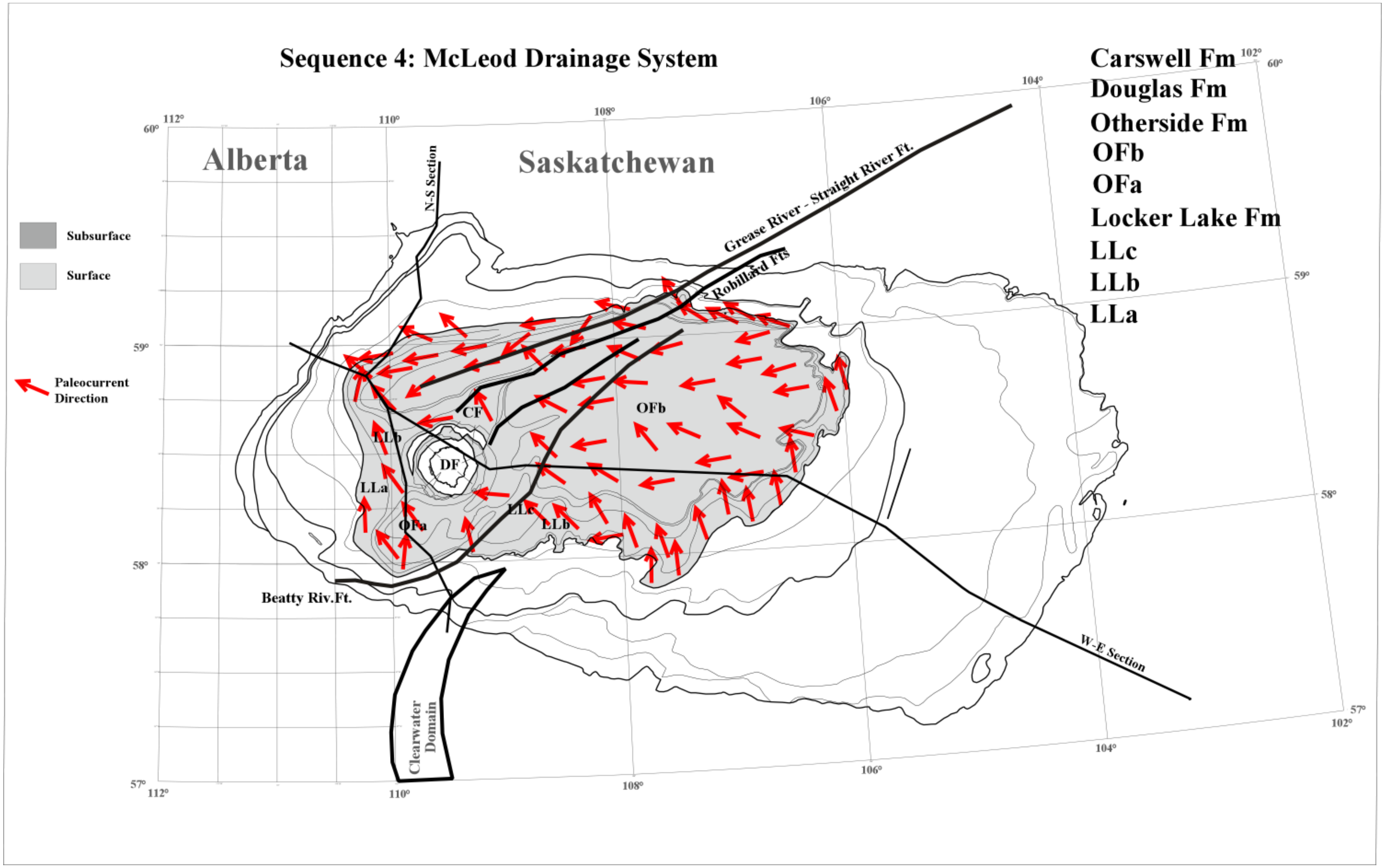


Figure 7. Sequence 4 of the Athabasca Group. Surface and subsurface extent; paleocurrent directions.

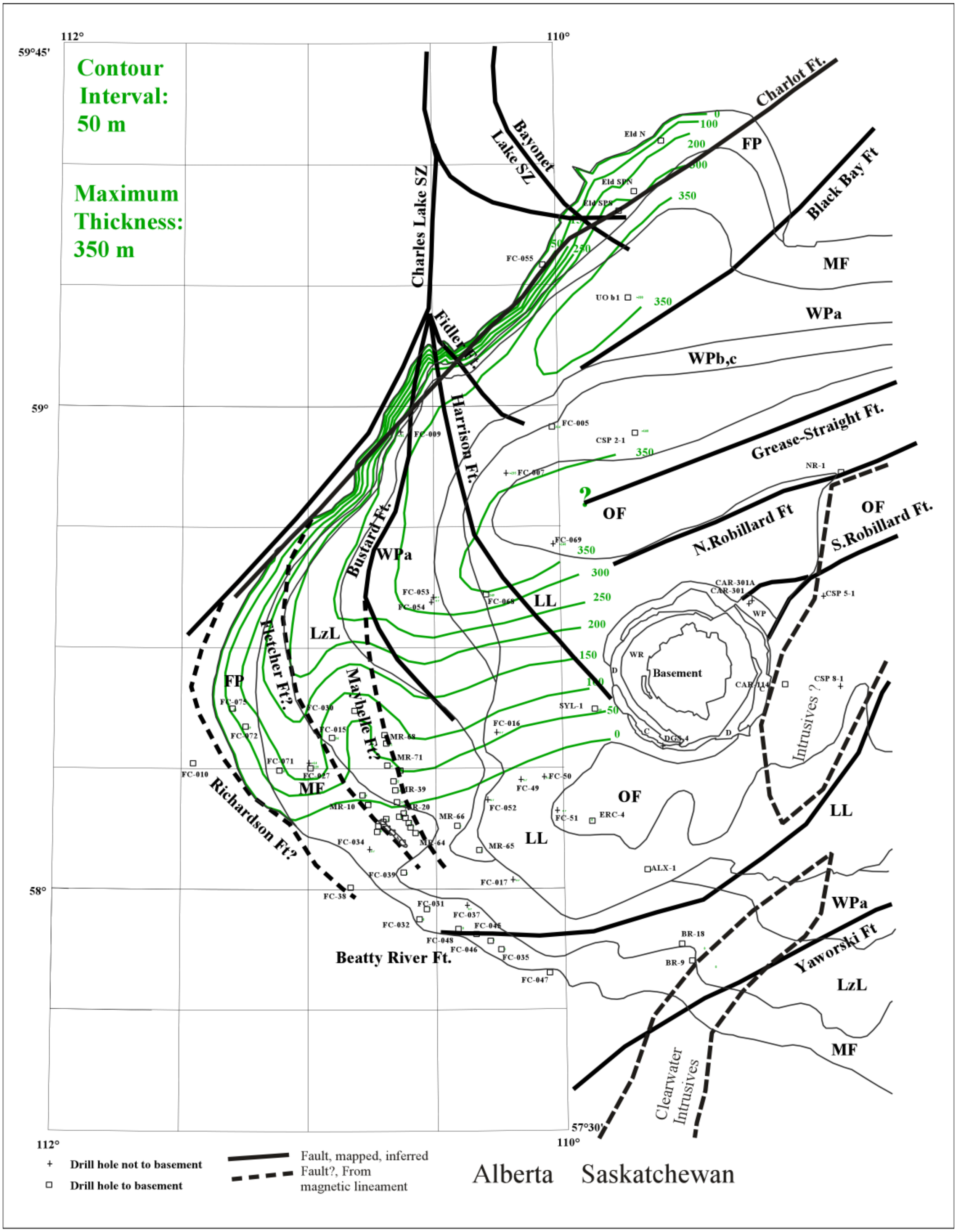


Figure 8. Isopach Fair Point Formation. Abbreviations of stratigraphic names on Table 2.

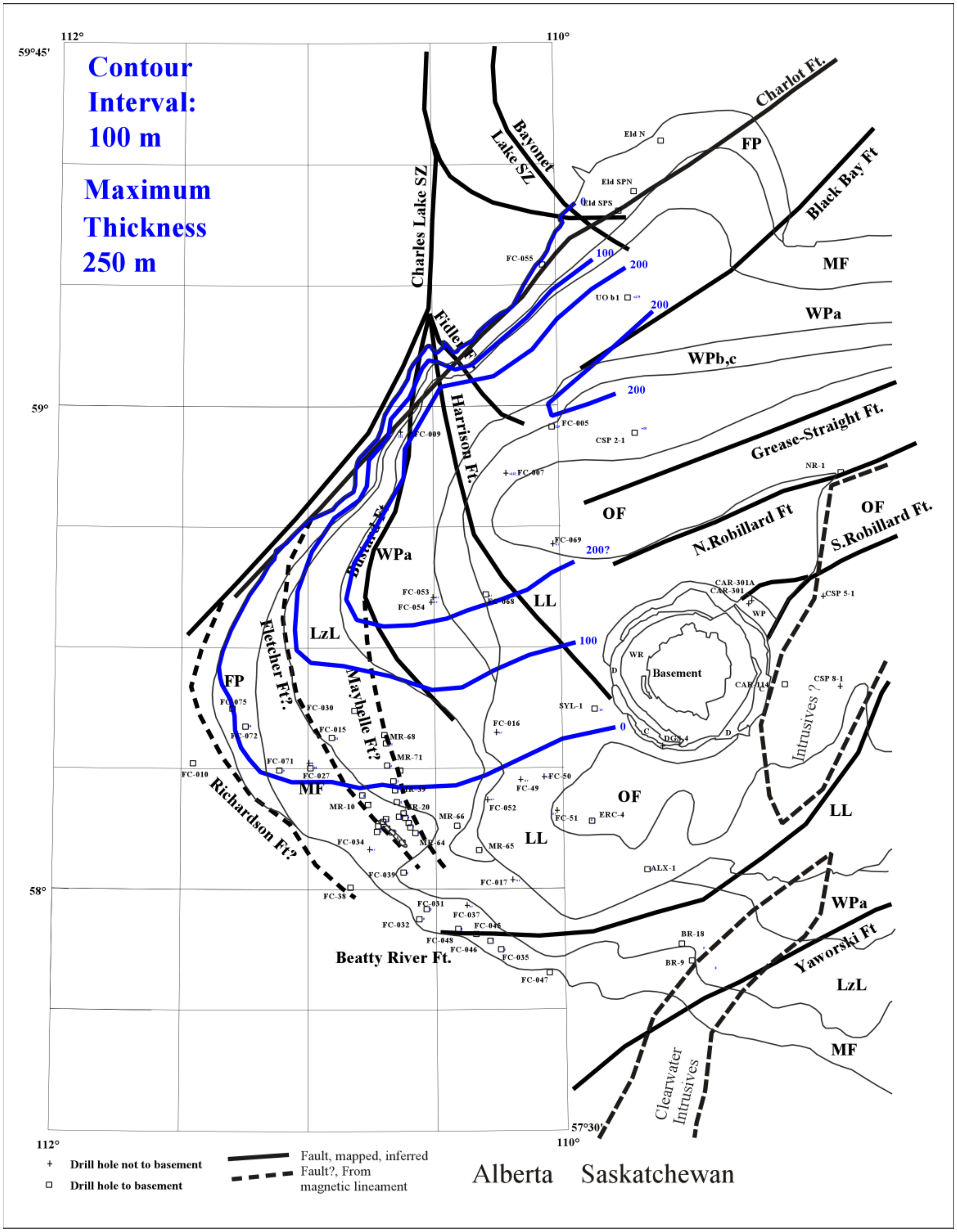


Figure 9. Isopach Fair Point b unit. Abbreviations of stratigraphic names on Table 2.

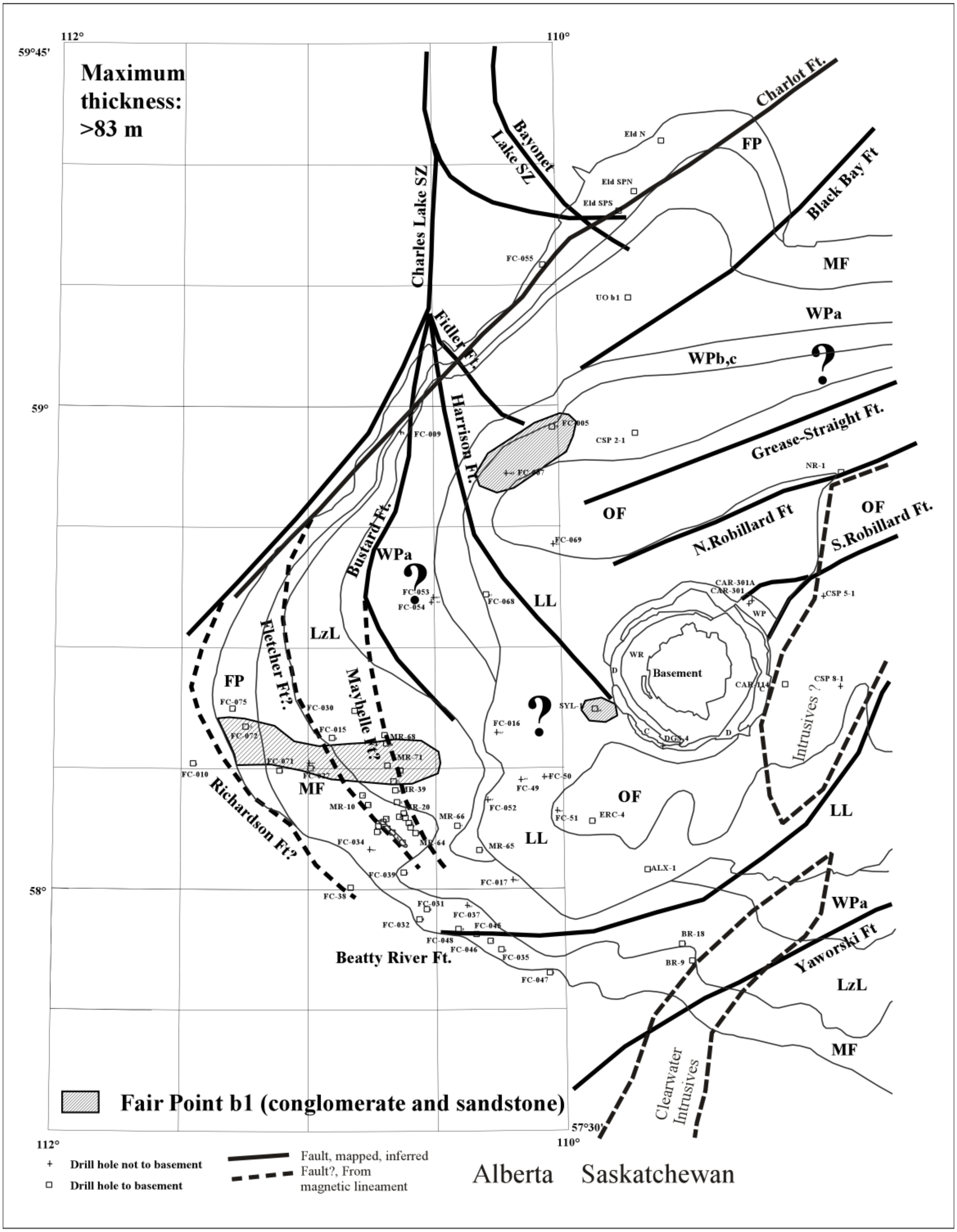


Figure 10. Distribution of the Fair Point b1 unit. Abbreviations of stratigraphic names on Table 2.

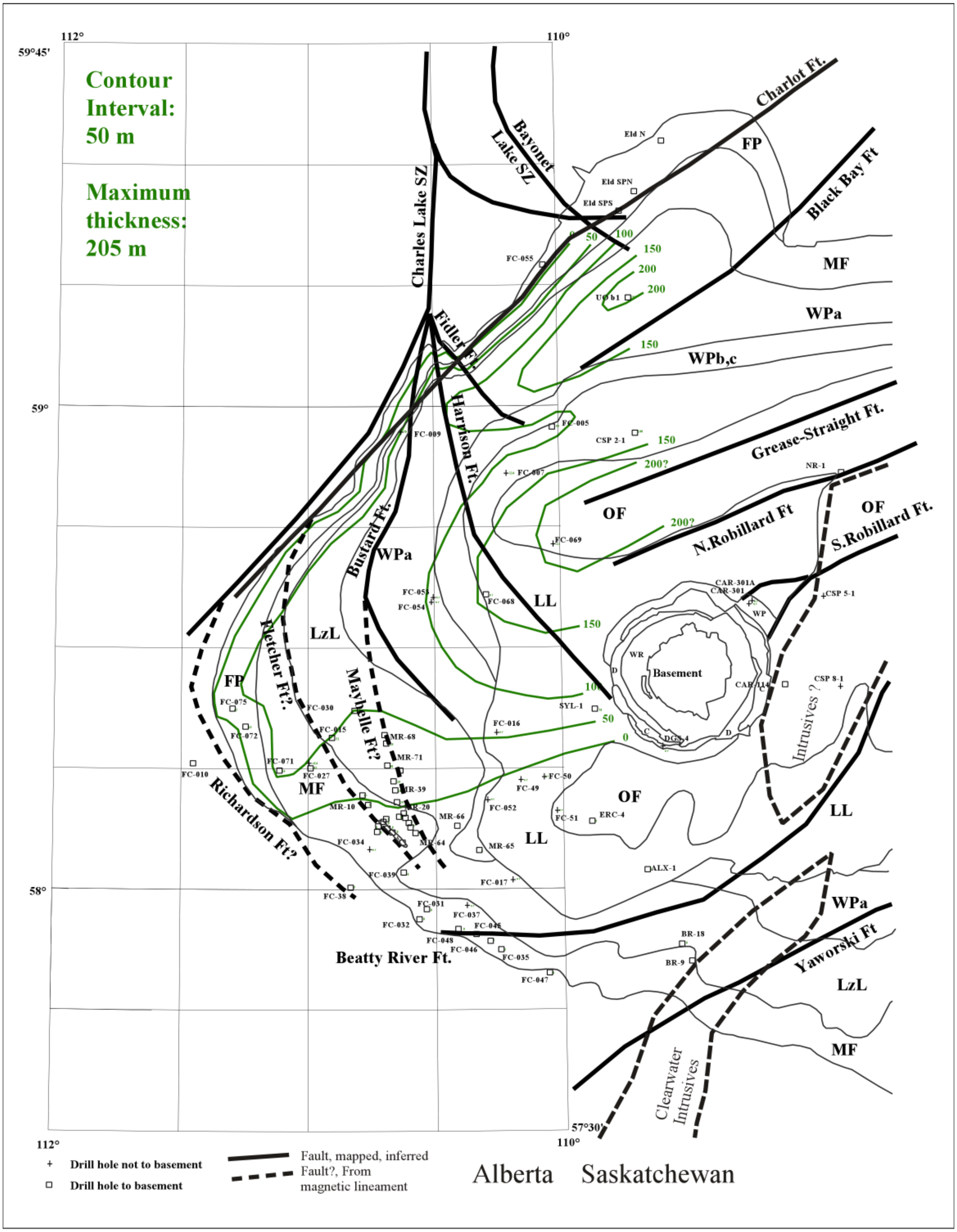


Figure 11. Isopach Fair Point c unit. Abbreviations of stratigraphic names on Table 2.

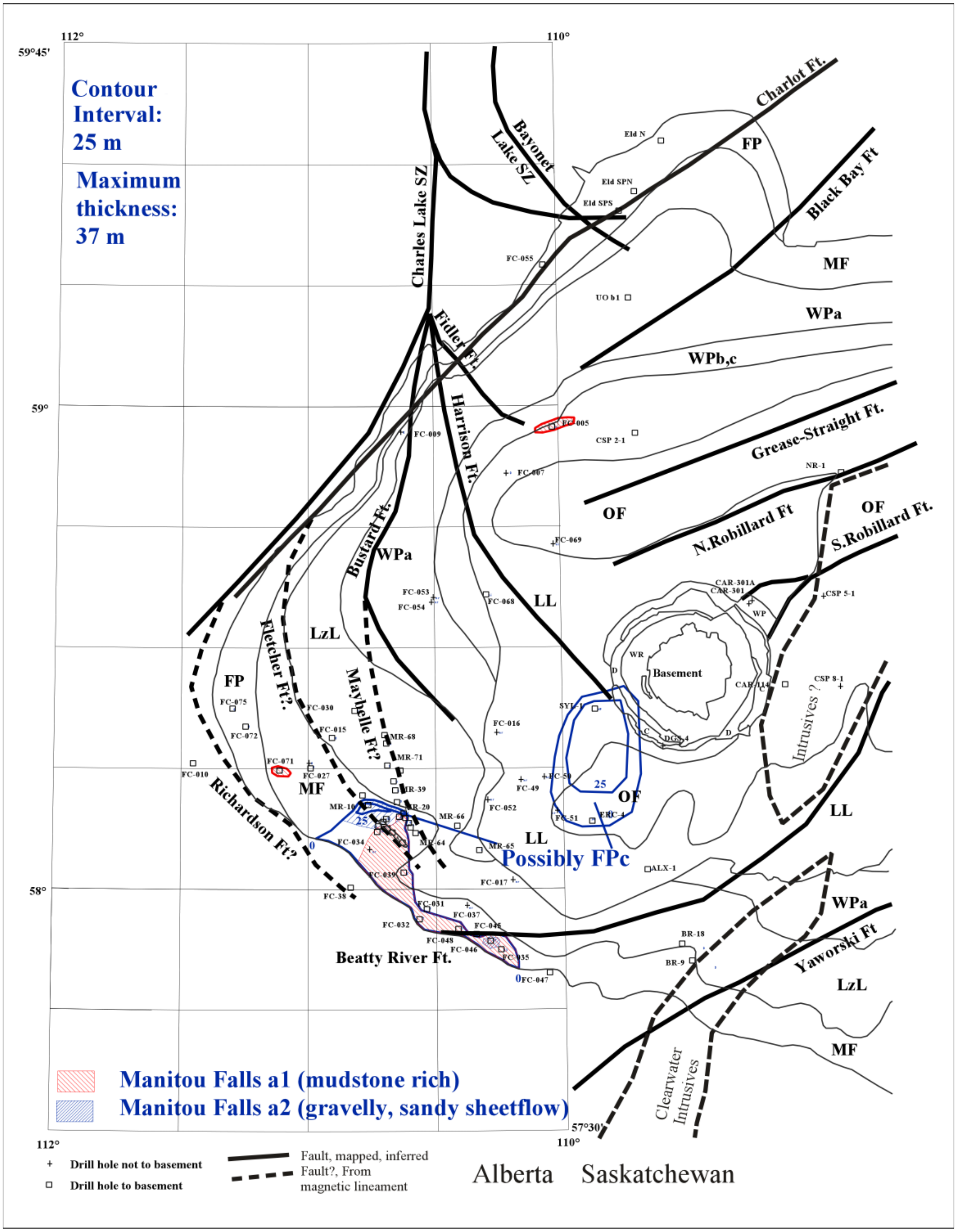


Figure 12. Isopach Manitou Falls a unit. Abbreviations of stratigraphic names on Table 2.

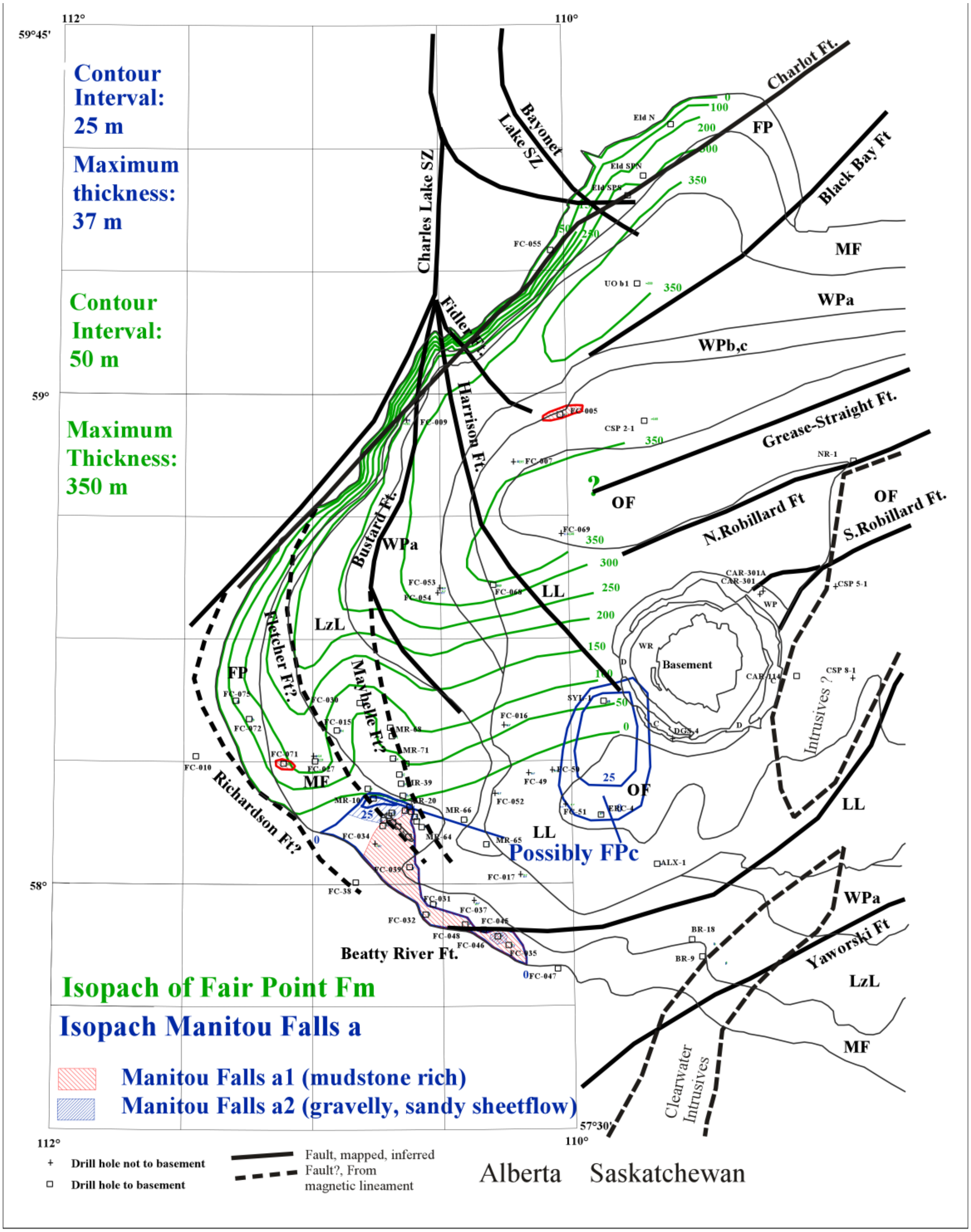


Figure 13. Isopach Fair Point and Manitou Falls a unit showing the apparent mutual exclusion of the gravelly, sandy sheetflow facies. Abbreviations of stratigraphic names on Table 2.

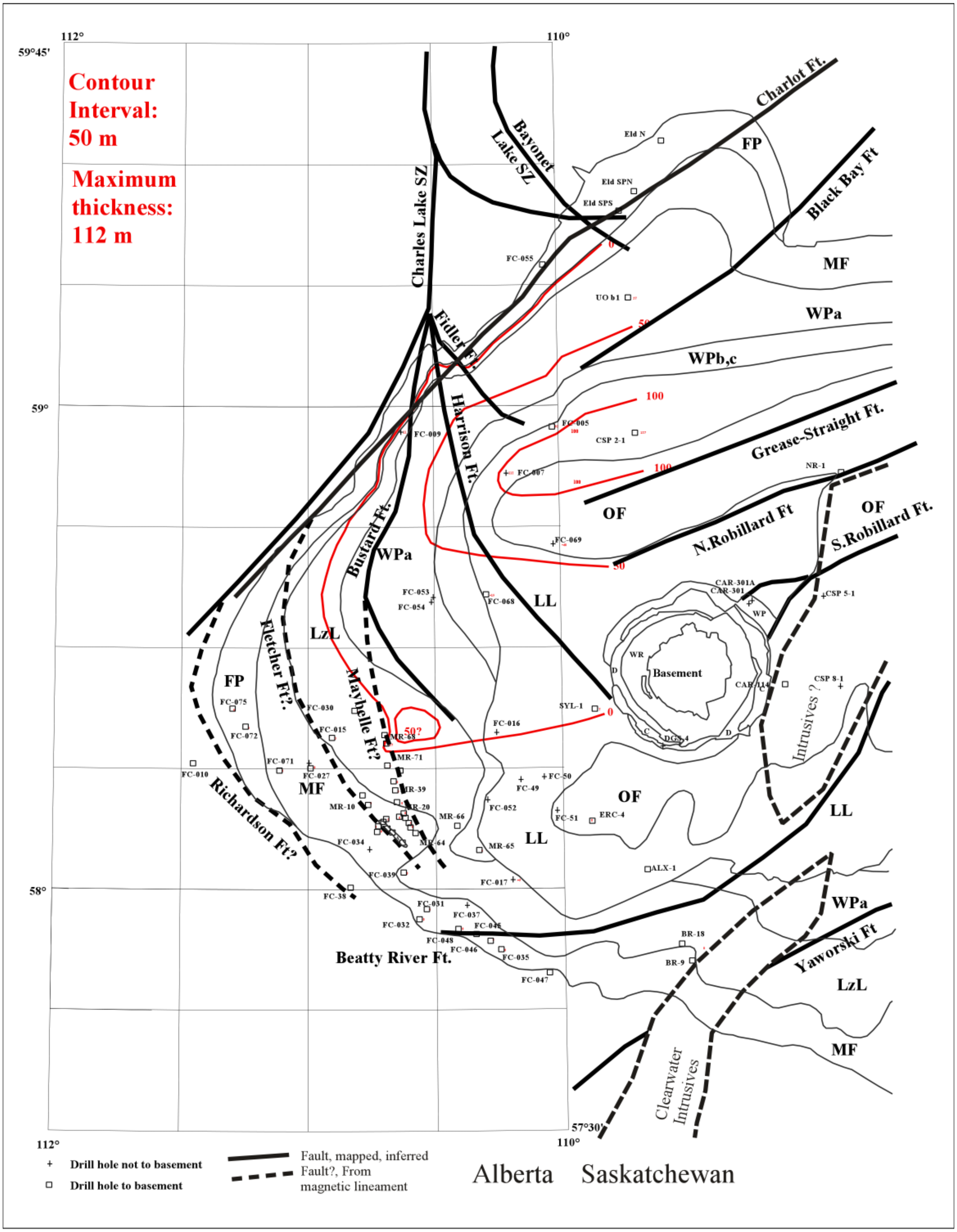


Figure 14. Isopach Manitou Falls b unit. Abbreviations of stratigraphic names on Table 2.

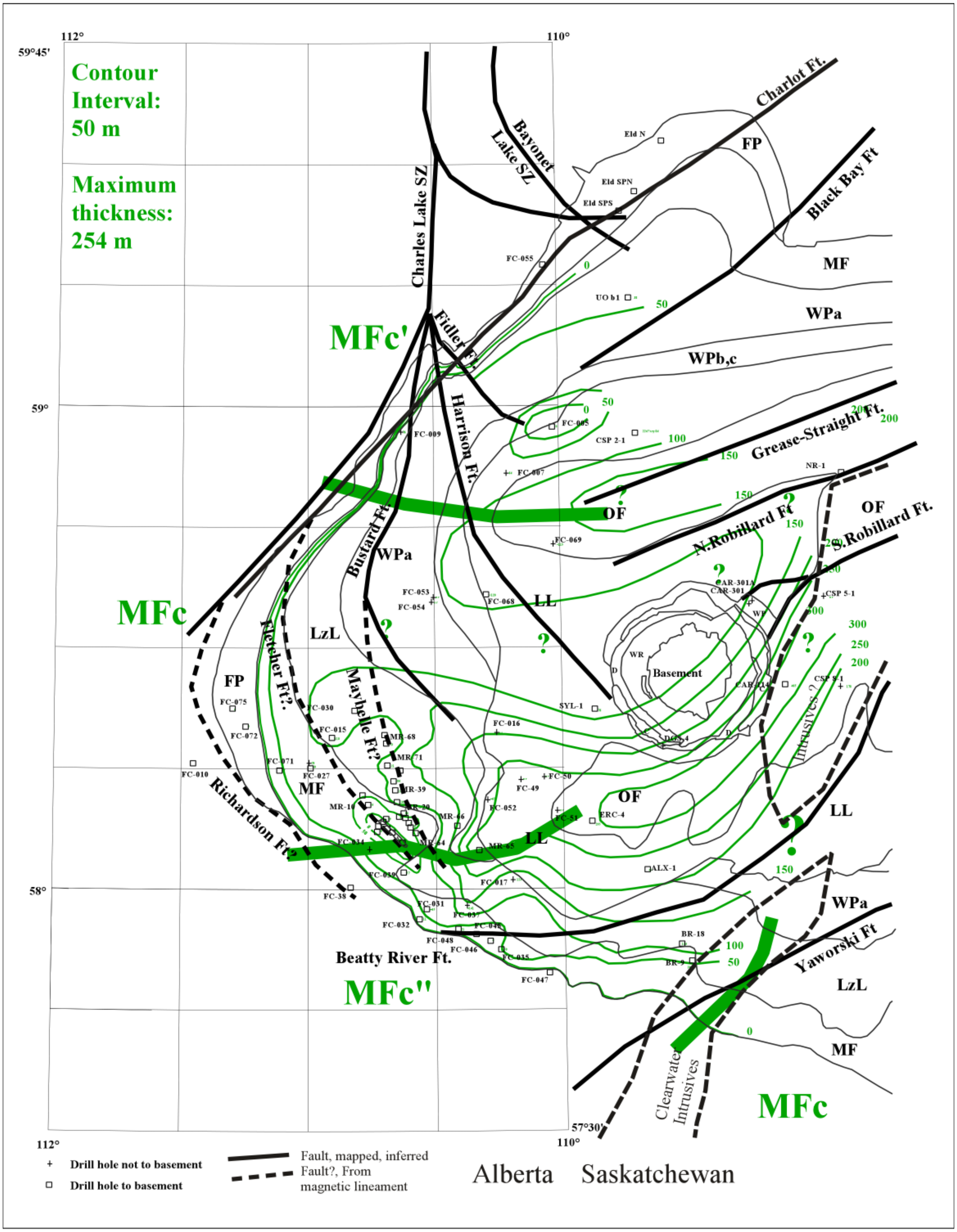


Figure 15. Isopach Manitou Falls c unit. Abbreviations of stratigraphic names on Table 2.

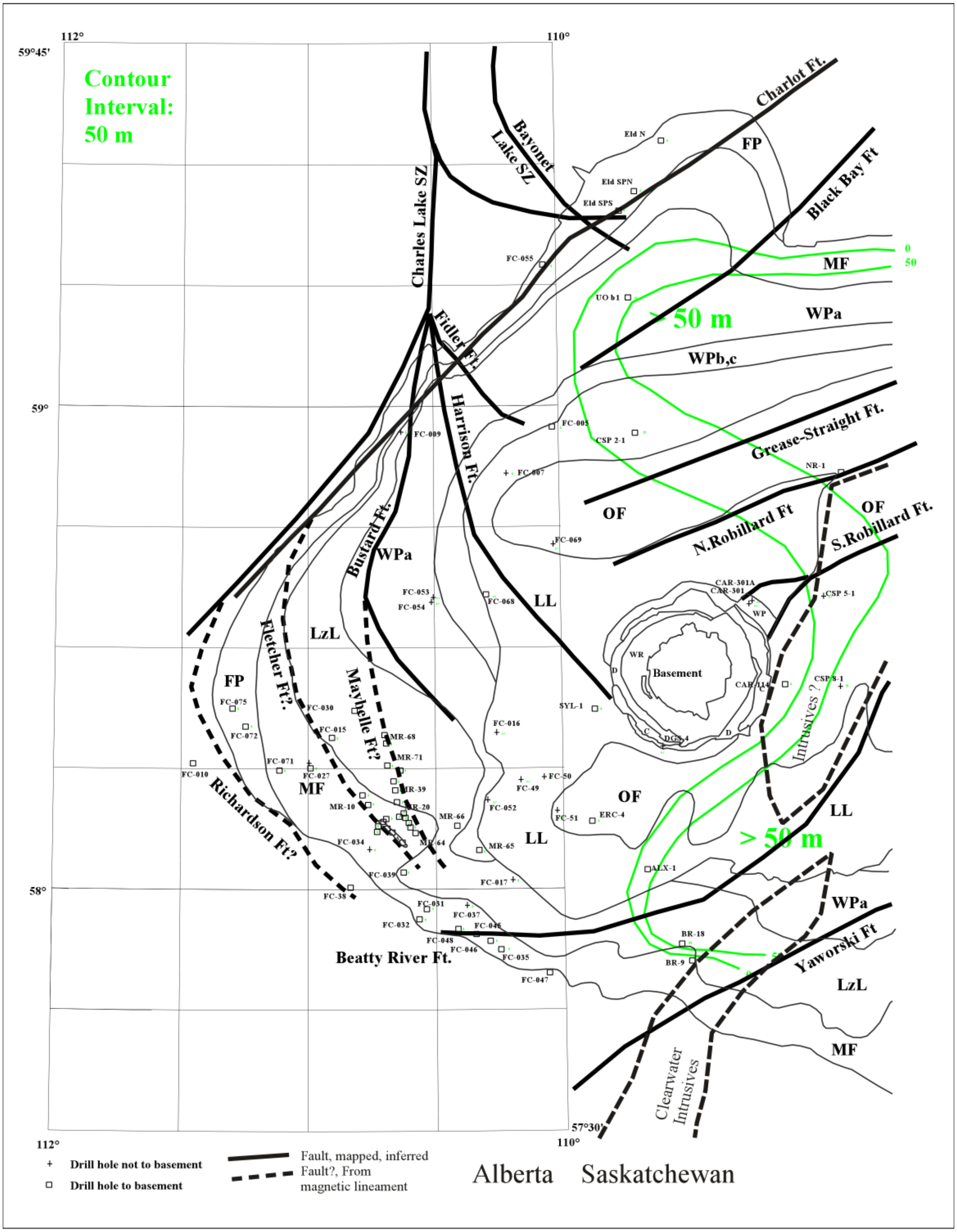


Figure 16. Isopach Manitou Falls d unit. Abbreviations of stratigraphic names on Table 2.

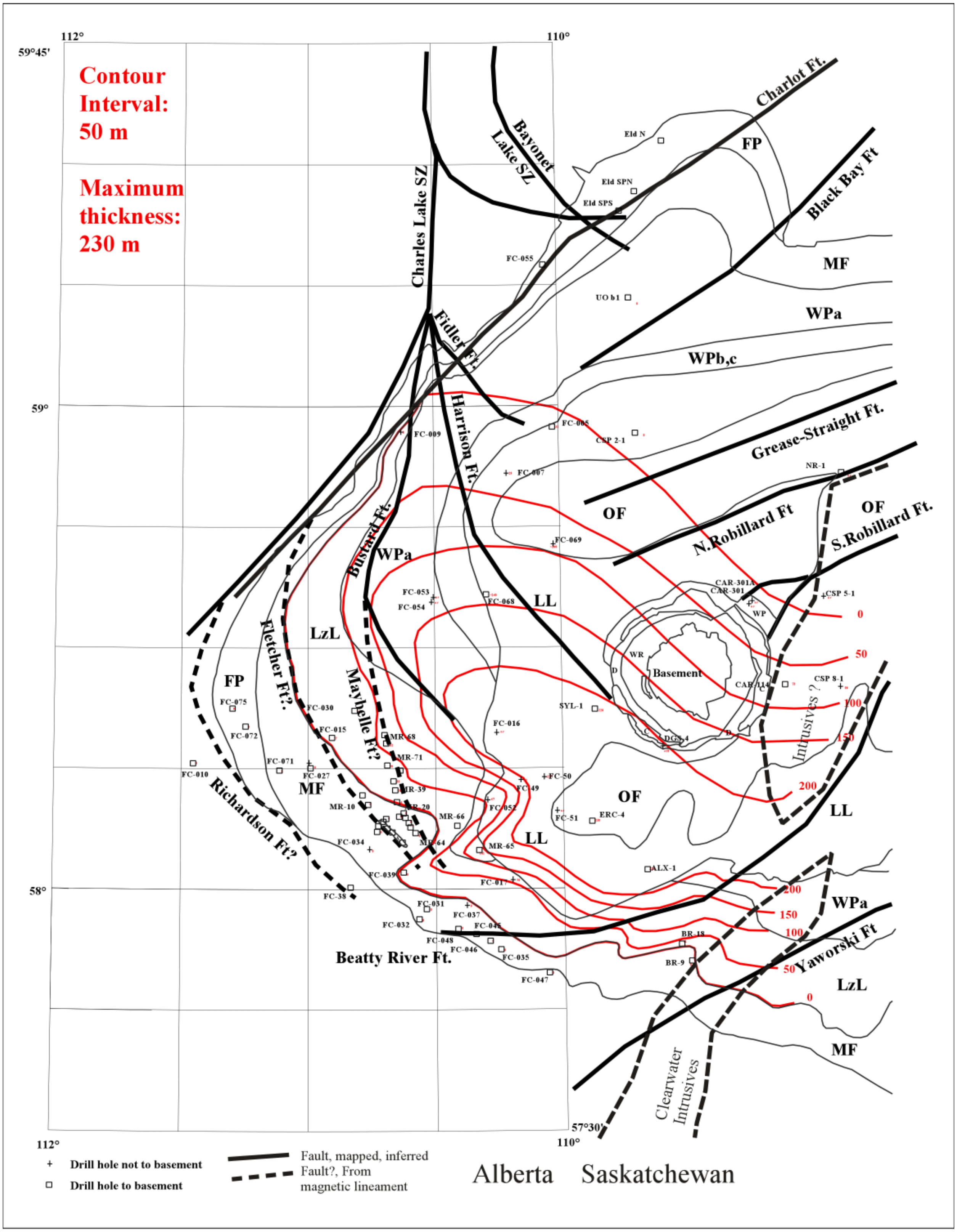


Figure 17. Isopach Lazenby Lake Formation. Abbreviations of stratigraphic names on Table 2.

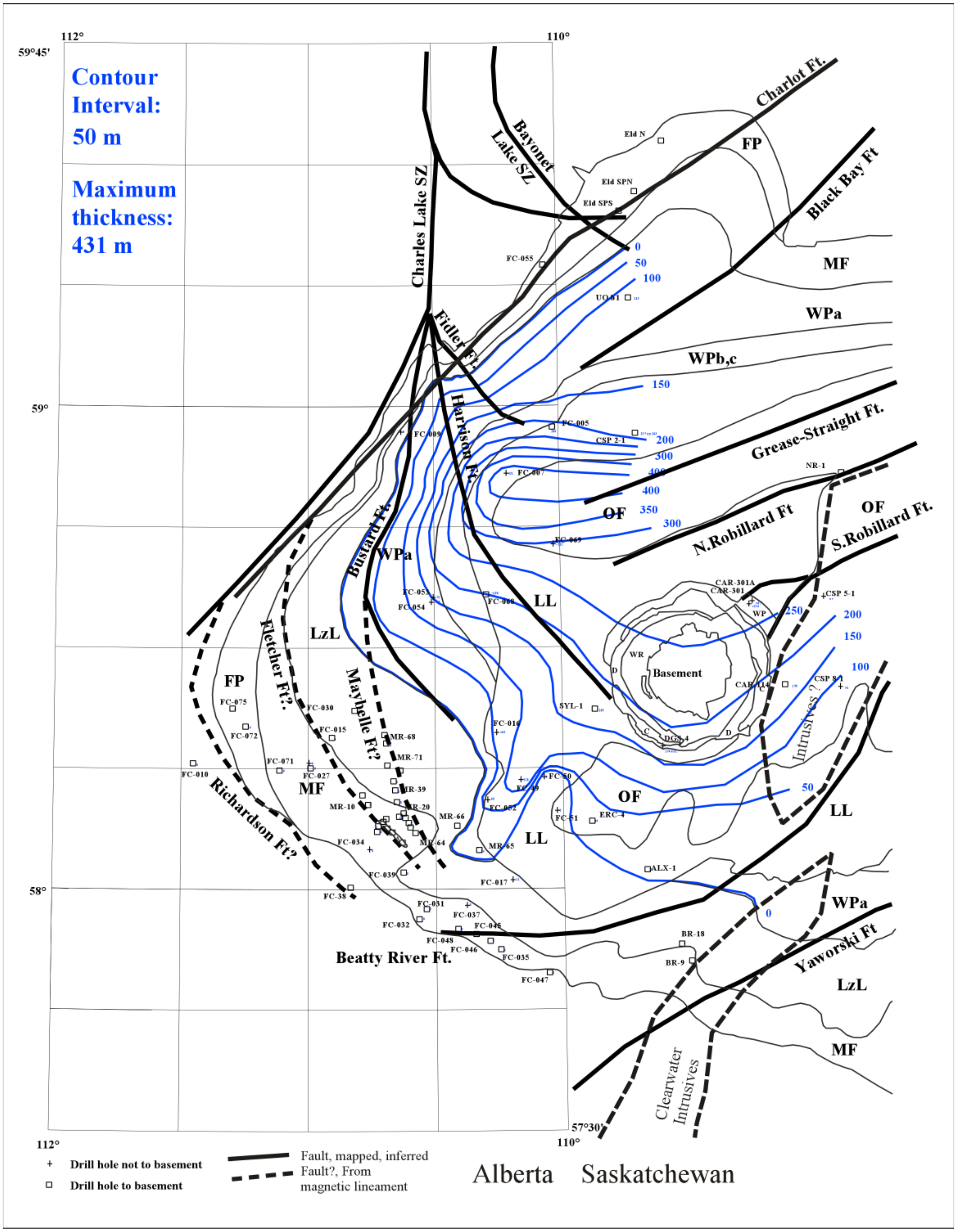


Figure 18. Isopach Wolverine Point a unit. Abbreviations of stratigraphic names on Table 2.

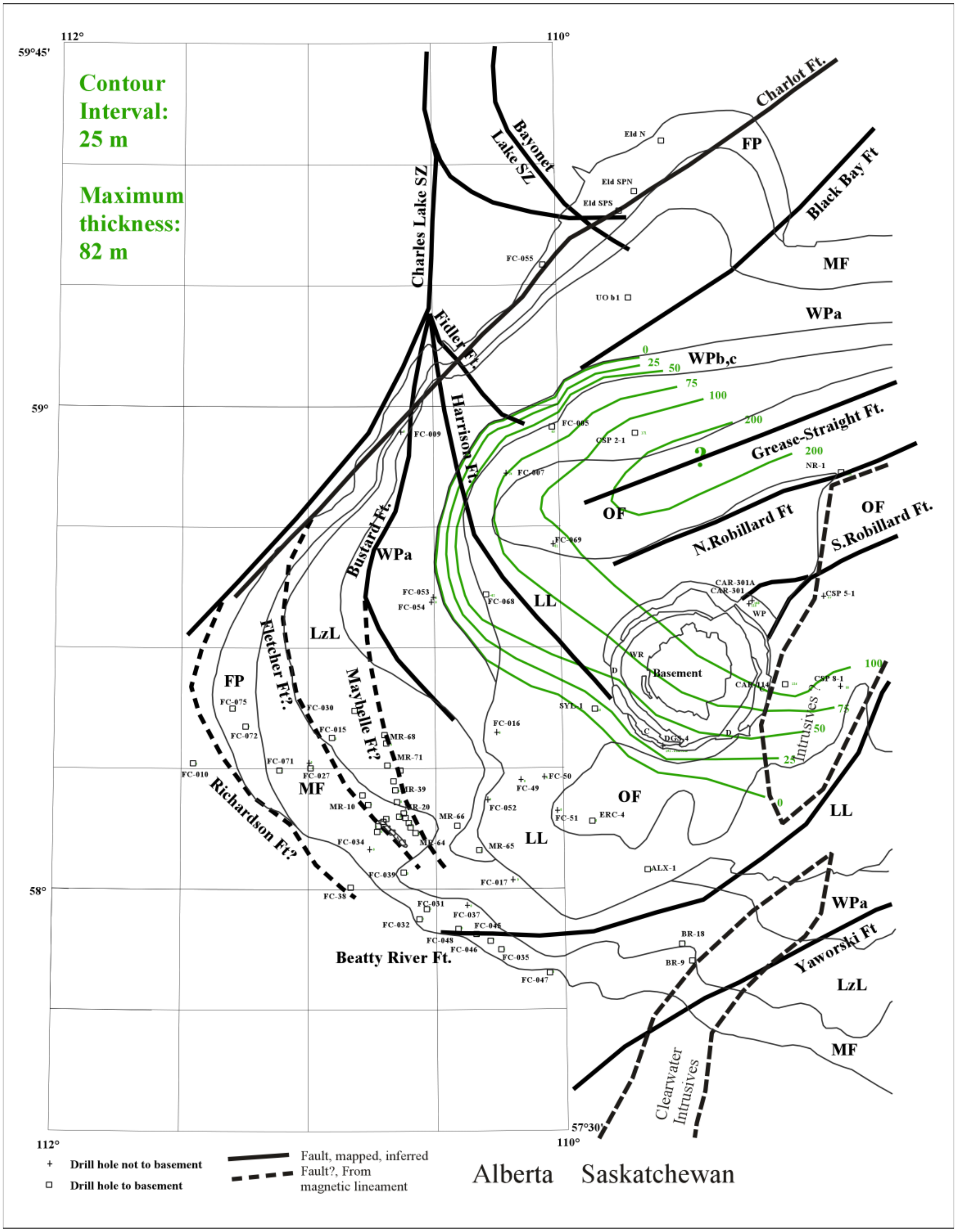


Figure 19. Isopach Wolverine Point b unit. Abbreviations of stratigraphic names on Table 2.

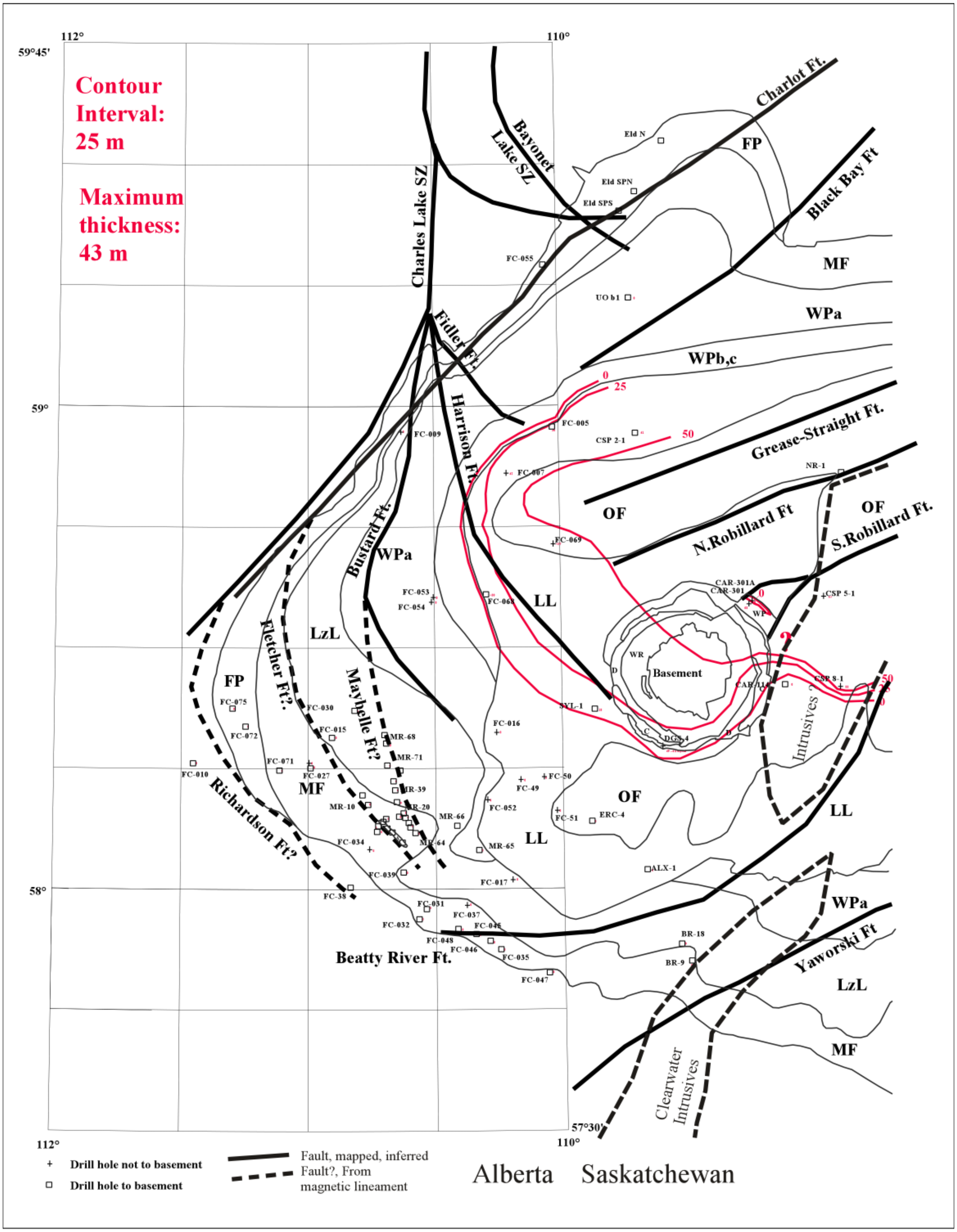


Figure 20. Isopach Wolverine Point c unit. Abbreviations of stratigraphic names on Table 2.

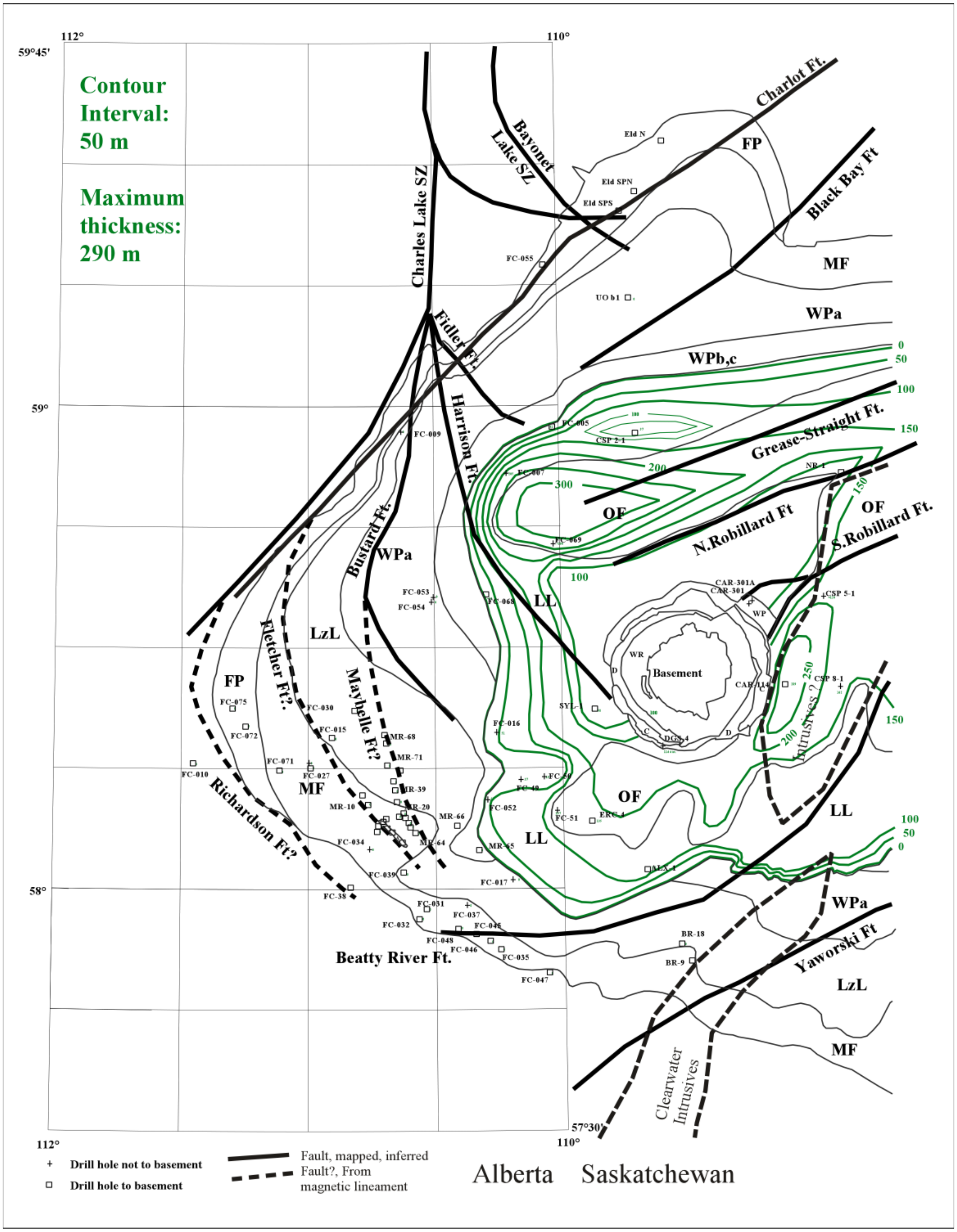


Figure 21. Isopach Locker Lake Formation. Abbreviations of stratigraphic names on Table 2.

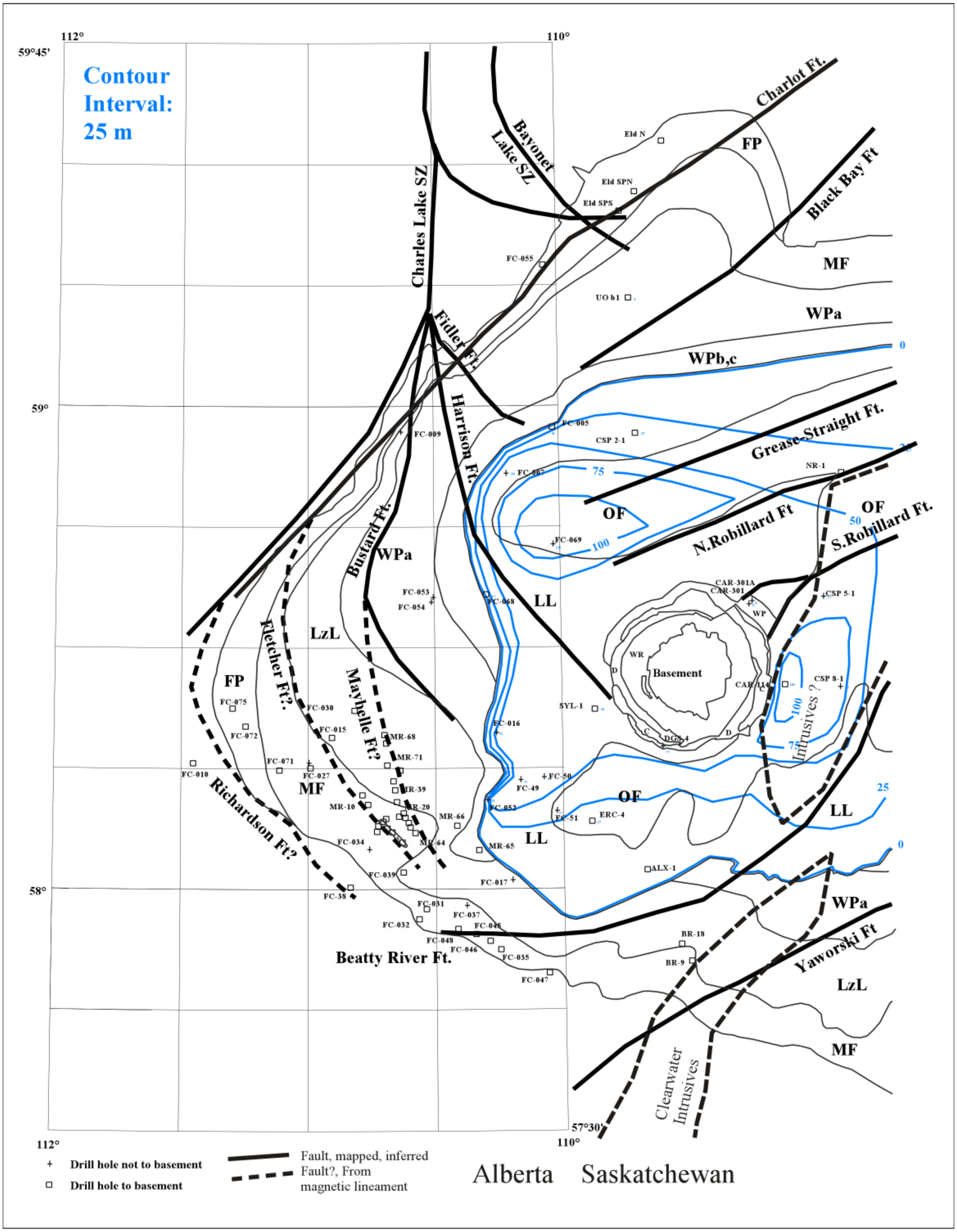


Figure 22. Isopach Locker Lake a unit. Abbreviations of stratigraphic names on Table 2.

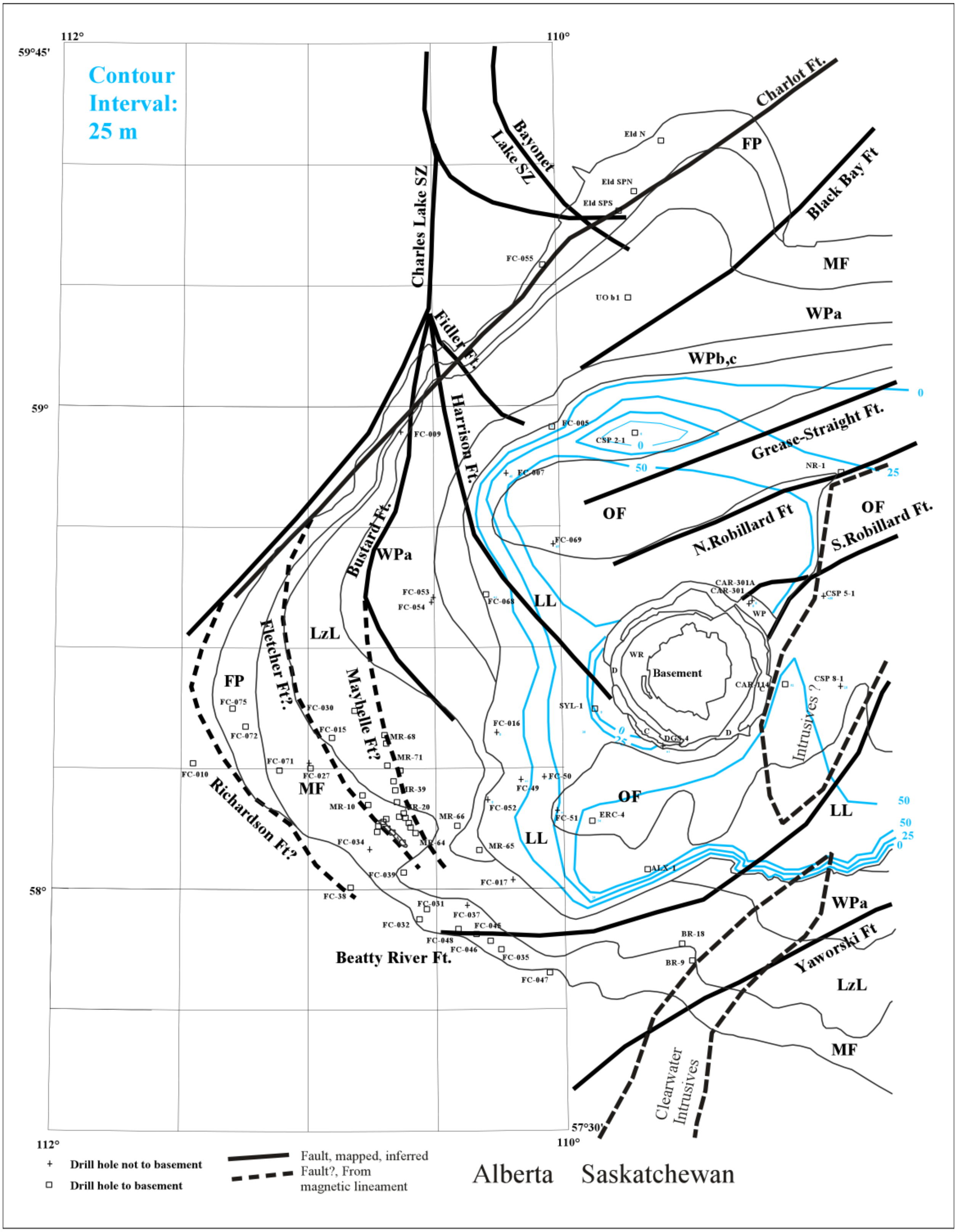


Figure 23. Isopach Locker Lake b unit. Abbreviations of stratigraphic names on Table 2.

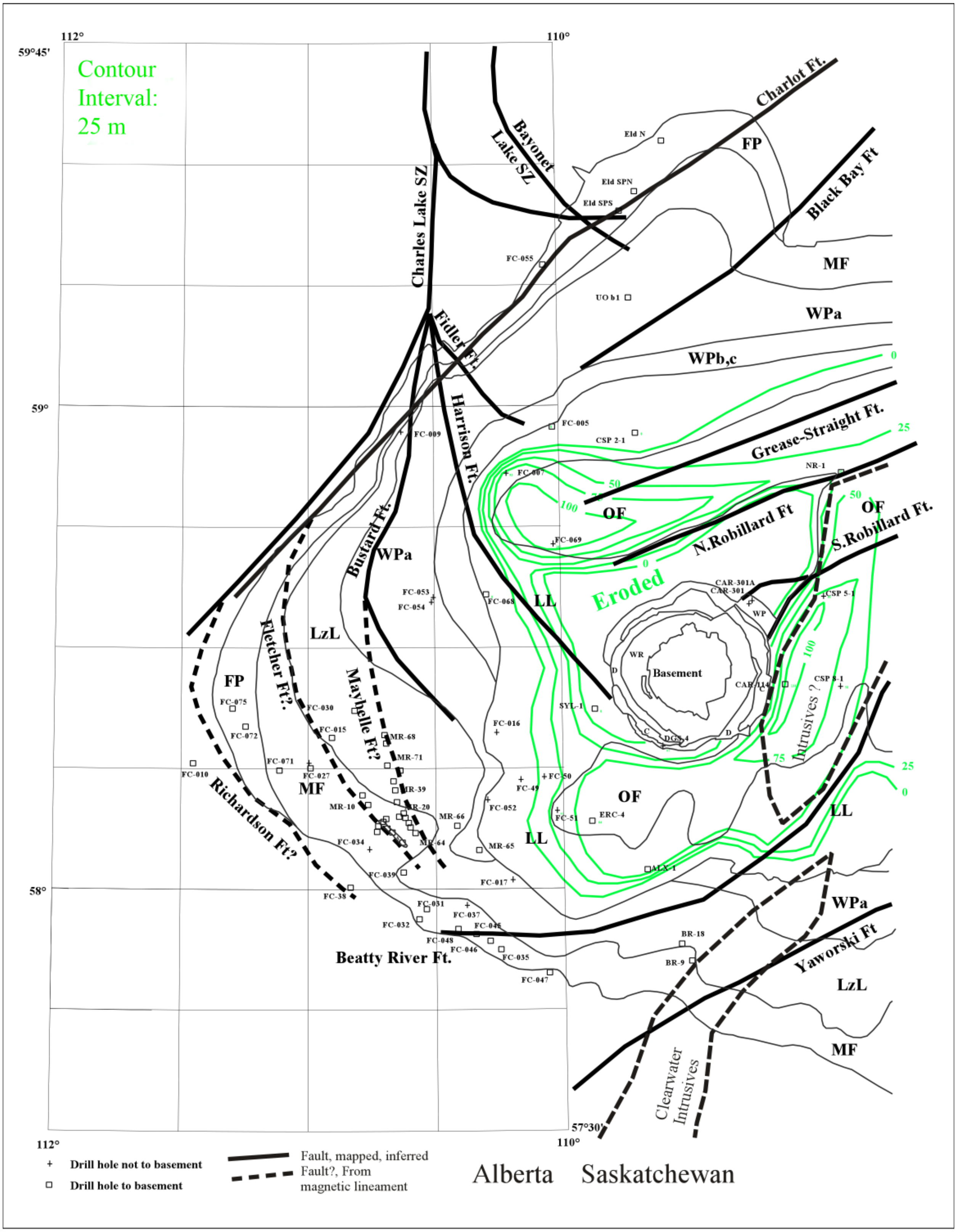


Figure 24. Isopach Locker Lake c unit. Abbreviations of stratigraphic names on Table 2

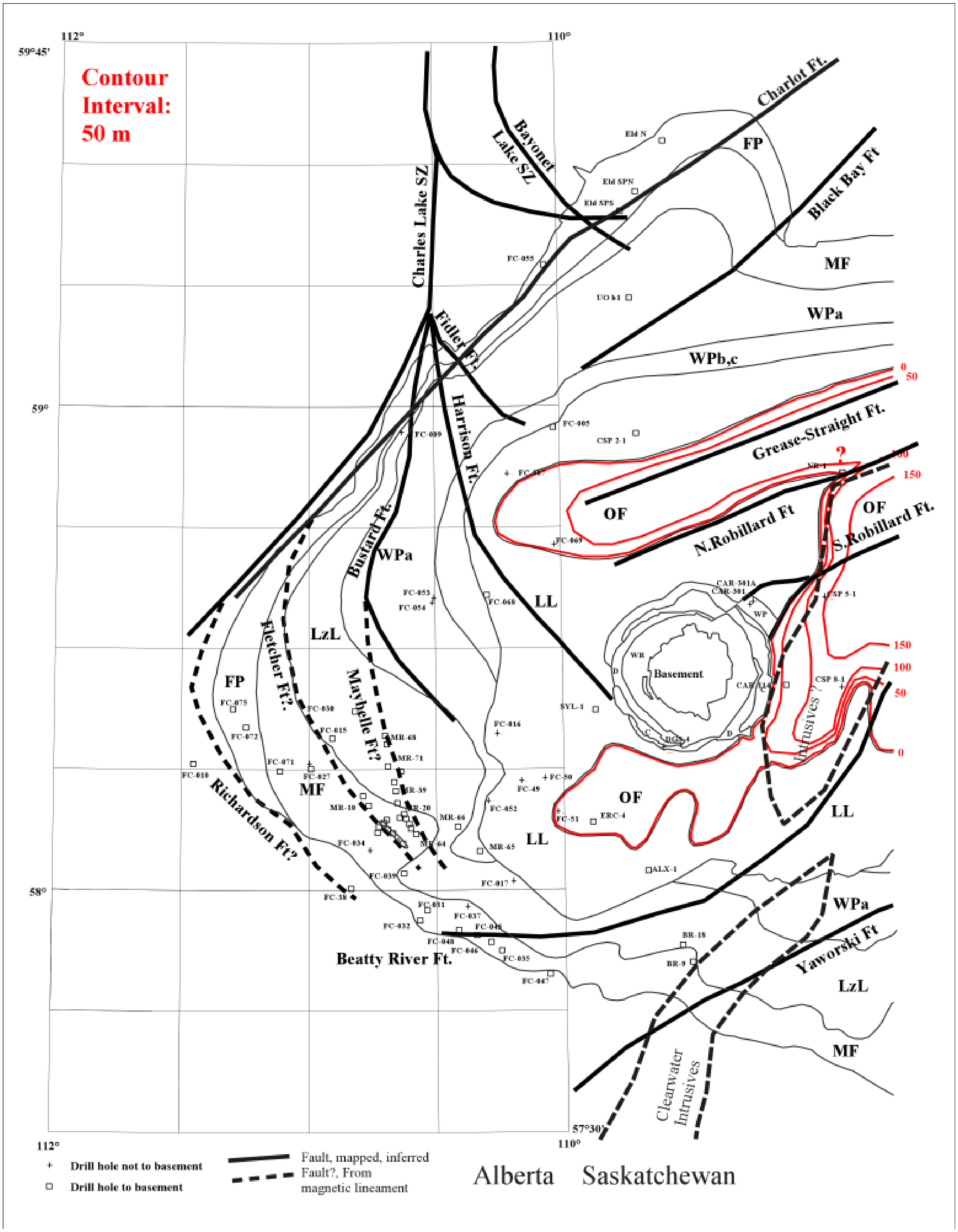


Figure 25. Isopach Otherside Formation. Abbreviations of stratigraphic names on Table 2.

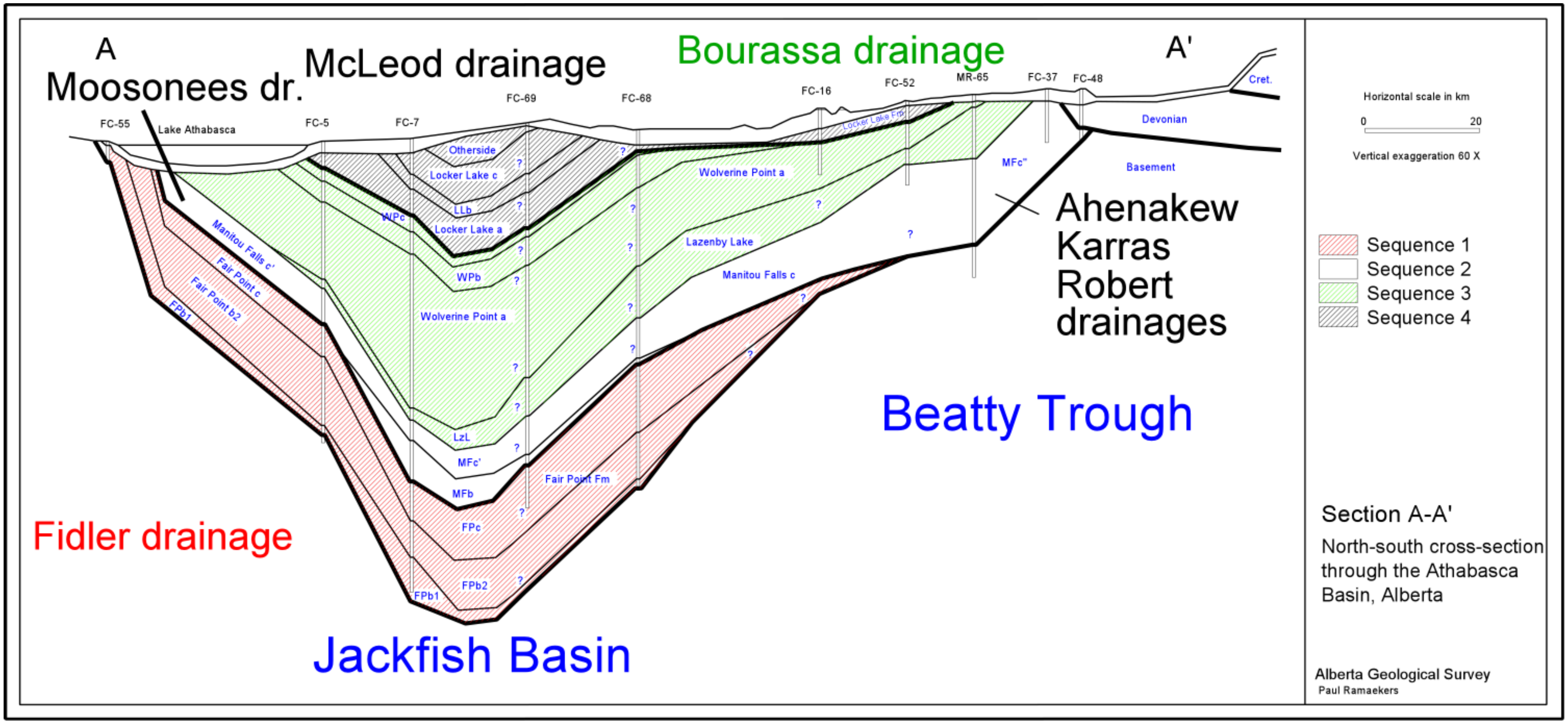


Figure 26. Section A-A'. A north-south section extending from hole FC-055, southerly to FC-048.

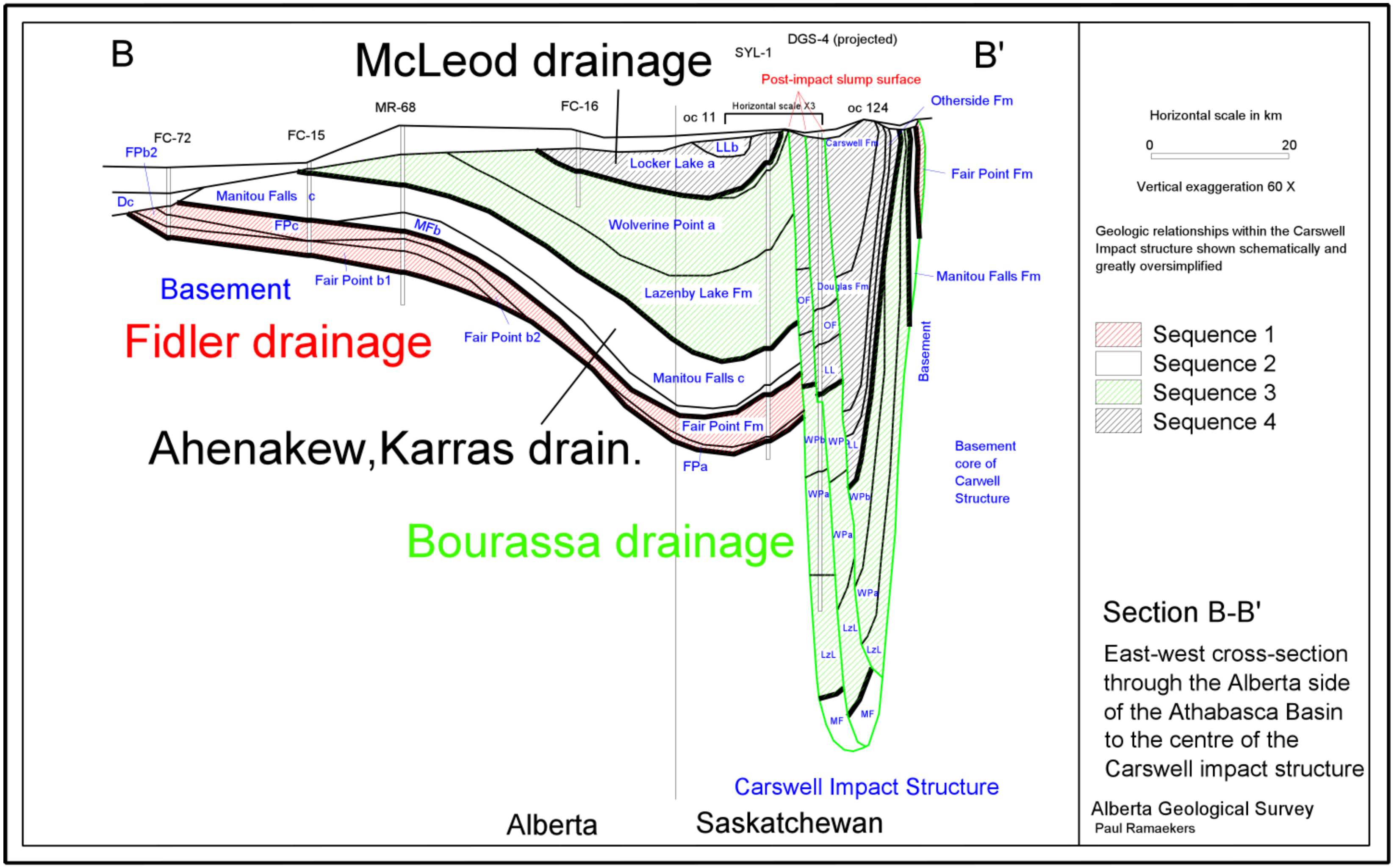


Figure 27. Section B-B', an east-west section extending from hole FC-072, easterly to FC-016 in Alberta, then continuing east to hole SYL-1 near the Carswell Structure in Saskatchewan.

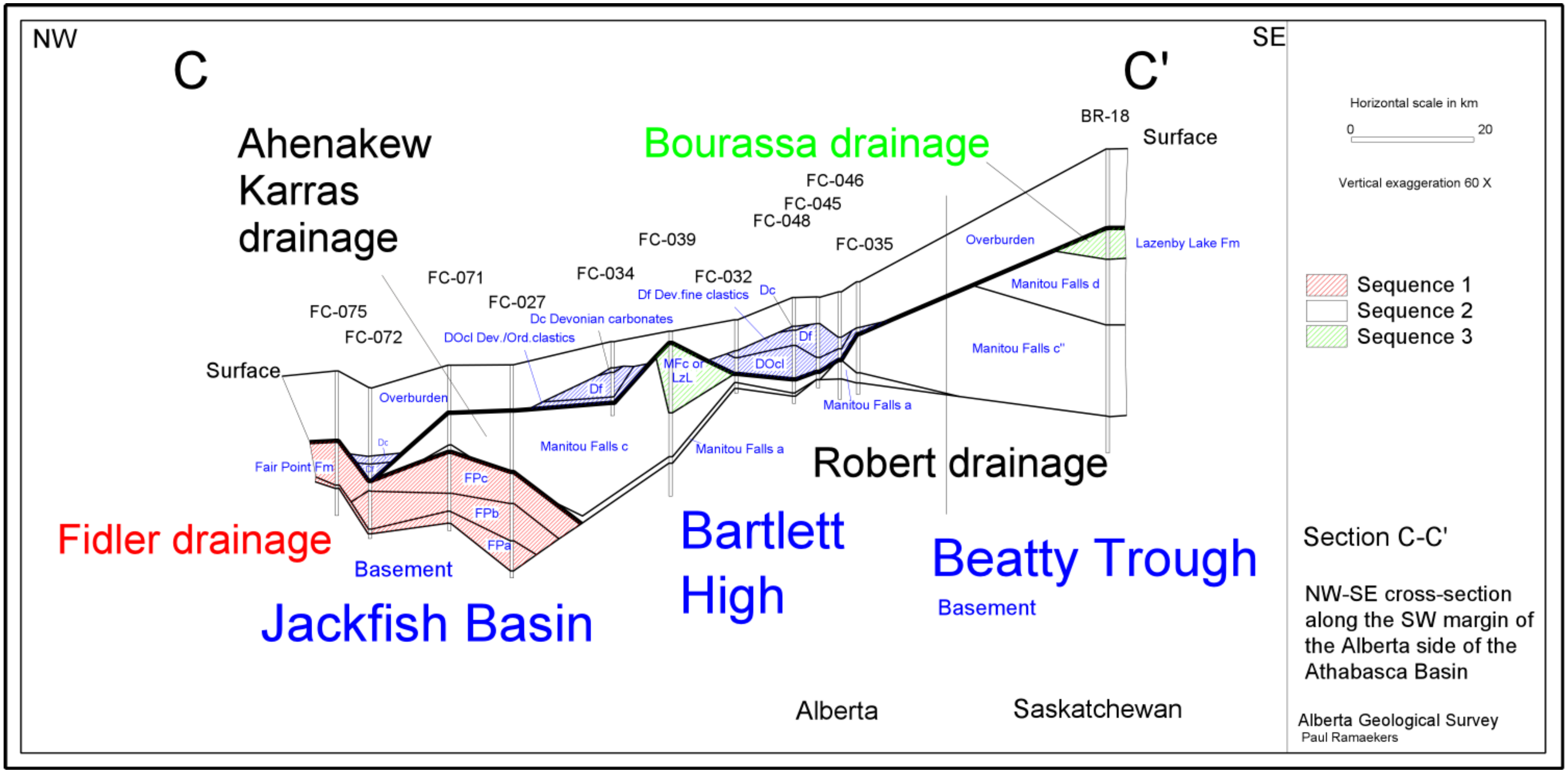


Figure 28. Section C-C', a southeasterly section extending from hole FC-075, southeasterly to FC-035 in Alberta, then easterly to hole BR-16 in Saskatchewan south of the Carswell Structure.

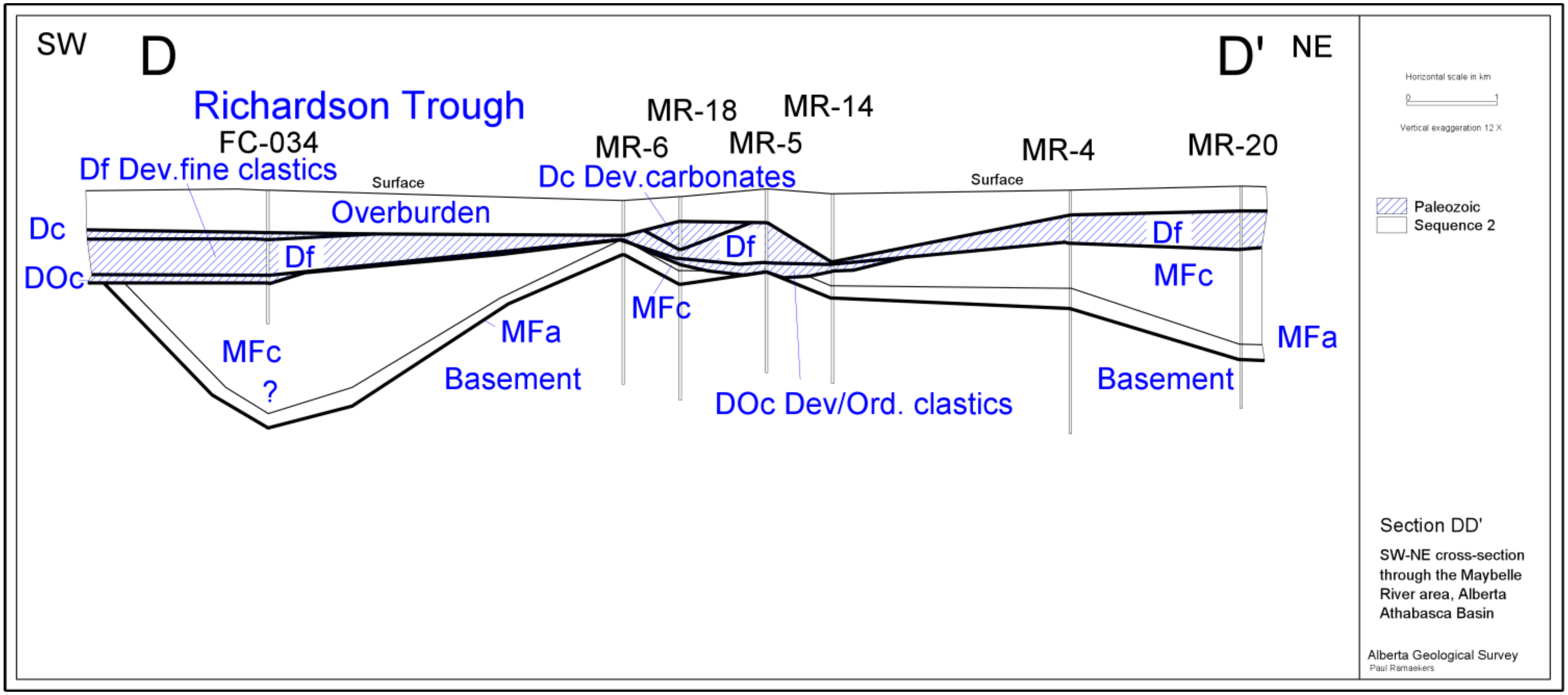


Figure 29. Section D-D', a northeasterly section extending from hole FC-034 to MR-20.

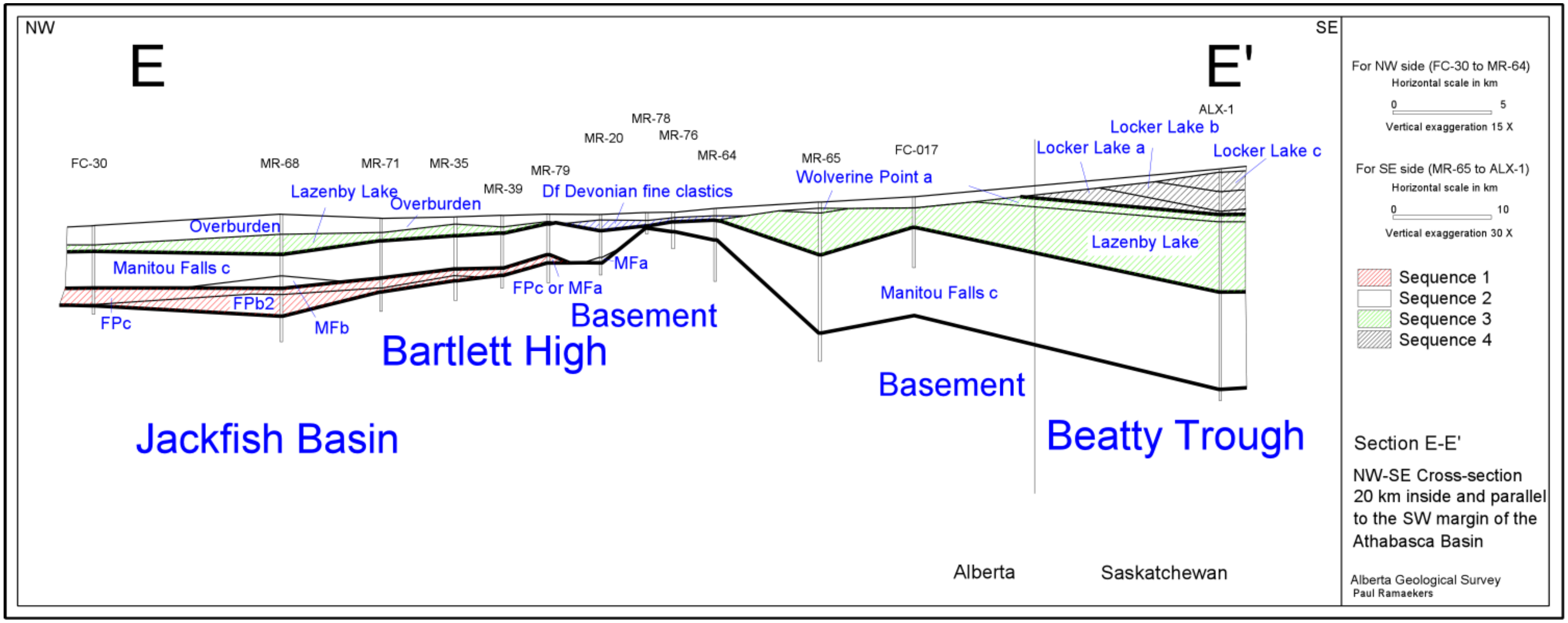


Figure 30. Section E-E', a southeasterly section extending from hole FC-030 southeasterly through the Maybelle trend to FC-017 in Alberta, then to ALX-1 in Saskatchewan.

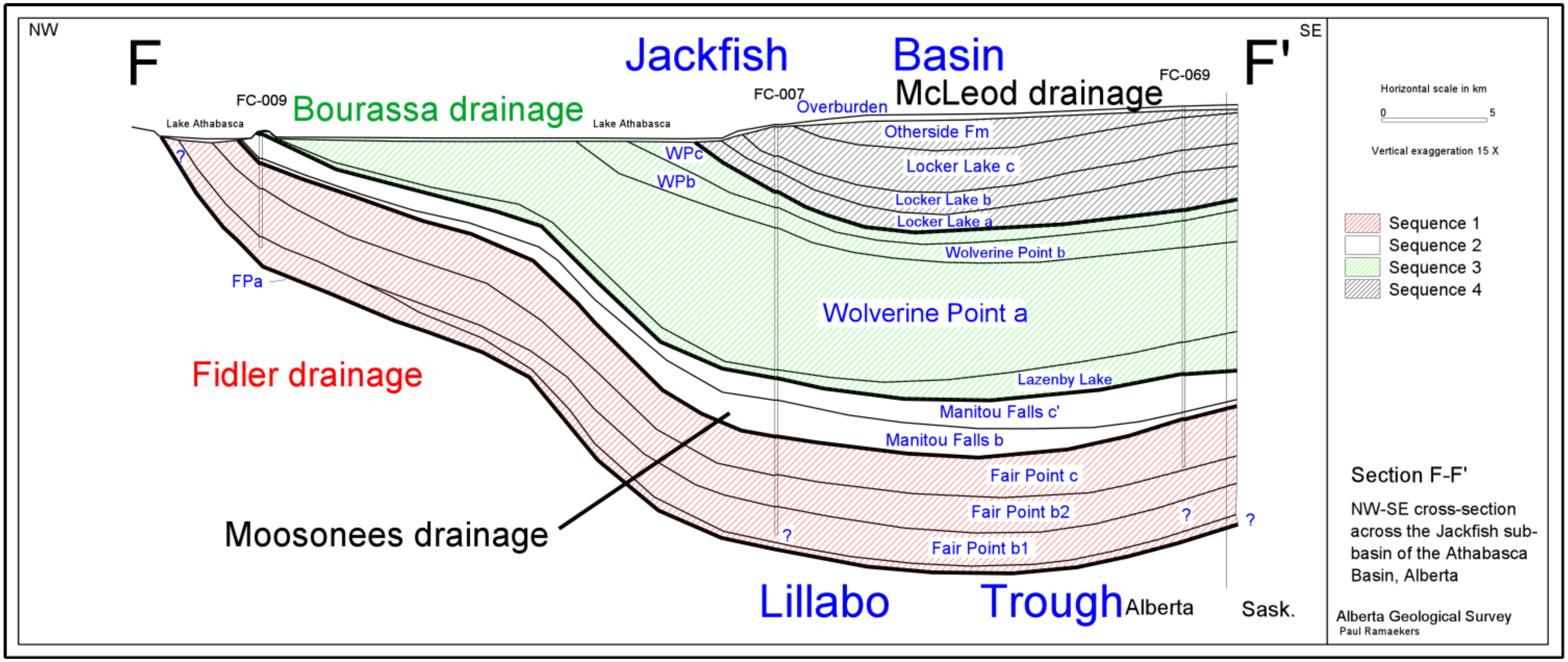


Figure 31. Section F-F', a southeasterly section extending from hole FC-009 southerly to hole FC-069 in Alberta.

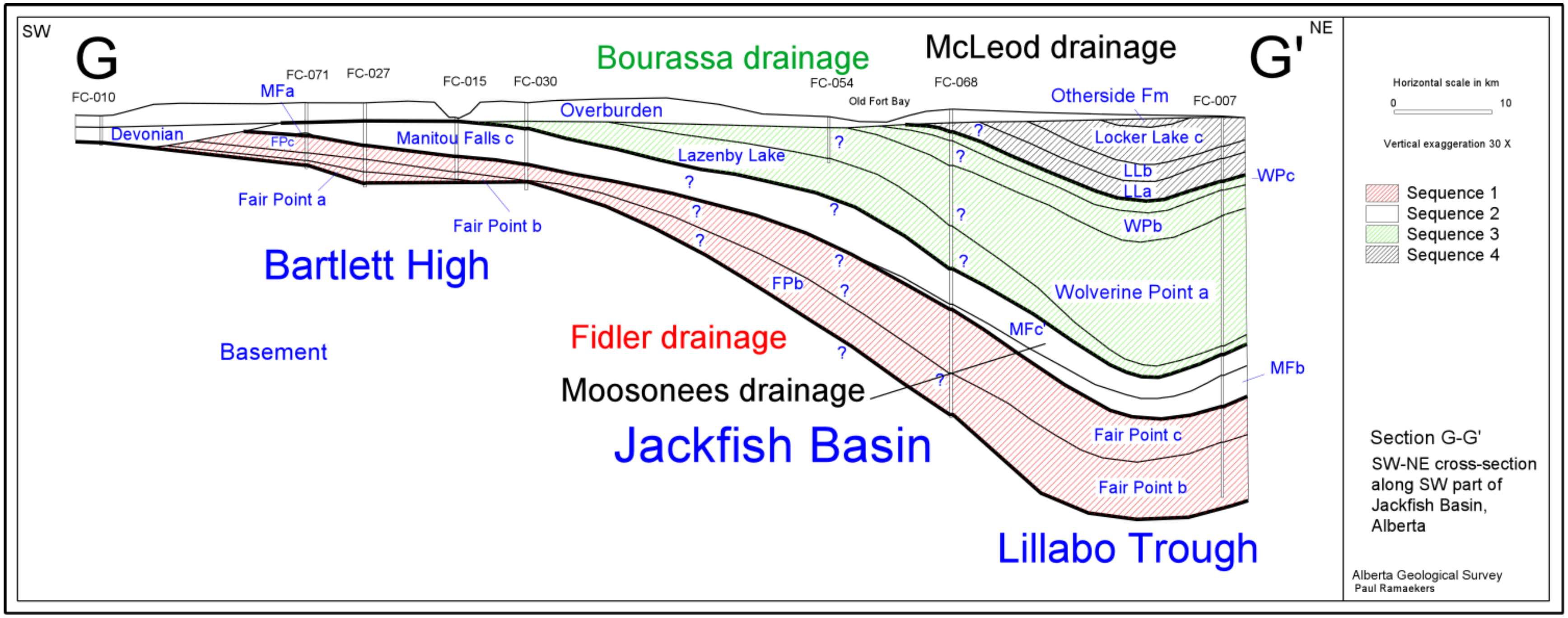


Figure 32. Section G-G', a northeasterly section extending from hole FC-071 northeasterly to FC-007.

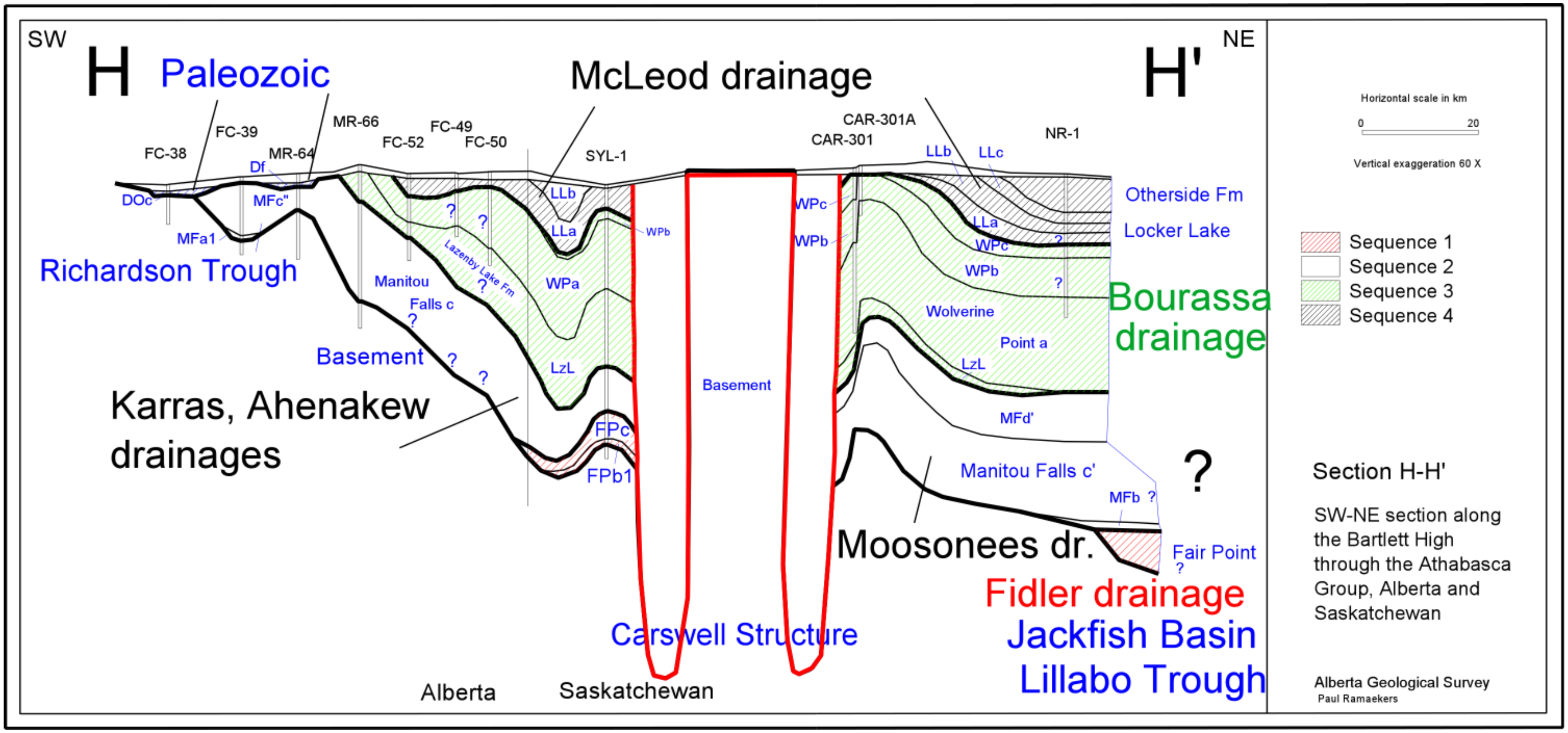


Figure 33. Section H-H', a northeasterly section extending from hole FC-039 northeasterly to hole FC-050 in Alberta, then to hole NR-1 in Saskatchewan.

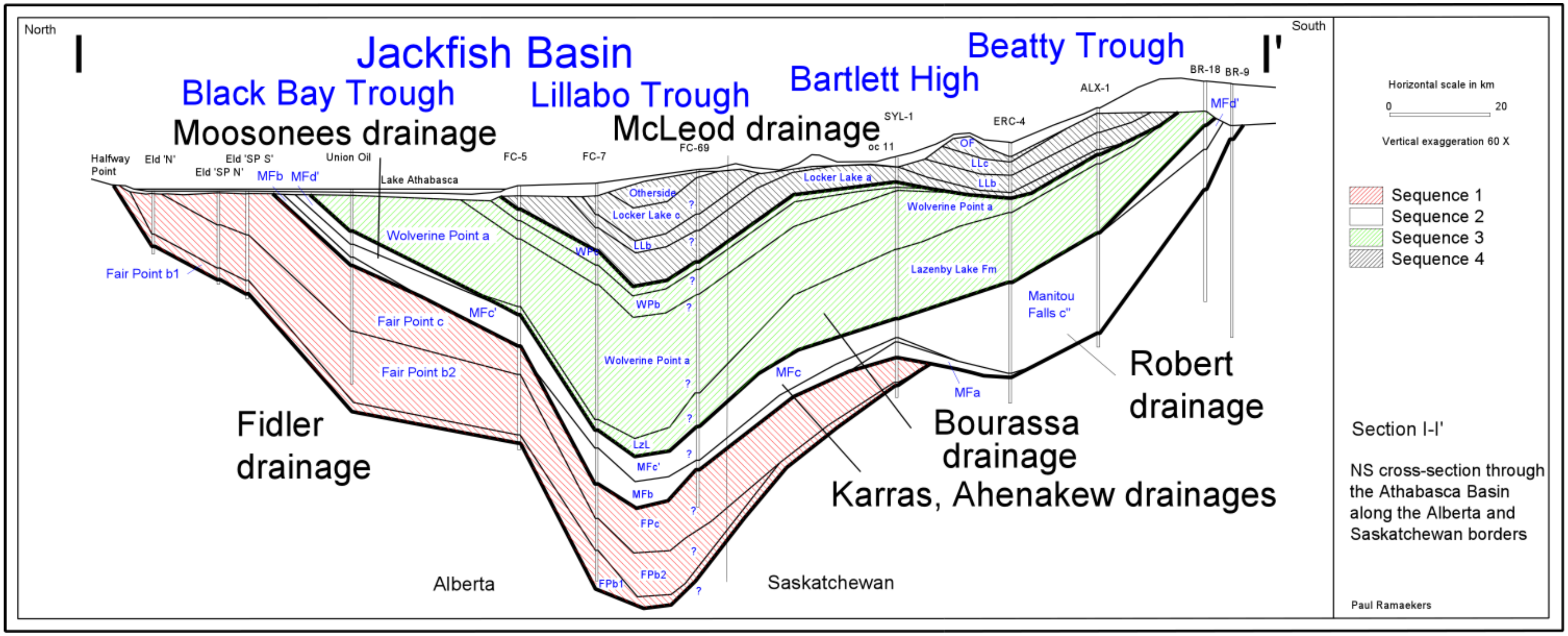


Figure 34. Section I-I', a north-south section just east of the Alberta-Saskatchewan border from Halfway Point on the northern tip of Lake Athabasca in Saskatchewan south through hole FC-005 to FC-069 in Alberta and on to hole BR-9 at the southern margin of the basin in Saskatchewan.

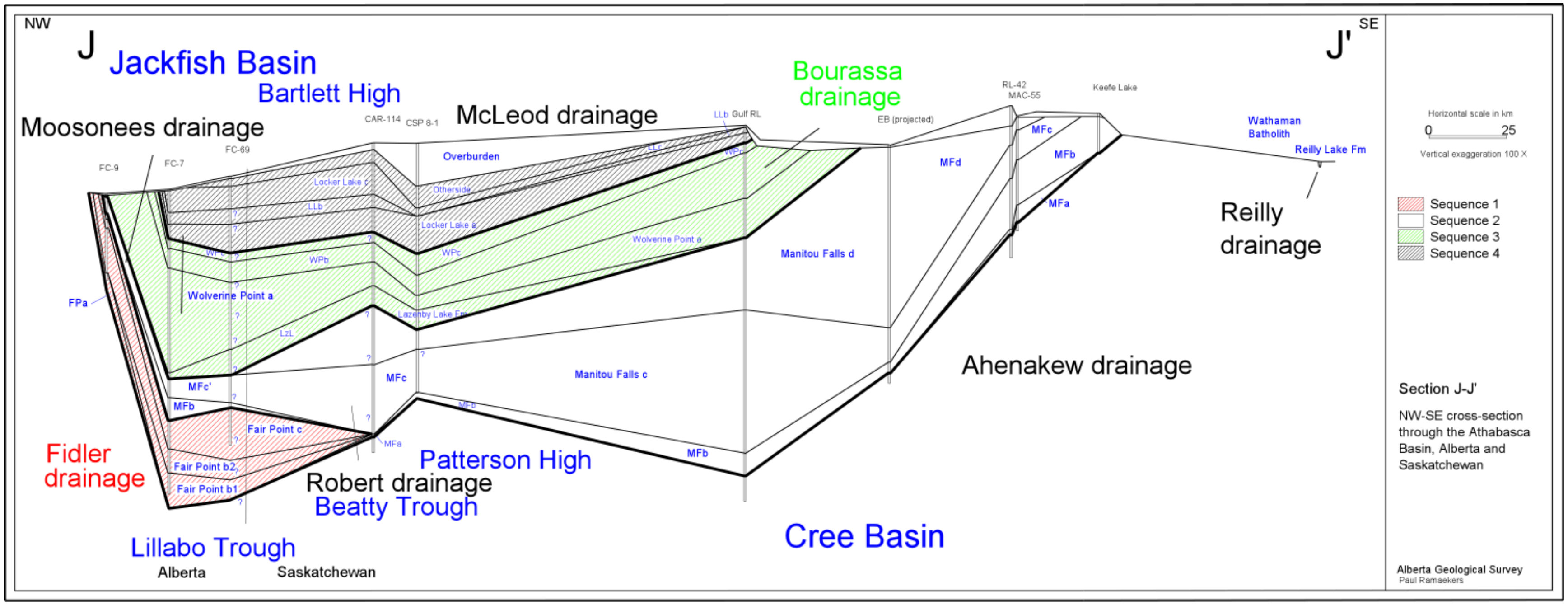


Figure 35. Section J-J', a southeasterly section along the longitudinal axis of the Athabasca Basin through Alberta and Saskatchewan.

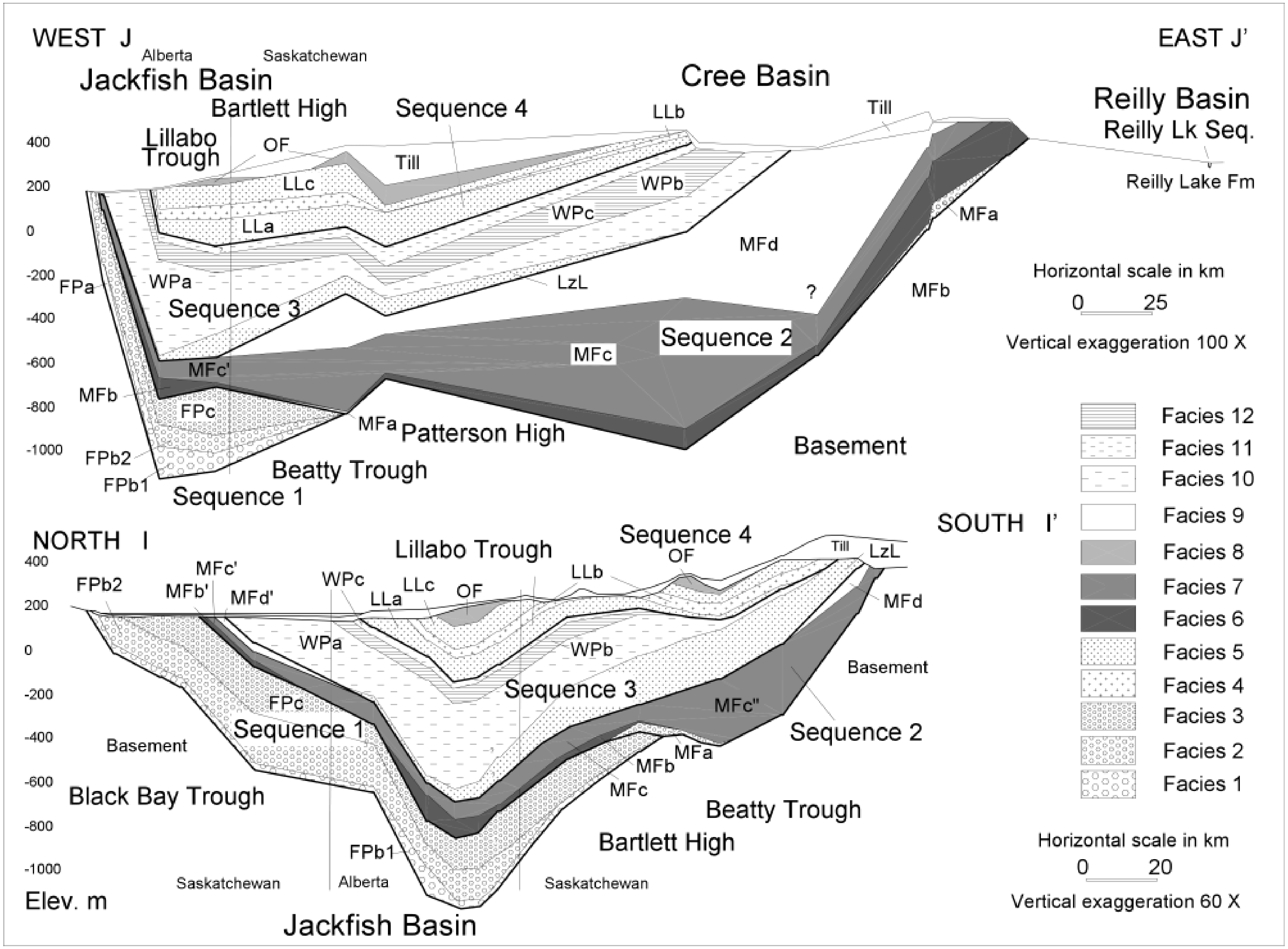


Figure 36. Sedimentary facies distribution along sections I-I' and J-J'. Abbreviations of stratigraphic names on Table 2.

2.1 Sequence 1: Fair Point Formation

Sequence 1 consists entirely of the Fair Point Formation (Ramaekers, 1979, 1980, 1990, 2002; Wilson, 1985) and is a single overall fining upward sequence, except for intermittently present minor coarsening up units at its base. It is restricted to an area northwest of the Robillard and Grease River-Straight River Faults (Figure 4). It reaches its greatest thickness in the Jackfish Basin and thins greatly on the Bartlett High along which the coarsest material was deposited, suggesting that provenance of the sequence lay largely to the south. Paleocurrent data are available only from the northwestern side and indicate drainage to the west and northwest. Distribution of coarse material and paleocurrents indicate that a single drainage system was involved, the Fidler drainage system (Ramaekers, 1978).

2.1.1 Fair Point Formation (FP)

The formation consists of coarse to granule-size, pebbly sandstones with minor conglomerates and mudstones and is discussed in more detail in Wilson (1985) and Ramaekers (2002). It is informally subdivided into three members characterised by the common, but by no means exclusive, presence of mudstones (FPa), conglomerates (FPb) and pebbly sandstones (FPc).

The Fair Point Formation overlies Archean and Paleoproterozoic granulite to greenschist-grade metamorphosed granites and metasediments (Wilson, 1986). This profound unconformity is marked by extensive lateritic paleoweathering overprinted by hydrothermal alteration along the unconformity and along fracture systems cutting through it from the basement into the overlying sandstone and is described in detail by Wilson (1986).

The upper boundary of the Fair Point Formation is marked by the abrupt disappearance of the coarse pebbly material, abrupt to gradational disappearance of much of the interstitial clays and a change in clast lithology. This suggests that a different sediment source has been tapped by the overlying Manitou Falls Formation (MF), with only the clay being reworked into the basal MF, and indicates the presence of a significant unconformity on lithological grounds alone.

Within the Fair Point Formation, three sandy to cobbly lithofacies (FPb1, FPb2 and FPc) are commonly present and are mappable over large areas. These are underlain by a variably present basal pebbly sand, mudstone and siltstone unit (FPa) that may grade up into a pebbly sandy unit with lithofacies like those of the FPc.

The pebbles of the Fair Point Formation are polymict, in contrast to the quartz and quartzite pebbles prevalent in the rest of the Athabasca Group. Well rounded, subspherical quartzite pebbles are common throughout, as are less common flatter, well indurated, fine sandstone to mudstone pebbles. Their proportion varies from hole to hole. The sandstone pebbles may be reworked Fair Point Formation, but more likely are reworked from unmetamorphosed older units equivalent to the Martin Group or other underlying units. Dark brown, fine-grained, often angular and bladed pebbles are referred to by Wilson (1985) as regolith material, and in hand specimen have a volcanic aspect. Given the stratigraphic position of some of them well above the base of the Fair Point Formation, their source must be distant if they are regolith; however, their angularity suggests a nearby source, possibly intrabasinal. The presence of rhyolitic shards seen in thin section (Pacquet and McNamara, 1985) suggests that it is not unreasonable to expect other volcanic material in this unit. Similar material is not present or rare in other units or in the Manitou Falls Formation where it overlies the basement directly. Gneissic pebbles are also present in places within the Fair Point Formation.

The isopach map of the Fair Point Formation (Figure 8) shows that the unit reaches its maximum thickness of about 350 m in a northeast trending trough developed at this time. This trough occupies the northern half of the Athabasca Basin in Alberta and is referred to as the Jackfish Basin (Figures 2 and 3). The formation appears to lap onto the Bartlett High which forms its southeastern margin. The thickness of the Fair Point Formation increases very rapidly along the northwest boundary of the basin suggesting a fault bounded basin margin, and perhaps tilting of the Jackfish basin to the northwest. The southern margin of the Jackfish Basin is poorly defined due to lack of drillhole data in the central part of the basin. The southern margin of the Fair Point Formation itself shows a more gradual thickness increase and a minor trough (Richardson Trough) and basement high trending southwest, parallel to the structural grain of the basement (Figure 3). The extent of the Jackfish Basin and the Fair Point Formation to the east in Saskatchewan is not known; both may underlie much of Lake Athabasca and the area north of the Grease-Straight Fault, if this fault was active at the time of deposition of the Fair Point Formation. The presence of FP in ddh CSP 2-1 suggests that this may be the case.

2.1.1.1 Fair Point a (FPa)

The FPa unit is only variably present (FC-009, FC-027, FC-071, FC-072, FC-075, FC-039, FC-068) and consists of an interval of pebbly sandstones interbedded with well-sorted silts and very fine sandstones and mudstones and may be over 30 m thick. It may grade up into coarser pebbly sandstones similar to those of the FPc unit, and is overlain by the conglomeratic FPb unit. It can be subdivided into the mudstone rich basal FPa1 unit and the sandier FPa2 beds. The overlying boundary with the FPb unit is taken as the appearance of coarser conglomeratic beds containing fewer fine-grained beds.

2.1.1.2 Fair Point b (FPb)

The FPb member commonly, but not always, overlies the FPa unit, and consists of pebbly sandstones with pebbles larger than 50 mm in diameter, thin conglomerates (typically smaller than 50 cm thick), and minor fine grained sandstones and mudstones. It consists of a lower unit (FPb1) that generally contains the coarsest material in the FP section and has a much higher percentage of coarse material than the overlying beds. Commonly it includes conglomerates up to 2 m thick, but it is known to date only from about 10 % of the area in which the Fair Point Formation is found. The FPb1 is overlain by an upper unit (FPb2) that has a lower percentage of the coarser material and few thin conglomerates, if any.

The isopach of the FPb member (Figure 9) shows that the member is present through most of the range of the FP. A thickness greater than 175m in ddh UOb1 in Saskatchewan coupled with a thickness of 219 m in FC-005 suggests that the Black Bay trough was a separate depocentre.

The thick conglomerates of the FPb1 beds are restricted to the southern margin of the Jackfish Basin and are also present in the centre of the FP depocentre (Figure 10). Note that most holes in the centre of the Jackfish Basin do not reach the depth of the FPb1 unit, so that its distribution may be wider in the basin centre. The basin-marginal position of the FPb1 unit indicates a southern source for FP formation at least along its southern margin and also that the FP did not extend much beyond its present limit along the southern margin of the Jackfish Basin.

2.1.1.3 Fair Point c (FPc)

The FPc is a finer grained unit, with pebbles less than 50 mm in diameter and a low percentage of coarse material (Figure 11). Fining upward units, typically 3 m to 6 m thick, are obvious in the FPc unit, but are rare to absent lower down, and usually show sharp lower as well as upper boundaries.

The FPc is almost as widely distributed as the FPb member of the Fair Point Formation (Figure 10).

Its presence along the southwestern margin of the Athabasca Basin where the underlying coarser FPb1 is absent suggests that the western margin of the basin is more distal than the southern, and that paleocurrents in this direction trend westerly. A depocentre is present in the Black Bay Trough and another one may be present north of the Grease-Straight Fault.

2.2 Sequence 2: Manitou Falls Formation, Reilly Lake Beds

Sequence 2 consists of the Manitou Falls Formation (Ramaekers, 1979, 1980, 1981; Wilson, 1985) and is an overall fining-upward unit with minor finer grained beds intermittently present at its base (Figure 5). Four drainage systems are evident (Figure 2) from the paleocurrent patterns measured in outcrop: the Moosonees along the northern side of the Athabasca Basin, the Ahenakew along the eastern side and the central part of the basin, the Karras in the south-central region, and the Robert in the southwestern part of the basin in the Beatty Trough. The lateral relations between the depositional systems are not certain at this point. The Robert drainage appears to underlie the Karras drainage. The Karras and Ahenakew drainages may be coeval, and the paleocurrent and maximum grain size patterns suggest that the Ahenakew drainage may underlie the Moosonees drainage at least in part. The Reilly Lake beds (Figure 2) consist of pebbly sandstones similar to those of the Manitou Falls a and b units. They are confined to a single outcrop along the eastern margin of the Wathaman Batholith and show paleocurrent directions to the southwest, opposite those of the nearest Manitou Falls sandstones, suggesting that they may have been deposited in a separate basin.

2.2.1 Manitou Falls Formation (MF)

The Manitou Falls Formation is present throughout the Alberta side of the Athabasca Basin, except along the western edge. It directly overlies the metamorphosed basement or the Fair Point Formation in the northwest of the study area with a usually well defined unconformity. The upper boundary with the Lazenby Lake Formation is less obvious. It is taken as the base of the prominent regionally extensive thin conglomerate or bed of conglomeratic sandstone of the Lazenby Lake Formation, but perhaps a coarsening-up pebbly sandstone that is present in places below this conglomerate should also be included with the overlying sequence. Paleocurrent patterns in the overlying sequence trend much more northerly that those of Sequence 2 (Figures 5 and 6), and indicated a change in basin tilt before the start of Sequence 3.

The Manitou Falls Formation consists of planar and trough crossbedded sandstones, sandstones with pebble beds, minor horizontally bedded sandstones and, occasionally, thin, well laminated fine sand to mudstone beds. Clay pebble beds are present, but form less than one per cent of the unit.

In the eastern part of the Athabasca Basin, the Manitou Falls formation has been subdivided into four informal members based on predominant lithofacies, commonly referred to, from base to top, as MFa, MFb, MFc and MFd. Within Alberta, a sporadically present basal unit with mudstones, often hematite rich and at times grading up into a pebbly, horizontally bedded sandstone similar to the FPc, is here referred to the MFa unit. This is overlain in the northern half of the Alberta portion of the Athabasca Basin with a unit containing bedded conglomerates more than two cm thick (MFb). Overlying this, but also serving as the basal MF unit in much of the southern part of the Alberta study area, is the MFc unit, which lacks the conglomerates of the underlying MFb and the > 1 % clay intraclasts that characterise the overlying MFd unit. The clay intraclast rich unit (MFd) that forms much of the Manitou Falls Formation in the eastern parts of the Athabasca Basin, is lacking in Alberta.

2.2.1.1 Manitou Falls a (MFa)

A sometimes pebbly, thin (< 25 m) siltstone and very fine grained strongly red hematitic sandstone unit is present between the Fair Point Formation and overlying units in DDH FC-005, FC-032, FC-035, FC-039, FC-046, FC-048, FC-071 and MR-06, and is referred to as MFa1 (Figure 12). Its presence, along with the occurrence of similar facies at the base of the Athabasca Group below the main body of the Manitou Falls and Fair Point Formations suggests that it may mark topographic lows, which perhaps were the result of erosion during a depositional hiatus.

In drillholes FC-046, MR-04, and MR-18 the MFa1 grades up into horizontally bedded sandstones with disseminated pebbles, the MFa2 unit, that are similar to the FPc unit and up to 37 m thick. Where the MFa2 beds directly overlie the basement (FC-046 , MR-10, MR-20 , MR-14) the possibility exists that these actually represents the FPc unit, particularly since most of these holes lie along the southern edge of the Fair Point Formation (Figure 13). As mapped, these MFa2 sections lack the bladed brown porous basement pebbles thought to be characteristic of the Fair Point Formation, but this might be sampling error due to the limited thickness of the unit and the small volume of core available. These units (MFa1 and MFa2) certainly represent similar depositional environments dominated by hyperconcentrated flow and sheetwash deposits.

In a general, overall way MFa is a coarsening up unit.

2.2.1.2 Manitou Falls b (MFb)

The MFb unit is restricted to the northern half of the study area (Figure 14), and shows some granule and small pebble layers more than 2 cm thick as well as a few intraclasts. The lower, specularite rich unit contains a few pebbly beds and is coarser. The amount and size of pebbles in the MFb in the study area are much less than that seen along the eastern side of the Athabasca Basin in Saskatchewan and show that this is a distal part of the drainage system. The sandstone coarsens towards the base, and throughout the MF and LzL formations are clay poor, except very near the base of the MF, especially where it overlies and reworked the clay rich Fair Point Formation. In the northern half of the Alberta Athabasca Basin much of the Manitou Falls below the Lazenby Lake Formation is relatively coarse, and in hole FC-005, the entire MF section is formed by the MFb.

The isopach map shows that the MFb unit is not present in the Beatty Trough, suggesting that this area may have been a topographic high at this time. The depocentre of the MFb in Alberta is in the Lillabo Trough area, and of note is that the Black Bay Trough is no longer a distinct depocentre. The small area of increased thickness at the southeastern limit of its extent overlies the area of coarse deposits during Fair Point deposition (FPb1), and may indicate that there is input into the basin from the southwest at this time.

2.2.1.3 Manitou Falls c (MFc)

The MFc unit is present through all but the western rim of the Alberta Athabasca Basin (Figure 15) and is up to 200 m thick. The MFc unit is generally a planar and trough cross-bedded sandstone or pebbly sandstone lacking conglomerates and with less than 1 % clay intraclasts. In the Ahenakew and Karras drainage systems the MFc typically has abundant pebble layers one layer thick, usually along bedding planes. Thin (< 10 cm thick) fine to very fine horizontally bedded sandstones and mudstones occur irregularly and sparsely through the unit.

In the Alberta part of the Athabasca Basin some holes show medium to fine-grained well-sorted sandstones of the MFc are present below the conglomeratic base of the Lazenby Lake Formation or below more typical MFc beds. They contain common horizontal bedding or low-angle cross-bedding. In the south (hole FC-048) such units are present at the base of the Athabasca Group, where they lack even a significant pebble lag above the unconformity with the basement. This very uniform lithofacies falls within the existing definition of the informal MFc member and is distinguished as the MFc''. It is found only in the Robert drainage system along the southern margin of the basin in the Beatty Trough. Its stratigraphic relations are unclear from the Alberta intersections mapped to date, but it may underlie the main body of the Manitou Falls c and possibly represent a distal, pebble-poor lithofacies of MFa. In the north (hole FC-009), the MFc unit includes more common thin horizontal mudstones, typical of the MFc', characteristic of the Moosonees depositional system seen in Saskatchewan in the northeastern part of the Athabasca Basin.

A few paleocurrent directions were measured with a core goniometer in the two angled holes studied: MR-68 and FC-48. Paleocurrent directions in the upper part of the MFc unit in DDH MR-68 were generally westerly. This agrees with the general pattern of paleocurrent directions in the MF. However, directions in the FC-48 hole trended easterly, a pattern also seen on the Saskatchewan side in beds similar to the MFc". This may be due to local topography close to the basement or to high paleocurrent directional variability in the fine grained MFc unit deposited in an area with low paleoslope. However, it may reflect the presence of a topographic high to the northwest along the Bartlett High and the Jackfish Basin beyond at the time of onset of Manitou Falls sedimentation.

The isopach map (Figure 15) shows two depocentres. A southern one confined largely to the Beatty Trough in Alberta and a northern one centred on the Lillabo Trough. The Bartlett High appears to have been an area with little sedimentation in MFc times. The apparent lack of MFc in ddh FC-005 is due to a coarsening of the unit in this area so that it is mapped as MFb in this area.

2.2.1.4 Manitou Falls d (MFd)

The MFd member has not been recognized in Alberta, but is present near the Saskatchewan border along both northern and southern margins of the Athabasca Basin (Figure 16). It is characterised by the presence of more than 1% clay intraclasts. These are generally soft, and the larger ones angular. Their presence suggests frequent ponding as water levels dropped after floods, and relatively low-energy flood waters, with current energy strong enough to erode the clay drapes and deposition rapid enough to bury the intraclasts before they disintegrated. Rather little data (three drillholes) suggest that the MFd was absent or thin over the Bartlett High.

2.3 Sequence 3: Lazenby Lake and Wolverine Point Formations

Sequence 3 (Figure 6) comprises the Lazenby Lake (LzL) and Wolverine Point (WP) formations (Ramaekers, 1979, 1980, 1990, 2002; Wilson, 1985), which is an overall fining-up sequence. In places minor coarsening up beds may be present at its base. The boundary between the Lazenby Lake and Wolverine Point formations is taken arbitrarily at the level where thin (< 20 cm thick) horizontally bedded mudstones to fine sandstones begin occurring with some regularity for the first time. The upper boundary of the sequence is an unconformity marked by the reappearance of granules and pebbles, and a marked decrease in interstitial clay content, except for some reworking of clays near the unconformity. The upper well sorted sandstones (WPc), siltstone and mudstone rich units (WPb) thin progressively to the south and indicate progressive erosion, or non-deposition to the south. Grain size distribution and paleocurrent directions indicate provenance from the southwest to southeast.

2.3.1 Lazenby Lake Formation (LzL)

The Lazenby Lake Formation is a sandy and pebbly unit overlying the non-pebbly sandstones of the MFc and grading into or overlain without significant discontinuity by the Wolverine Point Formation (WP), a unit that includes frequent horizontally laminated mudstones to very fine sandstones. A prominent, but generally thin (5-30 cm) pebble bed or pebbly sand bed forms a regionally mappable base that in most places abruptly overlies pebble free sandstones of the MFc unit. In a few places infrequent pebbles suggest that there may be some coarsening up beds below the marker pebble bed. This would place the boundary between sequence 2 and 3 within sandstone beds and make it very difficult to recognize in these places. The basal pebbly unit of the LzL is generally quite thin (5-20 m) and grades up into pebbly finer grained sandstones. The basal pebble bed usually has a maximum grain size of about 16-20 mm along the southern limits of the LzL and fines northwards until it becomes indistinguishable from MFc and WPa in the central part of the Athabasca Basin. This definition follows the original one of Ramaekers (1980). The redefinition of the LzL by Hoeve, Quirt and Alonso et al. (1985) is explicitly based on unmappable, diagenetic criteria, and thus does not conform to current stratigraphic criteria for the definition of formations. It mixes diagenetic facies with primary lithostratigraphy and is not followed here.

The presence of two coarse pebbly units in FC-049, FC-050, FC-051 and FC-052 without significant intervening fine sandstones and mudstones, indicates the absence of all or most of the intervening Wolverine Point Formation, with the pebbly Locker Lake Formation directly overlying the Lazenby Lake Formation.

The isopach map of the Lazenby Lake Formation (Figure 17) indicates that the depocentre of the LzL is in the Beatty Trough and that the formation thins to the north. A prominent offset of the contour lines along the northern margin of the Beatty Trough helps delimit this basin and is on strike with the Robillard Fault (Figures 2 and 3) and suggests that this fault was active during deposition of the LzL.

2.3.2 Wolverine Point Formation (WP)

The Wolverine Point Formation is present in the north-central part of the study area: an area characterised by lack of outcrop. This reflects the friable clay-rich nature of the formation, and the resultant greater excavation by the Pleistocene glaciers. Much of Lake Athabasca is underlain by the Wolverine Point Formation.

The Lazenby Lake Formation grades upward into the Wolverine Point Formation, which is characterised by the more common presence of mudstones and claystones. The base of the Wolverine Point is taken at the point where 5 to 20 cm thick mudstones first appear repeatedly within a 10 m interval and occur regularly, forming greater than 2 % of the section. Three informal members are recognized: WPa, WPb and WPc. WPa consists of a basal section with fairly regular, < 30 cm thick mudstones, and a sandier upper unit. It was deposited in a sheetwash and braided stream environment, perhaps with intermittent small shallow lakes. WPb is characterised by the presence of thicker (> 30 cm, up to 2 m) and mudstones forming greater than 10% of the section, plus layers of dark, hard and rounded small intraclasts (in contrast to the larger, angular, soft intraclasts of MFd). The WPc member consists of fine- to medium-grained, well-sorted sandstones with a few mudstone beds up to 50 cm thick. Except for a few granule and pebble layers in WPa the WP Formation lacks material coarser than sand.

The Wolverine Point Formation was deposited in a sheetwash, braided stream and playa lake environment. Hummocky cross-stratification (HCS) was not recognized; if this unit was subject to wave action (marine or lacustrine), HCS should have been well developed given the lithology of the unit, but it would still be difficult to recognize in core. The WP is the only formation of the Athabasca Group in

Alberta that has a significant non-fluvial component. The presence of very well sorted fine- to medium-grained sandstones suggests that the sand may have been cycled through an intermediate eolian stage, but was deposited below the waterline in a fluvial or lacustrine environment.

Beds of thin, hard, often rounded, fine-grained intraclasts are common in the WPb unit. In places these units are apatite-cemented, and in some of these beds apatite pseudomorphs of volcanic glass shards are present.

2.3.2.1 Wolverine Point a (WPa)

Below the WPa level there are no or very few of the thicker (10-30cm, typically 5-15 cm) silt units seen from there to the top of the WP Formation (and into the Locker Lake Formation). A few very thin pebble beds occur high into the WPa. Devising a consistently mappable boundary, arbitrary or otherwise, between the Wolverine Point Formation and the underlying Lazenby Lake Formation is difficult. Any discontinuity between such lithologically similar units would be difficult to detect in core or outcrop. The time and level in the section at which the short-lived ponds that deposited these thin siltstones and mudstones first occurred probably was not the same everywhere and the contact between the LzL and WPa may be gradational and diachronous. The coarse material high in the WPa suggests that to the south (where the amount of silt in the Wolverine Point Formation decreases) the unit may be laterally equivalent to all or part to the Lazenby Lake Formation. There often is a clay-poor interval between basal unit with thin mudstone layers (<20 cm) and the thick (>50 cm) mudstone beds of the WPb. This upper sandy unit of the WPa is referred to as the WPa2, and the lower unit with the more frequent thin mudstone layers the WPa1 unit. Because of the greater lithological heterogeneity of the WPa more detailed mapping will provide a better understanding of the internal complexity of the unit, something that is obscured by the lithological uniformity in the sandier components of the Athabasca Group.

The isopach map of the WPa (Figure 18) shows that the unit is present only to the NE of the Bustard Fault and has a depocenter in the Lillabo Trough. This suggests that the Bustard and Harrison faults may have been active at the time of deposition of the WPa and/or later. A trough in the area of FC-52 and MR-65 suggests that splays of the South Robillard Fault reached to this area and affected the deposition and/or preservation of sediments in this area.

2.3.2.2 Wolverine Point b (WPb)

The basal mudstone of the WPb overlies the WPa with an abrupt contact and without a discontinuity obvious in core. Lack of pebbles in the underlying beds make it difficult to establish the presence of a ravinement surface such as is seen to the northeast in Saskatchewan. The WPb consists of mudstones, siltstones and very well sorted, very fine- to fine-grained sandstones and contains mudstone beds greater than 50 cm thick. The WPb may be subdivided into three sub-units by the presence of a sandy unit (WPb2) that is similar in lithology to the WPc between a relatively thin basal siltstone unit (WPb1) of a few m thick and a thick upper siltstone rich unit (WPb3). Sedimentary structures in the sandstones are often indistinct, but do not seem to be much different from those lower down or higher up in the section. This lack of distinctness may indicate the presence of paleoweathering horizons.

At a few levels tuffaceous material may be recognized in thin section, invariably preserved and pseudomorphed by apatite cement. The apatite-cemented parts do not show the fresh feldspars seen in some of the Saskatchewan samples. This suggests that the origin of the apatite may not be syndepositional everywhere. The most prominent of these apatite rich units is close at the base of the WPb in the WPb1 unit. A similar pattern seems to be present at the eastern limit of the WP outcrops in Saskatchewan where some of the more spectacular tuffaceous apatite-cemented specimens have also come from very low in the section.

The isopach map of the WPb (Figure 19) shows that the unit is largely restricted to the area northeast of the Harrison Fault. Movement along this fault may have been a factor in limiting its distribution. The map also suggests that the Bartlett high developed after deposition of the WP. The absence of the WPb and c unit in the southern Beatty Trough area suggests that it was not deposited or eroded along its southern margin before deposition of the Locker Lake Formation of Sequence 4.

2.3.2.3 Wolverine Point c (WPc)

The basal contact of the WPc is gradational. The unit consists of very well sorted fine- to medium-grained sandstones with some thin silty units similar to those found in the WPa. Abundant matrix clay is present, largely in the form of clay pseudomorphs after sand-size clastic grains. Core is friable and has a coarse-grained appearance because of its rough pitted surface caused by washing out of the clay during drilling. The sandstone is typically mottled and overturned cross-bedding is common.

The WPc unit is best developed in ddh FC-005 and FC-007. It is less distinct in the neighbouring areas of Saskatchewan. The isopach map (Figure 20) again suggests erosion or non-deposition in the Beatty Trough area. The inlier of WPb along the northern rim of the Carswell structure is due to erosion after formation of the impact structure, and indicates a zone of uplift outside and next to the slumped areas of the crater margin.

2.4 Sequence 4: Locker Lake, Otherside, Douglas and Carswell Formations

Sequence 4 (Figure 7) forms a fining-up series. It ranges from the pebbly Locker Lake (LL) Formation (Ramaekers, 1979, 1980, 1990), the sandy Otherside Formation (Ramaekers, 1979, 1980, 1990), the mudstone-rich Douglas Formation (Amok (Canada) Limited, 1974; Ramaekers, 1990), to the dolomites of the Carswell Formation (Blake, 1956; Fahrig, 1961; Hendry and Wheatley, 1985; Ramaekers, 1990).

The sequence records changes in depositional environment from sheetwash dominated (Locker Lake), braided stream (Otherside Formation) to paralic (Douglas Formation) to lacustrine or marine (Carswell Formation). Good tidal indicators are lacking in the Carswell Formation, the best being the north-south elongation of stromatolite domes (Hendry and Wheatley, 1985).

2.4.1 Locker Lake Formation (LL)

The basal contact of the Locker Lake Formation is unconformable, and varies from abrupt to gradational, with some drillcores showing some reworking of underlying WPc material. Nevertheless, there is a marked change in the lithological character of the units, with renewed introduction of coarse material into the basin. The underlying Wolverine Point Formation is eroded or not deposited progressively more to the south, suggesting a considerable hiatus. This suggests a change in erosional rates in the source areas (climate or rate of uplift). Heavy mineral bands are less common in the Locker Lake Formation and detrital zircons are typically very small. This and the paucity of pebbles, often scattered along bedding planes in outcrop, suggests a more distal source area.

The Locker Lake Formation is divided into three informal members LLa to LLc, based on maximum grain size of the contained pebbles, with pebble size in the coarsest LLb unit greater than 16 mm. LLa coarsens up, and the maximum grain size and conglomerate content of the sequence is reached in LLb. Mudstones less than 50 cm thick are present, but are increasingly less common upwards in the Locker Lake Formation.

The LL reaches it greatest thickness of about 290 m in the Lillabo Trough (Figure 21). In ddh CAR-114, just east of the Carswell structure, an equally thick section of 289 m is found, suggesting that the depositional basin was continuous across the Bartlett High and had its greatest subsidence restricted to or preserved in an area northeast of the Harrison Fault.

The thickest section of the Locker Lake Formation available in Alberta is found in ddh FC-007. It shows a 60-metre basal, finer-grained section (LLa), much like what is present in ddh FC-005, where only about 40 m of the Locker Lake Formation is preserved. This is overlain by a coarser unit 50 m thick (LLb) that shows the large disseminated pebbles typical of the unit. Overlying that is about 90 m of finer material (LLc). Pebbles over 8 mm are still present at the top, making this entire section the Locker Lake Formation, using the criteria of Ramaekers (1990).

2.4.1.1 Locker Lake a (LLa)

The lower contact of the Locker Lake Formation with the Wolverine Point Formation occurs abruptly at a prominent lithological discontinuity in DDH FC-005, but is much more gradual in DDH FC-007 showing reworking of the uppermost WPc strata. Nevertheless, there is a prominent change in mean grain size, clay content and sorting. The unit coarsens upwards in an irregular fashion, and its upper contact is arbitrarily taken where pebble size reaches 16 mm. The LLa unit is also present in the northeastern part of the Athabasca Basin in Saskatchewan where there is an exposed section of the WP-LL contact area near Riou Lake, thus proving its regional extent.

The isopach of the LLa unit (Figure 22) shows the same distribution pattern as that of the formation as a whole.

2.4.1.2 Locker Lake b (LLb)

The LLb unit is defined as the middle unit of the LL containing pebbles larger than 16 mm, and has a gradational lower and upper boundary. The isopach map (Figure 23) shows that the distribution pattern of LLb differs from the underlying and overlying LLa and LLb units. Coarse material, and hence the LLb unit, is lacking along the northern margin in Saskatchewan, thinner to the east, and thickest north and south of the Carswell Structure. Erosion due to unroofing of the basin has resulted in an inlier of LLa around ddh CSP 2-1 in Saskatchewan and thinned the unit over the Bartlett High and along the southern margin outcrop belt.

2.4.1.3 Locker Lake c (LLc)

The fining-up LLc unit (Figure 24) has a similar depositional pattern as the LLa member: similar thicknesses are reached in the Lillabo Trough and CAR 114. It is half that thickness in the southern end of the Beatty Trough, and it thins towards the east in the central part of the Athabasca Basin in Saskatchewan.

2.4.2 Otherside Formation (OF)

The contact between the Locker Lake and Otherside formations is arbitrary and gradational, and marked by the return to a maximum size of less than 8 mm for the contained pebbles. The formation fines upwards relatively uniformly. It is divided informally into a lower member (OFa) with a maximum grain size between 8 and 2 mm, and an upper member (OFb) with the maximum grain size less than 2 mm. The OFb member is the uppermost unit of the Athabasca Group through much of the central Athabasca Basin. The isopach map of the OF (Figure 25) suggests the Bartlett High formed after deposition of the

Otherside Formation, but note that no incontrovertible data on thickness are available from the Lillabo Trough area due to problems with poorly preserved cores.

2.4.3 Douglas and Carswell Formations (Saskatchewan)

The Douglas and Carswell formations are preserved only in complexly deformed slump sheets in the Carswell meteor impact structure in Saskatchewan (Figures 2 and 27). The contacts between the Otherside, Douglas and Carswell formations are probably gradational, but as they are preserved only within the impact crater, this cannot be proven due to the disruption caused by the impact and subsequent slumping.

The Douglas Formation consists of medium and fine-grained sandstones with common mudstones. These are largely black and organic rich (Landais and Dereppe, 1985; Wilson et al., 2002), but altered sections show reduction to green and pale red colours, and colour patterns similar to those seen in the WPb mudstones. The Carswell Formation includes stromatolitic and oolitic dolostones and mudstones; siliciclastic input is virtually absent.

3 Proterozoic Post-Carswell Formation Units

The maximum depth of burial of the Athabasca Group has been estimated as 4 to 5 km above its base. This was on the basis of fluid inclusion studies (Pagel, 1975a, b), organic matter maturation studies (Landais and Dereppe, 1985), and illite crystallinity studies (Hoeve et al., 1981). A depth of burial of 4 to 5 km implies that about 2700 m of cover has been removed by erosion, as the preserved section is only about 2300 m thick. The main periods of primary uranium ore formation in the Athabasca Basin document extensive and prolonged hydrothermal activity (Figure 39; Cumming and Krstic, 1992) that may have been facilitated by basin deformation accompanying deposition of the later and now eroded units. The three main periods of ore formation and/or redeposition inferred by these authors are 1380-1330 Ma, 1288-1246 Ma and 1110-959 Ma, of which the period from 1380-1330 Ma is by far the most important. This follows initial deposition of uranium at the McArthur deposit at about 1514 Ma. The three main periods identified by these authors match times of deposition of the Dismal Lakes Group in the Amundsen Basin (Figure 39; Ross, 2000), that of the intrusion of the Mackenzie dikes and Coppermine Basalts (1267 Ma; LeCheminant and Heaman, 1989), and deposition of the Rae Group of the Shaler Supergroup in the Amundsen Basin, respectively (Figures 37 and 38). Fayek et al. (2002) using uranium ore samples from the McArthur and Sue deposits in Saskatchewan reach very similar conclusions: periods of ore deposition and/or remobilization at about 1500 Ma, 1350 Ma, 1250 Ma, 1100-950 Ma, 800 Ma, and late remobilization at about 260 Ma (Fayek et al., 2002, Figure 9).

Diabase dikes are not uncommon within the Athabasca Basin (Ramaekers, 1980) with dike complexes consisting of sills and dikes with shallow dip angles with various strikes, found along the southern (Cree Lake) and eastern margins (Moore Lakes). Both Mackenzie event ages (about 1267 Ma) and younger ones (1.0-1.3 Ga; Armstrong and Ramaekers, 1985; Hulbert et al., 1993) have been found. The Athabasca Basin Mackenzie dikes may have had an independent history relative to the rest of the Mackenzie swarm (Baragar et al., 1996). Both the presence of the dike complexes and the similarity in chemistry with the proximal dikes of the Coppermine area suggest that the Athabasca Mackenzie dikes may be part of a separate eruptive center. The proximal nature of the Athabasca Basin dikes may be seen by comparing the 400 km (Coppermine) and 1500 km (Athabasca Basin) samples of Figure 16 of Baragar et al., (1996). Thus, part of the missing overlying section in the Athabasca Basin may have been volcanics.

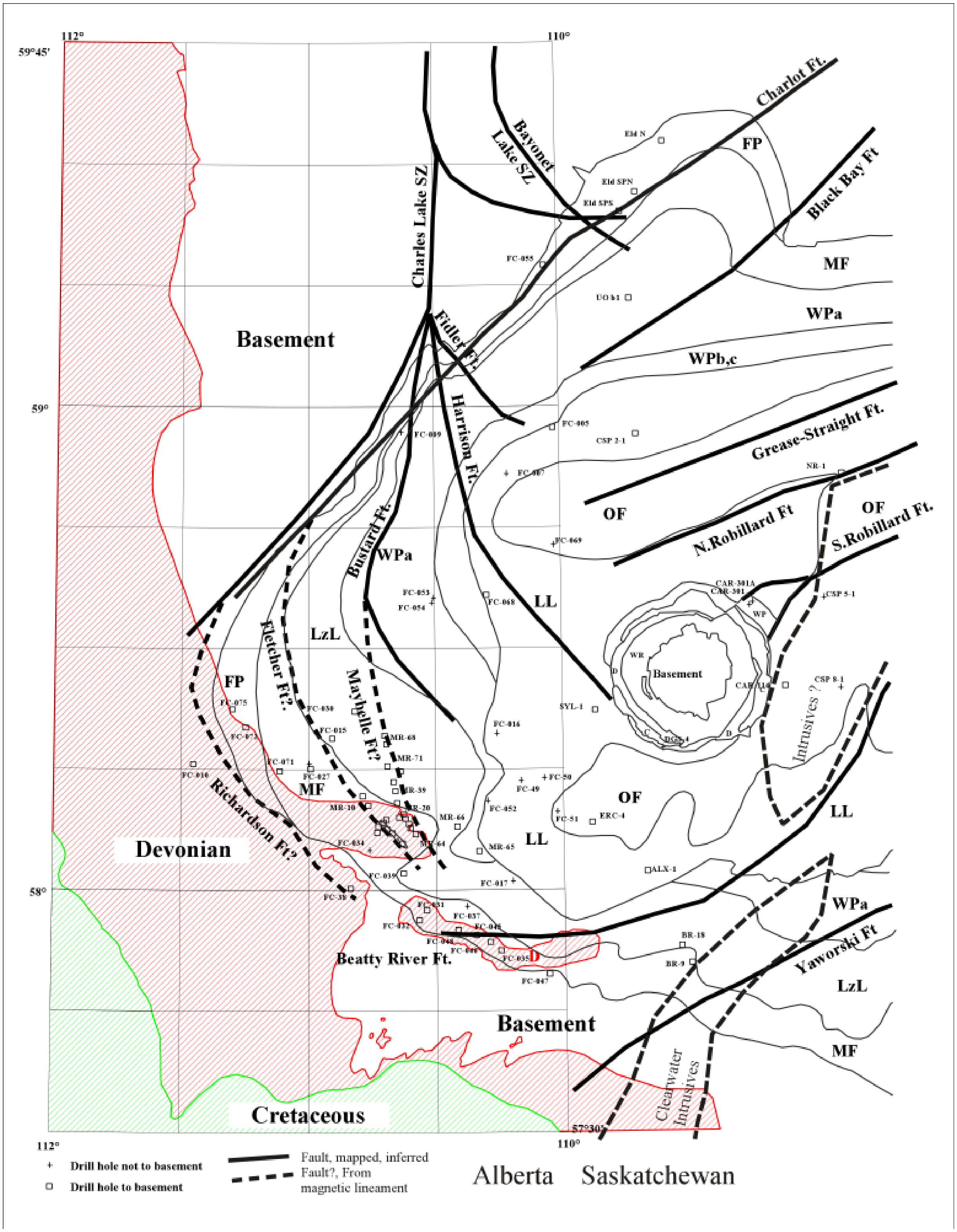
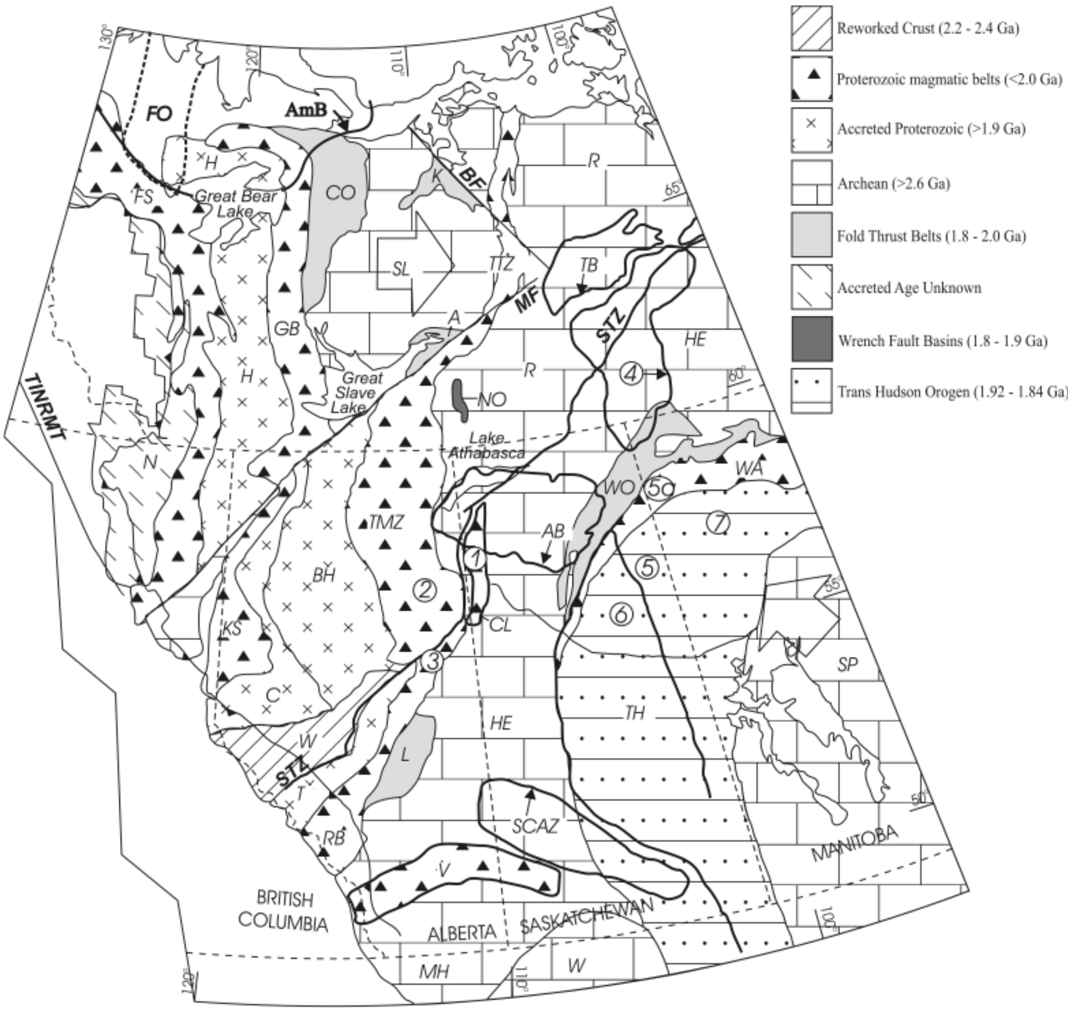


Figure 37. Ages of intrusive, volcanic, sedimentary and tectonic events affecting the Athabasca region. Modified after Cumming and Krstic (1992), Hoffman (1988), Kyser et al. (2000), Machado (1990), McGlynn and Irving (1981), Ross (2000), Santos et al. (2002), and Tran et al., (2002). Heavy lines connect orogens to possible related episodes of subsidence due to dynamic loading (Pysklywec and Mitrovica, 2000).



Possible sediment source areas for Athabasca Basin

1 Clearwater Magmatic Zone
2 Taltson Magmatic Zone
3 Rimbey Magmatic Zone
4 Area with Nueltin Intrusives
5a Wathaman Batholith
5 Trans Hudson Orogen
6 Post Collisional Folds and Uplifts
7 THO Reindeer-Superior Collision Phase 2

Faults & Shear Zones

MF	Macdonald Fault
BF	Bathurst Fault
STZ	Snowbird Tectonic Zone
TINRMT	Tintina/Rocky Mountain Trench

LEGEND

Cratons, Provinces, Domains, Zones, Basins

TH	Trans Hudson Orogen	(1.92 - 1.84 Ga)
FO	Forward Orogen	(about 1.66 Ga)
FS	Fort Simpson	(1.85 - 1.84 Ga)
GB	Great Bear	(1.85 - 1.84 Ga)
RB	Rimbey	(1.85 - 1.78 Ga)
WA	Wathaman	(1.86 Ga)
A	Athapuscow	
CO	Coronation	(1.97 - 1.89 Ga)
K	Kilohigok	
NO	Nonacho Basin	
L	Lacombe	(<2.3 Ga)
WO	Wollaston	
KS	Ksituan	(1.98 - 1.90 Ga)
TMZ	Taltson	(2.00 - 1.92 Ga)
TTZ	Thelon	(2.00 - 1.92 Ga)
H	Hottah	(1.94 - 1.90 Ga)
N	Nahanni	(unknown)
BH	Buffalo Head	(2.32 - 1.99 Ga)
C	Chinchaga	(2.10 - 2.00 Ga)
T	Thorsby	(2.3 - 1.91 Ga)
W	Wabamun	(2.32 Ga)
V	Vulcan Zone	(1.80-1.68 Ga)
CL	Clearwater Intrusives	(1.84 Ga)
HE	Hearne Province	
R	Rae Province	
MH	Medicine Hat Province	
SL	Slave Craton	
SP	Superior Craton	
W	Wyoming Craton	
AmB	Amundsen Basin	
TB	Thelon Basin	
AB	Athabasca Basin	
SCAZ	Swift Current Anorogenic Zone	

Figure 38. Regional setting of the Athabasca Group. Domain boundaries after Hoffman (1990) and Villeneuve et al. (1993).

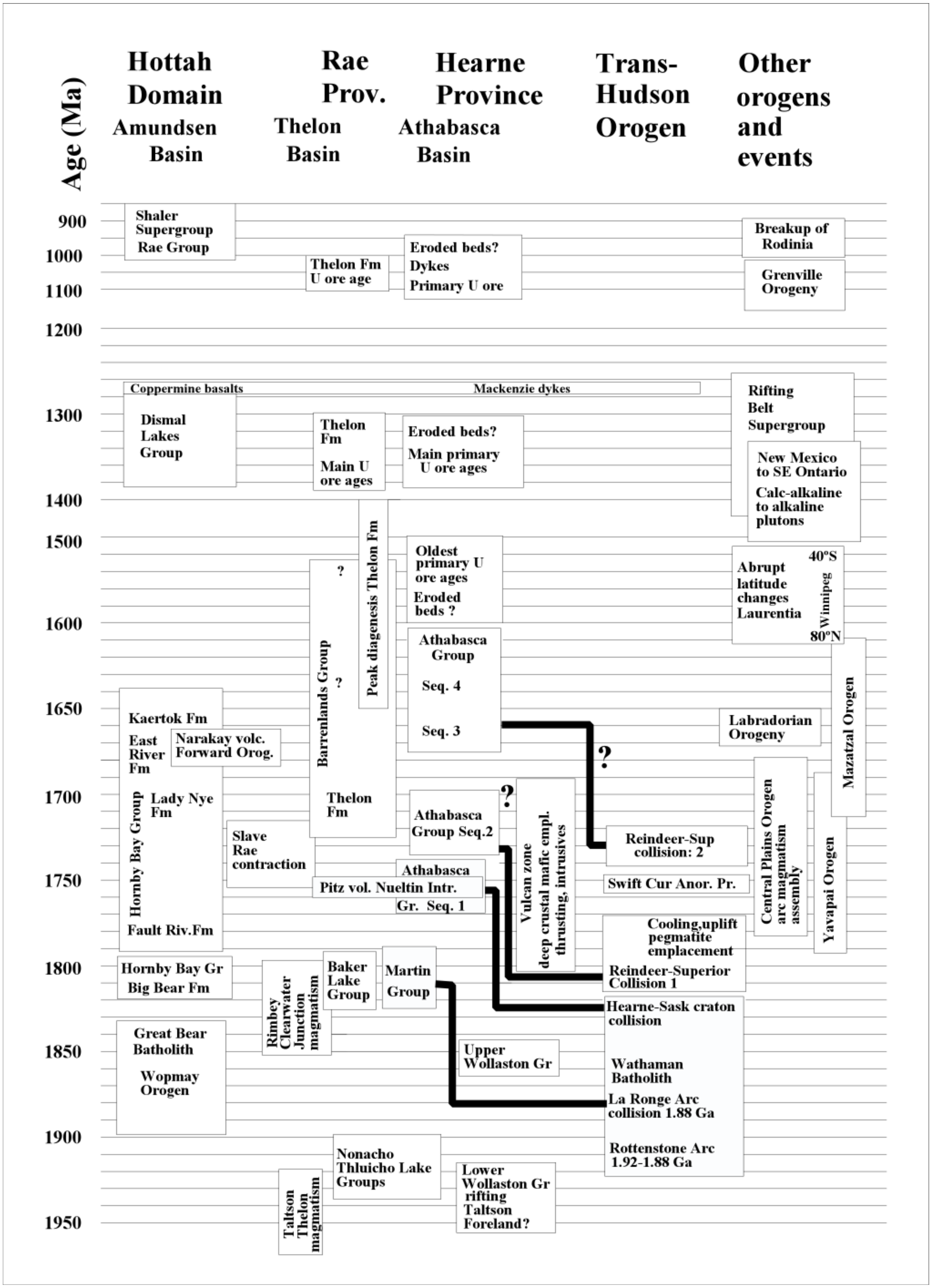


Figure 39. Paleozoic and Cretaceous cover in the Athabasca Basin area of Alberta. Abbreviations of stratigraphic names as on Table 2.

4 Stratigraphy of the Phanerozoic Cover Overlying the Athabasca Group

Paleozoic and Cretaceous strata subcrop to the south and west of the Athabasca Basin in Alberta (Figure 37 and cross-sections) and overlap it along its southwestern edge. Along the southern margin of the basin in Alberta a basal coarser clastic unit is developed (DOc) with granules and pebbles often set in fine sands or muds. In some areas these clastics are intensely silicified, suggesting development of silcrete weathering profiles in an arid environment. The age of the basal units is not known and may be Devonian or somewhat older, possibly Ordovician. Overlying these beds and often forming the thickest component of the Paleozoic section are fine-grained clastics (Df), mostly mudstones, often slightly dolomitic, typically grey, grey-green to dark grey, and occasionally reddish. At the top of the section thin carbonates (Dc) are present, ranging from grey and grey-green calcilutites to white recrystallized material.

No paleontological data are available from these units at present, but their lithology and stratigraphic position suggest that they may be referred to the Laloche Sandstone, and Methy Dolomite of the Elk Point Group, Middle Devonian.

5 Heavy Oil of the Phanerozoic Strata and Athabasca Group

The Paleozoic coarse and, to a lesser extent, the fine grained clastics and carbonates are not uncommonly stained or indurated with heavy oil, similar but heavier than the typical oil from the McMurray Formation (Wilson, 1985). Similar oil is found commonly within the sandstones of the Athabasca Group and its underlying basement in the area south and west of the Carswell structure. The degree of oil saturation varies from infrequent spotting to complete saturation of up to 29% of the entire thickness of the Athabasca Group in ddh FC-39. Wilson et al. (2002) report the presence of Paleozoic oil in trace amounts over much of the Athabasca Basin suggesting that Devonian or Cretaceous clastics overlay enough of the Athabasca Basin to permit the Paleozoic oil to migrate into it on a large scale, probably during the Cretaceous.

Phanerozoic poorly consolidated sediments in Saskatchewan overlying the Athabasca Group near the Alberta border have been described as Cretaceous in industry reports, presumably because of their clastic nature and partial impregnation with heavy oil. They probably are part of the clastic Devonian La Loche Formation.

6 Regional Setting and Development of the Athabasca Basin

The history of the Athabasca region in the Proterozoic is largely the record of the interaction between Archean plates. Three cratonic plates, the Slave, Superior and Wyoming were more or less stable throughout this period, while the Rae and Hearne provinces were subject to internal deformation as the cratons approached and collided during the early Proterozoic. The Athabasca Basin developed over the boundary between the Rae and Hearne provinces that lie between the stable Archean Slave, Superior and Wyoming cratons (Hoffman 1990; Figure 38). Thrust-fold belts developed at the margins of the stable cratons between 2.0-1.68 Ga. The main orogenic belts were the Thelon and Wopmay along the Slave Craton, the Trans-Hudson with the Wollaston Fold belt between the Hearne Province and the Saskatchewan and Superior Cratons (Figures 37 and 38), and the Central Plains, Yavapai and Mazatzal orogens along the southern margin of Laurentia. The Saskatchewan Craton is a small craton contained within the Trans-Hudson Orogen as shown on Figure 38. Magmatic belts associated with them include the Taltson and Wathaman belts. Subsequent compression of the region resulted in further orogenic belts (Forward Orogen) and further magmatic belts (Rimbey, Vulcan, Clearwater; Villeneuve et al., 1993).

The Clearwater magmatic belt and the Wollaston folded and thrusted continental margin belt are partially overlain by the Athabasca Basin. The time relationships of these tectonic and sedimentary events are shown in Figure 37.

The sedimentary record of the Athabasca region from 2.0 to 1.86 Ga is largely the record of the approach of the Slave and Superior cratons, their collision with the intervening Rae and Hearne provinces and the small Saskatchewan Craton between 1.86 and 1.8 Ga, ongoing or intermittent compression between the western margin of Laurentia, the Superior province and the southern continental margin until 1.6 Ga, (Forward, Central Plains, Mazatzal, Yavapai Orogens) and from then to the Grenville Orogeny largely tensile events whose effects is best seen today at the margins of the continent.

The earliest low-grade post-collisional sedimentary rocks of the Athabasca region are of greenschist grade and weakly to moderately deformed. They comprise the Thluicho Lake Group (Figure 2), which crops out north of Lake Athabasca (Scott, 1978) and the Nonacho Group farther north in the Nonacho Basin (Figure 38; Aspler and Donaldson, 1985). These basins formed in an episode of indentation tectonics manifested here as sinistral wrench faulting as part of the Rae province south of the Slave Craton moved towards the south as a result of the Slave-Rae collision (Gibb, 1978). The Thluicho Lake Group lies along another set of releasing bends along the same faults (e.g., Yatsore-Hill Island Fault, Figure 2) just north and also underneath the northwestern part of the Athabasca Basin (Harper, 1996).

The Manikiwan Ocean (Stauffer, 1984, Symons, 1991) separated the Slave-Rae-Hearne block from the Superior Craton at this time. Its closing and attendant subduction led to the development of the Wathaman magmatic belt at about 1.86 Ga along the eastern side of the future Athabasca Basin (Figure 37). Continuing movement of the Superior Craton towards the northwest resulted in the Reindeer-Hearne collision phase (1.86-1.84 Ga; Machado, 1990) of the Trans-Hudson Orogen, and the Reindeer-Sask Craton collision (1.822-1.816 Ga; Tran et al., 2002). The foreland basin sediments of the Trans-Hudson Orogen were metamorphosed in the prolonged collisional event and are incorporated in the Upper Wollaston Group (Yeo et al., 2000). Dextral movement along the Grease River-Straight River and related faults (Hanmer, 1997) suggests a second episode of escape tectonism accommodating movement of the Hearne Province to the southwest. This might be due to the ongoing movement of the Superior Province to the northwest. Whatever its cause, as the Grease River Fault terminates under the Athabasca Basin such displacement would lead to compression in the area of the Clearwater Domain that may possibly have led to the formation of the magmatic complex in that area. (Figures 2, 3 and 38). The magnetic and gravity anomaly pattern of the Clearwater Domain is similar to that of the Vulcan Zone in southern Alberta (maps in Villeneuve et al., 1993). In both cases the gravity high is distal (in the direction of movement of the Hearne block) to the magnetic high, and the magnetic high overlies a gravity low. Both the Clearwater Domain and the Vulcan Zone lie at an angle to the direction of movement of the Hearne block (Figure 38). Eaton et al. (1999) compare the Vulcan Zone to the Pyrenean compressive belt, and if this analogy is correct then it may also be made for the Clearwater Domain. Note that in the Clearwater Domain the intrusives that are only postulated for the Vulcan Zone are actually present in outcrop. Other examples of a wrench fault terminating at a compressive zone can be found in the Himalaya area, where Cenozoic escape movement along major wrench faults terminates with uplifts at constricting bends (Molnar and Tapponnier, 1975).

Farther to the west this episode of escape tectonism may have induced the dextral movement seen on the Black Bay, St. Louis and perhaps other faults along the western half of the Athabasca Basin area, such as the Charlot (Figures 2 and 3). This movement resulted in deposition of the Martin Group in wrench fault basins. The Martin Group (Beck, 1969; Tremblay, 1972; Langford, 1981; Mazimhaka and Hendry, 1984, 1985) consists of fluvial conglomerates, sandstones, mudstones and mafic volcanics, and is unconformably overlain by the Athabasca Group (Scott, 1978). The tectonic episode that led to the formation of the Martin Group basins may be the western Athabasca Basin equivalent of the D2 Oblique Collisional Stage (1820-1805 Ma) and possibly the Late D3 stage of oblique collision of the Trans-Hudson Orogen of Portella and Annesley (2000), assigned by them to a 1795? - 1775 Ma tectonic event. The lateral extrusion episode at 1820-1805 Ma (Portella and Annesley, 2000) lead to sinistral movement on faults in the eastern Athabasca Basin that may record the movement on the eastern side of the blocks showing dextral movement in the western Athabasca Basin.

Another reason for subsidence in the Athabasca region from 1.82 to 1.65 Ga may have been dynamic loading of the crust due to passage of accumulated subducted crust through the boundary between the upper and lower mantle. Pysklywec and Mitrovica (2000) in modelling studies suggest that this occurs 50 to 90 Ma after initiation of subduction, at about 1000 km from the trench margin if the angle of subduction is about 30º. In this model the rates of subsidence reach around 30 m/Ma at the peak of the dynamic loading at 70 Ma after onset of subduction. This provides about 300-500 m of dynamic subsidence in the model that in a real situation is amplified by the isostatic loading of the infill. The Martin Group basins at present are about 500 km away from the trench east of the Wathaman Batholith, but were farther away at the time because of folding and thrusting during formation of the Wollaston Fold Belt during the orogeny. They are also at a comparable distance from the Wopmay Orogen (1900-1830 Ma). Thus, subsidence or its augmentation in northwestern Alberta at the time of deposition of the Martin Group may be related to the Reindeer-Hearne collision and/or subduction at the western margin of the Slave Province about 70 Ma previously (Figures 37 and 38). The same mechanism may have been the main or a contributing factor to subsidence and deposition of the four sequences of the Athabasca Group. Possible links between subsidence caused by dynamic loading due to this cause have been indicated on Figure 37 by heavy lines linking subduction events to basin formation 70 Ma later at the appropriate distance from the former trench margin. Cross-sections through the Athabasca Basin showing the development of the basin by plotting the data using the base of the overlying sequence as a datum, are shown in Figures 40 to 44.

6.1 Development of Sequence 1 and the Jackfish Basin

After deposition of the Martin Group the next tectonic episode that may be linked to recorded sedimentation in the Athabasca region is the Reindeer-Sask Craton collision (1.822-1.816 Ga; Tran et al., 2002). Subsidence about 70 Ma after this event due to dynamic loading caused by passage of the subducted slabs into the lower mantle may relate to Sequence 1 of the Athabasca Group and would indicate an age of around 1750 Ma for this sequence. The collision was along the western side of the Trans-Hudson Orogen, and thus Sequence 1 and the Jackfish Basin would be expected to form in the same area as the Martin Group in this model. U-Pb dates on apatites from the Fair Point Formation give a date of around 1700 Ma (Cumming et al., 1987). Petrographic evidence shows that these apatites formed in fractures after deep burial, and thus provide a minimum age for this unit. Paleomagnetic dates on the oldest generation of diagenetic hematite found in the Athabasca Basin formed at a temperature of about 150º C and thus give a minimum date of 1750-1600 Ma (Kotzer et al., 1992).

Ongoing crustal shortening of the area between the Slave and Superior cratons is considered to be a reason for the formation of the Athabasca Basin by Gibb (1983). Such contraction may have resulted in crustal scale wrench faulting, perhaps along the Needle Falls and Tabbernor systems as indicated by Gibb (1983), as well as crustal scale thrust faults (White and Lucas, 1994; Beaumont et al., 1995; Ross et al., 1992; Portella and Annesley, 2000; Hajnal et al., 1996). Associated with the latter were uplifts dated from 1.8 to 1.7 Ga (Hajnal et al., 1996) of up to 10 km that were probably the main sediment sources of the first two sequences of the Athabasca Group. Such thick-skinned thrusts and associated hanging wall domes are very well shown on Lithoprobe sections in southern Alberta to the south of the Athabasca region (Ross et al., 2000).

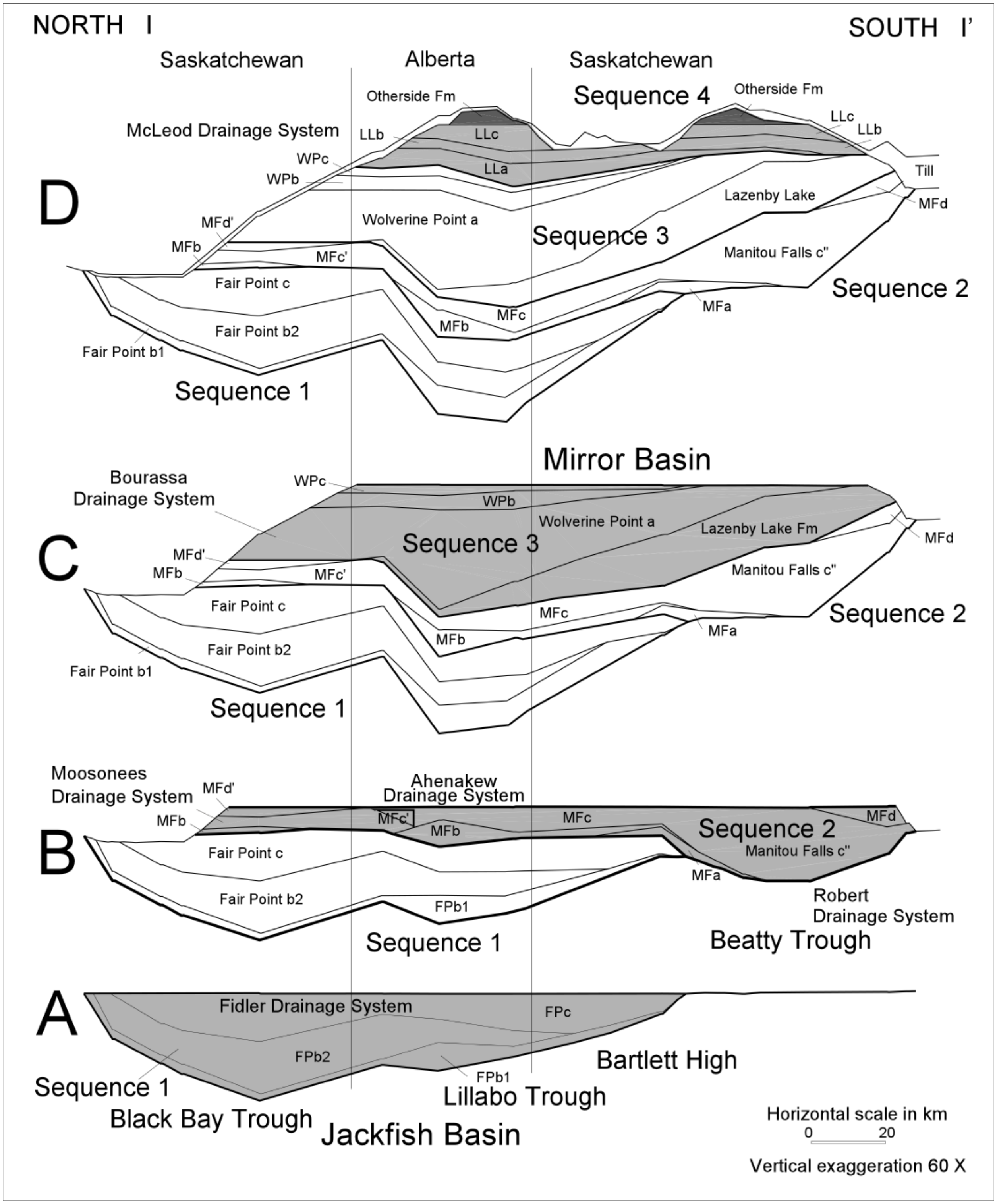


Figure 40. Section I-I' showing Sequences 1 to 4 of the Athabasca Group plotted with the base of the overlying sequence (Sequences 1-3) or the base of the uppermost unit (Sequence 4) as a datum.

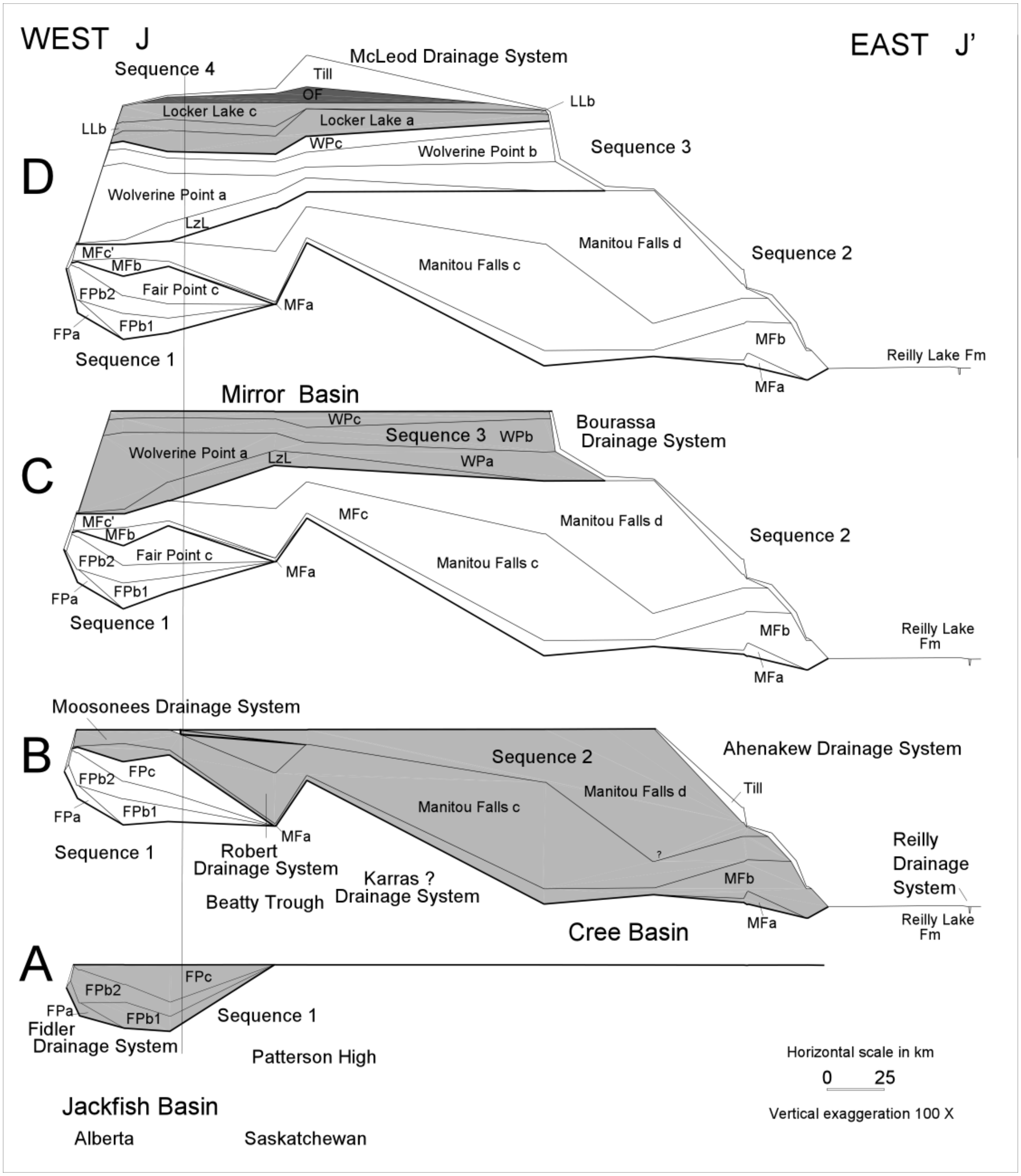


Figure 41. Section J-J', showing Sequences 1 to 4 of the Athabasca Group plotted with the base of the overlying sequence (Sequences 1-3) or the base of the uppermost unit (Sequence 4) as a datum.

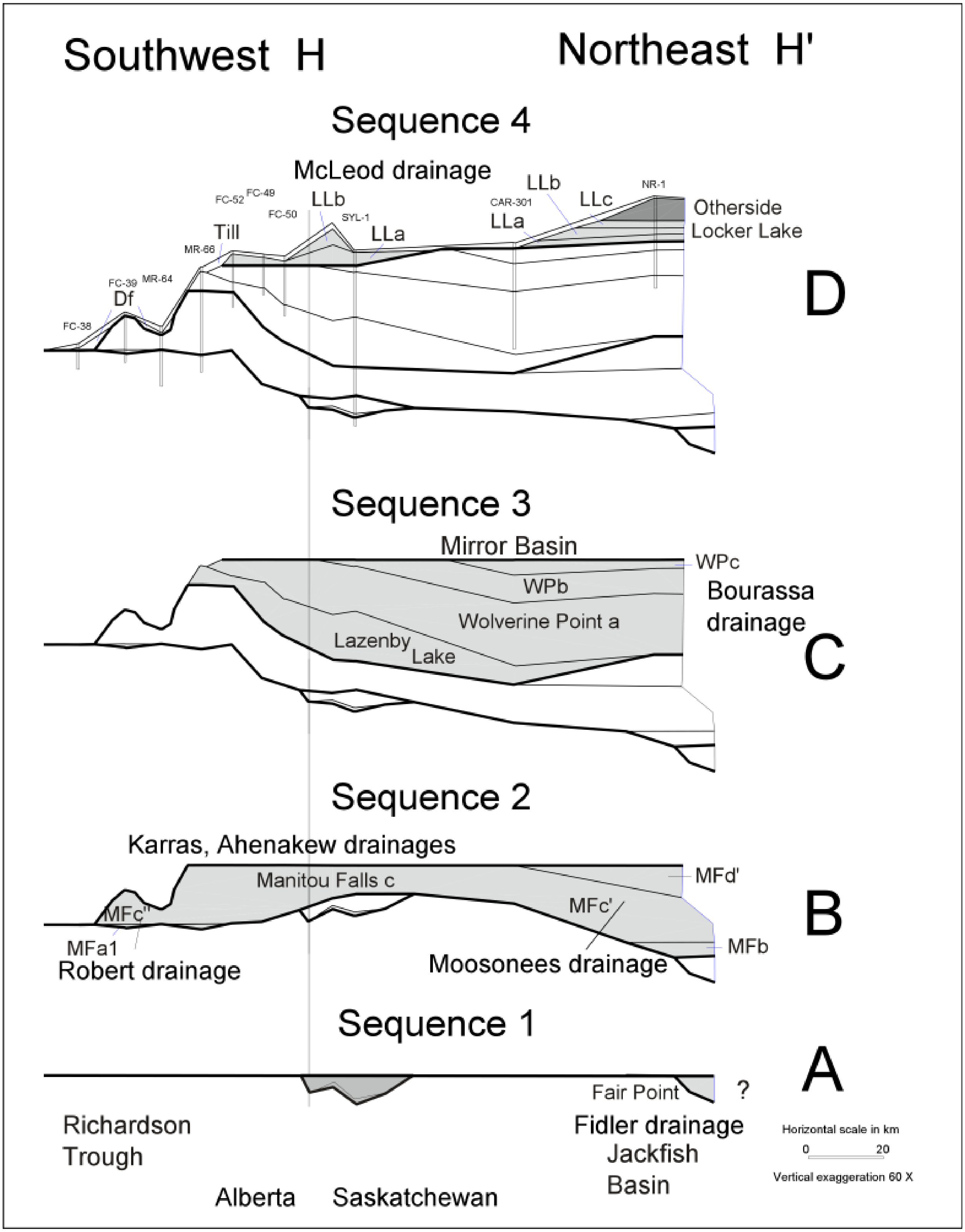


Figure 42. Section H-H', showing Sequences 1 to 4 of the Athabasca Group plotted with the base of the overlying sequence (Sequences 1-3) or the base of the uppermost unit (Sequence 4) as a datum.

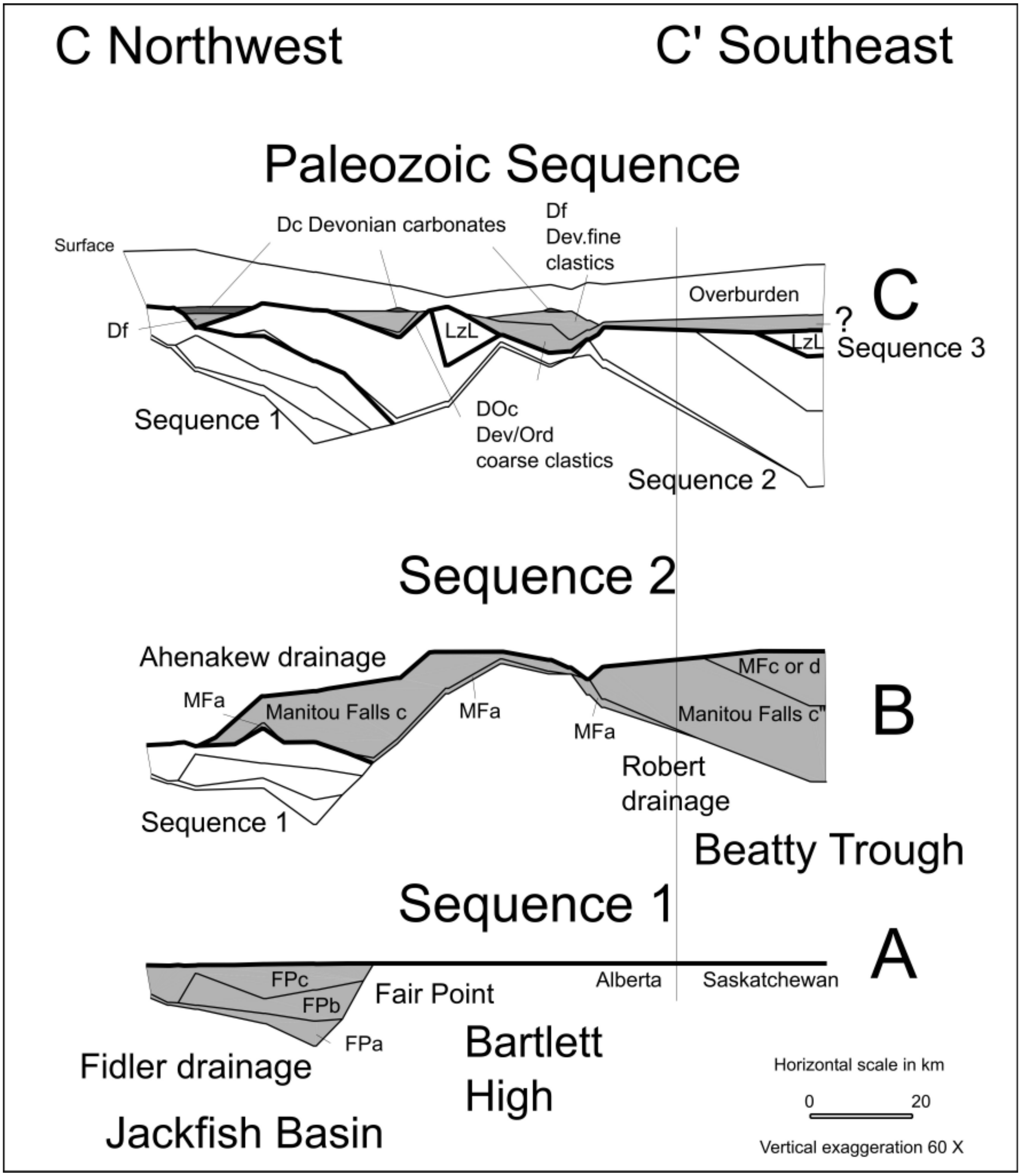


Figure 43. Section C-C', showing Sequences 1 to 3 of the Athabasca Group plotted with the base of the overlying sequence (Sequences 1-2) or the base of the uppermost Paleozoic unit (Sequence 3) as a datum.

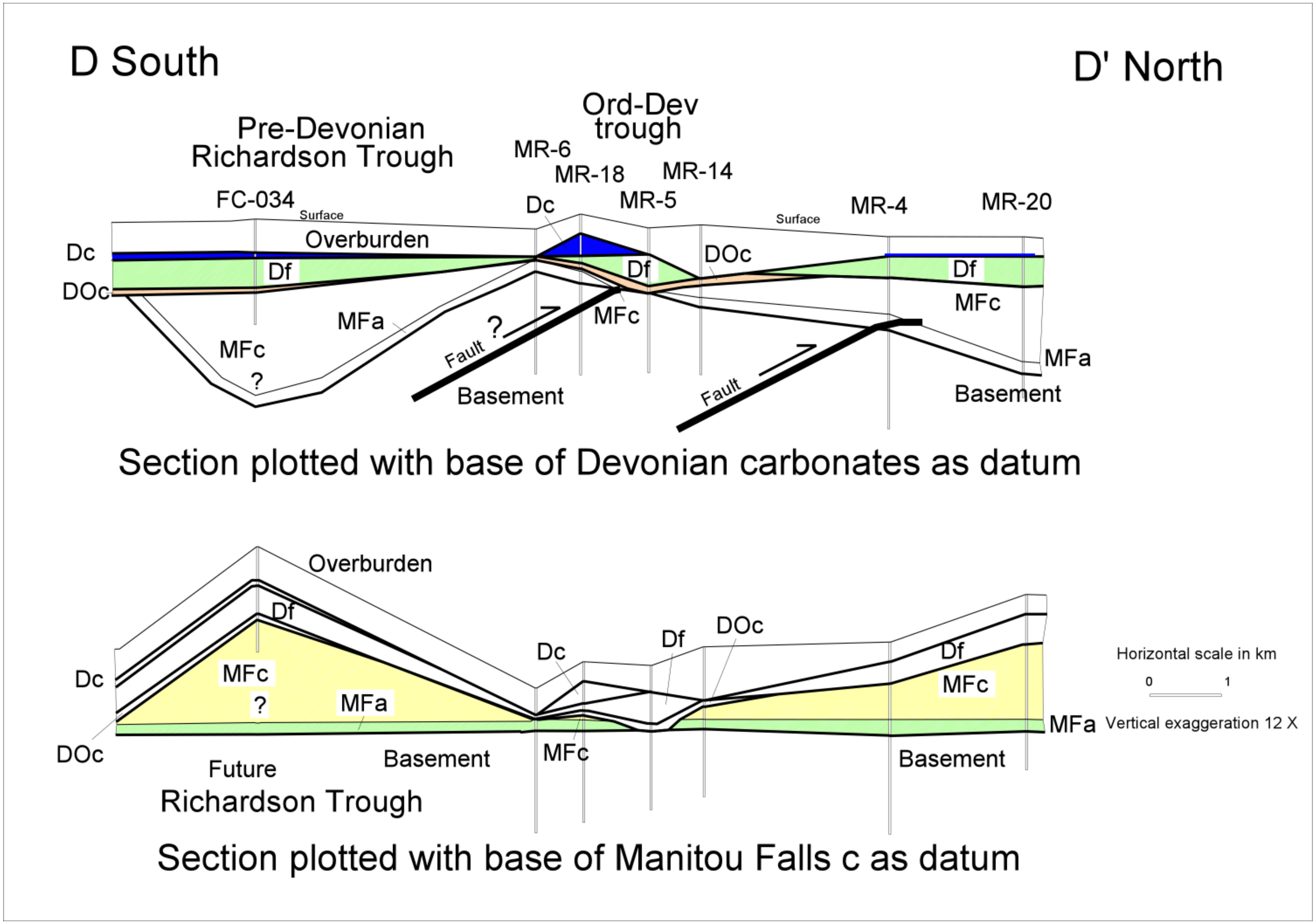


Figure 44. Section D-D', showing Sequence 2 of the Athabasca Group plotted with the base of the Manitou Falls c and the uppermost Paleozoic unit as a datum.

The depocentre of the Jackfish Basin is along the northern side (Figure 40A), perhaps indicating some tilting of the basin to the north. Loading of the crust may lead to tilting of basins towards the developing crustal load for great distances. Quinlan (1987) suggests such dynamic tilting of the Hudson Bay basin to the east towards the developing East Greenland subduction zone. Howell (1993), and Howell and van der Pluijm (1990) made similar observations with respect to tilting in the Michigan Basin in the Silurian and Ordovician, relating it to developing Ordovician subduction in the Appalachian region. Modelling results indicate that tilting towards a subduction zone is possible up to 1400 km away from that zone (e.g., Gurniss, 1990; Gurniss and Russell, 1993). A crustal shortening phase of about the same age as Machado's Phase 2 Reindeer-Superior collision (1740-1720 Ma) has also been recorded in the Thelon Basin area (Henderson et al., 1990; Rainbird et al., 2001, 2002a) and is thought by Henderson et al. (1990) to be the cause for the formation of the Thelon Basin at 1735 ± 20 Ma. A possible effect in the Athabasca Basin area may be the tilting of the Jackfish Basin to the north during development of Sequence 1 of the Athabasca Group, if the asymmetry of the basin is indeed due to tilting.

Cross-sections through Sequence 1 flattened on the base of the overlying sequence (Figures 40 and 41) and paleocurrent maps (Figure 4) show that at the time of deposition of Sequence 1 most of the Athabasca Basin was still a topographic high and may have supplied sediment to the Jackfish Basin. Detrital zircon studies of one sample from ddh FC-005 (Rainbird et al., 2002b) indicate a mainly Archean and Taltson age source area.

The distribution of Sequence 1 sediments (Figure 4) outlines the Jackfish Basin, and indicates that the preserved sediments are confined largely between the Charles Lake Shear Zone and Charlot Fault in the west and the Grease-Straight/Robillard Fault systems in the east (Figure 2). The original area of deposition may have been somewhat larger, with the Beatty Fault the eastern and southern limit. This suggests a pattern of subsidence more closely related to that of the Martin Group than that of the overlying Athabasca Group Sequences, and indicates that escape tectonics may still have been a contributing factor to Sequence 1 deposition. The coarseness and immaturity of the sediments of Sequence 1 also are more akin to the Martin Group sediments than to the bulk of Sequences 2 to 4 of the Athabasca Group.

Basin morphology in the Black Bay area and the north end of Lake Athabasca suggests that the trough between the Charlot and Black Bay Faults forms a depocentre, with another one to the south of it between the Black Bay and Grease-Straight Fault (Figure 8). To what extent this is due to postdepositional faulting and unroofing is not known at present.

A post-quartz overgrowth age of 1700 Ma for the Fair Point Formation (Sequence 1) apatite was obtained by Cumming et al. (1987). This suggests that Sequence 1 was buried to a depth of 4 km *before* deposition of the overlying Wolverine Point b unit (Sequence 3), if the assumptions about thermal gradient and the temperature of formation of the quartz overgrowths discussed in the section on diagenesis are correct. The WPb unit has been dated as younger than 1666 Ma. As the WPb unit is less than 1 km above the base of the Fair Point Formation this implies that several km of sediment were eroded from the Fair Point Formation before deposition of Sequence 3. This is reasonable given the large contrast in grain size and textural maturity between Sequences 1 and 2.

6.2 Development of Sequence 2, the Cree Basin and the Beatty Trough

The Reindeer –Superior collision Phase 1 (1810-1790 Ma) and Phase 2 (1740-1720 Ma) of Machado (1990) both may have influenced the formation of Sequence 2 of the Athabasca Group.

A crustal shortening phase occurring at about the same age as Machado's Phase 2 of the Reindeer-Superior collision has also been recorded in the Thelon Basin area (Henderson et al., 1990; Rainbird et al., 2001, 2002a). It is thought by Henderson et al. to be the cause for the formation of the Thelon Basin at 1735 ± 20 Ma.

Dynamic loading about 70 Ma after the Reindeer-Superior Phase 1 collision may have been a factor in causing the subsidence forming the Cree Basin in the eastern two-thirds of the Athabasca Basin (Figures 2 and 41B). Both the Reindeer-Superior collisional event and the Cree Basin lie to the east of the subduction event and the resultant basin (Jackfish) that formed during Sequence 1 deposition.

The Manitou Falls Formation that comprises Sequence 2 is derived largely from the northeast, east, and southeast (Figure 5) and thickens markedly towards the east (Figure 42). This shows that the Trans-Hudson Orogen area reactivated by phase 2 of the Reindeer Superior collision was its main sediment source. This is supported by detrital zircon studies that provide a dominantly Archean (2.5 Ga) and Trans-Hudson (1.85 Ga) age for Ahenakew drainage at the MFb unit level. Zircon ages of around 1.83 Ma dominate a Moosonees drainage MFd unit sample (Rainbird et al., 2002b) and suggest that the sediments from its source area to the northeast of the Athabasca Basin drained predominantly uplifted Trans-Hudson rocks. Samples derived from the northwest in the Robert drainage in Alberta have not been tested thus far.

Unmetamorphosed pebbly sandstones at Reilly Lake are separated from the Athabasca Basin by the 1860 Ma Wathaman Batholith and may be the remnants of a distinct basin, the Reilly Basin (Figure 2). They are similar lithologically to the base of Sequence 2 of the Athabasca Group, but show paleocurrent directions trending to the southwest, opposite to those of the nearest Manitou Falls Formation.

The paleocurrent patterns (Figure 5), details in grain size distribution (Ramaekers, 1990), and stratigraphy suggest that Manitou Falls deposition and subsidence may have started with the Robert drainage and the formation of the Beatty Trough. Sediments were derived from the Bartlett High area, and deposited in the developing Beatty Trough northwest of the Beatty Fault (Figure 3) and south of the Harrison Fault (Figure 15). Next formed the Karras and Ahenakew drainages as the Cree Basin began to form (Figures 5 and 41) perhaps with the Moosonees drainage forming last. The Cree Basin was restricted in large part to the eastern half of the Athabasca Basin. In Alberta most of the development of the later drainage systems remained relatively thin. Thus, regional subsidence may have progressed from west to east in the course of deposition in Sequence 2; a hypothesis that will only be proven when the age of deposition of the MFa member in the Beatty Trough and Cree Basin are known.

6.3 Development of Sequences 3 and 4, the Mirror Basin, and the Lillabo Trough

The Wolverine Point b unit of Sequence 3 has maximum age of 1666 Ma (Rainbird et al., 2002). Thus, crustal shortening associated with the Reindeer –Superior collision Phase 2 (1740-1720 Ma) of Machado (1990) and the dynamic loading 70 Ma later may have induced the subsidence involved in deposition of Sequence 3 (Figure 37). If so, it suggests that the late adjustments along the collisional suture indicated by Machado may have involved further subduction during Phase 2.

The upper two sequences of the Athabasca Group were derived from the south (Figures 6 and 7), but thicken to the northwest (Figures 40 and 41). Overstepping of the Lazenby Lake Formation to the north by the Wolverine Point Formation suggests basin tilting to the north and northwest during deposition of Sequence 3.

This is in marked contrast to Sequence 2, which was derived from and thickens to the Trans-Hudson Orogen to the east. The tilting to the north may have been due to developing crustal loads to the northwest, caused by crustal imbrication during the Forward Orogen at about 1.633 Ga (Cook and MacLean, 1995; Bowring and Ross, 1985) in the area west and north of Great Bear Lake. Seismic sections from that area show that it was undergoing shortening with development of thick-skinned thrusting and compression from the southeast. If the tilting of the Athabasca Basin during deposition of the Wolverine Point Formation is due to the developing Forward Orogen, then Sequence 3 was deposited at about 1.63 Ga. The inference is supported by a maximum age on detrital zircons of 1.66 Ma derived from the Wolverine Point b unit of Sequence 3 derived from ddh FC-005 (Rainbird et al., 2002; see below). The sample also shows a broad mode of zircon ages of 2.7 to 2.5 Ga with the most prominent mode spanning the 1.88 to 1.78 Ga interval that reflects the ages of the Hudsonian age intrusives of the southern source area (Rimbey, Clearwater, Junction).

The southern derivation of the upper two Athabasca Group Sequences indicates that some of their sediments were supplied from uplifts in this direction. These may have been related to orogenic events to the south of the Superior and Hearne crustal blocks such as the Central Plains (1780-1680 Ma, Sims and Peterman, 1986; Klasner and King, 1990), Yavapai (1.79-1.69 Ga; Karlstrom and Bowring, 1987) and the Mazatzal Orogeny (1.71-1.62 Ga; Karlstrom and Bowring, 1987).

A detrital zircon sample from the Douglas Formation of Sequence 4 has an age distribution similar to that of the Wolverine Point sample (Rainbird et al., 2002), as might be expected given that paleocurrent studies (Figures 6 and 7) indicate a similar source area.

Sequences 3 and 4 sediments are confined between the Charles Lake Shear Zone in the west and the area between the Black Lake and Cable Bay Shear Zones in the east, forming a basin with its depocentre in the western half of the Athabasca Basin: the Mirror Basin. The initial Mirror Basin subsidence appears to have been strongest in the area between the Black Bay, Bustard and Beatty faults (Figure 42C). This basin was partitioned by later uplifts along the Bartlett and Patterson Highs into separate troughs: the Lillabo in the northwest, a deepening of the northern end of the Beatty Trough, and possibly a trough in the central part of the basin west of the uplifts of the Dufferin High (Figures 2, 17-25).

Comparison of section D of Figure 40 (which shows basin configuration at the time of deposition of the Otherside Formation) and section I on Figure 34 (which shows the present configuration of the same section) indicates that the Lillabo Trough continued subsiding more rapidly than the rest of the basin for some time after deposition of the Otherside Formation, but exactly when this more rapid subsidence occurred is not clear from available evidence. It may have occurred during deposition of the now eroded parts of Sequence 4 preserved only in the Carswell meteor impact structure (Douglas and Carswell formations) or during deposition of the now eroded 2700 m of Proterozoic sedimentation.

6.4 Basin Development During Deposition of the Now Eroded Strata

The three main periods of primary uranium ore formation and/or reworking in the Athabasca Basin are 1380-1330 Ma, 1288-1246 Ma, and 1110-959 Ma (Figure 37; Cumming and Krstic, 1992). These periods of hydrothermal activity in the Athabasca Basin also match or overlap times of deposition in the Amundsen Basin: the Dismal Lakes Group at 1380-1270 Ma, and the Rae Group of the Shaler Supergroup at 1000 to 820 Ma (Figure 37; Ross, 2000) and the intrusion of the Mackenzie dikes (1267±4 Ma; LeCheminant and Heaman, 1989). They also match ages of uranium ore formation in the Thelon Basin, indicating that it also was tectonically active at these times (Figure 37). Thus the Athabasca region was affected by continent wide events at these times.

The period of deposition of the Dismal Lake Group, which is the period of main primary ore deposition in the Athabasca Basin overlaps with a period of widespread intrusive activity along the southern margin of Laurentia from New Mexico to southeastern Ontario. More importantly it also coincides with major rifting events along western North America including the Belt Supergroup in Montana, Alberta and British Columbia (Winston, 1990; Ross et al., 1992), and the Pinguicula Group and other units in the Ogilvie and Wernecke Mountains of the Yukon (Ross, 2000). The Mackenzie event is also related to continental breakup by Heaman et al. (1992). The last period of primary ore deposition overlaps with the age of the Grenville Orogeny in eastern North America, but also with the breakup of Rodinia (Hoffman, 1991; Ross et al., 1992; Idnurm and Giddings, (1998). At this time deposition was once again widespread along the western margin of North America, virtually continuous from the Yukon to the Amundsen Basin (Ross, 2000).

Thus, sometime after deposition of Sequence 3 and before the rifting at the western margin of the continent at about 1450 Ma the main mode of basin formation and deepening in the region changed from a compressive style to a tensional style of tectonism. The switch to a regionally tensile tectonic regime can only have promoted the development of the deep-seated fracturing necessary for the hydrothermal systems that emplaced the unconformity orebodies.

6.5 Post-Athabasca Group Tectonism

Flattening section C-C' on progressively higher data (Figure 43) shows that the western end of the Athabasca Basin became tilted sometime after deposition of the Lazenby Lake Formation of Sequence 3, but before peneplanation of the area and before deposition of the Devonian sediments. If the inference that basin deepening occurred as late as about 1000 Ma (the times of the latest episode of widespread primary uranium deposition), then this tilting likely took place during the unroofing of the basin between 1000 and about 400 Ma (beginning of Devonian).

Flattening of section D-D' on the base of the MFc and the Devonian (Figure 44) shows that the Richardson trough (Figure 3) developed after deposition of Sequence 2 and before the Devonian. A small trough also developed just prior to deposition of the Devonian fine clastics and was filled with sediments of the DOc unit.

Comparison of Figure 43C with the present-day section (Figure 28) shows that the western side of the Athabasca Basin has tilted to the west since the Devonian, probably during the growth of the Western Canada Sedimentary Basin, thus facilitating entry of hydrocarbons into the Athabasca Basin.

Modelling of dynamic loading during development of a continental margin trench indicates that the initial subsidence of the trench with subduction and thrusting is deeper and extends farther away from the trench margin than at any time in its ongoing development (Pysklewec and Mitrovica, 2000, their Figure 4). Thus, the amount of tilting of the Devonian beds to the west shown in Figure 28 underestimates the maximum slope, which developed within the first 20 Ma after initiation of the trench in the Cretaceous. This means that the Athabasca Basin was sloping more steeply to the west in the early Tertiary, possibly in the order of another 600 m more than at present. Thus, the oil that is found today well into the basement below the Athabasca Group strata may have reached its present position as part of a normal upslope migration.

7 Geochronology of the Athabasca Basin

The Martin Group has not been precisely dated. The underlying metasediments and plutonic rock are of greenschist to granulite grade, indicating a long period of uplift and erosion of the underlying Hudsonian and older rock units. Scott (1978) suggests an age for the Martin Group between 1830 and 1780 (+/- 20) Ma on the basis of a literature review. The Martin Group has often been correlated with the Baker Lake

Group, and if this is valid it would suggest an age of about 1830 Ma (Rainbird et al., 2002a).

Rhyolitic volcanism was widespread in the Athabasca region at the end of the main phases of the Trans-Hudson Orogen. The rhyolitic shards in the Fair Point Formation in the Carswell Structure (Pacquet and McNamara, 1985) could have been derived from a number of sources. These include the Pitz volcanics and associated Nueltin intrusives 200 km to the northeast of the Athabasca Basin (1765 Ma; Peterson and van Breemen, 1999; Peterson et al., 2000), the Swift Current Anorogenic Province 600 km to the south (1760 Ma; Collerson et al., 1988; Figure 38), or the little studied volcanics present at the northwestern margins of the basin lying just below or within the basal units of the Athabasca Group (Harper, 1996). Derivation of these rhyolitic shards from the Pitz or Swift Current Anorogenic Province would provide a maximum age for Sequence 1 of the Athabasca Group of about 1760 Ma.

Apatite cement from the Fair Point Formation (Sequence 1 of Athabasca Group) and the base of the Wolverine Point b unit (Sequence 3 of the Athabasca Group) provides poorly constrained U-Pb dates of 1700 and 1650 Ma (Cumming et al., 1987). The latter is considered an age of reworking of material deposited near the time of deposition at about 1700 Ma (Cumming et al., 1987). The material dated by Cumming et al. (1987) from the Fair Point Formation comes from a fracture filling. Thin sections show that the apatite covers quartz overgrowths within the fracture and in the adjacent wall rock, contrary to Wilson (1985). The rock was compacted before quartz overgrowths developed. Thus, the apatite did not form early, and if the quartz overgrowths here formed at a temperature of 130-150º C (similar to those studied by Kotzer et al. (1992) and Renac et al. (2002) elsewhere in the Athabasca Basin), then the age of 1700 Ma for this material represents a time of considerable depth of burial, and may be considerably later than the time of deposition of Sequence 1.

Other workers (e.g., Kotzer et al., 1992) have suggested there are similarities between the Athabasca, Thelon and Amundsen basins, and thus the age of the Athabasca Basin is similar to those obtained for the Thelon Basin (1720 ±6 to 1685 ±4 Ma, Miller et al. 1989) and 1850 to 1660 ±8 Ma for the Amundsen Basin Hornby Bay Group (Bowring and Van Schmus, 1982; Bowring and Ross, 1985).

Detrital zircons from the Wolverine Point b unit give a maximum age of c. 1.66 Ga (Rainbird et al., 2002b) for this unit. Apatite cement from this unit in places pseudomorphs volcanic glass shards that were derived from post-Hudsonian volcanic and intrusive suites. The fine grained nature of much of this material suggests an airfall origin for the shards, but occasional pumice pebbles are also present and indicate that a local source is a possibility. Paleocurrents from the Wolverine Point and underlying beds show a sediment source to the south, and suggest that the Central Plains (1.78-1.68 Ga; Sims and Peterman, 1986), Yavapai (1.79-1.69 Ga; Karlstrom and Bowring, 1988) or the Mazatzal orogens (1.71-1.62 Ga; Karlstrom and Bowring, 1988) may have contributed material. Tilting of the basin to the northwest at this stratigraphic level suggests crustal loading in that direction and that deposition of this unit was coeval with the Forward Orogen (1.633 Ga; Cook and MacLean, 1995; Bowring and Ross, 1985). Armstrong and Ramaekers (1985) obtained a Rb-Sr whole rock age of 1430 ± 30 Ma from illitic sediments of the Wolverine Point b member, and interpreted this as close to depositional age; it is better regarded as the age of recrystallization of the illites with deep burial.

A K/Ar age of 1292±27 Ma has been obtained from illites in the Douglas Formation near the top of the Athabasca Group (Clauer et al., 1985) and provides a minimum age for the top of the Athabasca Group. It may record a phase of basin deepening.

8 Diagenesis of Athabasca Basin Sediments

This study was focussed on stratigraphy and tectonics rather than diagenesis, but some comments on diagenesis are provided here as background for the discussion on how these related to uranium mineralization. They serve mainly to interpret the observations of Wilson (1985) in the light of new data.

The main outlines of the history of diagenesis in the Athabasca Basin are established. A recent summary and comparison with diagenesis in the Thelon Basin is given by Renac et al. (2002). The diagenesis of the Alberta Athabasca Group was described by Wilson (1985) using petrographic and XRD methods. It provides detail on diagenetic minerals not studied by Renac et al. (2002), but lacks the radiometric age, stable isotope, PIMA and paleomagnetic data available to the later workers.

8.1 Early Diagenesis: Early Hematite Followed by Early Syntaxial Quartz Overgrowths

Early diagenesis of the Athabasca sediments may have been similar to that of modern continental redbeds, and involved limonite and hematite coating on detrital quartz grains. This material, plus iron released by intra-stratal breakdown of detrital minerals, recrystallized to hematite on burial. These iron oxides are the earliest stage preserved, and they are referred to as 'early' diagenetic hematite in the literature on the Athabasca Group. A paleomagnetic age of 1750-1600 Ma is indicated for the early hematite (Kotzer et al., 1992). The large age range reflects the lack of suitable well-dated rocks with a similar paleopole from the early Proterozoic. Isotope studies show that this 'early' hematite next to detrital quartz cores was deposited at temperatures of 120-160º C from relatively ^{18}O depleted fluids (Kotzer et al., 1992). Syntaxial quartz overgrowths generally formed at temperatures around 130º C (Renac et al., 2002) or 120º -150º C (Kotzer et al., 1992). Thus, the 'early' hematite in the Athabasca Group was formed well after initial deposition of the base of the Athabasca Group.

At a thermal gradient of 35º C/km, considered reasonable for intracratonic basins in general and the Athabasca Basin in particular (Pagel et al., 1980), a temperature of 130º C indicates a depth of burial of about 3-5 km. This agrees with petrographic evidence that show the sandstones have suffered considerable compaction with point contacts between the detrital cores ubiquitous and long contacts not uncommon. Similarly, the average slope of crossbedding in trough-crossbedded sandstones from the Manitou Falls Formation is typically around 20º, indicating about 20 % compaction from the initial angle of repose of 33º. The preserved thickness of the Athabasca Group is about 2300 m, including an estimated 800 m of Douglas and Carswell Formation now seen only in the Carswell Structure. This means that the isotopic temperature evidence indicates that the entire presently preserved sedimentary sequence plus at least another 700m of sediment was in place at the time of this earliest diagenetic event,

The maximum age for the Wolverine Point b unit of Sequence 3 is 1666 Ma (Rainbird et al., 2002), at a level of about 1000 m above the base of the group. This point is separated by a hiatus from Sequence 4, and must have been buried by a farther 2-4 km of sediments before the onset of the formation of the earliest hematite studied by Kotzer et al. (1992). If the commonly made assumption of a thermal gradient of 35º C/km is correct, the temperature of formation of the early hematite and early quartz overgrowths of 120º-150º C imply that these were precipitated well after deposition of the Wolverine Point Formation and Sequence 4 and hence are younger than 1666 Ma. Thus, the age of the early hematite and early quartz overgrowths, which are restrained by the paleomagnetic ages to between 1750 and 1600 Ma, can be further restrained to between 1666 and 1600 Ma. By the same reasoning the age of Sequence 4 is limited by the paleomagnetic age of the early hematite to between 1666 and 1600 Ma.

8.2 Peak Diagenesis: Desilicification Followed by Dickite, Illite, Minor Dravite, Goyazite and Chlorites

Development of secondary porosity by desilicification occurred as peak diagenesis was reached around 1600 Ma. This was followed by the crystallization of widespread illite and dickite, with minor dravite, goyazite and related aluminophosphates and clinochlore. Isotope studies of quartz and illites give a basin temperature range from 180-240º C and salinities ca. 30 wt. % equivalent NaCl. These conditions, including isotopic compositions, prevailed until about 900 Ma (Renac et al., 2002). Hematite was recrystallized around major fault zones, and is especially noted around ore zones. A paleomagnetic age of 1600-1450 Ma is indicated for this hematite (Kotzer et al., 1992). The oldest uranium ore ages in the Athabasca Basin fall in this range, although there are relatively few of them. Illitic intergrowths in this generation of hematite provided a Rb-Sr age of 1477 ± 57 Ma at the Key Lake uranium mine (Kotzer and Kyser, 1990). A third episode of hematite recrystallization occurred widely through the basin, and has been dated at 970 Ma by Rb-Sr on illites from the Rabbit Lake uranium mine area (Kotzer and Kyser, 1990). It occurs up to 900 Ma with fluids of salinities, temperatures and isotopic composition the same as those of peak diagenesis (Renac et al. 2002). Peak diagenesis lasted from about 1600 Ma to about 950 Ma based on the presence of primary uranium (Cumming and Krstic, 1992). The oldest uranium ores formed around 1514 Ma and is found only at the McArthur mine, the most frequently and widely distributed mineralizing events are from 1380-1330 Ma, and lesser events occur from 1288 to 1246 Ma and from 1110 to about 950 Ma.

The three diagenetic hematization events occurred widely throughout the basin judging by the distribution of remnant inclinations found in drillcores (data from Fahrig et al., 1978; interpretation from Ramaekers, 1978; and Kotzer et al., 1992), and all may occur within a single core.

8.3 Late Diagenesis: Uranium Mobilization and Hematite Recrystallization

Late regional diagenetic effects consist largely of hematite recrystallization, the formation of late low temperature kaolinite, and the remobilization of uranium (Renac et al. 2002), peaking at ages of 575 and 225 Ma (Cumming and Krstic, 1992). Influx of surface waters along reactivated structures resulted in vein filling carbonates, largely siderite and limonite. The fluids were of low temperature and salinities according to their isotopic compositions.

The single most outstanding fact about the diagenetic history of the Athabasca Basin is the length of the period during which hot deep basin brines circulated through it and the upper part of the underlying basement. The ages of primary ore deposition, fluid inclusion studies and isotope studies (Kotzer and Kyser, 1995) indicate that hydrothermal systems with temperatures of around 250º C and salinities of ca. 30 wt. % equivalent NaCl were present from around 1640 Ma to 900 Ma. This corresponds to the time period during which the Athabasca region and western North America was subject to periods of regional tensional stress as evidenced by rifting and continental breakup events.

8.4 Diagenesis in the Alberta Athabasca Basin

8.4.1 Hematite

Three colour patterns of hematite are seen regularly throughout the Athabasca Basin sandstones, sometimes overprinting each other. These are:

1) Limonitic, near the surface and deeper along fractures.
2) Pale to bright red liesegang banding, with or without reduction spots, occasionally pervasive.
3) Dark grey to dark purple liesegang banding, grading into pervasive hematite.

Less common habits of hematite in the Athabasca Group sediments are the often bright to dark red stain of mudstones, and the bright metallic specular hematite seen at the Fair Point-Manitou Falls contact.

If the common colour patterns here are similar to those dated by Kotzer et al. (1992), then the dark grey to purple hematite may include both their early and late hematite, and the paler reds are more likely to correspond to their intermediate age. The regolith clays are often red and carried the oldest generation of hematite in the material studied by Kotzer et al (1992). Note that the intermediate ages were found by Kotzer et al. (1992) only around the ore zones, and that they tested the hematite only in two areas. However, the similarity of the inclinations of their grouping compared to those of Fahrig et al. (1978) whose material was obtained from sites widely scattered throughout the Athabasca Basin, does indicate that these three ages represent widespread events and are likely to have affected the Athabasca sandstones in Alberta.

8.4.2 Clay Alteration

Several habits of clay minerals may be distinguished petrographically:

1) Pseudomorphs after sand-sized grains. These are found frequently in the Fair Point and Wolverine Point c unit, and less commonly to rarely elsewhere. They may be distorted by compaction.
2) Interstitial clay after detrital micas, often with hematite intergrowths. Depending on the degree of compaction these masses may sometimes easily be recognized as pseudomorphs after micas. They grade from much distorted grains bent around detrital quartz grains to irregular iron-rich clay masses between and around detrital quartz. This range of morphology suggests that much of the interstitial clay in the sandstones may have originated as pseudomorphs of micas, feldspars and other minerals during diagenesis.
3) In sedimentary laminae. The presence of clays in laminae shows that detrital clays were present as well. Much of the fine-grained material proves to be quartz-rich muds in thin section.
4) Clay accumulations along stylolites. Large crystals of illite are often present along stylolite seams. They formed after compaction, and after quartz dissolution ceased, as shown by their lack of distortion.

The detrital clay was deposited largely as fine-grained kaolinite. This is most commonly seen in clay layers and clay pebbles: areas with low permeability. The clay pseudomorphs after detrital grains are most often illites, but kaolinite pseudomorphs are also known (Wilson, 1985). During deep burial the kaolinites recrystallized into coarse books, shown to be dickite by PIMA methods, and this occurs preferentially in the coarser grained more porous units (Percival et al., 2002) such as the Fair Point and Manitou Falls b units. Late diagenetic pore filling illites are also present, and typically are alterations after the kaolinite and dickite.

Near the hot ascending parts of hydrothermal systems, illite alteration is more pervasive and sandstone may be replaced totally along faults and fractures to form nearly pure clay zones up to several m thick, but usually in the range of cm in areas away from the basal unconformity. These zones form around and above the areas where uranium may be precipitated if the hydrothermal system is uraniferous. The late pale-green to white alteration along some stylolites that extends up to several cm away from the actual stylolite itself may also be part of the more distal hydrothermal alteration, marking areas where the hot fluids moved horizontally along the more permeable bedding planes.

B. Kupsch (personal communication, 2002), in an ongoing M.Sc. study for the University of Alberta and for the Alberta Geological Survey studied the clays in 10 drillholes in the Maybelle River mineralized area using PIMA techniques. Lazenby Lake, Manitou Falls, and the Fair Point formations are present in all 10 drillholes. Illite was the dominant clay in the Lazenby Lake and Manitou Falls formations, with minor amounts of kaolinite, dickite and chlorite up to 20%. The Fair Point Formation contains dickite and illite in various proportions. In the two mineralized holes (MR-34 and 39), chlorite forms up to 90% of the clays at the base of the Fair Point Formation.

Clay alteration patterns in drillholes near the McArthur uranium orebody in Saskatchewan are described by Percival et al. (2002). They include illitization of dickites and kaolinites, chlorite deposition near the unconformity, and dravite alteration at various levels. Clay alteration patterns in the Maybelle River area similar to those observed in mineralized areas in the eastern Athabasca Basin include massive replacement of sandstone by illite along fault and fracture zones, and the chloritization of the beds at the base of the Athabasca Group. This indicates that the Maybelle River hydrothermal systems in Alberta were of similar nature to those that emplaced the large unconformity orebodies in Saskatchewan.

8.4.3 Phosphates

Hydrous aluminophosphates such as goyazite and related minerals are widely present in very small quantities as a late pore mineral, usually disseminated in clays.

Apatites, usually fluorapatite, are present in the Wolverine Point b member and also have been reported in the Fair Point Formation (Wilson, 1985). The Wolverine Point apatite is present as a pervasive, but patchy, cement that has sealed the rock and inhibited further diagenetic changes, thus preserving detrital feldspars. The lack of feldspars elsewhere in this unit indicates that the apatite cement in this environment formed close to the time of deposition. The apatite replaces volcanic glass shard debris in places. Volcanic shards are very rarely seen within the Athabasca Group except where they have been pseudomorphed by the apatite cement. This suggests that fine volcanic debris may have been more widely distributed originally, but is not preserved except where protected from the intense diagenetic reactions by early cement.

In the Fair Point Formation, in ddh FC-009, at 113.5m fluorapatite is found as a vein filling (Wilson, 1985), the only occurrence of apatite in the Fair Point Formation noted to date. Outcrops near drillhole FC-009 show bedding dips of 10º with azimuths from southeast to northeast (Wilson, 1985). The bedding dips indicate the presence of tectonically disturbed sandstone, probably due to disruption along the Bustard Fault, a splay of the Charles Lake Shear Zone system, which is a major shear zone with a deep connected system of listric faults (McDonough et al., 2000, p.1569). Apatite in this type of environment is often fracture-related and relatively common along the northern side of the Athabasca Basin.

Both occurrences of apatite were used by Cumming et al. (1987) to derive two distinct ages between 1700-1650 Ma using U-Pb isotope techniques. Cumming et al. (1987) consider the age of deposition of the Athabasca Group as ‘closely defined by the oldest dates obtained’ and the younger one a reworking of earlier material. Given the maximum age of the Wolverine Point b unit of 1666 Ma (Rainbird et al., 2002) the 1650 Ma age for the Wolverine Point Formation may be relatively close to the time of deposition of the top of Sequence 3 of the Athabasca Group rather than a reworking age. The age of the Fair Point Formation apatite was discussed in the section on geochronology.

8.4.4 Permeability Changes in the Athabasca Group

The in-situ generation of clays due to the alteration of labile minerals suggests that the permeability of the Athabasca Group sediments may have changed over time. Figures 45 and 46 indicate the nature of such alterations. Figure 45 shows early aquifers and aquitards in the Athabasca Basin along section A-A’. The lack of significant bedded clays in all but the Wolverine Point b unit, the evidence of an eolian influenced environment, and the sandy nature of the strata all indicate that interstitial detrital clay was minor, and that consequently all but the Wolverine Point b strata had large early porosities and permeabilities.

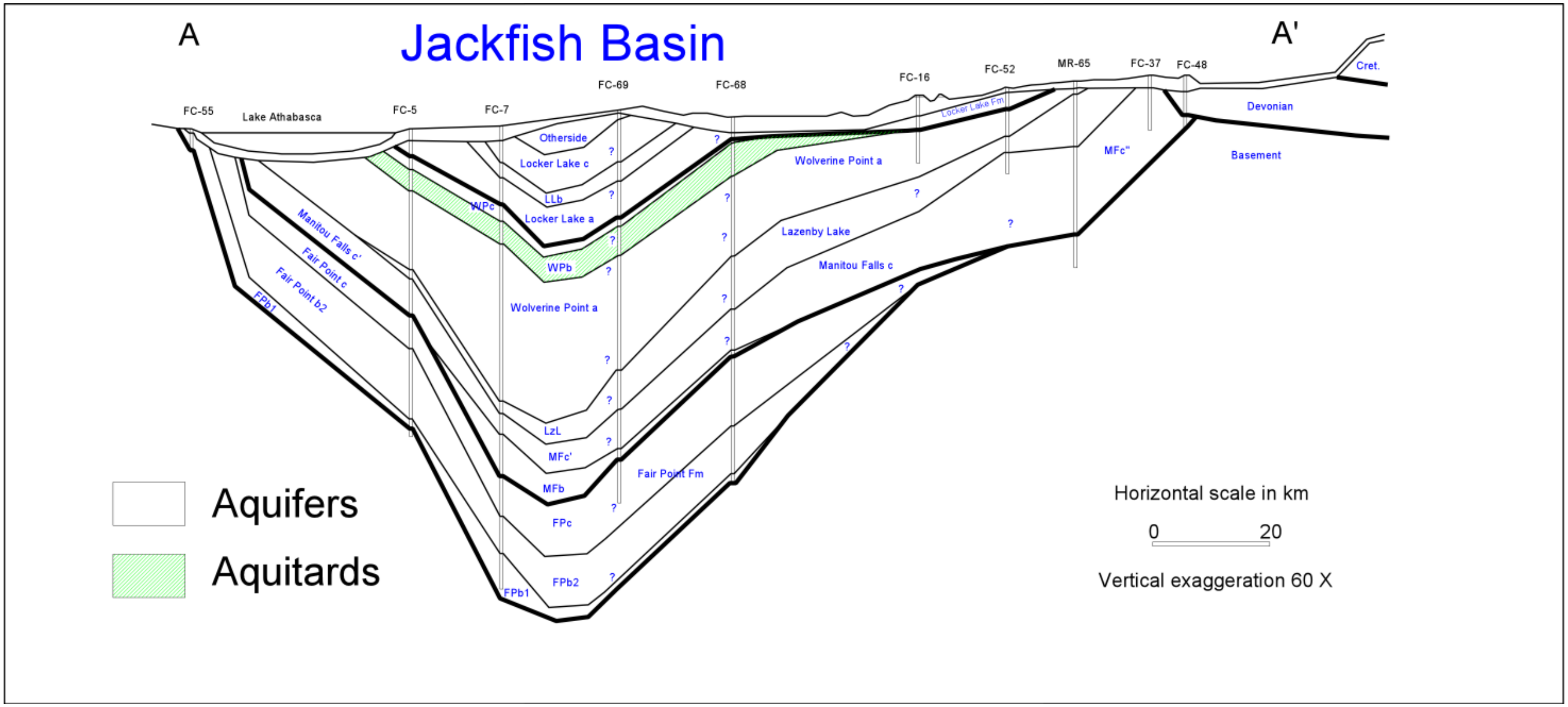


Figure 45. Early aquifers and aquitards in the Athabasca Basin; shown along section A-A'.

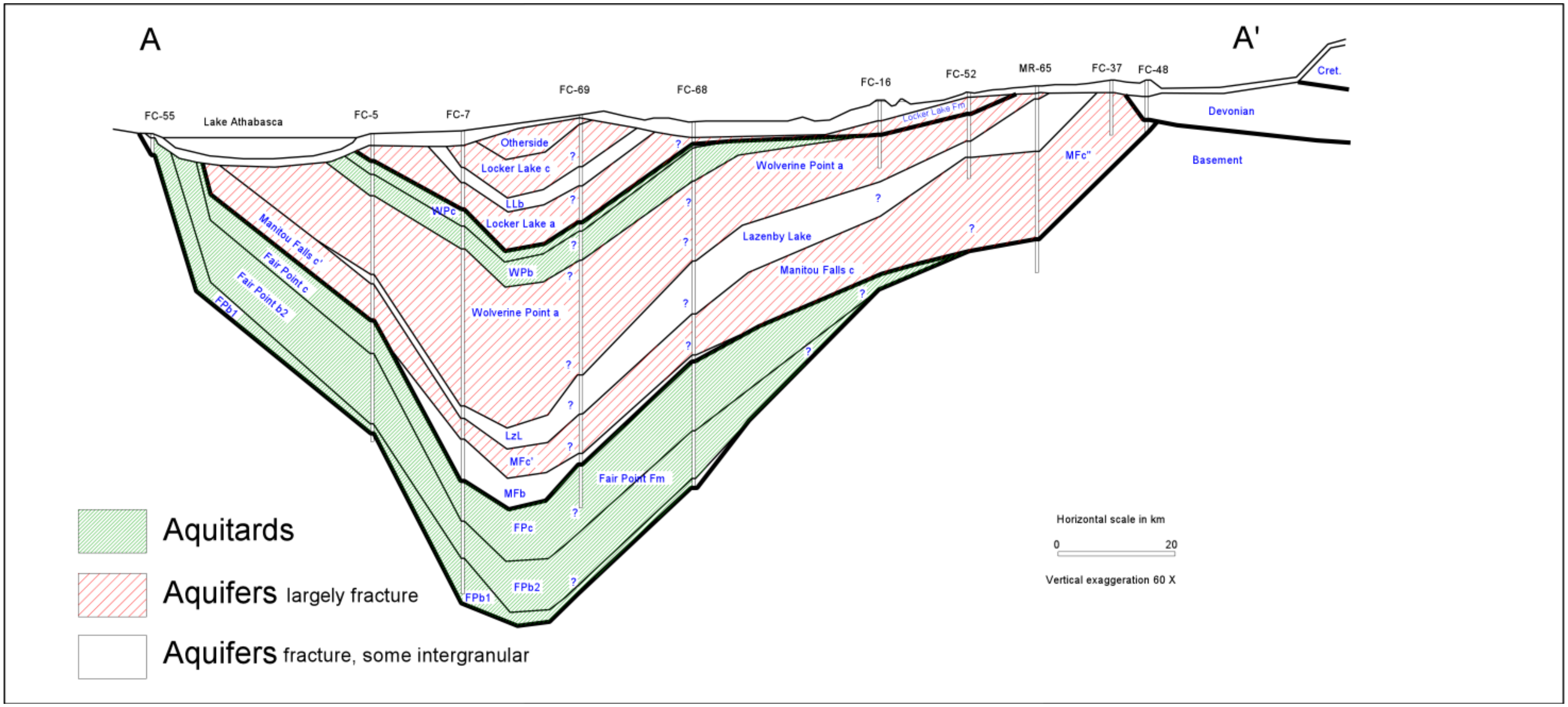


Figure 46. Late aquifers and aquitards in the Athabasca Basin; shown along section A-A'.

The early permeability persisted until compaction and the precipitation of hematite and syntaxial quartz overgrowths. The isotopic evidence indicates that this occurred at a temperature of around 130º C, and likely only after deposition of the entire Athabasca Group, no later than about 60 Ma after the deposition of Sequence 3. With the formation of diagenetic clays the strata that contained labile detrital minerals (Fair Point and WPb and c) probably lost some of their permeability. The sandy strata similarly lost porosity and permeability due to quartz cementation and compaction. The degree to which permeability was lost was complex judging by present permeability in the Athabasca Group sandstones. The degree of compaction was a factor in the extent to which permeability was altered by the diagenetic clays. Compaction served to squeeze the clay pseudomorphs into neighbouring pores and seal them. Thus, partial silica cementation might serve to prevent or slow further compaction and preserve some permeability in diagenetic clay rich sandstones. Lithification of the sandstone also permitted the development of fracture porosity and permeability.

Quartz dissolution at peak diagenesis increased permeability, in some (quantitatively small) areas leading to total disaggregation of the sandstone. In Alberta the variable nature of the permeability of the Athabasca Group sandstones is shown by their penetration in the southern third of the Alberta Athabasca Basin by hydrocarbons during the Phanerozoic, probably the Cretaceous. The oil at present varies from fairly light (only stains left in the core boxes), to thick heavy oil, which are the most common, to areas where only solid tarry materials are left in pores. Evidently the oil was lighter at time of introduction into the basin. In most areas it penetrated only along fractures and a few cm into the adjacent sandstone, presumably areas of sandstone with microscopic fracturing induced by the stresses that caused the fracture itself. Most noticeably in the coarser parts of the Locker Lake, Lazenby Lake and Manitou Falls b units the permeability at this time was great enough to permit complete saturation of the rock in some areas. It is noteworthy that no oil-saturated areas are found in the Fair Point Formation. This unit only shows oil stains along a few fracture zones. In many instances, these oil stains are the only evidence that a fracture is present. Despite the low permeability of the Fair Point Formation, oil penetrated many tens of metres into the crystalline basement along fractures, below considerable thicknesses of Fair Point Formation. A very generalized estimate of the areas of late permeability within the Athabasca Group sediments at present is given in Figure 46.

9 Uranium Mineralization Potential of the Athabasca Group in Alberta

The following is an outline of the implications of the stratigraphic data and the history of development of the Athabasca Basin in Alberta on the potential for uranium mineralization in the area. It is not intended as a study of unconformity orebodies or a review of exploration methods for uranium. The location of uranium mineralization in the Athabasca Basin region is shown in Figure 47. A discussion of the Hudsonian tectonism in the eastern part of the Athabasca Basin and the basement faulting hosting the uranium orebodies may be found in Portella and Annesley (2000). This discussion focuses on the post-Athabasca Group reactivation of such structures.

9.1 Characteristics of Unconformity Uranium Deposits

Many of the uranium unconformity orebodies have structural characteristics in common. These include:

1) Their location at major pre-Athabasca Group basement structures.
2) The reactivation of these structures after deposition of the Athabasca Group.
3) Repeated reactivation of these structures.
4) Emplacement of the oldest uranium ores after deep burial.
5) Variety of movements on the faults. These include early (syndepositional) normal movement and generally late reverse and/or normal movement in post-Athabasca Group times.

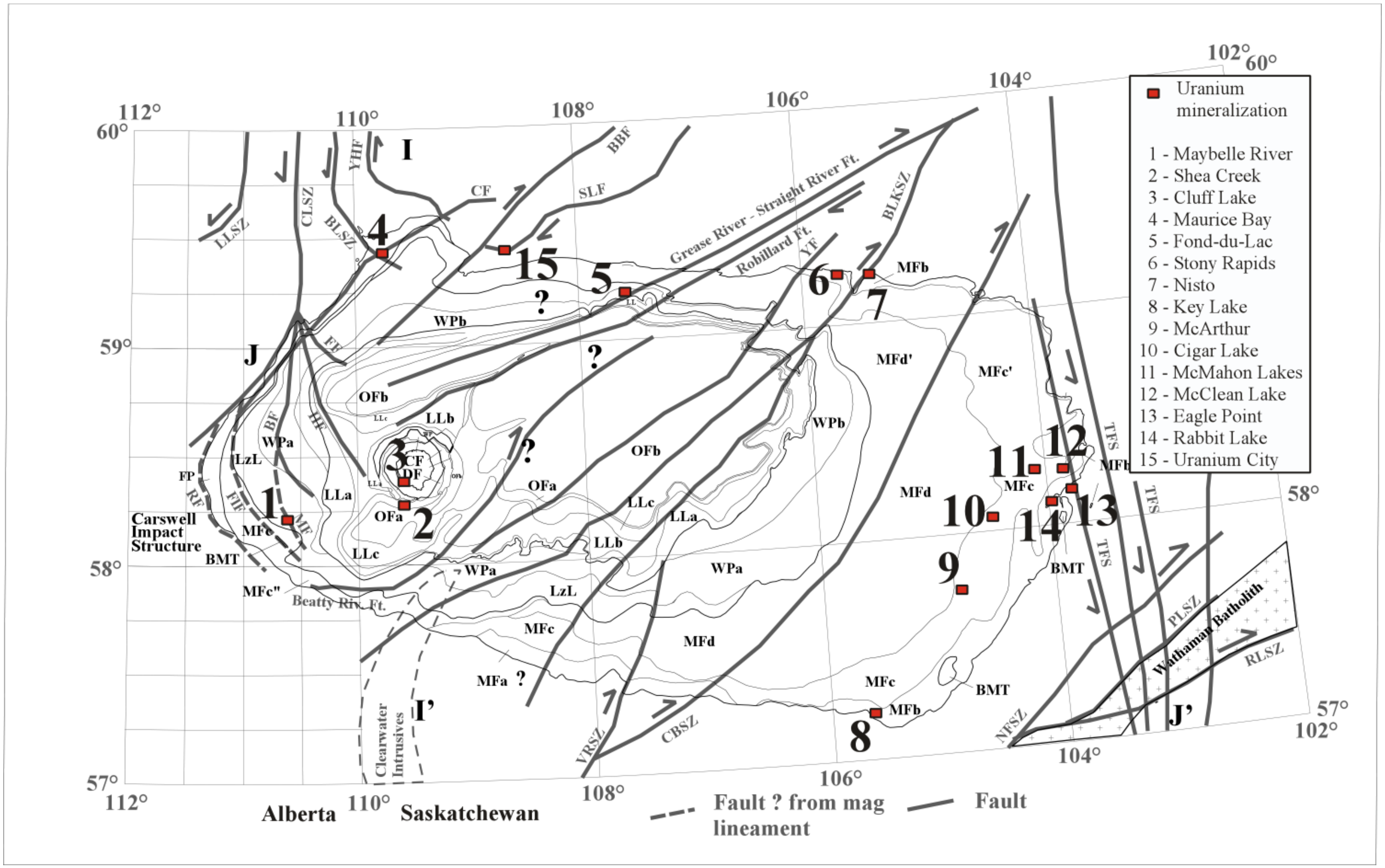


Figure 47. Uranium mineralization in the Athabasca Basin

6) Minor net movement along orebody faults. Despite the repeated movements only small net offsets in the order of tens of meters are present along the faults.
7) The major orebodies are found in structures parallel to the basin margins.

There are two major primary ore types: a simple U-Pb pitchblende ore, found in the earliest generation of mineralization (1600-1500 Ma; Cumming and Krstic, 1992) and the much more common and later polymetallic U-sulphides-arsenide ores (1380-1320 Ma) including significant amounts of Ni, Co, As, Cu, Zn and pyrite.

Athabasca Basin orebodies are found along major shear zones (Maurice Bay, some of the orebodies in the Uranium City camp, Fond-du-Lac, Stoney Rapids). The major orebodies are often in faults parallel to the basin margin (e.g., Key Lake, Cluff Lake, McArthur, Rabbit Lake, Eagle Point); these faults may show both reverse and normal movement.

The oldest ore was emplaced between 1600 and 1500 Ma at the McArthur orebody, and seems to have been free of the Ni arsenides that are common in younger orebodies. Three further episodes of widespread primary ore emplacement and/or remobilization occurred at 1380-1330 Ma, about 1270 Ma, and at 1100-900 (Cumming and Krstic, 1992). These ores were reworked a number of times with peaks at 575 and 225 Ma.

The later three ages of primary ore formation coincide with sediment deposition in a number of basins in western Canada.

Many of the structural features held in common by the major unconformity uranium orebodies occurring at reverse faults may be explained by reactivation of the fault systems during episodes of basin deepening and unroofing. Development of a basin involves repeated minor movement at the basal unconformity with initial normal and later reverse movements as the basin deepens and is later unroofed. Such pressures preferentially reactivate existing faults oriented perpendicular to the direction of stress, i.e. often parallel to the basin edge in case of reverse faults, and reactivate the shallower dipping deeper parts of the fault preferentially. They tend to generate new and flatter faults in the sandstone at the basal unconformity (Letouzey et al., 1990). This is the pattern documented by Tourigny (2002) in the Sue C pit of the McLean deposit in Saskatchewan.

Uranium orebodies often occur at the intersection of several shear zones. At Maurice Bay splays of the Charles Lake Shear Zone intersect with the Bayonet Lake Shear Zone and a set of parallel faults that align with the Charlot Fault and form the western margin of the Athabasca Basin (Figure 3). In the Cluff and Shea Creek areas mineralization occurs intermittently along a northwest trend in the area where the Harrison Fault intersects prominent northeasterly faults that are splays from the South Robillard fault system (Figure 3). Note that the northwest trending mineralization in the Cluff area has been displaced to the northeast about 13 km by the collapse of the meteor impact crater.

9.2 Regional Structural Patterns

The Athabasca Basin is located at the intersection of the distal splays of major crustal scale wrench faults (Figures 2 and 3) many of which originated in the Archean or early Paleoproterozoic and have a long history of reactivation. Note that on Figures 2 and 3 the more distal ends of these faults were not drawn because at the scale of the map it would lead to illegibility, some of these are shown on a map by Alonso et al. (1985). In the Alberta part of the Athabasca Basin the main fault systems are:

1) Charles Lake and related shear zones (Bayonet Lake, Yatsore-Hill island) at the west side of the Jackfish Basin. These are northerly trending largely sinistral wrench fault systems, with prominent splays curving to the southeast forming releasing bends that generated the Nonacho and Thluicho Lake Groups.

2) Black Bay and parallel faults: northeasterly trending dextral fault systems. This may include the Charlot Fault. The Martin Group was deposited in releasing bends along these faults. The Charlot and Black Bay faults border the Black Bay Trough of the Jackfish Basin.

3) Grease River-Straight River, Robillard, Beatty River faults and their splays. These form the eastern side of the Jackfish Basin, encompass the Mirror Basin, and flank the Patterson, Bartlett and Dufferin Highs that partitioned this basin after it formed. All of these faults are related to or are splays of the fault system separating the Hearne and Rae Provinces: the Snowbird Tectonic Zone.

Subsidence patterns along these faults suggest that in post Athabasca Group times many of these faults formed the margins to half-grabens showing only minor displacement.

9.2.1 Splays of the Charles Lake Shear Zone: The Fidler, Harrison, Bustard, Maybelle, Fletcher and Richardson Faults

The splays of the Charles Lake Shear Zone in the southern half of the Athabasca Basin have not been studied in detail. North of Lake Athabasca they are marked by prominent topographic lineaments easily traceable at the 1: 250,000 scale NTS maps. Drilling in the Maurice Bay area shows that the faults of these splays have seen post-Athabasca Group movement in the order of 50 m of apparent vertical displacement (Harper, 1996).

Topography and offsets in the shoreline at Fidler Point indicates the presence of several splays from the same shear zone, here named the Fidler, Harrison, Bustard, Maybelle, Fletcher and Richardson faults (Figure 3).

The Fidler Fault is indicated at Fidler Point by the inflection of outcrop patterns to the northwest. The large difference in thickness of the Athabasca Group between ddh FC-005 and FC-007 may be due to displacement along the Fidler Fault.

The Harrison Fault originates as a splay of the Charles Lake Fault Zone at the same point as the Fidler and Bustard Faults. An inflection of the Lake Athabasca shoreline suggests its presence just south of the Fidler Fault (Figure 3). Farther to the south it marks the discontinuity in magnetic field pattern between north trending basement to the west and southwest trending basement to the east, and curves to the south-southeast. The presence of the fault may a reason for the northwesterly trend of the Harrison River along much of its course. It meets the Carswell structure at its southwestern side. In this area the direction of dike emplacement and the drainage direction of the Douglas River may have been affected by it (Lainé et al. 1985, map).

The Bustard Fault is indicated and mapped (but not named) by Wilson (1985) on the north shore of Lake Athabasca. Its projection intersects Burntwood Island where tilted outcrops of Athabasca Group sandstones are mapped by Wilson (1985) and fractures with apatite cement have been found in drillcore from ddh FC-009 (Wilson, 1985). Both the tilted sandstone and the apatite filled fractured characterize the vicinity of fault zones along much of the northern side of the Athabasca Basin. Aeromagnetic maps suggest that this fault flanks the southwest side of a prominent northwest trending magnetic high, and curves to the southeast. At the south shore of Lake Athabasca a group of channels of the Athabasca River (Goose Island, Big Point, and Tokyo Snye channels) indicate a topographic low that may mark faultweakened bedrock, and the course of the Bustard Fault. It may terminate at the north side of the Beatty Trough, and possibly intersect the distal ends of splays of the South Robillard Fault.

A magnetic lineament splays from the Bustard Fault at the southern end of the Athabasca River channels mentioned above, and trends to the south. This is here named the Maybelle Fault. Basement topography (Figure 3) suggests that the Maybelle Fault lies along the northeastern side of a basement topographic high. Reverse faulting and intense hydrothermal alteration has been found at a number of points along the Maybelle Fault, for example at ddh MR-39 and MR-71.

The Fletcher Fault is marked by topographic lows along the southwest shore of Lake Athabasca and a train of lakes to the south and may connect to a magnetic lineament subparallel to the Maybelle Fault. Basement topography (Figure 3) suggests that it forms the southwestern edge of the basement ridge of which the Maybelle Fault marks the northeastern side.

The southwestern edge of the Athabasca Basin is marked by a very prominent magnetic discontinuity that suggests a fault contact, here named the Richardson Fault. It parallels the splays of the Charles Lake Shear Zone to the northeast, and forms the last of this series.

9.2.2 The Charlot Fault and Basin Margin Faults of the Northwestern Athabasca Basin

The Charlot Fault is subparallel to the Black Bay Fault and borders the Charlot Point Formation of the Martin Group near Charlot Point on the north shore of Lake Athabasca (Figure 2). On line with this fault is a prominent series of parallel faults intersected in drillholes at Maurice Bay (Figures 3 and 47), where apparent vertical offsets of over 100 m are recorded in the Athabasca sandstone (Harper, 1996). These displacements contribute to the very steep basin slope of the northwestern margin of the Athabasca Basin and indicate that this margin is largely a fault contact. Whether the post-Athabasca Group faulting along the western margin of the basin is a rejuvenation of the Charlot Fault remains to be proven, as little data are available between Maurice Bay and Charlot Point.

9.2.3 Black Bay Fault

The Black Bay Fault (Figures 2 and 3) is a northeast trending Archean fault that has been reactivated a number of times during its development (Bergeron et al., 2002). Topographic relations, areal extent of the Fair Point Formation (Figure 3) and the isopach of the Fair Point Formation (Figure 8) indicate that it was active during or after deposition of the Fair Point Formation. The magnetic field patterns suggest that the fault terminated against the Taltson domain beneath the Alberta side of Lake Athabasca.

9.2.4 Grease River-Straight River Fault

The Grease River - Straight River Fault forms a prominent southwest trending topographic lineament where it is exposed north of Lake Athabasca in Saskatchewan. It can be traced into the Athabasca Basin where it deflects formational boundaries near Fond-du-Lac (Figure 47) and may be traced as far as the Saskatchewan-Alberta border by a series of lake trains. It appears to underlie the central part of the long axis of the Lillabo Trough.

9.2.5 Robillard Faults

A series of faults parallel the Grease River-Straight River Fault to the southeast. The most prominent of these is the Robillard Fault, which runs along the southeast margin of a trough (Lillabo Trough) south of Fond-du-Lac, and may be traced by lake trains to the Carswell area as the North Robillard Fault. A fault parallel and farther to the southeast of it is here referred to as the South Robillard Fault (Figure 3). Lake trains suggest that it splays northeast of the Carswell structure. These branches may be traced through the Carswell structure; the northern one may form the northern boundary of the Beatty Trough southwest of the Carswell structure, and the southern one appears to flank a northeast trending high in the Beatty Trough indicated by formational boundaries, based on grain size.

9.2.6 Beatty River Fault

The Beatty River Fault follows a major ductile shear zone in the basement rocks shown on magnetic field maps. The traces of the Mackenzie dikes are offset where they cross the Beatty Fault, indicating that the fault was a zone of weakness at the time of dike intrusion, well after deposition of the preserved Athabasca Group sediments. The fault borders areas of uplift of the Locker Lake Formation, indicating that it was active after deposition of Sequence 4.

9.3 Uranium Mineralization in the Athabasca Group Sandstones

Many of the major shear zones are mineralized where they enter the Athabasca Basin, not uncommonly at intersections of several shear zones; examples are:

1) Splays of Charles Lake Shear Zone and Bayonet Lake SZ at Maurice Bay where they intersect with a fault system on line with the Charlot fault.

2) 1500 Ma mineralization in the Martin Group at Uranium City (Black Bay and Saint Louis faults).

3) Grease River-Straight River Fault at Fond-du-Lac.

4) Black Lake Fault at Nisto, and a parallel fault at Stoney Rapids.

Mineralized areas also occur at the intersection of shear zones within the Athabasca Basin. In the Cluff Lake-Shea Creek area a 30 km belt of mineralization is present in the area where a splay of the Charles Lake SZ (the Harrison Fault) and the Robillard Faults intersect (Figures 2 and 3).

Mineralization also has developed where faults lie along margins of Athabasca Group sub-basins. Examples are:

1) Black Bay, Charlot faults: these delimit the Black Bay Trough, and both have uranium deposits along them.

2) Bayonet Lake, Charles Lake Shear Zone: these delimit the western side of the Jackfish and predecessor basins, and have a uranium orebody at their intersection.

3) Grease River-Straight River, N. Robillard faults: these faults delimit the Lillabo Trough, with the Fond-du-Lac mineralization along the Grease River-Straight River fault.

4) Beatty River, S. Robillard faults: these delimit the Beatty Trough. Splays of the Robillard faults run through the Cluff mining camp.

5) Harrison Fault: The differential subsidence of the Mirror Basin appears to be bounded by the Harrison Fault in the Cluff-Shea Creek area of Saskatchewan during much of the deposition of Sequences 3 and 4 (Figures 17, 19, 21, 24 and 25). This is the site of a series of uranium unconformity orebodies and shows that extend over 30 km along this structural zone.

Mineralization in some of the largest orebodies in the eastern part of the Athabasca Basin occurs along reactivated faults that parallel the strike of basement units where this is parallel to the basin edge. Examples of this in and near Alberta are:

1) Maybelle River trend. Mineralization and alteration are present along the Maybelle Fault.

2) Shea Creek

9.4 Areas With Uranium Exploration Potential

These observations on structure and basin development patterns suggest that the following areas within Alberta may have good exploration potential:

1) Fidler Point area: it is basin marginal, at a place where splays of the Charles Lake Shear Zone enter the Jackfish Basin and intersect the basin marginal faults much as at Maurice Bay.

2) The trace of the Harrison Fault. The area near the Carswell Structure may be uplifted somewhat just outside the Carswell Structure.

3) The trace of the Maybelle Fault and its projection to the southeast bordering the Beatty Trough.

4) The trace of the Fletcher Fault (equivalent to the “Net Lake Trend” of Post, 2003) and its projection to the southeast bordering the Beatty Trough.

5) The intersection of the Maybelle and Fletcher and Robillard trends, at the edge of the Beatty Trough.

6) Margins of the Richardson Trough: it may be a late tensional feature, and the main ore emplacements occurred in a time when the regional stresses were tensile (rifting and continental breakups).

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