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Evidence for Early Pleistocene Glaciation from Borecore Stratigraphy in North-Central Alberta

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L.D. Andriashek[1] and R.W. Barendregt[2]

[1] Alberta Energy Regulator
Alberta Geological Survey
[2] University of Lethbridge
Geography Department

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Author addresses:
René W. Barendregt
Alberta Water & Environmental
Sciences Building
University of Lethbridge
4401 University Dr
Lethbridge, Alberta T1K 3M4
barendregt@uleth.ca

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

Tel: 780.638.4491
Fax: 780.422.1459
E-mail: AGS-Info@aer.ca
Website: ags.aer.ca

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Abstract

Borecores collected from Quaternary sediments in north-central Alberta, Canada, were sampled and studied for paleomagnetic remanence characteristics. A magnetostratigraphy has been established for sediments previously assumed to represent multiple continental (Laurentide) glaciations but for which no geochronology was available. Based on the Quaternary record elsewhere in Alberta and Saskatchewan, it was thought that some of these sediments were deposited during pre-late Wisconsinan glaciations. The Quaternary sedimentary succession of north-central Alberta attains thicknesses up to 300 m within buried valleys and is composed of diamict interbedded with glaciolacustrine and outwash sediments. Most of the sampled units are not accessible from outcrop and their sedimentology and stratigraphy is derived from core data only. In 4 of 16 borecores sampled to date, diamict that correlates with the Bronson Lake Formation till is reversely magnetized, indicating an Early Pleistocene age. Depending on location, this formation is underlain by either Empress Formation sediments or Colorado Group shales, and is overlain by one or more normally magnetized glacigenic sedimentary units of the Bonnyville, Marie Creek, and Grand Centre formations, respectively. This new record of Early Pleistocene glaciation in north-central Alberta places the westernmost extent of earliest Laurentide ice at least 300 km farther west than its previously established limit in the Saskatoon and Regina regions of the Canadian Interior Plains, but still to the east of the maximum extent of the late Wisconsinan (Late Pleistocene) Laurentide Ice Sheet, which extended into the foothills of the Alberta and Montana Rocky Mountains.

1 Introduction

While late Neogene paleoclimate records depicting isotopic evidence of Pleistocene glaciations (Lisiecki and Raymo, 2005) are well known from cores of ocean-floor sediments, the timing and extent of Early Pleistocene glaciations in the western Canadian portion of the Interior Plains are poorly constrained, apart from sites in southwestern Alberta and northern Montana (summarized in Cioppa et al., 1995, and Karlstrom and Barendregt, 2001), where well-developed paleosols separate Cordilleran tills of both reversed and normal polarities, and sites from Saskatchewan (Barendregt et al., 1998, 2012), where dated tephras (fission track ages) constrain the earliest glaciation in Saskatchewan to the Early Pleistocene.

This study forms part of a broader examination of glacial deposits in northwestern North America to better define the ages and extent of Laurentide glaciations during the Pleistocene (Barendregt and Duk-Rodkin, 2011; Barendregt, 2011). Although the ages and extent of Late Pleistocene continental glaciations in the western Canadian Interior Plains are relatively well constrained, they are less well defined for the Middle and Early Pleistocene. With improved age control, glacial deposits can be assigned to the appropriate cold peaks of the global marine oxygen isotope record.

Multiple tills underlie much of the Canadian Interior Plains, but few opportunities exist for dating these deposits. Most fall outside the range of ^{14}C dating, and few outcrops expose the older Pleistocene record. Paleomagnetic measurements of samples collected from unoriented borecores drilled in buried valleys and adjacent uplands provide an opportunity for correlation of sediments with the global polarity time scale. Where till magnetostratigraphy can be combined with other geochronological controls (e.g., tephrochronology, exposure dating, and paleontology), glacial events can be placed in a time-stratigraphic framework (Barendregt and Irving, 1998; Balco et al., 2005; Jennings et al., 2007; Balco and Rovey, 2008; Barendregt and Duk-Rodkin, 2011). In this report we present paleomagnetic data from five borecores in which the lowermost sediments were assumed to be pre-Illinoian (pre-Saalian) but for which no geochronology was previously available (Barendregt et al., 2014).

2 Location and Physiography of the Study Area

The study area is located in north-central Alberta, Canada, between 54°–57° N latitude and 110°–116° W longitude (Figure 1, Figure 2). The physiography of the area (regional relief) ranges from 550 to 800 m above sea level (asl). The areas of higher relief include bedrock uplands with thin sediment cover as well as areas of exceptionally thick sediment that rise above the regional landscape. In places, buried bedrock valleys are infilled with up to 300 m of fluvial and glacial sediment (Atkinson and Lyster, 2010a, b; Andriashek, 2003). Of the sixteen borecores sampled (Appendix 1), five record the most complete till stratigraphy found to date (Figure 2, yellow symbols). Other borecores reveal a less complete record or did not reach to the base of the glacial deposits. Three of the five borecores reported here are located in uplands composed of thick sediment overlying the buried Wiau Valley (borecores WEPA99-1, WEPA00-1, WEPA00-3; Andriashek, 2003). Borecore WEPA99-2 is located in a lowland above a thickly-filled buried valley (Amesbury Valley; Andriashek, 2003), and borecore BHH02-11 is located on a bedrock upland surface (Buffalo Head Hills) which is overlain by a relatively thin sediment cover (Fenton et al., 2006).

Figure 1. Location of the study area in Alberta, Canada (yellow box). Pink stars indicate major cities.

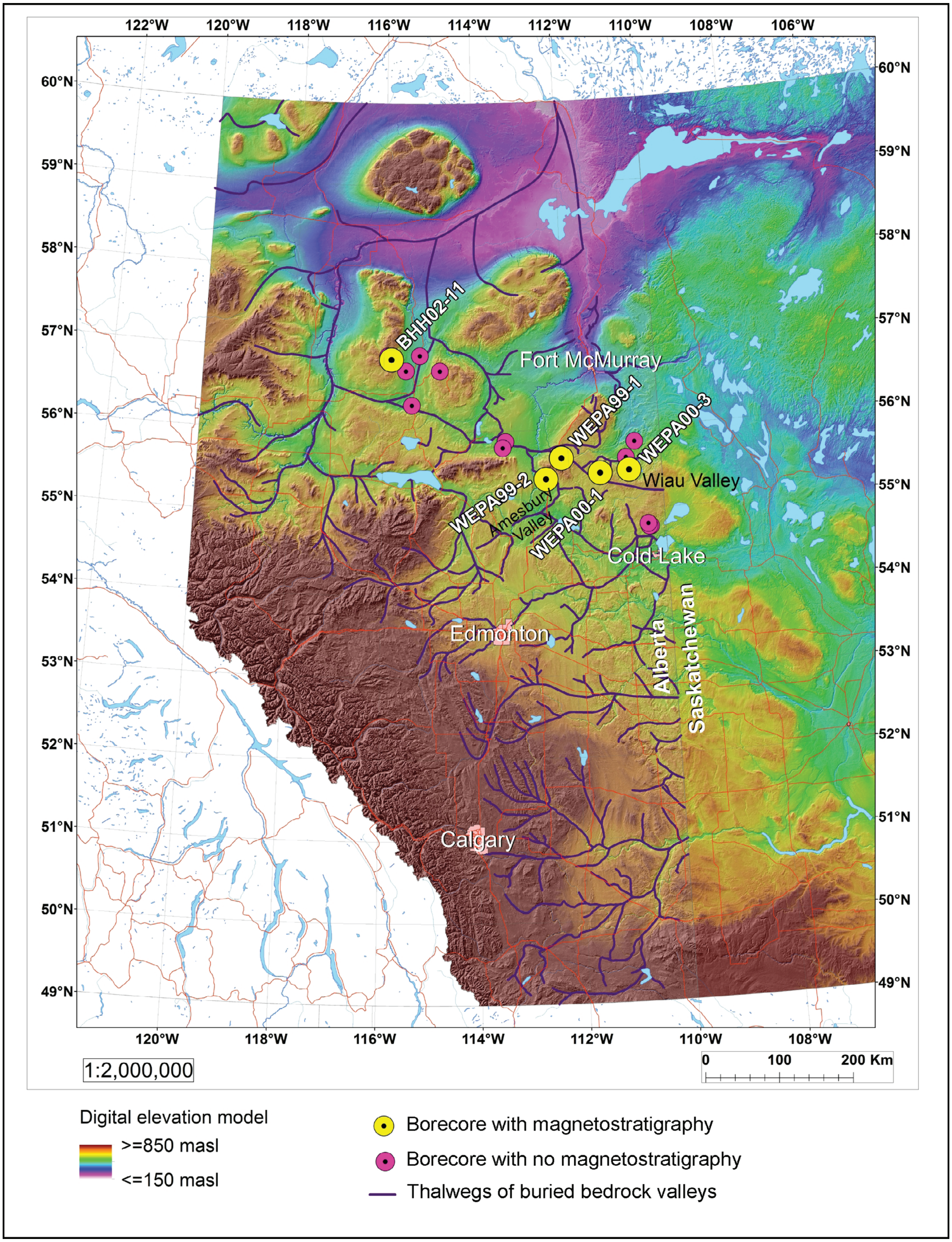

Figure 2. Location of borecores sampled for magnetostratigraphy superposed on a digital elevation model.

3 Paleomagnetic Sampling and Analyses

3.1 Background

Between 1995 and 2005, the Alberta Geological Survey (AGS) collected cores of near-surface (~150 m) sediment as part of its characterization of the geology and hydrogeology of north-central Alberta and analyzed sediments for diamond indicator minerals. Cores were collected using a variety of drilling methods, including wet-rotary and hollow-steam auger, down to depths of as much as 180 m. None of the cores were referenced with respect to azimuthal direction, so only the vertical orientation is known. In addition to descriptive lithologs and downhole geophysical logs, a suite of analyses including grain size, matrix carbonate, and geochemistry were conducted on core subsamples to develop a lithostratigraphic framework. The results of these investigations, including the development of a stratigraphic model for east-central Alberta, have been reported in previous studies (Andriashek and Fenton, 1989; Andriashek and Parks, 2002; Fenton et al., 2003; Andriashek, 2003). Borecores are currently archived and stored in Alberta Energy Regulator's (AER's) Mineral Core Research Facility in Edmonton, where samples from sixteen borecores, including cores submitted by the energy industry, were recently evaluated for paleomagnetic measurements.

Paleomagnetic sampling intervals were determined based on previously defined lithostratigraphic units (Andriashek, 2003). Matrix carbonate content, occurrence of buried oxidized weathered horizons, and geophysical electric log responses were used to differentiate and correlate units between borecores (Andriashek and Fenton, 1989; Andriashek and Parks, 2002; Andriashek, 2003), similar to the criteria used to correlate lithostratigraphic units east of the study sites in Saskatchewan (Christiansen, 1992). The lowermost tills (Bronson Lake Formation and Bonnyville Formation Unit 1 and Unit 2) contain relatively low carbonate content (Figure 3; Andriashek and Fenton, 1989; Andriashek, 2003) and are differentiated primarily on the basis of differences in electrical log response (the Bronson Lake Formation having a lower response than either of the Bonnyville Formation tills) and the occurrence of weathered profiles on unit surfaces (Andriashek and Parks, 2001; Andriashek, 2003). In many places the tills are separated by stratified sediment. The uppermost two tills (Marie Creek and Grand Centre formations) are characterized by relatively higher carbonate content than the lowermost tills noted above (Andriashek and Fenton, 1989; Andriashek, 2003). Paleosols, tephras, or datable organic materials were not found in the borecores analyzed in this study.

3.2 Sampling Procedures

Borecores are unoriented with respect to azimuthal direction; however, vertical orientation is known. It is assumed that cores were correctly oriented with respect to vertical (downhole) direction during boxing and storage. Some cores that were slabbed with a water-cooled rock saw were found to be unsuitable for paleomagnetic sampling because of a slurry coating on the slabbed face, which could not be removed without disaggregating the core segment.

The matrix of tills in north-central Alberta is dominated by silt and clay-sized grains (Andriashek and Fenton, 1989; Andriashek, 2003), resulting in cores which, in a dry state, are very hard and consolidated (Figure 4a and b). We inspected core for any visible evidence of disturbance or deformation imparted during the coring process and avoided sampling such intervals. Sediments were sampled using polycarbonate cylinders (of standard paleomagnetic rock specimen dimensions, 2.5 cm diameter, 2.2 cm length) inserted over core stubs made with a portable drill (Figure 4c and d). Four to six samples were collected in a vertical sequence, each approximately 5 cm apart, from selected depth intervals within each of the major stratigraphic units. Samples were taken only from fine-grained sediments, including diamicts (interpreted as till) and stratified sediments, avoiding coarse grains and pebbles where possible. We also looked for consistency in sediment characteristics, which would be expected for samples from a single diamict unit. The lowermost (oldest) diamict units, in contact with either preglacial sediments (Empress Formation) or bedrock (upper and mid-Cretaceous formations), were sampled in more closely spaced intervals (see Appendix 1 for sample depths in each borecore). Previous work carried out to the east of this study area, in Saskatchewan, revealed the lowermost till to be reversely magnetized, and therefore in this study reversely magnetized lower units would not be unexpected. Thick units (>10 m thickness) were sampled at two or more intervals, with more frequent sampling (3 or 4 intervals) conducted in the Bronson Lake and Bonnyville formations to establish polarity boundaries within the sedimentary succession. Sediments that yielded low quality or incoherent data were discarded and new samples were obtained from nearby sections within the core. In a few cases, resampling improved the results.

3.3 Paleomagnetic Measurements

Paleomagnetic remanence measurements were made at the University of Lethbridge using an AGICO JR6-A spinner magnetometer. Stepwise alternating field demagnetization in peak fields up to 200 millitesla (mT) was carried out using a D-2000 ASC high performance AF demagnetizer. Samples were typically demagnetized at 5, 10, 20, 30, 40, 50, 60, 70, 80, and for some samples, 90 and 100 mT steps until all the magnetization was essentially destroyed through AF demagnetization. Sample remanence directions were determined by principal component analysis (Kirschvink, 1980). Magnetic susceptibility and anisotropy measurements were made with an SI-2B Sapphire Instruments susceptibility meter.

Late Neogene and Quaternary Stratigraphic Units, East-Central Alberta

Carbonate content	Formation
	Recent surficial sediment
Moderate	Grand Centre Formation - Till
	Sand River Formation - Stratified sediment
High	Marie Creek Formation - Till
	Ethel Lake Formation - Stratified sediments
Low	Bonnyville Formation Unit 2 - Till Unit 1- Till and stratified sediment
	Muriel Lake Formation - Stratified sediments
Low	Bronson Lake Formation - Till
	Empress Formation Unit 3 Coarse stratified sediment Unit 2 Fine stratified sediment Unit 1 Coarse stratified preglacial sediment

Figure 3. Late Neogene and Quaternary units in north-central Alberta based on the stratigraphic framework established in previous studies (Andriashek and Fenton, 1989; Andriashek and Parks, 2002; Andriashek, 2003). Tills of the Bonnyville and Bronson Lake formations are characterized by a lower carbonate content compared to that of the overlying Marie Creek and Grand Centre formations.

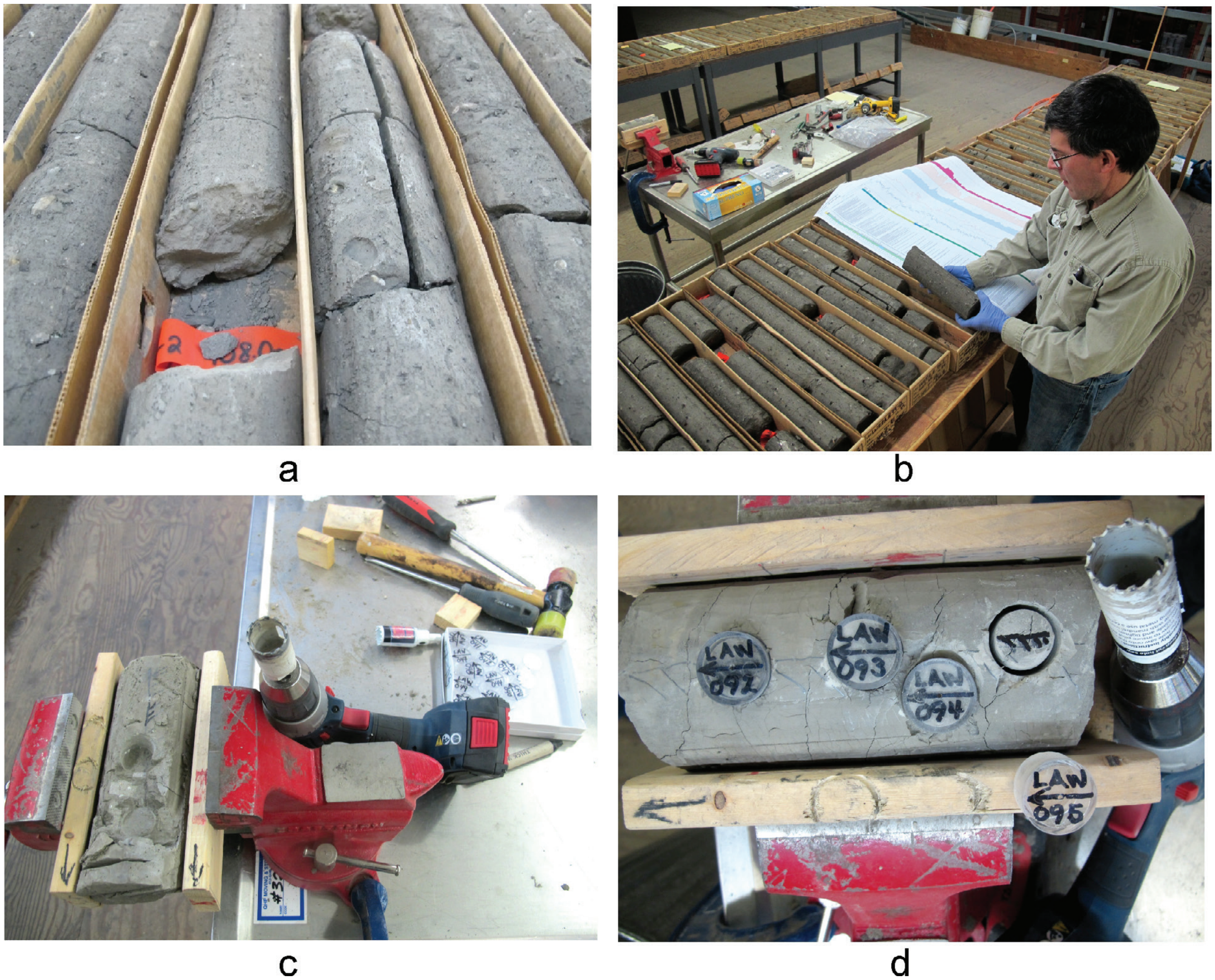

Figure 4. Paleomagnetic sampling procedure: (a) close-up of dry, consolidated sediment archived in core boxes; (b) selecting 7.5 cm diameter representative core segment on which a downhole direction has been marked (WEPA99-2); (c) extraction of 2.5 cm diameter stubs using hand-held drill and circular steel bit (note downhole direction indicated by arrows on wooden cauls and on sediment); (d) insertion of labelled plastic cylinders into stubs of core (WEPA99-2).

4 Paleomagnetic Results

4.1 General Observations

The polarity data for all 323 samples obtained from the sixteen borecores are listed in Appendix 1. In this study we report results from five borecores that provide the most extensive Quaternary stratigraphic record. Four of the five borecores yield reversely magnetized sediments in the lower units. Of the 196 samples that were collected from the five borecores, 137 (70%) gave coherent results. Based on previous paleomagnetic studies of tills, up to 50% of samples may be rejected as a result of weak or unstable magnetizations or incoherent remanence directions held by randomly oriented sand-sized grains or pebbles within the sample (Barendregt et al., 1991, 1998). In this study, 59 samples, not restricted to any particular unit, gave low quality or incoherent results. Low quality data were generally associated with very weakly magnetized sediments (low magnetic susceptibility values), and incoherent data with coarser grained particles exhibiting multidomain magnetizations, often yielding bedding plane directions. Where sediment grains are predominantly coarse (i.e., sand-sized or greater), mechanical energies outweigh the aligning influence of the geomagnetic field on ferromagnetic particles (Butler, 1992).

4.2 Characteristic Remanent Magnetization

The majority of samples (83%) were collected from diamicts previously interpreted as tills, and the remainder from fine-grained fluvial and lacustrine deposits. Magnetic susceptibility of the sediments ranges from 2.0×10^{-5} to 1.0×10^{-3} SI units/vol (median = 2.0×10^{-4} SI/vol). Most samples reveal magnetizations typical of magnetite, likely derived from source rocks located in the Canadian Shield to the northeast. Median destructive fields for magnetite-bearing sediments typically range from 30 to 60 mT. The demagnetization data for coherent samples typically reveal a single high coercivity component so that directions were fit using principal component analysis of lines that were forced through the origin of orthogonal plots. Normal and reversed magnetizations occur in four of the sixteen borecores sampled, and polarities can be assigned to all of the sampled units. For the sampling latitude of this study (~55.5°N), positive inclinations indicate normal polarity of Earth's magnetic field at time of deposition and "lock-in" of remanence directions, while negative inclinations indicate reversed polarity.

Figure 7 provides examples of orthogonal plots of well-behaved normal and reverse polarity after alternating field demagnetization. It should be noted that the declination values for the stereographic and orthogonal plots are unoriented because samples were taken from cores for which only a downhole direction is known. Arithmetic means for normal and reversed inclinations are provided in Table 1. The mean inclination values were adjusted through block-rotation Fisher analysis of unoriented core segments (Enkin and Watson, 1996) and provide values of −49° for reversed samples, and +48° for normal samples Inclination flattening is observed in many of the samples (Figure 7c and d) and occurs in both normal and reversed units. Inclination flattening has been reported in many borecore sediments, especially tills (Verosub, 1977; Verosub et al., 1979; Roy et al., 2004; Barendregt, 2011; Barendregt et al., 2012). The geocentric axial dipole (GAD) field for sampling latitude 55.5°N has an inclination of 71°, therefore a mean inclination of 49° suggests an average flattening of 22°.

4.3 Borecore WEPA00-3

Borecore WEPA00-3 is the easternmost borecore reported in this study and is located at 650 m asl in an upland composed of thick sediment above a bedrock interfluve that separates two buried bedrock valleys, the Wiau and Christina valleys (Figure 2 and Figure 5; Andriashek, 2003). The hole was drilled to a depth

Reverse: 69 samples, 41 core segment azimuths

Block-Rotation Fisher Analysis: **−48.6°±4.6°, *k*=8.1** Mean Inclination only: **−46.2°±4.4°, *k*=11.4**

Normal: 68 samples, 43 core segment azimuths

Block-Rotation Fisher Analysis : **48.1°±3.7°, *k*=13.5** Mean Inclination only: **48.1°±3.7°, *k*=13.5**

All: 137 samples, 84 core segment azimuths

Block-Rotation Fisher Analysis: **48.4°±3.0°, *k*=10.1** Mean Inclination only: **47.1°±2.7°, *k*=12.5**

Table 1. Arithmetic mean of inclinations from unoriented borecores. Methodology described in Enkin and Watson (1996).

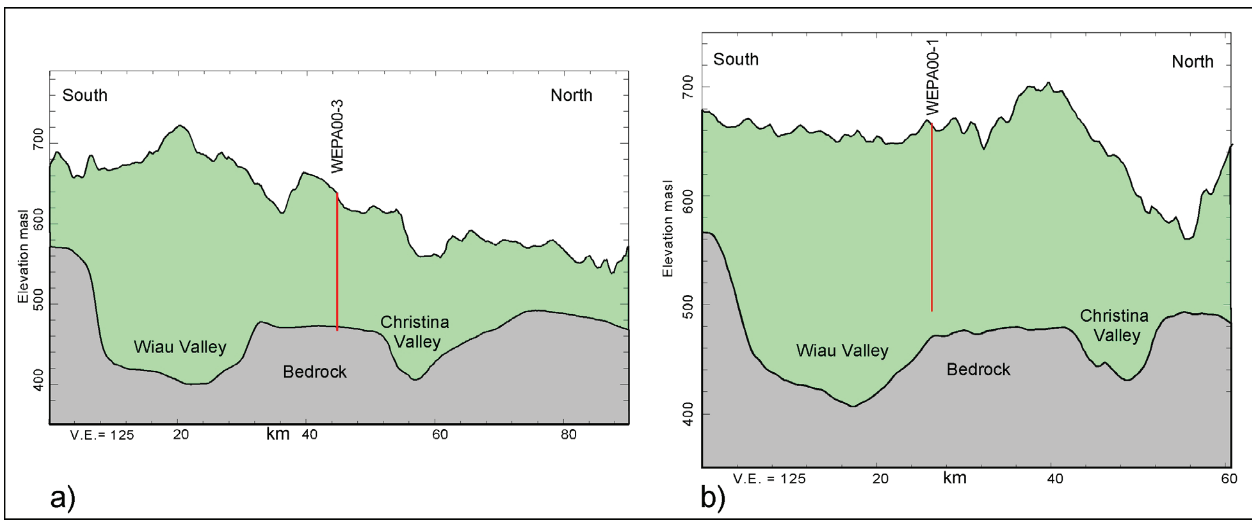

Figure 5. Physiographic setting of borecores WEPA00-3 and WEPA00-01. Borecore WEPA00-3 (a) is located above a bedrock interfluve that separates the Wiau and Christina valleys. Borecore WEPA00-1 (b) is located above the northern margin of the Wiau Valley, about 40 km west of WEPA00-3. Sediment thickness exceeds 180 m at both locations.

of about 182 m where it terminated a few metres into Colorado Group shale (Figure 6a). From top down, the Quaternary stratigraphy at this site is characterized as follows:

- 78 m of relatively high-carbonate till (Marie Creek Formation);
- 12 m of low-carbonate, highly resistive till (Bonnyville Formation Unit 2), the top of which has a weathered, oxidized profile;
- 55 m of low-carbonate and low-resistive till and minor stratified sediment (Bonnyville Formation Unit 1);
- low-carbonate, low-resistive till containing numerous shale clasts (Bronson Lake Formation); and
- 25 m fluvial sand and gravel (Empress Formation) containing granitic and metamorphic clasts from the Canadian Shield, resting on Colorado Group shale.

Samples for paleomagnetic measurements were collected at twelve intervals, between core depths of 40 m to 152 m (Figure 6a). The three lower sampling intervals (between 147 and 152 m), all within the Bronson Lake Formation, are reversely magnetized and exhibit shallow inclination values, presumably due to flattening during sediment dewatering and compaction (Figure 7). Normal polarities are recorded in all of the overlying formations, with inclination values in the Bonnyville Formation close to the expected GAD field for the sampling latitude (~71°, Figure 7).

4.4 Borecore WEPA00-1

Borecore WEPA00-1 was obtained at 668 m asl from an upland comprising 195 m thick sediment above the northern flank of the buried Wiau bedrock valley, about 40 km west of borecore WEPA00-3 (Figure 2 and Figure 6). The borehole was drilled to a depth of about 174 m where it terminated in glacigenic sediment (till). From top down, the stratigraphy is characterized as follows:

- 15 m of high-carbonate till (Marie Creek Formation);
- 7 m of stratified sediment (Ethel Lake Formation);
- 15 m of low-carbonate till (Bonnyville Formation Unit 2), the top of which is oxidized, overlying about 45 m of stratified sediment and 70 m of low-carbonate till and minor stratified sediment (Bonnyville Formation Unit 1); and
- 23 m of low-carbonate Bronson Lake Formation (Figure 6b).

Eleven intervals, between core depths of 25 m and 174 m, were selected for paleomagnetic sampling, of which the bottom five samples (between 154 m and 174 m) are reversely magnetized. All reversely magnetized samples are from the low-carbonate till of the Bronson Lake Formation, the top of which is defined by a lower resistivity log response at a depth of 150 m (517 m asl, Figure 6b). One sample interval within the Bronson Lake Formation (interval LAW166-169) gave incoherent results. Normal polarities were obtained for the Marie Creek and Bonnyville formations, with two intervals revealing incoherent results for sandier beds of the Bonnyville Formation Unit 1 (Figure 6b).

Inclination values for both normal and reversed polarities range between 33° and 61° (Figure 8). These values are shallower than the expected GAD inclination of 71°, again suggesting some flattening during dewatering and compaction of sediments.

4.5 Borecore WEPA99-1

Borecore WEPA99-1 is located about 50 km west of borecore WEPA00-1, directly north of the May Hills bedrock highland (Figure 2 and Figure 9). The borehole is located at 661 m asl within an upland directly above the southern flank of the buried Wiau bedrock valley (Figure 9a). It was drilled to a depth of about

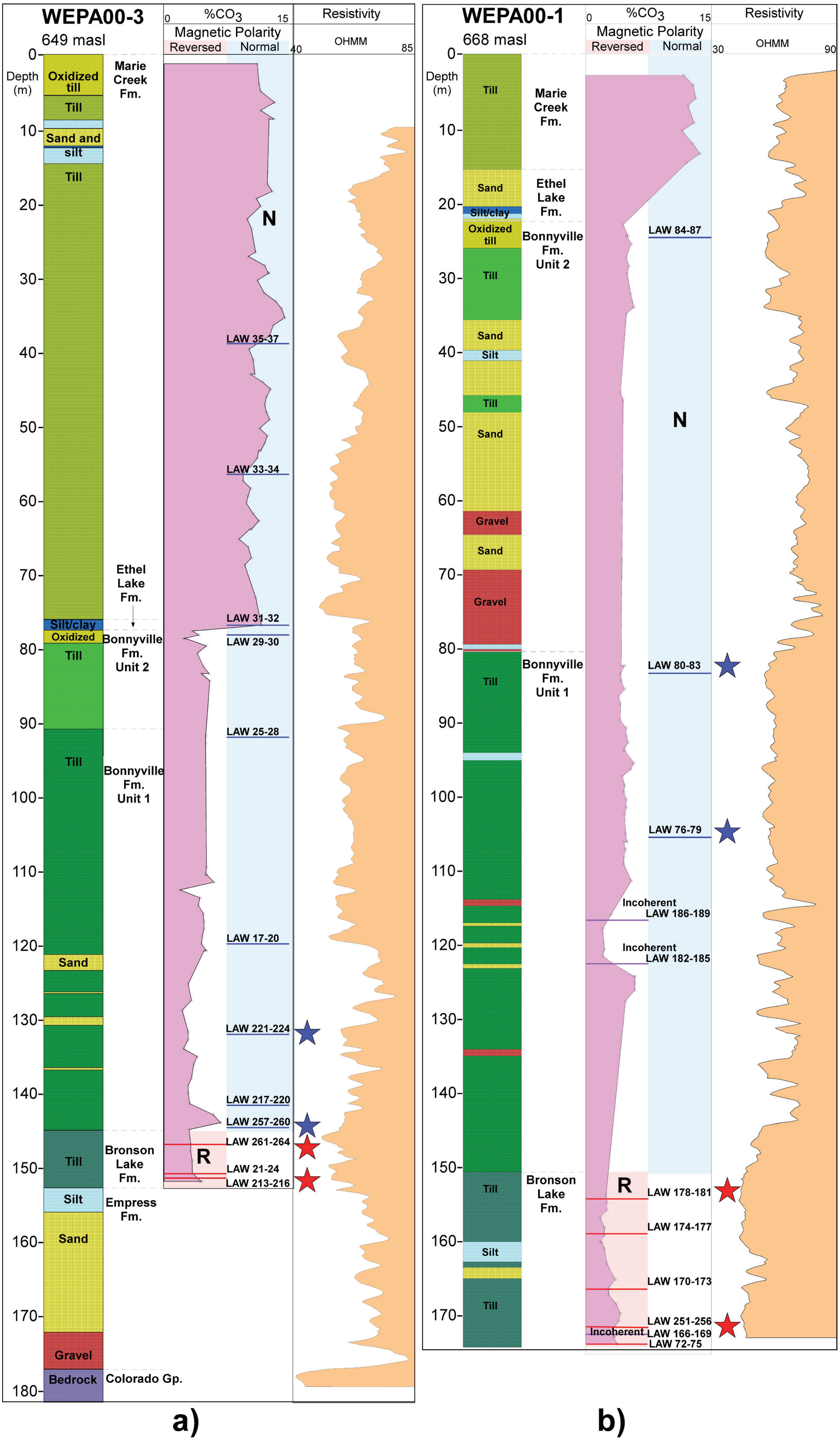

Figure 6. Stratigraphic interpretation of borecores WEPA00-3 (a) and WEPA00-1 (b) based on lithological, geochemical, geophysical, and paleomagnetic properties (stratigraphy reinterpreted from Andriashek, 2003). Reversed polarity values (red bars) in the lowermost part of the sequence differentiate low-carbonate till of the Bronson Lake Formation from normal polarity (blue bars), low-carbonate tills of the overlying Bonnyville Formation. Blue (normal), and red (reversed) bars denote downhole locations of sampling intervals. Stars are sampling horizons from which representative samples are shown in Figure 7.

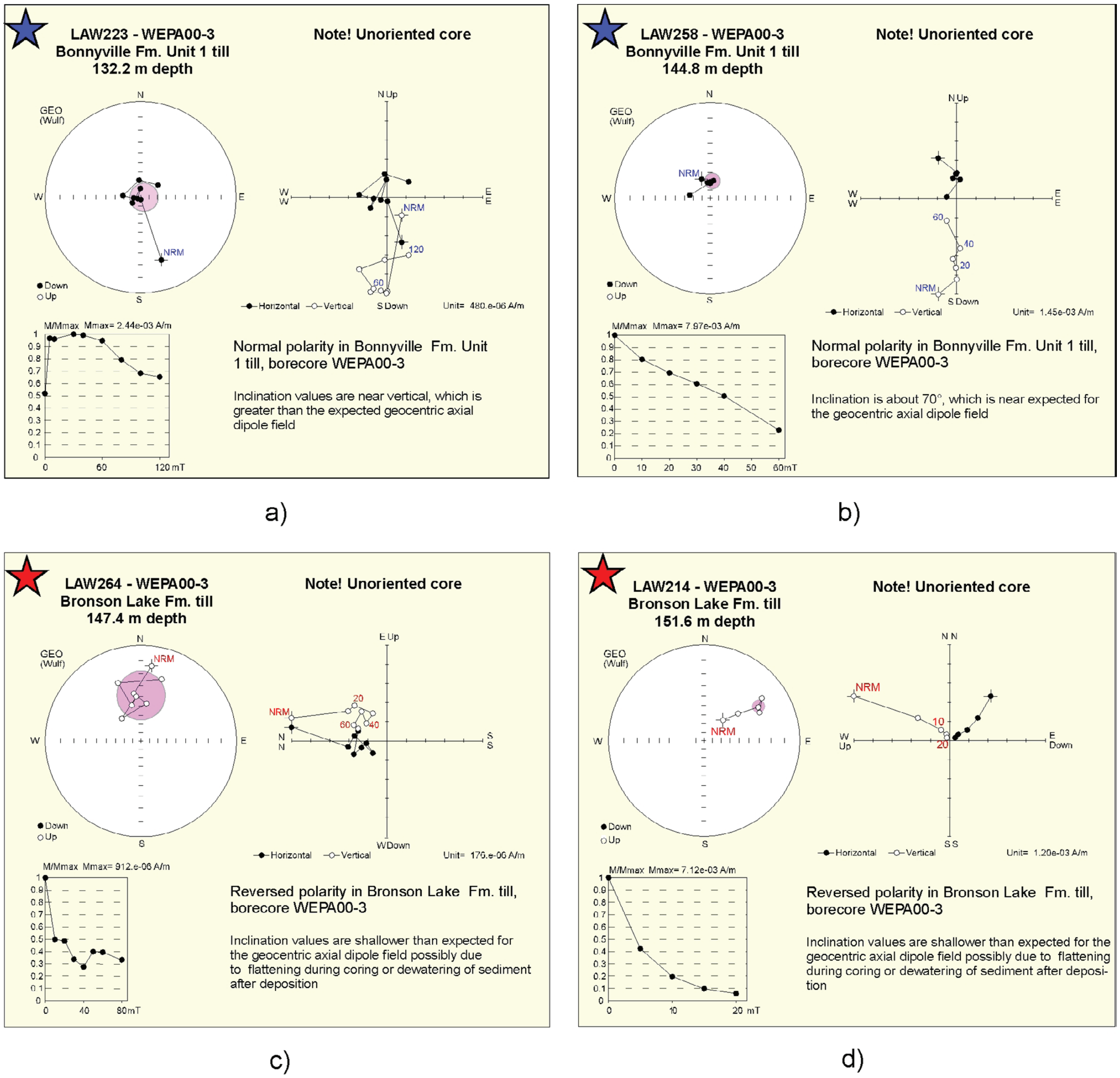

Figure 7. Representative stereographic and orthogonal plots of polarity data from WEPA00-3. The orthogonal plots on the right of each figure show horizontal and vertical projections of each demagnetization step with closed or open circles, respectively. Inclination (vertical projection) is upward (normal polarity) in (a) and (b), shown by open circles below the horizontal axis, and is downward (reverse polarity) in (c) and (d). Stereographic plots (on left) show the magnetization direction at each step, where solid circles (open circles) lie on the lower (upper) hemisphere. Shaded circles are the maximum angular deviation (MAD) of the directions determined through principal component analysis (PCA) (Kirschvink, 1980). Core is unoriented with respect to azimuth, therefore declination values are not used. Coloured stars denote sample locations on magnetostratigraphic log (Figure 6a). NRM = natural remanent magnetization; A/m = amperes per metre; mT = millitesla.

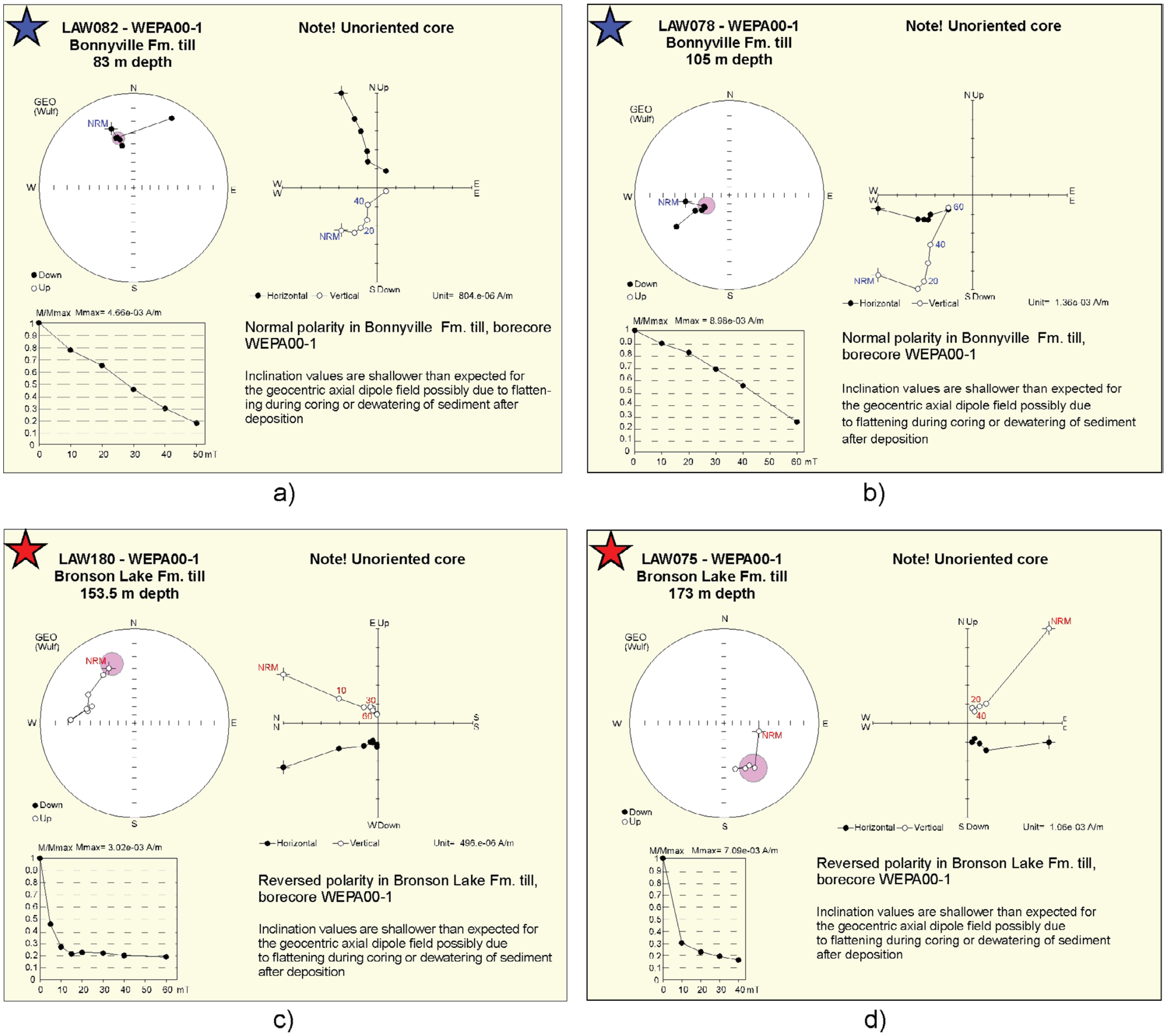

Figure 8. Representative stereographic and orthogonal plots of polarity data for normal ([a] and [b]) and reversed ([c] and [d]) samples from borecore WEPA00-1. Legend as in Figure 7. Coloured stars denote sample locations on magnetostratigraphic log (Figure 6b).

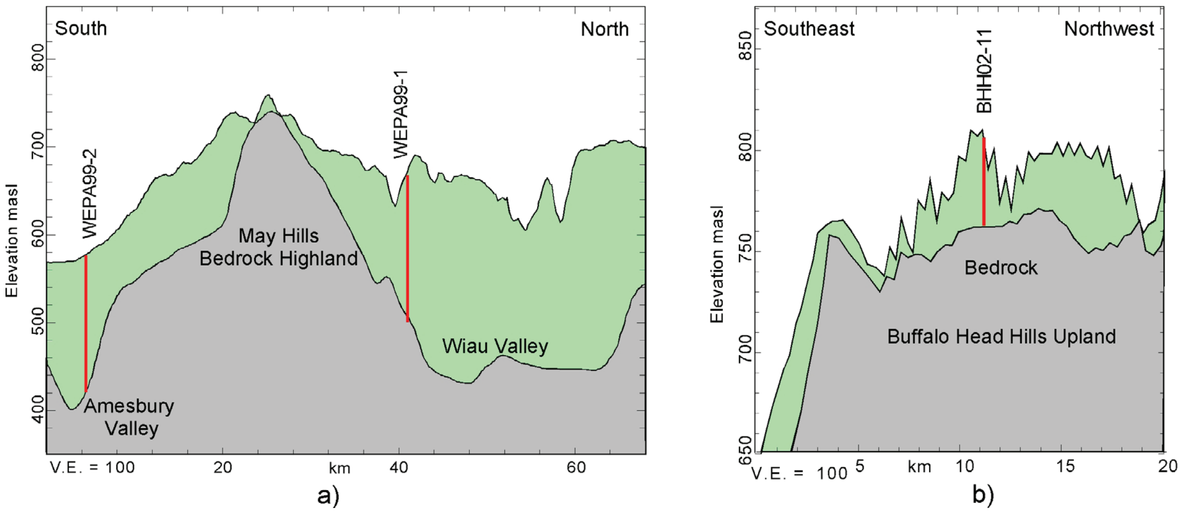

Figure 9. Physiographic setting of borecores WEPA99-1 and WEPA99-2 (a) and borecore BHH02-11(b). Borecore WEPA99-1 is located in an area of thick sediment on the southern margin of the buried Wiau Valley, north of the May Hills bedrock highland. Borecore WEPA99-2 is located in a lowland where thick sediment has infilled the buried Amesbury Valley, located on the south side of the May Hills bedrock highland. In contrast, borecore BHH02-11 is located in an area of relatively thin sediment above the Buffalo Head Hills bedrock upland, situated approximately 260 km to the northwest.

168 m where it terminated in Colorado Group shale (Figure 10a). Sediment thickness at this location is about 155 m.

From top down, the stratigraphy can be summarized as follows:

- 18 m of Holocene stratified sediment;
- 43 m of moderate-carbonate till (Grand Centre Formation);
- 39 m of high-carbonate till (Marie Creek Formation), the top of which is highly oxidized (Figure 11); and
- about 54 m of low-carbonate till formerly interpreted as Bonnyville Formation (Andriashek, 2003), now reinterpreted as the Bronson Lake Formation based on paleomagnetic data.

Sixteen intervals were selected for paleomagnetic sampling, spanning core depths of 70–154 m (Figure 10a). Normal polarities were obtained for the Grand Centre and Marie Creek formations, with one incoherent interval near the base of the Marie Creek Formation (LAW162-165). Eight intervals with reversed polarity are recorded within the Bronson Lake Formation, including one interval of incoherent data (LAW145-148).

Inclination values for both normal and reversed polarity intervals reveal a range from shallow (24°, Figure 12c) to near-expected GAD values of 69° (Figure 12b,d).

4.6 Borecore WEPA99-2

Borecore WEPA99-2 is located about 35 km southwest of borecore WEPA99-1 and is on the opposite side of the May Hills Highland (Figure 2 and Figure 9a). The site is located at 583 m asl on thick sediment above the buried Amesbury bedrock valley (Figure 2). The borehole was drilled to a depth of 161 m and intersected Colorado Group shale at a depth of about 158 m (Figure 10b; Andriashek, 2003).

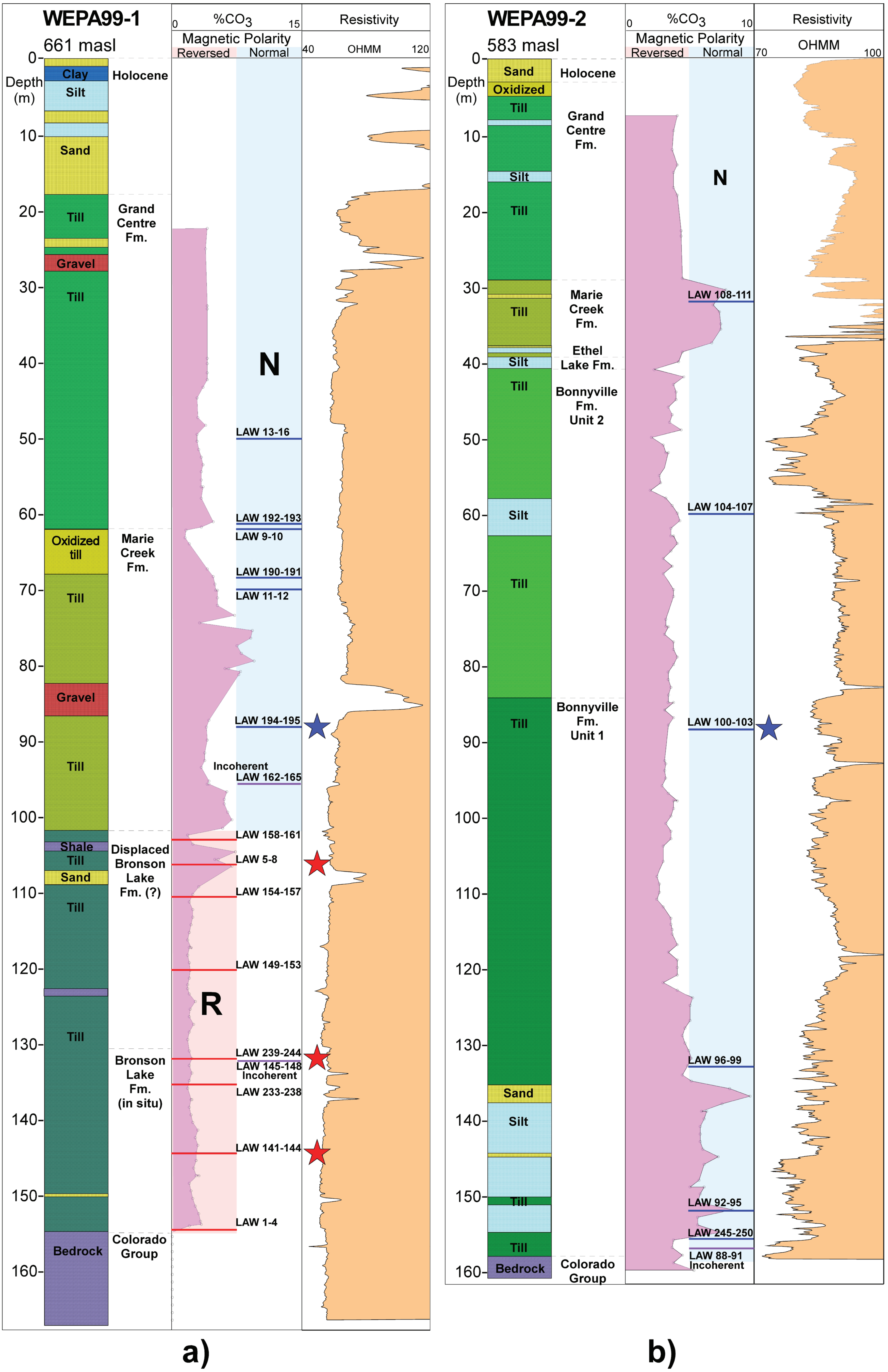

Figure 10. Stratigraphic interpretation of borecores (a) WEPA99-1 and (b) WEPA99-2 based on lithological, geochemical, geophysical, and paleomagnetic properties of sediments. Blue (normal) and red (reversed) bars denote downhole locations of sampling intervals, and stars are sampling horizons from which representative samples are shown in Figure 12 and Figure 17.

Figure 11. Contact between unoxidized Grand Centre Formation till and oxidized, calcareous Marie Creek Formation till at 61 m depth in borecore WEPA99-1. Both tills are normally magnetized.

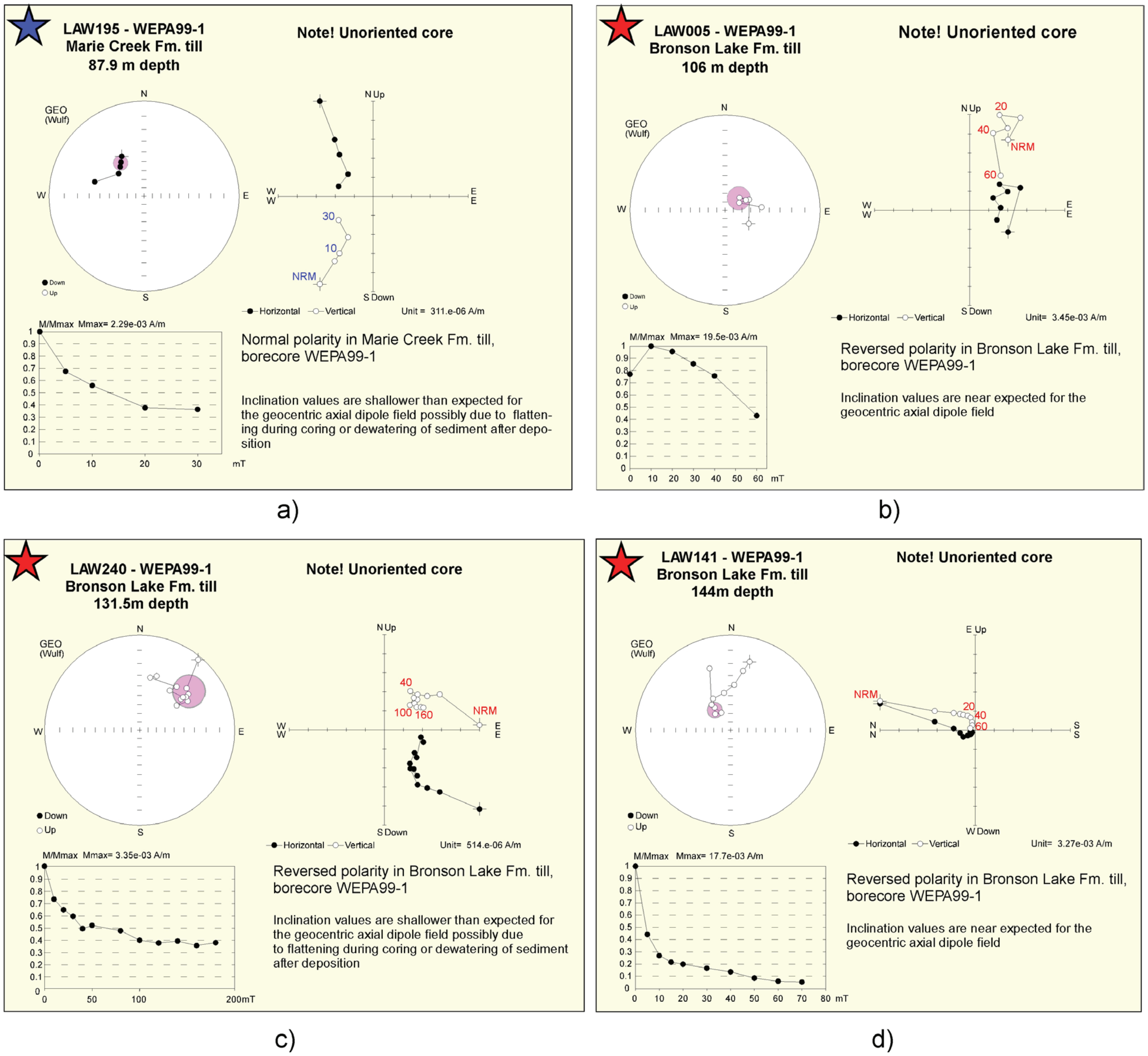

Figure 12. Representative stereographic and orthogonal plots of polarity data from borecore WEPA99-1. The orthogonal plots on the right of each figure show horizontal and vertical projections of each demagnetization step with closed or open circles, respectively. Inclination (vertical projection) is upward (normal polarity) in (a), shown by open circles below the horizontal axis, and is downward (reverse polarity) in (b), (c), and (d). Stereographic plots (on left) show the magnetization direction at each step, where solid circles (open circles) lie on the lower (upper) hemisphere. Shaded circles are the maximum angular deviation (MAD) of the directions determined through principal component analysis (PCA) (Kirschvink, 1980). Core is unoriented with respect to azimuth, therefore declination values are not used. Coloured stars denote sample locations on magnetostratigraphic log (Figure 10a). NRM = natural remanent magnetization; A/m = amperes per metre; mT = millitesla.

From top down, the stratigraphy can be summarized as follows:

- 3 m Holocene fluvial sediment;
- 26 m till (Grand Centre Formation);
- 10 m high-carbonate till (Marie Creek Formation);
- 1.6 m of stratified sediments (Ethel Lake Formation);
- 43 m low-carbonate till (Bonnyville Formation Unit 2);
- 51 m low-carbonate till (Bonnyville Formation Unit 1);
- 21 m contorted silt and diamict (Bonnyville Formation Unit 1); and
- 2 m of low-carbonate till resting on shale, also interpreted as Bonnyville Formation till.

Seven intervals, spanning a depth from 32 to 157 m, were selected for paleomagnetic sampling. Of these, the upper six intervals recorded normal polarity. The lowermost sampling interval (Figure 10b) at 157 m depth was collected from a low-resistivity, low-carbonate till consistent with the properties of either the Bonnyville Formation Unit 1, or the Bronson Lake Formation in other borecores. Paleomagnetic samples from this depth interval (LAW 088-091) provided incoherent results.

Inclinations for normal and reversed polarity samples range between 35° and 50° (Figure 13) and are generally shallower than the expected GAD value of about 71°.

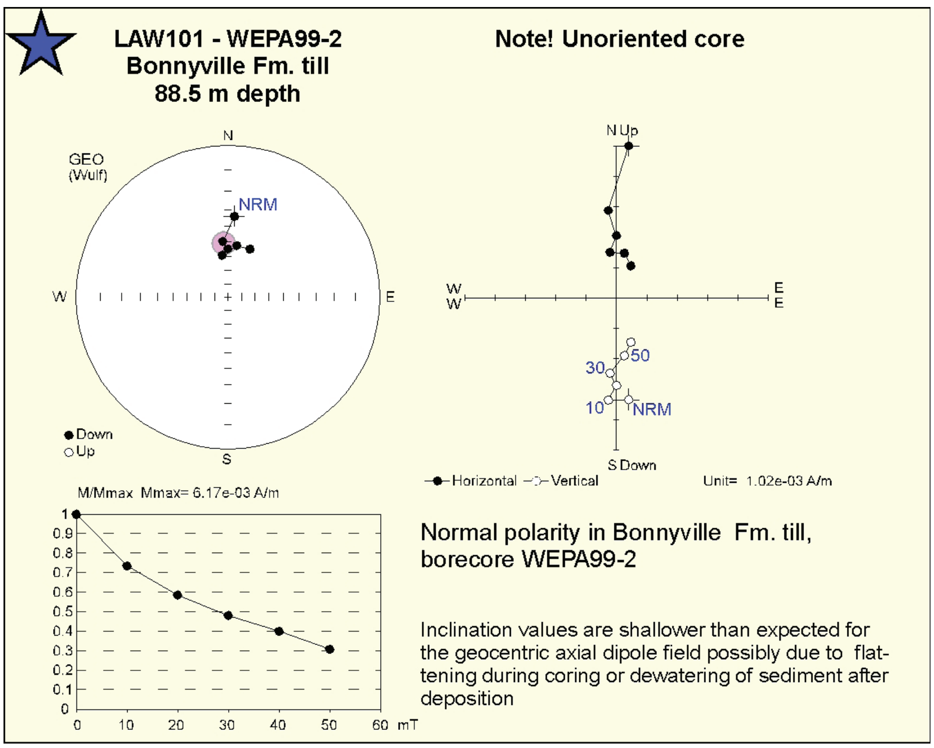

Figure 13. Representative stereographic and orthogonal plot of polarity data from borecore WEPA99-2. The orthogonal plot on the right of the figure shows horizontal and vertical projections of each demagnetization step with closed or open circles, respectively. Inclination (vertical projection) is upward (normal polarity), shown by open circles below the horizontal axis. Stereographic plot (on left) shows the magnetization direction at each step, where solid circles lie on the lower hemisphere. Shaded circle is the maximum angular deviation (MAD) of the directions determined through principal component analysis (PCA) (Kirschvink, 1980). Core is unoriented with respect to azimuth, therefore declination values are not used. Coloured star (blue) denotes sample location on magnetostratigraphic log (Figure 10b). NRM = natural remanent magnetization; A/m = amperes per metre; mT = millitesla.

4.7 Borecore BHH02-11

Borecore BHH02-11 is the westernmost sampling site, located about 265 km northwest of borecore WEPA99-1 and 365 km northwest of borecore WEP00-3, the easternmost site for which paleomagnetic data were obtained (Figure 2). Unlike the buried valley settings of the previously described four borecores, BHH02-11 is located in the Buffalo Head Hills, a bedrock upland where sediment thickness is generally less than 50 m (Figure 9b). The site occurs at 796 m asl, which is at least 120 m higher than the other borecore sites. The borehole was drilled and cored to a depth of 42 m, terminating in glacigenic sediment (Figure 14b).

From top to bottom, the stratigraphy comprises the following:

- 7.5 m of high-carbonate till (Marie Creek Formation);
- 4–10 m sand;
- 12 m unoxidized, bedded silt and clay; and
- 12 m of low-carbonate till (Figure 10b), the top of which has a well-developed oxidized profile (Figure 15).

Five intervals were selected for paleomagnetic sampling, between 22 and 41 m depth. Of these, the upper two are within the glaciolacustrine sediments and yielded normal polarity. The lower three sampling intervals record a reversed polarity, two within the oxidized till, and one within unoxidized till near the base of the unit (Figure 14).

Inclination values for normal and reversed polarity samples range between 47° and 56° (Figure 16), again, somewhat shallower than the expected GAD value of 71°.

5 Magnetostratigraphic Interpretation

Recently obtained paleomagnetic data has enabled a refinement of the Quaternary stratigraphy previously developed for the five borecore records that underpin the regional Quaternary stratigraphy of north-central Alberta (Andriashek, 2003; Fenton et al., 2006; Paulen and McClenaghan, 2014).

5.1 Borecore WEPA00-3

The addition of the paleomagnetic data provides a geophysical means to differentiate low-carbonate till of the Bronson Lake Formation from overlying low-carbonate tills in borecore WEPA00-3. Previous interpretations of the Bronson Lake Formation, based primarily on geophysical log responses, placed the top of the formation at 125 m depth, with a thickness of 25 m (Andriashek, 2003). The new data establishes the top of the Bronson Lake Formation at 145 m (503 m asl) where the change from reversed to normal polarity coincides with a decrease in electrical resistivity (Figure 6). This reduces the thickness of the formation at this location from 25 m (Figure 7.13 in Andriashek, 2003) to about 7 m.

5.2 Borecore WEPA00-1

Paleomagnetic data corroborates the previous identification and interpretation of the Bronson Lake Formation in borecore WEPA00-1 (Andriashek, 2003). The top of the formation is defined by a decrease in resistivity on the geophysical log, which also corresponds to the top of the reversed-polarity sequence in this core, as shown in Figure 6b.

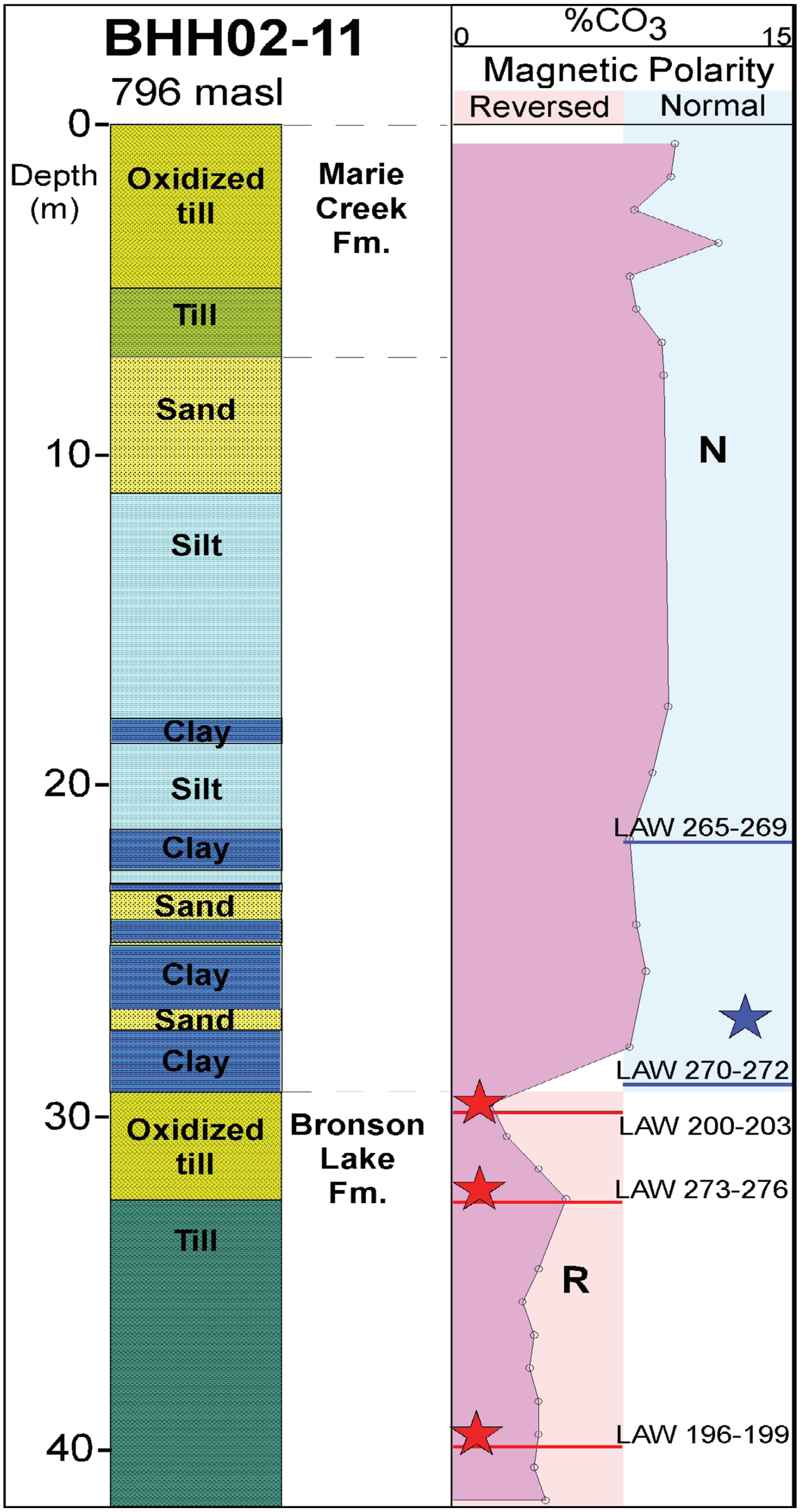

Figure 14. Stratigraphic interpretation of borecore BHH02-11 based on lithological, geochemical, and paleomagnetic properties of sediment. Blue (normal) and red (reversed) bars denote downhole locations of sampling intervals, and stars are sampling horizons from which representative samples are shown in Figure 16.

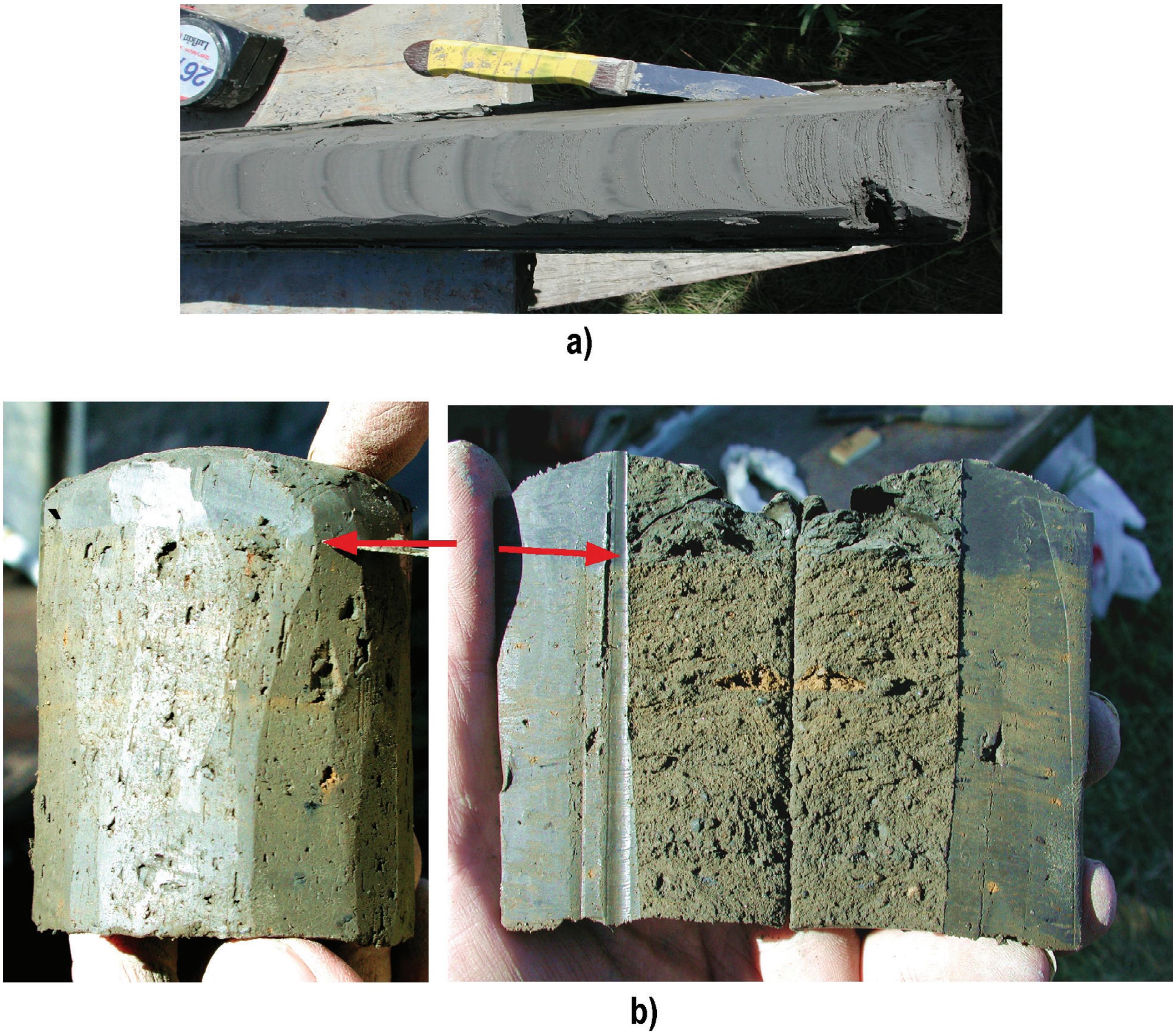

Figure 15. (a) Unoxidized glaciolacustrine silt and clay (normal polarity) at 20 m depth overlying yellow-brown till (reversed polarity) of the Bronson Lake Formation at 29.8 m depth (b), borecore BHH02-11. Change from grey to yellow-brown colour is interpreted as oxidation of iron-rich minerals in the till matrix (from Fenton et al., 2006, Figure 3a and b).

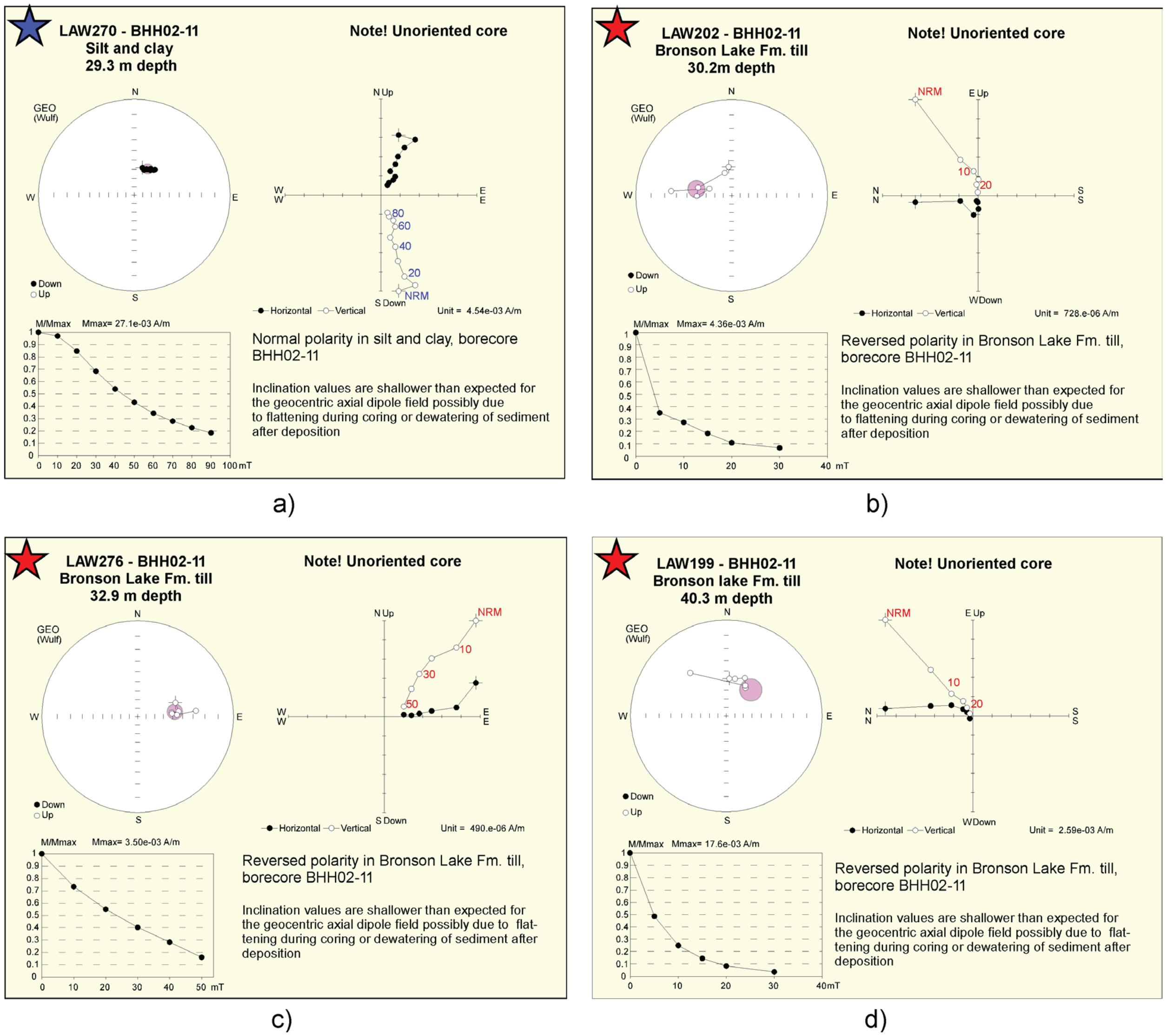

Figure 16. Representative stereographic and orthogonal plots of polarity data from borecore BHH02-11. The orthogonal plots on the right of each figure show horizontal and vertical projections of each demagnetization step with closed or open circles, respectively. Inclination (vertical projection) is upward (normal polarity) in (a), shown by open circles below the horizontal axis, and is downward (reverse polarity) in (b), (c), and (d). Stereographic plots (on left) show the magnetization direction at each step, where solid circles (open circles) lie on the lower (upper) hemisphere. Shaded circles are the maximum angular deviation (MAD) of the directions determined through principal component analysis (PCA) (Kirschvink, 1980). Core is unoriented with respect to azimuth, therefore declination values are not used. Coloured stars denote sample locations on magnetostratigraphic log (Figure 6b). NRM = natural remanent magnetization; A/m = amperes per metre; mT = millitesla.

5.3 Borecore WEPA99-1

Assuming that there is only a single till unit in north-central Alberta with reversed polarity, the incorporation of paleomagnetic data significantly changes the stratigraphic interpretation in borecore WEPA99-1 from that defined by Andriashek (2003). Based on reversed polarity, the thick unit of low-carbonate till below the Marie Creek Formation, previously defined as the Bonnyville Formation, is now interpreted as the Bronson Lake Formation. This places the top of the Bronson Lake Formation in this core at a depth of 101 m, or an elevation of about 560 m asl. It also means that the Bonnyville Formation, which is one of the thickest till units in the region, is conspicuously absent at this site.

There are some aspects of the till composition that make it difficult to establish the contact between the Bronson Lake Formation and the overlying Marie Creek Formation in this borehole. First, carbonate values in the upper 6 to 8 m of the Bronson Lake Formation are higher than in correlative tills in the other boreholes. Second, the resistivity log illustrates possible repeat cycles of coarsening-upward sediments, with a lower resistivity cycle between 154 m and 130 m depth (labelled as "in situ" in Figure 10a) overlain by a similar coarsening-upward cycle between depths 130 m and 101 m (labelled "displaced" in Figure 10a). Repetition of log signatures can reflect cyclicity in depositional processes but can also be evidence of the imbricate stacking of a single unit by glacial thrusting. Glacial thrusting and displacement of pre-existing sediment is also supported by field lithologs of the core in which high-angle beds of shale occur within the Bronson Lake Formation at depths of 105 m and 122 m (Figure 10a). Third, the paleomagnetic data are less coherent in the upper half of the formation, above a depth of 130 m, compared to the lower half, between 130 m and 154 m. All this suggests the possibility that a slice of glacially displaced Bronson Lake Formation may be stacked on top of in situ Bronson Lake Formation at this core site. Presumably, glaciotectonism occurred after the deposition of the Bronson Lake Formation, possibly associated with an ice flow that was responsible for depositing the Bonnyville Formation till elsewhere in the area, or much later during the glaciation that deposited the Marie Creek Formation. Glaciotectonism is documented in the sedimentary record in other buried valleys south of the study area (Andriashek and Fenton, 1989; Andriashek et al., 1999).

5.4 Borecore WEPA99-2

There remains uncertainty regarding the genesis and age of the bottom 3 m of diamict that lies above bedrock and beneath lacustrine sediment in borecore WEPA99-2. In previous studies this unit was interpreted as part of the Bonnyville Formation (Andriashek, 2003). Based on just a single, weakly magnetized, reversed-polarity sample (LAW089) among a number of incoherent samples from a sampling interval very near the base of the unit (and in contact with Colorado Group shale), and normal-polarity data from the top of this interval, it is unlikely that a thin unit of reversely magnetized Bronson Lake Formation is present at the bottom of the sequence at this site. The lithostratigraphy certainly does not reveal a significant change or break that would warrant the recognition of the Bronson Lake Formation. Until additional data can support the single reversed-polarity value, it is concluded that the Bronson Lake Formation is not present in borecore WEPA99-2 and that the low-carbonate till in the bottom part of the borecore is part of Unit 1 of the Bonnyville Formation

5.5 Borecore BHH02-11

Previous studies of the stratigraphy at the Buffalo Head Hills in north-central Alberta referred to the lower till in borecore BHH02-11 as an "older till," related to the Burke Lake, or possibly older, glaciation (Fenton, 1984; Fenton et al., 2003, 2006). The overlying silt and clay sediments were interpreted as distal glaciolacustrine sediments deposited during the onset of a later, likely late Wisconsinan, glaciation. Sandier sediments higher in the sequence were interpreted as ice-proximal outwash deposited as the ice sheet advanced into the area.

On the basis of reversed-polarity data and carbonate content, the oxidized low-carbonate till in the bottom of the sedimentary sequence in borecore BHH02-11 is here interpreted as the Bronson Lake Formation. This site is the farthest west, and represents the highest elevation at which the Bronson Lake Formation has been mapped in Alberta. The upper till that was attributed to a late Wisconsinan advance of the Laurentide Ice Sheet (Fenton et al., 2003, 2006) is here correlated to the Marie Creek Formation based on its relatively high carbonate content.

6 Discussion

6.1 Correlations and Chronology

In the absence of any other differentiating criteria other than carbonate content, all reversely magnetized samples are considered to be from the Bronson Lake Formation, while normal samples are from the overlying Bonnyville, Marie Creek, and Grand Centre formations (Figure 17). Normal and reversed polarities are indicated for each sampling horizon within stratigraphic units. Based on previously published lithostratigraphic records and the new polarity data reported here, at least four Laurentide (continental) glaciations are recognized in north-central Alberta, one of which occurred in the late Matuyama Chron (Early Pleistocene). A single, reversely magnetized diamict (located in a similar stratigraphic position as previously interpreted Bronson Lake Formation till) occurs near the base of four sampled borecores and is overlain by three normally magnetized tills (Bonnyville, Marie Creek, and Grand Centre formations, respectively). The Mennon Formation, located to the east of the study sites, in Saskatchewan (Christiansen, 1992), occurs in a similar stratigraphic position as the Bronson Lake Formation and is also reversely magnetized (Figure 18; Barendregt et al., 1998, 2012). If the Bronson Lake Formation is correlative to the Mennon Formation, then it can be assigned to Marine Isotope Stage (MIS) 20, which spans the interval from ~0.83 to ~0.79 Ma (Figure 19) and is the last cold peak within the Matuyama Reversed Chron. The age of the Mennon Formation is constrained by bracketing tephra dates and polarity data (Figure 18; Barendregt et al., 2012).

6.2 Preservation of the Stratigraphic Record

During each successive glaciation, drainage networks were rearranged, accounting for the development of numerous but discrete buried valleys and associated deposits. Stacking of fluvial deposits during and following these glacial events resulted in a labyrinth of superposed aquifers that are now important to the development of Alberta's hydrocarbon resources. Weathering and erosion that followed each glaciation likely removed large parts of the pre-late Wisconsinan sedimentary record in Alberta, accounting for the difficulty in mapping their areal extent. Establishing the southwestern extent of the Early Pleistocene Laurentide glaciation in Alberta may prove to be a greater challenge given the poor preservation of the sediment record.

From the perspective of future stratigraphic investigations, the most complete stratigraphic record in north-central Alberta appears to be in uplands of thick sediment located above or on the margins of deep bedrock valleys. This possibly reflects subglacial dewatering across buried valleys, which facilitates the accretion of greater thicknesses of glacigenic sediment (diamict) on adjacent uplands. These greater thicknesses in turn may have served to armour the underlying older deposits. Previous observations of lithologically distinct tills at sites south of the Buffalo Head Hills (Fenton et al., 2006; Paulen and McClenaghan, 2015; Saint Onge, 1972a, b) may warrant further examination and paleomagnetic sampling to help establish the southwestern extent of earlier glacial records and, in particular, the reversely magnetized Early Pleistocene Laurentide till in Alberta.

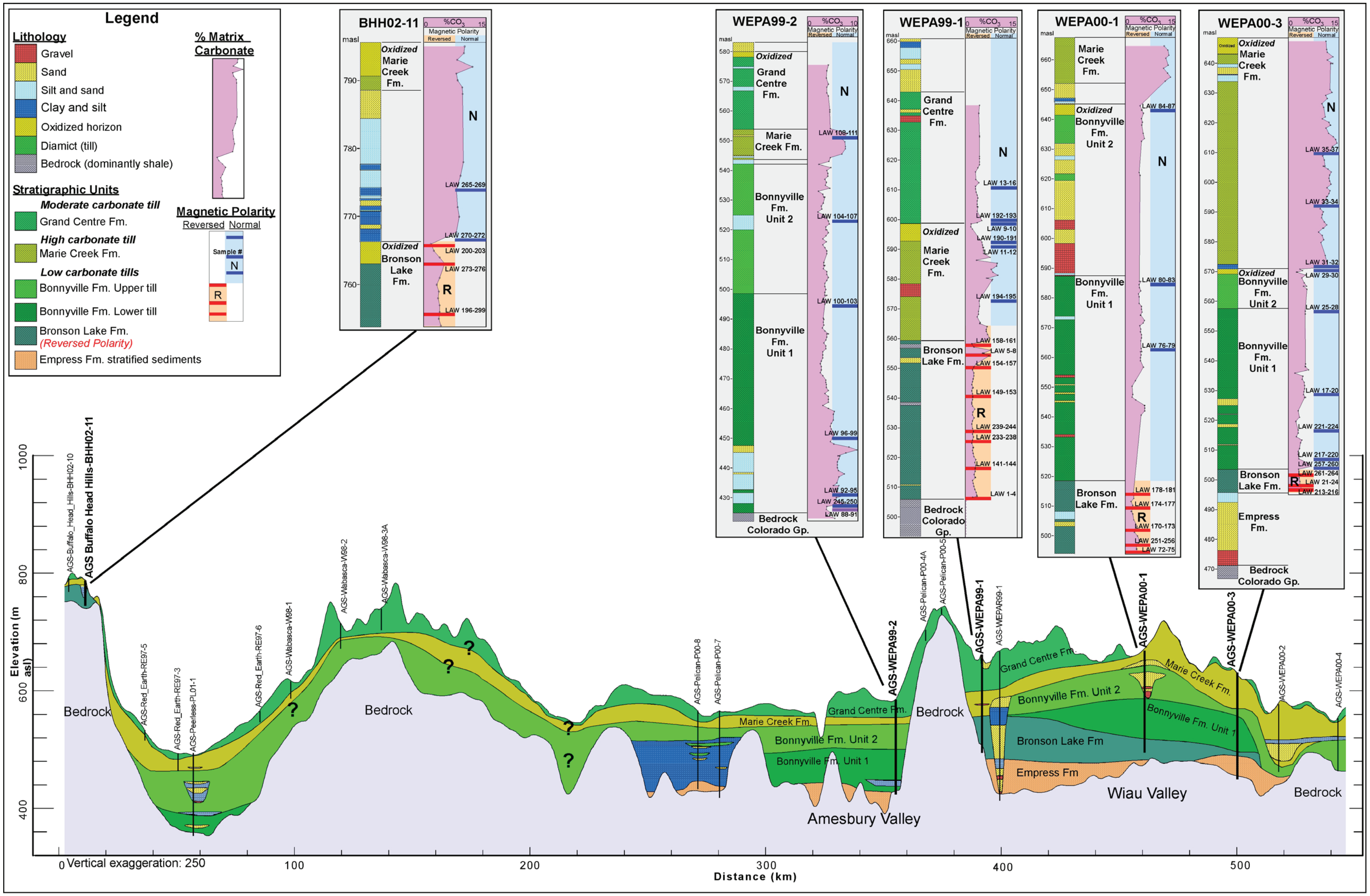

Figure 17. Structural cross-section showing correlation of paleomagnetic data and lithostratigraphic units in north-central Alberta. Normal (blue) and reversed (red) polarities are indicated for each sampling horizon within stratigraphic units. The lowermost, reversely magnetized Bronson Lake Formation is best preserved either in areas mantled by thick accumulations of glacial sediment located above buried bedrock valleys or along their flanks or on bedrock uplands.

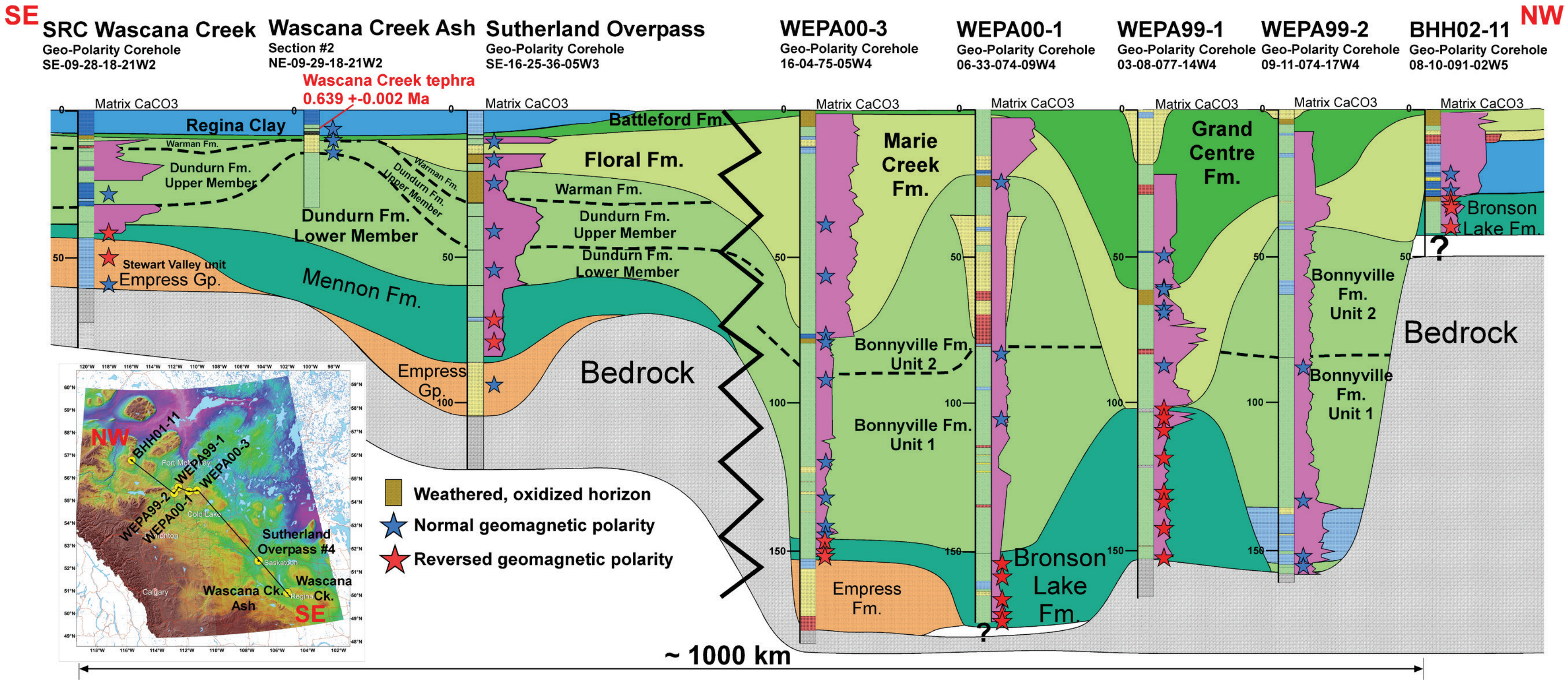

Figure 18. Stratigraphic cross-section of paleomagnetic data and lithostratigraphic units in Alberta and Saskatchewan, western Canada. Correlations are based on carbonate content, presence of buried weathered horizons, tephra chronology, and magnetic polarity of major till formations. Normal (blue star) and reversed (red star) polarities are indicated for each sampling horizon within stratigraphic units. The Bronson Lake Formation is correlated to the Mennon Formation in Saskatchewan on the basis of its reversed polarity, low carbonate content, and stratigraphic position. Note – Empress Group is used in Saskatchewan to describe stratified sediments resting on bedrock, and overlain by till (Whitaker and Christiansen, 1972). Equivalent deposits are named the Empress Formation in Alberta (Andriashek, 1989, 2003; Alberta Geological Survey, 2015).

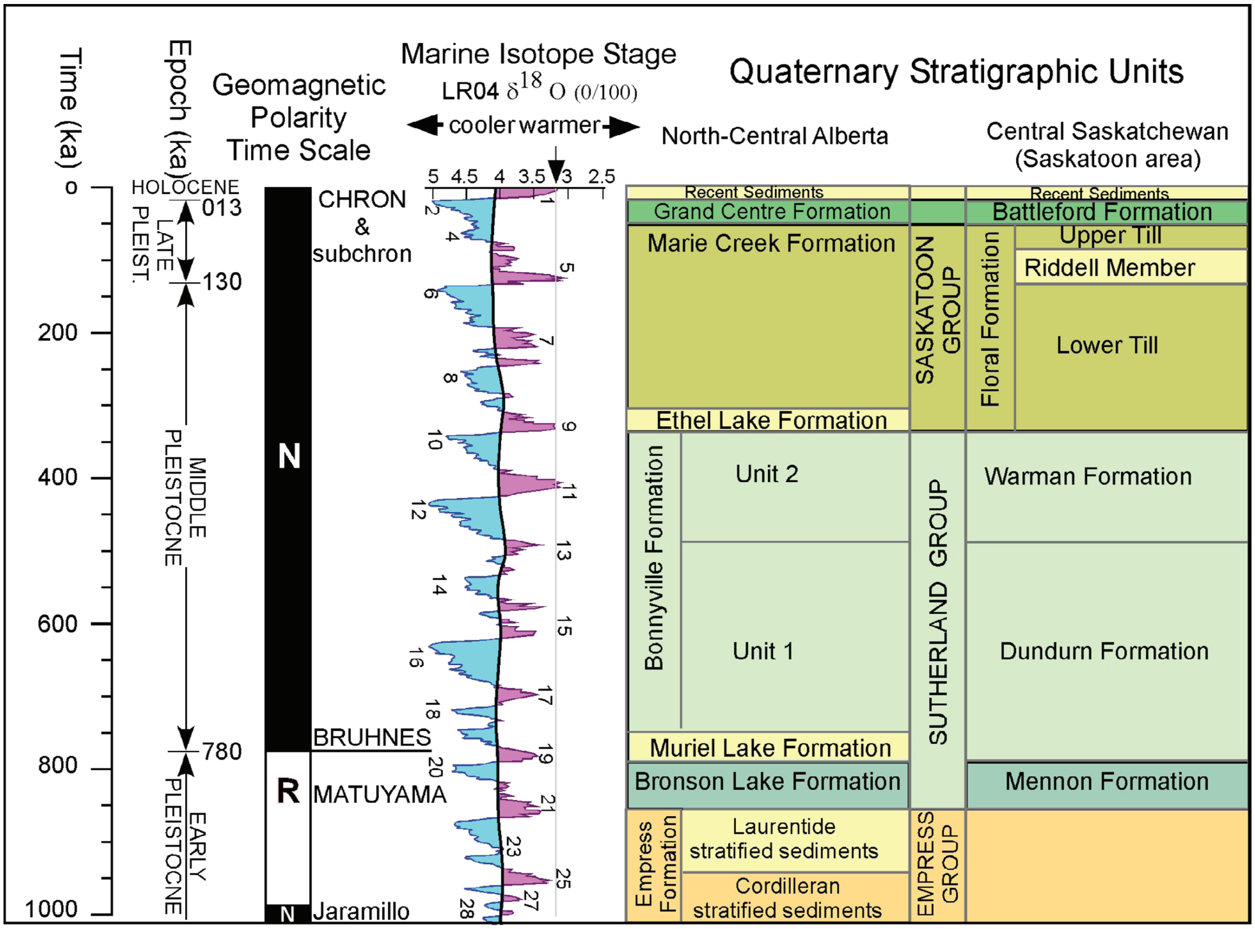

Figure 19. Geomagnetic polarity time scale (Cande and Kent, 1995) for LR04 benthic δ^{18}O paleotemperature profile (Lisiecki and Raymo, 2005). Black/white intervals represent normal/reversed polarity. Marine isotope stages (MIS) are labelled on LR04 (even numbers represent glacials; odd numbers interglacials). MIS numbering scheme follows Ruddiman et al. (1986, 1989) and Raymo et al. (1989) and Raymo (1992) from present to MIS 28. Arrow denotes Holocene mean δ^{18}O (Raymo, 1992). Pleistocene as defined in Gibbard et al. (2010). Reversely magnetized till of the Bronson Lake Formation in Alberta is correlated to the reversely magnetized Mennon Formation (till) in Saskatchewan (Barendregt et al., 1998, 2012). Both are inferred to have been deposited during MIS 20, approximately 800 000 yr. B.P.

7 Conclusions

Magnetostratigraphy obtained from four borecore records reveal both reversed and normal polarities and places Laurentide (Keewatin-centred) ice into northern Alberta prior to the Middle Pleistocene (0.78 Ma). These new data extend the proposed western margin of Laurentide ice during the latest Early Pleistocene (Late Matuyama Chron) by almost 300 km and to an elevation of at least 765 m asl in north-central Alberta (Figure 20). Moreover, it appears likely that multiple glaciations occurred in northern Alberta between the Early and Late Pleistocene. Buried oxidized horizons that are sporadically encountered on the surfaces of petrologically and mineralogically distinct tills in this part of the province may be evidence of weathering during successive interglacial periods.

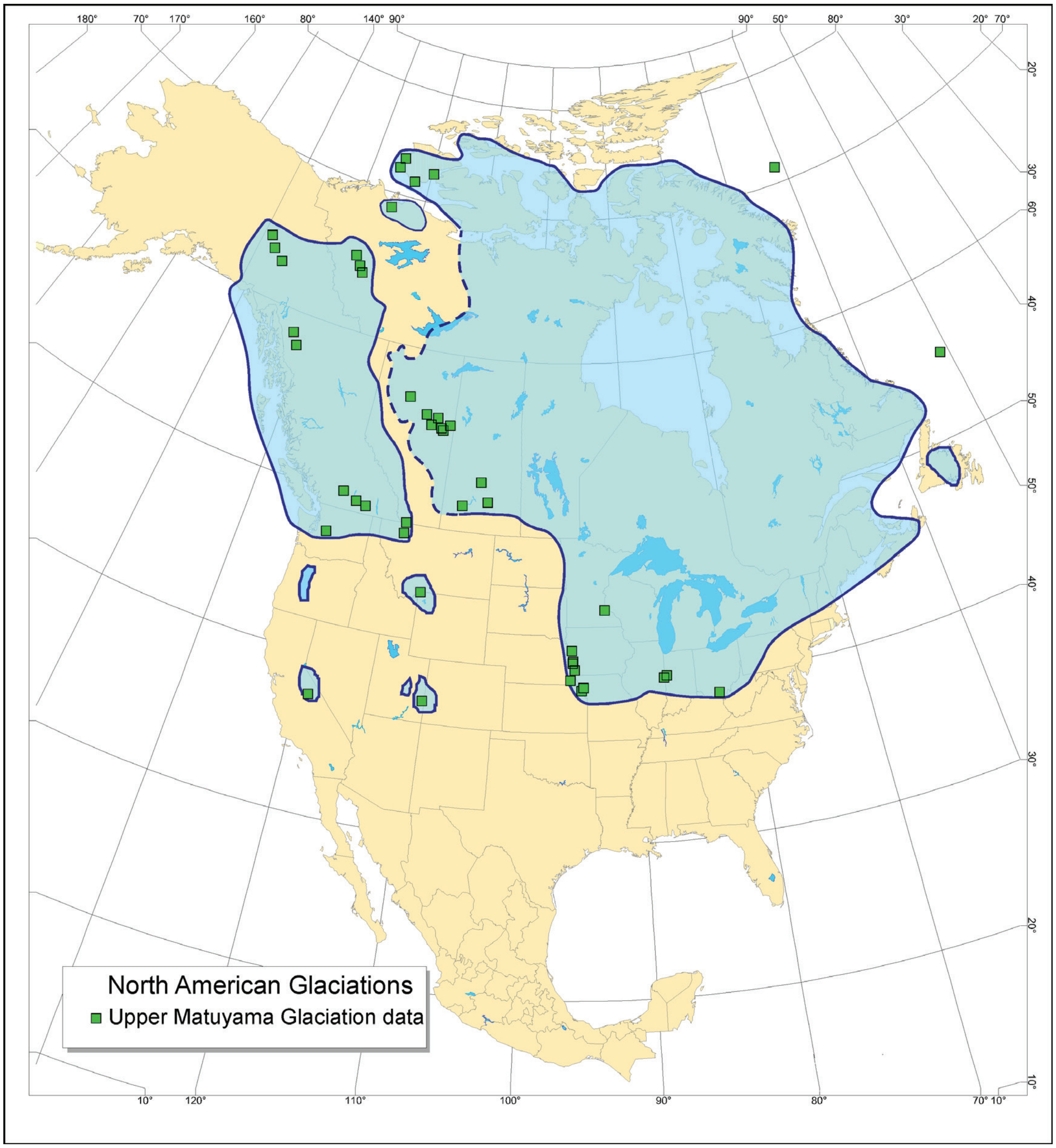

Figure 20. Inferred extent of Upper Matuyama Glaciation in North America (modified from Barendregt and Duk-Rodkin, 2011). Polarity data and magnetostratigraphy from north-central Alberta extends the western limit of an Early Pleistocene Laurentide glaciation by at least 300 km from previous interpretations.

8 References

Alberta Geological Survey (2015): Alberta Table of Formations; Alberta Energy Regulator.

Andriashek, L.D. (2003): Quaternary geological setting of the Athabasca Oil Sands (In Situ) Area, northeast Alberta; Alberta Energy and Utilities Board, EUB/AGS Earth Sciences Report 2002-03, URL<http://ags.aer.ca/publications/ESR_2002_03.html> [June 2016].

Andriashek, L.D. and Fenton, M.M. (1989): Quaternary stratigraphy and surficial geology of the Sand River area (NTS73L); Alberta Energy and Utilities Board, EUB/AGS Bulletin 057, URL<http://ags.aer.ca/publications/BUL_057.html> [June 2016].

Andriashek, L.D. and Parks, K. (2001): The Glacio-stratigraphic organization of Tertiary and Quaternary sediments in the Athabasca Oil Sands (In Situ) Area, Alberta: implications for groundwater exploration; 54th Canadian Geotechnical Conference, September 16–19, Calgary, Alberta, poster session H-246.

Andriashek, L.D. and Parks, K. (2002): Baseline investigations into the groundwater resources of the Athabasca Oil Sands (In Situ) Area, northeast Alberta; Alberta Energy and Utilities Board, EUB/AGS Special Report 098, URL <http://ags.aer.ca/publications/SPE_098.html> [June 2016].

Andriashek, L.D., Fenton, M.M., de Freitas, T. and G. Mann (1999): Glaciotectonics in the Cold Lake area and implications for steam-assisted heavy-oil recovery; CSPG and Petroleum Society Joint Convention, June 14–18, v. 1, Abstract 99-25-O, 2 p.

Atkinson, N. and Lyster, S. (2010 a): Bedrock topography of Alberta, Canada; Alberta Energy Resources Conservation Board, ERCB/AGS Map 550, scale 1:1 500 000, URL <http://ags.aer.ca/publications/MAP_550.html> [June 2016].

Atkinson, N. and Lyster, S. (2010b): Thickness of Quaternary and Neogene sediment in Alberta, Canada; Alberta Energy Resources Conservation Board, ERCB/AGS Map 551, scale 1:1 500 000, URL <http://ags.aer.ca/publications/MAP_551.html> [June 2016].

Balco, G. and Rovey, C.W. (2008): An isochron method for cosmogenic-nuclide dating of buried soils and sediments; Journal of Science, v. 308, p. 1083–114.

Balco, G., Stone, J.O.H. and Mason, J.A. (2005): Numerical ages for Plio-Pleistocene glacial sediment sequences by 26Al/10Be dating of quartz in buried paleosols; Earth and Planetary Science Letters, v. 232, p. 179–191.

Barendregt, R. W. (2011): Magnetostratigraphy of Quaternary sections in eastern Alberta, Saskatchewan and Manitoba; *in* Quaternary glaciations: extent and chronology; a closer look, J. Ehlers, P.L. Gibbard, and P.D. Hughes (ed.), Elsevier, Amsterdam, p. 591–600.

Barendregt, R.W. and Duk-Rodkin, A. (2011): Chronology and extent of late Cenozoic ice sheets in North America: a magnetostratigraphic assessment; *in* Quaternary glaciations: extent and chronology; a closer look, J. Ehlers, P.L. Gibbard and P.D. Hughes (ed.), Elsevier, Amsterdam, p. 419–426.

Barendregt, R.W. and Irving, E. (1998): Changes in the extent of North American ice sheets during the late Cenozoic; Canadian Journal of Earth Sciences, v. 35, p. 504–509.

Barendregt, R.W., Thomas, F.F., Irving, E., Baker, J., Stalker, A. M. and Churcher, C.S (1991): Stratigraphy and paleomagnetism of the Jaw Face section, Wellsch Valley site, Saskatchewan; Canadian Journal of Earth Sciences, v. 28, p. 1353–1364.

Barendregt, R.W., Irving, E., Christiansen, E.A., Sauer, E.K. and Schreiner, B.T. (1998): Stratigraphy and paleomagnetism of Late Pliocene and Pleistocene sediments from Wellsch Valley and Swift Current Creek areas, southwestern Saskatchewan, Canada; Canadian Journal of Earth Sciences, v. 35, p. 1347–1361.

Barendregt, R.W., Enkin, R.J. and Tessler, D.L. (2012): Magnetostratigraphy of late Neogene glacial, interglacial, and preglacial sediments in the Saskatoon and Regina areas, Saskatchewan, Canada; Studia Geophysica et Geodaetica, v. 56, p. 705–724.

Barendregt, R.W., Andriashek, L.D. and Jackson, L.E. (2014): Evidence for Early Pleistocene glaciation obtained from borecores collected in North-Central Alberta, Canada; American Geophysical Union Fall Meeting, December 15, San Francisco, California, abstract ID 17306, poster no. GP13A-3574, session GP13A.

Butler, R.F. (1992): Paleomagnetism: magnetic domains to geologic terranes; Blackwell Scientific, Oxford, UK.

Cande, S.C. and Kent, D.V. (1995): Revised calibration of the geomagnetic timescale for the Late Cretaceous and Cenozoic; Journal of Geophysical Research: Solid Earth, v. 100, no. B4, p. 6093–6095.

Christiansen, E. A. (1992): Pleistocene stratigraphy of the Saskatoon area, Saskatchewan, Canada: an update; Canadian Journal of Earth Sciences, v. 29, p. 1767–1778.

Cioppa M.T., Karlstrom, E.T., Irving, E. and Barendregt, R.W. (1995): Paleomagnetism of tills and associated paleosols in southwestern Alberta and northern Montana: evidence for Late Pliocene – Early Pleistocene glaciations; Canadian Journal of Earth Sciences, v. 32, p. 555–564.

Enkin, R.J. and Watson, G.S. (1996): Statistical analysis of paleomagnetic inclination data; Geophysical Journal International, v. 126, p. 495–504.

Fenton, M.M. (1984): Quaternary stratigraphy, Canadian Prairies; *in* Quaternary stratigraphy of Canada – a Canadian contribution to IGCP Project 24, R.J. Fulton (ed.), Geological Survey of Canada, Paper 84-10, p. 57–68, doi:10.4095/119769.

Fenton, M.M., Paulen, R.C. and Pawlowicz, J.G. (2003): Evidence of pre-late Wisconsin glacial deposits in central and northern Alberta; Canadian Quaternary Association – Canadian Geomorphology Research Group meeting, June 8–12, Halifax, Nova Scotia, Program and Abstracts, p. A28.

Fenton, M.M., Pawlowicz, J.G., Paulen, R.C. and Prior, G.J. (2006): Quaternary stratigraphy and till geochemistry of the southern Buffalo Head Hills, Alberta: results of an auger coring program; Alberta Energy and Utilities Board, EUB/AGS Geo-Note 2005-10, 30 p., URL<http://ags.aer.ca/publications/GEO_2005_10.html> [June 2016].

Gibbard, P.L., Head, M.J. and Walker, M.J.C. (2010): Formal ratification of the Quaternary System/Period and the Pleistocene Series/Epoch with a base at 2.58 Ma; Journal of Quaternary Science, v. 25, p. 96–102.

Jennings, C.E., Aber, J.S., Balco, G., Barendregt, R.W., Bierman, P.R., Rovey, C.W., Roy, M. and Thorleifson, L.H. (2007): Mid-Quaternary in North America; *in* Encyclopedia of Quaternary Science, S.A. Elias (ed.), Elsevier, v. 2, p. 1044–1051.

Karlstrom, E.T. and Barendregt, R.W. (2001): Fabric, paleomagnetism, and interpretation of pre-Illinoian diamictons and paleosols on Cloudy Ridge and Milk River, Alberta and Montana; Géographie physique et Quaternaire, v. 55, no. 2, p. 141–157.

Kirschvink, J.L. (1980): The least-squares line and plane and the analysis of paleomagnetic data; Geophysical Journal of the Royal Astronomical Society, v. 62, p. 699–718.

Lisiecki L.E. and Raymo M. (2005): A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records; Paleoceanography, v. 20, doi:10.1029/2004PA001071.

Paulen, R.C. and McClenaghan, M. B. (2015): Late Wisconsin ice-flow history in the Buffalo Head Hills kimberlite field, north-central Alberta; Canadian Journal of Earth Science, v. 52, p. 51–67.

Raymo, M.E. (1992): Global climate change: a three million year perspective; *in* Start of a glacial, G.K. Kukla and E. Went (ed.), NATO ASI Series, v. 3, p. 207–223.

Raymo, M.E., Ruddiman, W.F., Backman, J., Clement, B.M. and Martinson, D.G. (1989): Late Pliocene variation in northern hemisphere ice sheets and North Atlantic Deep Water circulation; Paleoceanography, v. 4, p. 413–446.

Roy, M., Clark, P.U., Barendregt, R.W., Glasmann, J.R. and Enkin, R.J. (2004): Glacial stratigraphy and paleomagnetism of late Cenozoic deposits of the north-central United States; Geological Society of America Bulletin, v. 116, p. 30–41, doi:10.1130/B25325.1.

Ruddiman, W.F., Raymo, M.E. and McIntyre, A. (1986): Matuyama 41,000-year cycles: North Atlantic Ocean and northern hemisphere ice sheets; Earth and Planetary Science Letters, v. 80, p. 117–129, doi:10.1016/0012-821X(86)90024-5.

Ruddiman, W.F., Raymo, M.E., Martinson, D.G., Clement, B.M. and Backman, J. (1989): Pleistocene evolution: northern hemisphere ice sheets and North Atlantic Ocean; Paleoceanography, v. 4, p. 353–412, doi:10.1029/PA004i004p00353.

Saint Onge, D. A. (1972 a): La stratigraphie du Quaternaire des environs de Fort-Assiniboine, Alberta, Canada; Revue de Geógraphie de Montreal, v. 26, no. 2, p. 153–163.

Saint Onge, D. A. (1972b): The geomorphology of the Swan Hills area, Alberta; Geological Survey of Canada, Paper 74-26.

Verosub, K.L. (1977): Depositional and postdepositional processes in the magnetization of sediments; Review of Geophysics and Space Physics, v. 15., no. 2, p. 129–143.

Verosub, K.L., Ensley, R.A. and Ulrick, J.S. (1979): The role of water content in the magnetization of sediments; Geophysical Research Letters, v. 6, no. 4, p. 226–228, doi:10.1029/GL006i004p00226.

Appendix 1 – Magnetic Polarity Data Obtained from Borecore Samples

Borehole Name	Latitude	Longitude	Elevation (m)	Hole Depth (m)	Sample Depth (m)	Formation	Material	Sample Nos.	Polarity
AGS-WEPA99-1	55.651737	112.14686	660.92	167.3	50	Grand Centre	Till, clayey	LAW 13-16	**Normal**
					61.2	Grand Centre	Till	LAW 192-193	**Normal**
					61.9	Marie Creek	Till, oxidized	LAW 9-10	**Normal**
					68.3	Marie Creek	Till	LAW 190-191	**Normal**
					69.8	Marie Creek	Till	LAW 11-12	**Normal**
					87.9	Marie Creek	Till	LAW 194-195	**Normal**
					95.2	Marie Creek	Till	LAW 162-165	**Incoherent**
					102.7	Bronson Lake	Till	LAW 158-161	**Reversed**
					106	Bronson Lake	Till	LAW 5-8	**Reversed**
					110.3	Bronson Lake	Till	LAW 154-157	**Reversed**
					119.8	Bronson Lake	Till	LAW 149-153	**Reversed**
					131.5	Bronson Lake	Till	LAW 239-244	**Reversed**
					131.7	Bronson Lake	Till	LAW 145-148	**Incoherent**
					134.9	Bronson Lake	Till	LAW 233-238	**Reversed**
					144	Bronson Lake	Till	LAW 141-144	**Reversed**
					154	Bronson Lake	Till	LAW 1-4	**Reversed**
AGS-WEPA99-2	55.398582	112.49329	583.07	160.5	32	Marie Creek	Till	LAW 108-111	**Normal**
					60	Ethel Lake	Silt	LAW 104-107	**Normal**
					88.5	Bonnyville	Till	LAW 100-103	**Normal**
					133	Bonnyville	Till	LAW 96-99	**Normal**
					152	Bonnyville	Silt	LAW 92-95	**Normal**
					155.8	Bonnyville	Till	LAW 245-250	**Normal**
					157	Bonnyville	Till	LAW 88-91	**Incoherent**

Borehole Name	Latitude	Longitude	Elevation (m)	Hole Depth (m)	Sample Depth (m)	Formation	Material	Sample Nos.	Polarity
AGS-WEPA00-1	55.451416	111.32983	667.64	173.5	24.5	Bonnyville U2	Till, oxidized	LAW 84-87	**Normal**
					83	Bonnyville U1	Till	LAW 80-83	**Normal**
					105	Bonnyville U1	Till	LAW 76-79	**Normal**
					116.4	Bronson Lake	Till	LAW 186-189	**Incoherent**
					122.2	Bronson Lake	Till	LAW 182-185	**Reversed**
					153.5	Bronson Lake	Till	LAW 178-181	**Reversed**
					158.2	Bronson Lake	Till	LAW 174-177	**Reversed**
					165.6	Bronson Lake	Till	LAW 170-173	**Reversed**
					170.6	Bronson Lake	Till	LAW 251-256	**Reversed**
					172.2	Bronson Lake	Till	LAW 166-169	**Incoherent**
					173	Bronson Lake	Till	LAW 72-75	**Reversed**
AGS-WEPA00-2	55.627533	110.76144	558.977	115	21.5	Marie Creek	Till	LAW 68-71	**Normal**
					46	Ethel Lake	Silty clay	LAW 64-65	**Normal**
					46.5	Ethel Lake	Silty clay	LAW 66-67	**Normal**
					90	Bonnyville	Till	LAW 62-63	**Normal**
					107.7	Bronson Lake	Till, oxidized	LAW 58-61	**Normal**
					110.3	Empress	Clay	LAW 54-57	**Normal**
					114.5	Empress	Sand	LAW 50-53	**Normal**
AGS-WEPA00-3	55.473042	110.7073	648.78	182	39	Marie Creek	Till	LAW 35-37	**Normal**
					56.6	Marie Creek	Till	LAW 33-34	**Normal**
					77	Ethel Lake	Silt and clay	LAW 31-32	**Normal**
					78.3	Bonnyville U2	Till, oxidized	LAW 29-30	**Normal**
					92	Bonnyville U1	Till	LAW 25-28	**Normal**
					120	Bonnyville U1	Silt	LAW 17-20	**Normal**
					132.2	Bronson Lake	Till	LAW 221-224	**Normal**
					141.8	Bronson Lake	Till	LAW 217-220	**Normal**
					144.8	Bronson Lake	Till	LAW 257-260	**Normal**
					147.4	Bronson Lake	Till	LAW 261-264	**Reversed**
					151	Bronson Lake	Till	LAW 21-24	**Reversed**
					151.6	Bronson Lake	Till	LAW 213-216	**Reversed**

Borehole Name	Latitude	Longitude	Elevation (m)	Hole Depth (m)	Sample Depth (m)	Formation	Material	Sample Nos.	Polarity
AGS-WEPA00-4	55.815643	110.55764	569.349	90	41	Marie Creek	Till	LAW 46-49	**Normal**
					49	Ethel Lake	Clay	LAW 42-45	**Normal**
					74	Bonnyville U2	Clay	LAW 40-41	**Normal**
					85	Bonnyville U2	Till	LAW 38-39	**Normal**
14-01-067-03W4	54.774893	110.32735	658.86	103.6	12.8	Undefined	Till unoxidized	LAW 136-140	**Normal**
					31.4	Undefined	Till, unoxidized	LAW 132-135	**Normal**
					47.2	Undefined	Till, unoxidized	LAW 128-131	**Normal**
					56	Undefined	Till, unoxidized	LAW 124-127	**Normal**
					75.3	Undefined	Silt, oxidized	LAW 122-123	**Normal**
					80.5	Undefined	Till, oxidized	LAW 118-121	**Normal**
					86	Undefined	Sand, oxidized	LAW 116-117	**Normal**
					89.6	Undefined	Till, oxidized	LAW 112-115	**Normal**
AGS-P00-7	55.793336	113.40527	571	148.3	109	Undefined	Silt and clay	LAW 308-311	**Normal**
					118.7	Undefined	Silty clay	LAW 312-315	**Normal**
					123.5	Undefined	Silt and clay	LAW 307	**Normal**
					145	Undefined	Clayey silt	LAW 303-306	**Normal**
AGS-P00-8	55.868713	113.343	579	133.8	56.5	Undefined	Till	LAW 229-232	**Normal**
					64.7	Undefined	Clay, distorted	LAW 316-319	**Normal**
					66	Undefined	Clay	LAW 225-228	**Reversed**
AGS-Wabasca-W98-2	56.738445	114.7591	721	43.6	25.1	Undefined	Till, oxidized	LAW 208-212	**Normal**
					37.9	Undefined	Till	LAW 204-207	**Normal**
AGS-BHH02-07	56.855076	115.76937	774	13.1	8	Undefined	Clay diamict	LAW 277-281	**Incoherent**
AGS-BHH02-10	56.920679	115.91082	781	23.8	23.5	Undefined	Till	LAW 282-286	**Reversed**
AGS-BHH02-11	56.876184	115.83039	796	43.6	22	Marie Creek	Silt and clay	LAW 265-269	**Normal**
					29.3	Marie Creek	Silt and clay	LAW 270-272	**Normal**
					30.2	Bronson Lake	Till, oxidized	LAW 200-203	**Reversed**
					32.9	Bronson Lake	Till	LAW 273-276	**Reversed**
					40.3	Bronson Lake	Till	LAW 196-199	**Reversed**

Borehole Name	Latitude	Longitude	Elevation (m)	Hole Depth (m)	Sample Depth (m)	Formation	Material	Sample Nos.	Polarity
AGS-RE97-4	56.926211	115.20449	478	46.6	18.8	Undefined	Silt	LAW 299-302	**Incoherent**
					35	Undefined	Pebbly silty clay	LAW 295-298	**Incoherent**
					42	Undefined	Clayey silt diamict	LAW 291-294	**Normal**
AGS-RE97-5 A	56.738806	115.50924	541	18.3	17.5	Undefined	Till, dark	LAW 287-290	**Incoherent**
AGS-PL01-2	56.321041	115.37533	494	132.6	125	Undefined	Silty clay	LAW 324-326	**Normal**
					132	Undefined	Till	LAW 320-323	**Normal**