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Chapter 49

Stratigraphical Record of Glacials/ Interglacials in Northwest Canada

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s0005 49.1. INTRODUCTION

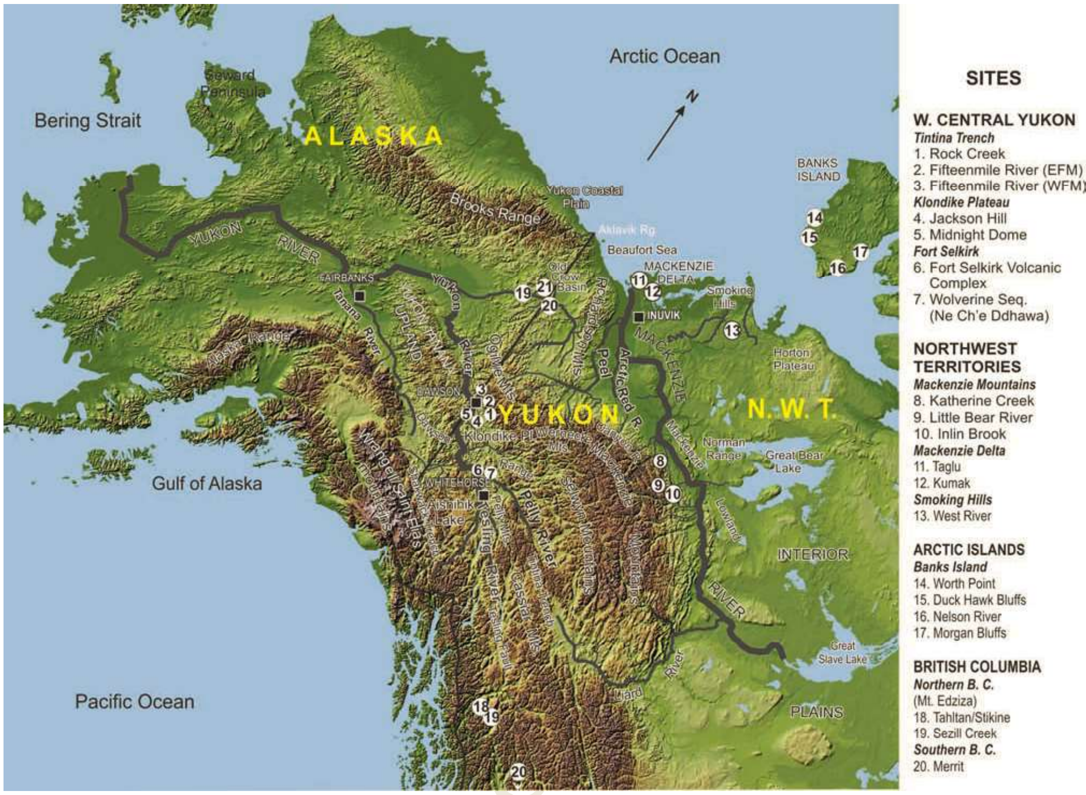
p0005 The glacial record of north-western (NW) North America is one of the most extensive of any preserved worldwide. This record was left by Cordilleran, montane, continental and plateau glaciers. The oldest glacial sediments deposited by Cordilleran glaciations are found near the Yukon/Alaska border (Canada/USA). Regional scale glaciations (Cordilleran and continental) commenced in NW Canada and east central Alaska between 2.9 and 2.6 million years ago (Ma). Multiple glaciations have been recorded in the mountains (Cordilleran and montane ice) and in the interior plains (ice caps and continental ice sheets) of northern Canada. Cordilleran and plateau ice cap glaciations occurred repeatedly throughout the Late Pliocene to Late Pleistocene. Local montane glaciers were widespread throughout glacial periods; however, they were more susceptible to local changes of climate and moisture supply. They often extended only relatively short distances from their source, leaving only loess deposits beyond their terminus. Only during the Late Pleistocene is a continental (Laurentide) ice sheet record documented in NW Canada.

p0010 New data are presented here to complement the record of glaciations (Duk-Rodkin et al., 2004). The summary of northwestern Canadian glacial history is presented here with more detailed stratigraphical descriptions and some additional data from the Fort Selkirk (Yukon), Smoking Hills (northern Interior Plains), Mount Edziza (northern British Columbia) and Merrit (southern British Columbia) areas.

p0015 The wide variety of surficial deposits exposed across the northern Canadian mainland provides a record of glaciations which span the Late Pliocene to Late Pleistocene. Glacial tills were deposited across the northern Canadian Shield and northern Interior Plains during a succession of plateau glaciations and a single continental glaciation (Figs. 49.1 and 49.2). Retreats of these ice sheets were accompanied by the development of large glacial lakes and deposition of glacio-lacustrine silts and clays across large areas within the northern Interior Plains.

Post-glacial erosion and downcutting of streams, in part related to post-glacial isostatic rebound, removed surficial deposits from large areas of the Canadian Shield in Nunavut and the Northwest Territories. Glacial deposits are absent across most of northern and west-central Yukon Territory because this area remained unglaciated (Fig. 49.2). Old Crow Basin occurs within this unglaciated region and was the depositional centre for extensive glacio-lacustrine sediments resulting from damming of rivers to the east by the Late Pleistocene continental (Laurentide) glaciation. p0020

The record of Cordilleran glaciations is mostly found in the Yukon Territory, while continental and plateau glacial records are found in the Northwest Territories (NWT) and Banks Island (Fig. 49.1). Before the development of the first ~~continental~~ glaciation in NW Canada, tidewater glaciers are thought to have formed as early as the Late Miocene in south-eastern Alaska (Denton and Armstrong, 1969; Lagoe et al., 1993). Stratigraphical sequences described for Cordilleran and/or montane glaciations in the central Yukon ~~and Mackenzie Mountains~~ indicate that glaciation commenced there only in the Late Pliocene. The record of the first Cordilleran glaciation in the Latest Pliocene (late Gauss) between 2.7 and 2.8 Ma (Marine Isotope Stage (MIS) G10–G6) in the Yukon is reported in Duk-Rodkin and Barendregt (1997), Froese et al. (2000) and Duk-Rodkin et al. (2001, 2004); and is summarised in the stratigraphical correlations of Fig. 49.3. Multiple glaciations spanning the Matuyama Reversed Chron (2.58–078 Ma) and Brunhes Normal Chron (0.78 Ma–present) were deposited after this first glaciation and are documented in the magnetostratigraphy of tills, outwash and loess deposits. The most complete record is found in the Tintina Trench of ~~the~~ central Yukon. However, other sites such as those in the Klondike Plateau, Fort Selkirk and Mackenzie Mountains (NWT) provide records which are complementary to those of the Tintina Trench (Figs. 49.1 and 49.3). p0025



f0005 **FIGURE 49.1** Relief map of NW North America and locations of sites described in text.

p0030 Northern Interior Plains ice was present in northwest Canada, but the available record is neither as complete nor as well defined as that of the Cordilleran. In the continental Arctic, older diamicts have been reported from the Taglu and Kumak cores in the Mackenzie Delta (Fig. 49.3; Dallimore and Matthews, 1997). In the Smoking Hills area, there are as many as four tills of local plateau (Horton Plateau) origin separated by up to four silty clay beds (Fig. 49.3; Au4 Duk-Rodkin and Barendregt, unpublished field notes, 2004). The palaeomagnetic measurements of these tills and intertill beds indicate a sequence of glacial events within the Matuyama Chron (Early Pleistocene). The lowest till overlies reversely magnetised preglacial sands and gravels (presumably the late Beaufort Formation) containing large ice-wedge casts. Evidence of continental glaciation extending back to the Late Pleistocene is found on Banks Island at 1.6 Ma (Vincent et al., 1984; Barendregt and Vincent, 1990; Vincent, 1990; Fyles et al., 1994; Barendregt et al., 1998). Based on the Banks Island data, the first Keewatin-centred glaciation postdates Cordilleran glaciation in the Yukon by about 1 Ma.

49.2. WEST-CENTRAL YUKON (TINTINA TRENCH, KLONDIKE PLATEAU, FORT SELKIRK) s0010

49.2.1. Tintina Trench s0015

A long stratigraphical record extending from Late Cretaceous to Middle Pleistocene has been preserved along the walls of the Tintina Trench where it is exposed in modern landslide scars or along slopes (Duk-Rodkin et al., 2001, 2004). Stratigraphical sites are located on both sides of the trench along a distance of approximately 100 km near the Yukon/Alaska border (Figs. 49.1 and 49.2). At the Trench sites (sites 1–3; Figs. 49.3–49.6), tills and/or outwash gravels conformably overlie Pliocene preglacial gravels, which are unconformably underlain by faulted alluvial fan deposits of Miocene age (Duk-Rodkin et al., 2001). p0035

Sections in the Trench show well-exposed beds below and above the Pliocene/Miocene unconformity at all three sites. Strata beneath the unconformity are composed of faulted alluvial fan deposits and have been grouped into p0040

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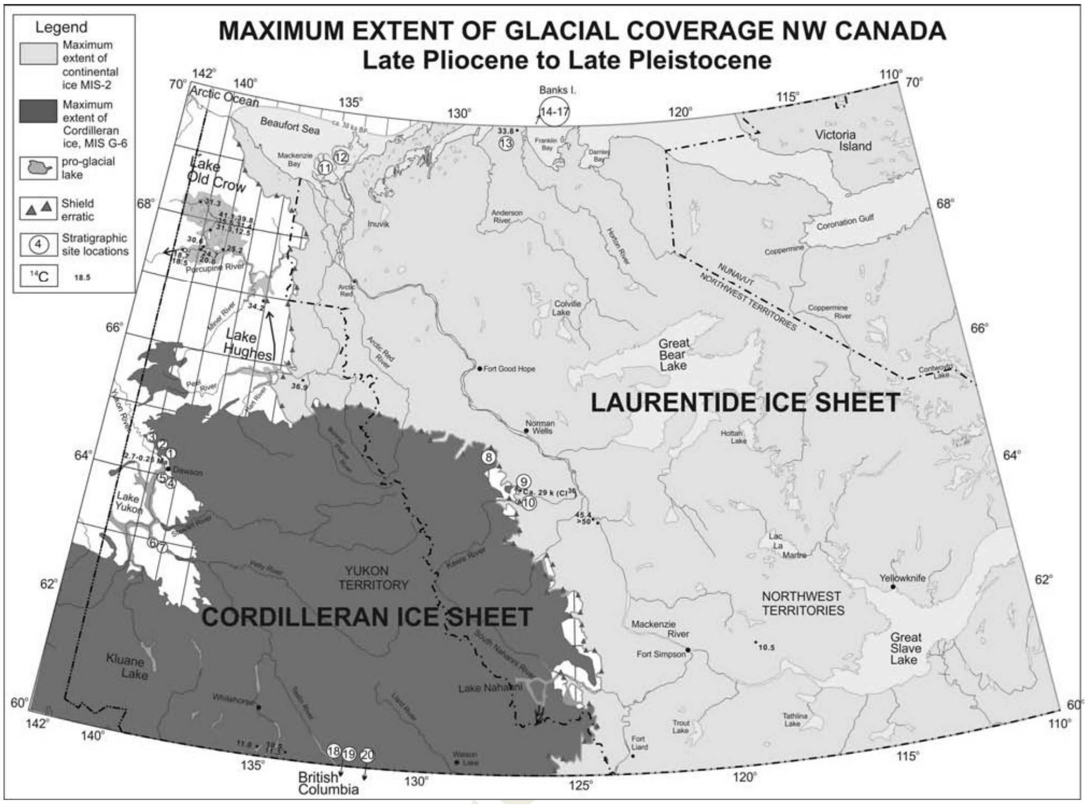
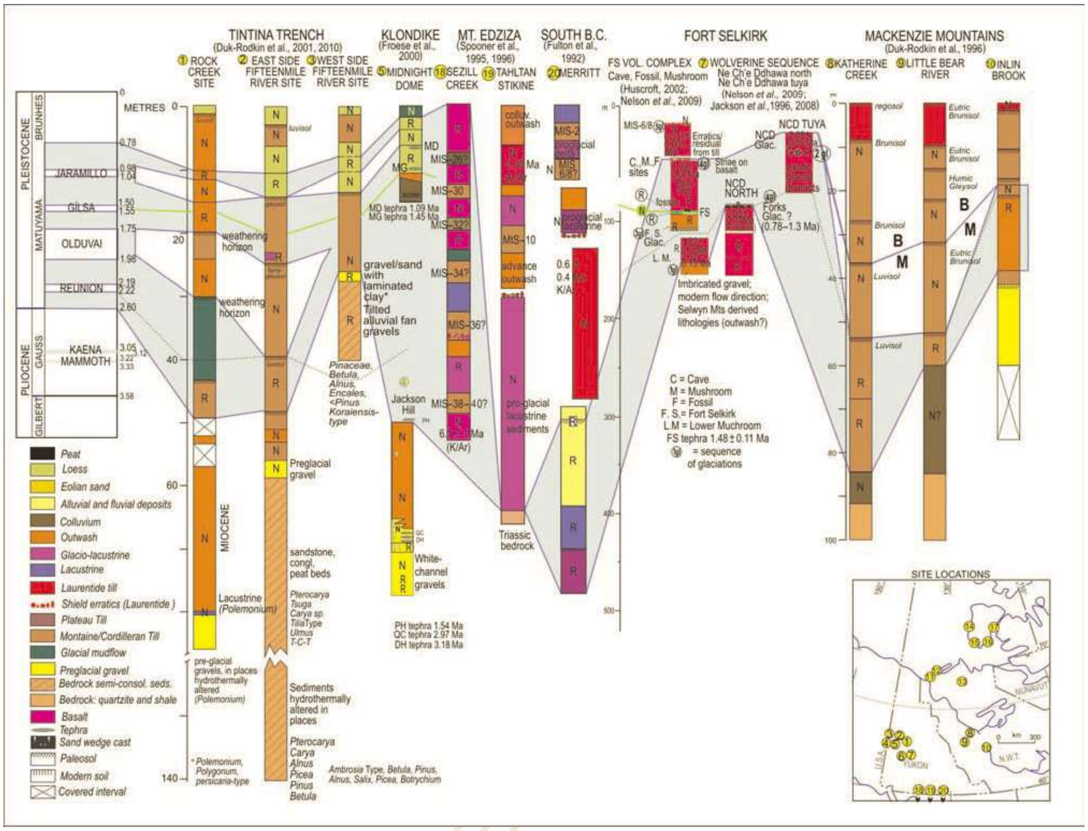


f0010 FIGURE 49.2 Maximum extent of glaciations in Northwest Canada. The maximum extent of Cordilleran ice occurred during the Late Pliocene, MIS G6, while the maximum ice extent of continental ice occurred during the Late Pleistocene (MIS 2).

two parts: a lower recessive succession of claystone and very coarse grained, pebbly sandstone with coal beds (Eocene–Cretaceous age) and an upper succession of interbedded conglomerate, sandstone and organics (peat) with in most places indurated silt beds at the top of the strata (Miocene age; Duk-Rodkin et al., 2001).

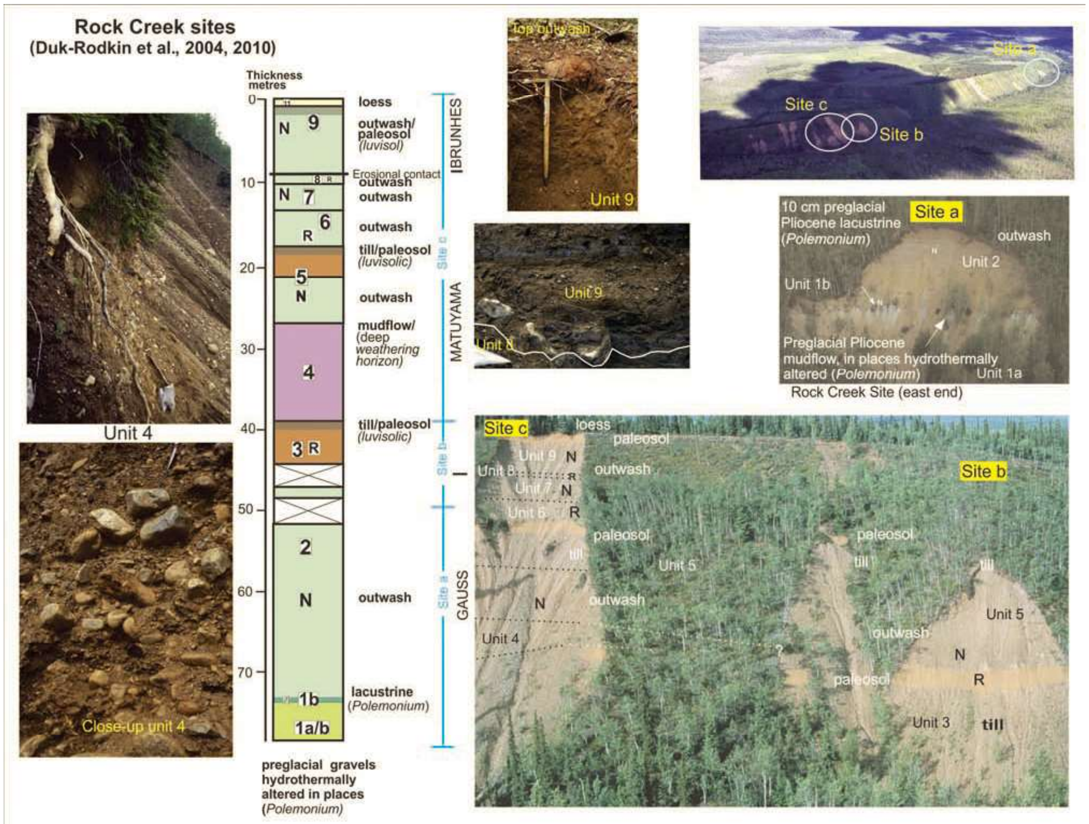
p0045 During the glaciations recorded in the trench, Cordilleran ice advanced along the trench to the west, merging with local glaciers in the Southern Ogilvie Mountains and transporting erratic pebbles from both Cordilleran (continental divide: Selwyn/Wernecke mountains) and Ogilvie Mountain (local) sources. Depending on the locality within the Trench, glacial clast lithologies may be either entirely local in origin or of both local and mixed provenance, but in all cases, sites reveal similar stratigraphical sequences of tills with palaeosols, outwash and loess. Collectively they record seven pre-Middle Pleistocene glacial events (Fig. 49.3). These sections have a normal–reverse–normal–reverse–normal–reverse–normal palaeomagnetic sequence extending from late Gauss to late Middle Pleistocene (Barendregt et al., 2010; Duk-Rodkin et al., 2010).

1. *Rock Creek site* (RC site 1, Figs. 49.1–49.4) in the Tintina Trench reveals beds above the unconformity which contain records of both Cordilleran and local glaciations (Duk-Rodkin et al., 2010). This site exposes preglacial gravels consisting of a debris flow deposit (unit 1a) overlain by a thin lacustrine bed (unit 1b). The shallow lacustrine deposit contains *Polemonium* sp. pollen and is normally magnetised. *Polemonium* sp. first appears in the upper Miocene (Muller, 1981) and is present in this region today. It is present in the Lost Chicken beds (ca. 2.9 Ma) of the Yukon and Alaska ~~(Matthews et al., 1990;~~ White et al., 1999) which are thought to be correlative with this unit. Preglacial sediments are capped by outwash gravels (unit 2) and sand, deposited by glaciers associated with the first regional glaciation (Figs. 49.2–49.4). These deposits and the underlying unit 1 are normally magnetised. Outwash deposits only document this first glaciation in the Tintina Trench and in the Klondike Plateau to the south. The outwash is overlain by a reversely magnetised till (unit 3) with a luvisolic palaeosol developed at its upper contact. This palaeosol is u0005



f0015 **FIGURE 49.3** Late Pliocene to Late Pleistocene stratigraphical correlations of Cordilleran and Northern Interior Plains sites in Northwest Canada. Light blue colour band identifies Reversed Matuyama Chron stratigraphy, while Normal Gauss and Normal Brunhes Chron strata lie below and above, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this chapter.)

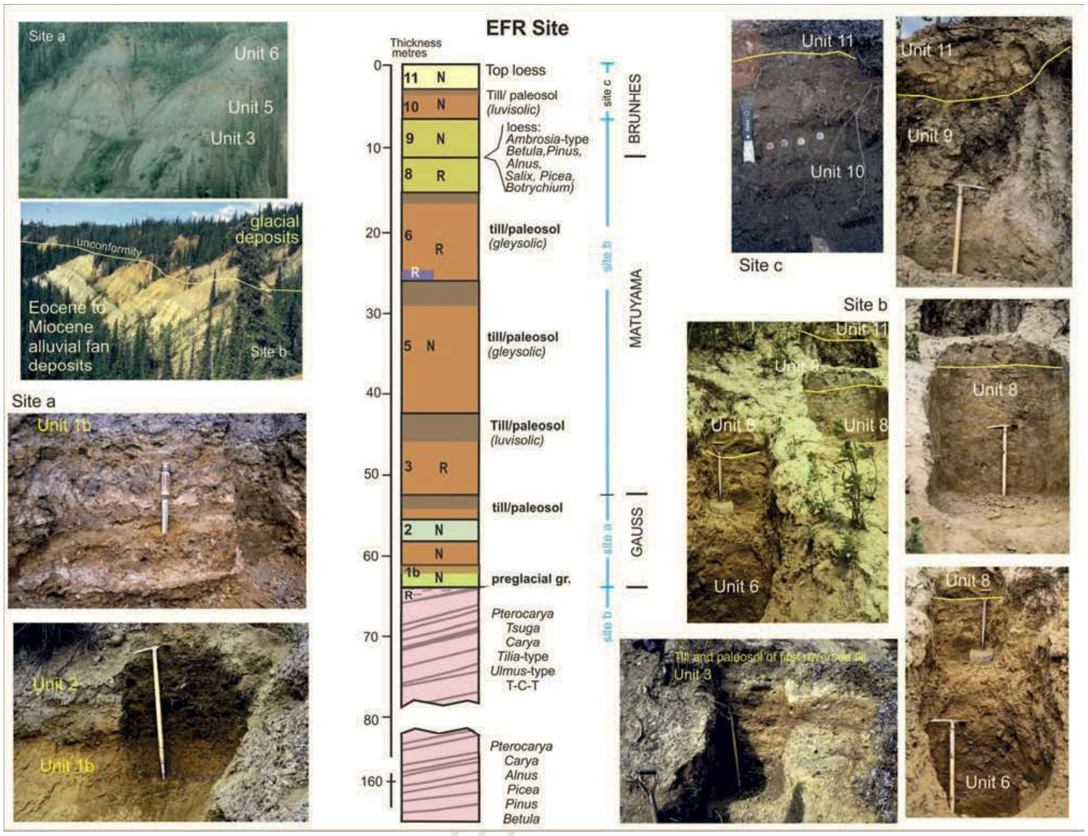
similar to soils associated with the southern limit of boreal forest vegetation today. The pebble lithologies of the till are of mixed origin (Cordilleran and local). The age of this deposit has been bracketed between 1.97 and 2.6 Ma (Early Pleistocene, Matuyama Reversed Chron). Unit 4 is a very coarse deposit enriched in clay content as a result of a prolonged period of moderate weathering and translocation of surface clays. It is a thick glacial mudflow deposit for which no polarity was determined; however, it is overlain by a normally magnetised outwash so must fall within the early Matuyama Chron (Figs. 49.3 and 49.4). Unit 5 consists of an outwash and a till. The till has a weathering horizon developed at its surface suggesting that it may represent the lowermost part of a truncated luvisol. There is no weathering horizon between the outwash and the till and therefore both are considered to be part of the same glacial event. A normal polarity was obtained from the outwash, indicating an Olduvai age based on its stratigraphical position (Figs. 49.3 and 49.4). Unit 6 is reversely magnetised outwash gravel assigned to the middle Matuyama, based on its stratigraphical position between the Olduvai and Jaramillo subchrons. Unit 7 comprises crude to well-stratified outwash gravels. Silty sand beds have normal polarity and are assigned to the Jaramillo normal subchron. They occur between reversely magnetised units above and below, assigned to the late Matuyama Chron. Unit 8 sediments are outwash sands and silts containing pockets of deformed material. Silts have reversed polarity and are underlain by normally magnetised outwash deposits (Jaramillo) and overlain by normal sediments (Brunhes Chron), and can therefore be assigned to the latest Matuyama Chron. Unit 9 is the uppermost glacial outwash at RC site and has a luvisolic palaeosol developed at its surface (comparable to a Wounded Moose palaeosol; Smith et al., 1986). Unit 9 is overlain by loess (unit 11, described below) and underlain by outwash (unit 8).



f0020 **FIGURE 49.4** Stratigraphy of Rock Creek (RC) site, Tintina Trench, Yukon. Stratigraphy extends from Late Pliocene (Gauss Normal Polarity Chron) preglacial and glacial deposits to Late Pleistocene loess cover at top of sections. The RC stratigraphy is a composite of three sites which lie in close proximity to each other. Unit numbers in the text correspond to numbers on left of stratigraphical column. Note hydrothermally altered preglacial sediments at base of strata.

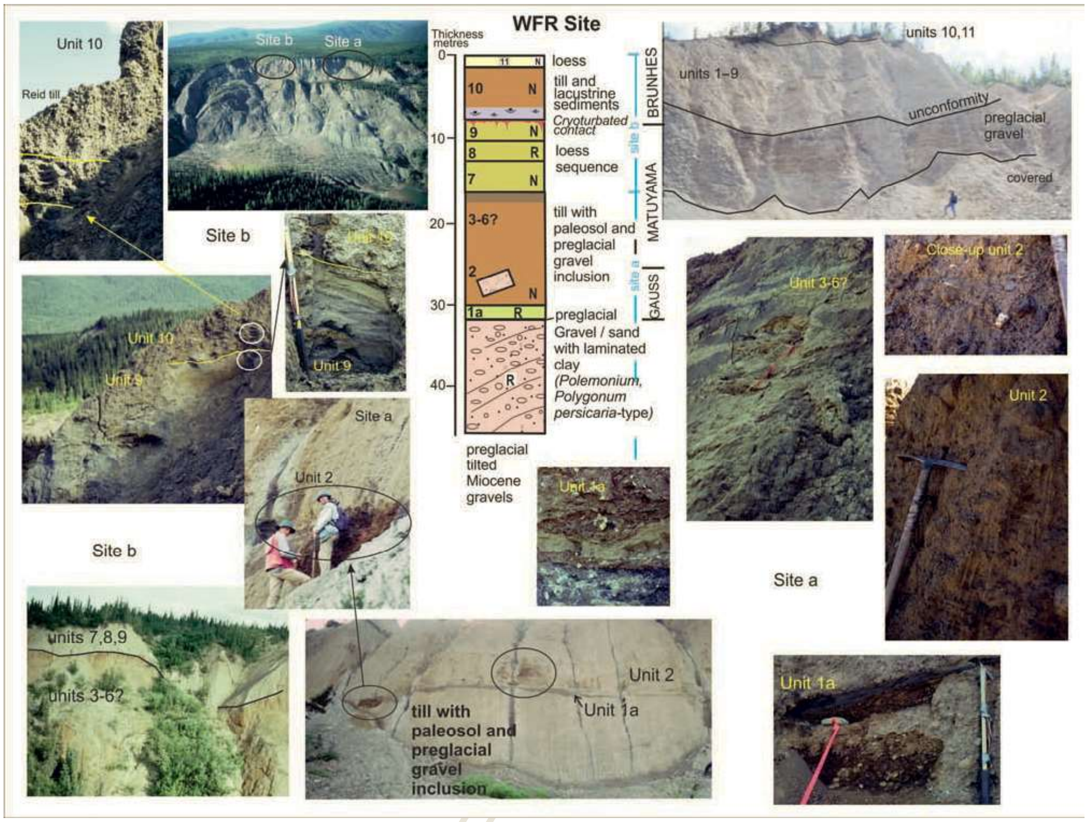
Clasts within the soil exhibit clay skin coatings. The normal polarity recorded in fine-grained sand lenses is assigned to the Brunhes Normal Chron. Unit 11 forms the uppermost loess unit (<20 cm) at RC. This regionally extensive unoxidised surface loess lacks structure, suggesting little or no reworking. It is normally magnetised and overlies Reid till (MIS 6/8; Westgate et al., 2008), and is therefore younger than 126 ka, probably of McConnell age (<23 ka, MIS 2).

u0010 **2.** *Fifteenmile River* (EFR site 2, Figs. 49.1–49.3 and 49.5) stratigraphy outcrops in a Holocene landslide scar on the north side of the Tintina Trench, 4.0 km east of Fifteenmile River (Figs. 49.3 and 49.5). The EFR outcrops expose a package of Plio–Pleistocene preglacial and glacial sediments separated unconformably from the underlying tilted Miocene beds. The latter are predominantly alluvial deposits laid down following extensional faulting in the trench. Glaciers from the continental divide area did not reach this portion of the trench, and only deposits of local provenance (Ogilvie Mountains) are present. Unit 1 exposes preglacial alluvial sand and gravel deposits that overlie tilted alluvial Miocene deposits. These preglacial sediments contain a ~~partially truncated~~ palaeosol (feragleysol) at its upper contact. The ~~soil is~~ truncated and deformed (Fig. 49.5, unit 1b) and in places incorporated into the overlying till, forming a wavy upper contact. Fine-grained beds are normally magnetised and correlated to the Gauss Normal Chron. Unit 1b overlies the Miocene/Pliocene unconformity and reveals the same polarity (and palaeomagnetic directions) as the overlying (unit 2) glacial deposits. This relationship is also seen at RC site. Unit 2 is a till with an interbed of silty fine sand, which is normally magnetised and is correlated to the latest Gauss Au5



f0025 **FIGURE 49.5** Stratigraphy of Fifteenmile River, east side (EFM), Tintina Trench. Stratigraphy extends over a similar span of time as that seen at RC, but includes an MIS 8/6 till near the top. It is a composite of two sites located about 100 m apart. Note deformation and incorporation of unit 1b into the overlying till.

Normal Chron (2.7–2.58 Ma) based on its stratigraphical location above alluvial deposits of unit 1 and its comparable polarity and palaeomagnetic directions (Barendregt et al., 2010). The weathering horizon at the top of the unit has characteristics of a truncated luvisol. Unit 3 is interpreted as a till with a well-developed luvisol at its surface, and has a reversed polarity assigned to the early Matuyama Chron (2.58–1.97 Ma). It occurs between the Gauss Normal Chron (unit 2) and the Olduvai subchron (unit 5) and is stratigraphically similar to unit 3 at RC site. Unit 5 is a till, with a gleysolic palaeosol developed in the top of the till. It forms a sharp contact with lacustrine unit 6 above. The base and upper parts of the unit 5 till have normal polarity, and because it occurs between reversely magnetised sediments of the early Matuyama (unit 3) and a pre-Jaramillo reversed till (unit 6), is assigned to the Olduvai subchron (1.97–1.78 Ma). Unit 6 comprises a basal lacustrine clay subunit, overlain by till with meltout characteristics. The top of the unit exhibits a gleysolic weathering horizon that formed under poorly drained conditions and is highly disturbed, probably due to cryoturbation. The lacustrine subunit and till are reversely magnetised, and unit 6 is assigned to the early late Matuyama Chron (1.78–1.05 Ma; pre-Jaramillo) because it lies stratigraphically between sediments assigned to the Olduvai and Jaramillo subchrons (Figs. 49.3 and 49.5). Unit 8 is a silt and fine sand deposit with mottled appearance. The lower contact is sharp. Samples collected for palaeomagnetic measurements were also used for pollen identification. Only one sample yielded some identifiable pollen grains at the transition to unit 9. There were 51 grains identified revealing the following: *Ambrosia*-type 33%, *Betula* 29%, *Pinus* 20%, *Alnus* 6%, *Salix* 6%, *Picea* 4% and *Botrychium* 2%. Unit 8 is reversely magnetised loess



f0030 **FIGURE 49.6** Stratigraphy of Fifteenmile River, west side (WFM), Tintina Trench. It is exposed in a major landslide scar and extends over a similar time span as that of EFR. The contacts between units 3 and 6 were not studied due to the steep terrain and were observed only through field glasses. WFM is a composite of two transects located about 70 m apart. Note blocks of preglacial sediments incorporated in the lowermost till.

and is assigned to the latest Matuyama. This assignment is based on its stratigraphical position between Jarmillo and Brunhes age deposits, and comparable palaeomagnetic directions for unit 8 at RC and WFM sites (Barendregt et al., 2010). Unit 9 is a silt and fine sand deposit with mottled appearance and minor stratification marked by fine clay beds. Unit 9 is normally magnetised loess, assigned to the early Brunhes based on stratigraphical position (Fig. 49.5) and similarities to the record found at WFR (Barendregt et al., 2010). It is reasonable to suppose that the boundary between units 8 and 9 at the EFR and WFR sites is correlative with the boundary between units 1 and 2 at Midnight Dome (MD) in the Klondike area (Froese et al., 2000) and that this stratigraphical contact marks the Brunhes–Matuyama (B/M) boundary. The Brunhes/Matuyama boundary (0.78 Ma) falls within marine oxygen isotope stage (MIS) 19, an interglacial period (Fig. 49.5). Pollen obtained from the base of unit 9 reveals *Pinus*, *Ambrosia*-type, *Betula*, *Alnus*, *Salix*, and *Picea* and suggests deposition during an interglacial. Unit 10 is a diamicton (till) with a silty-clay matrix and 20% clasts up to 15 cm in size. It forms a sharp contact with underlying unit 9. Unit 10 has a normal polarity, is assumed to have been deposited by the Reid glaciation and is correlated with unit 10 at WFR (Fig. 49.5). Unit 11 is a 0.2-m-thick, massive silt and fine sand bed loess which corresponds to the regionally extensive unoxidised surface loess that discontinuously covers much of the western Yukon. Its massive characteristic suggests little or no reworking. It is normally magnetised, overlies unit 10 at EFR and WFR sites, and is therefore considered to be the Late Pleistocene (<23 ka) McConnell loess.

3. *Fifteenmile River* (WFR site 3, Figs. 49.1–49.3 and 49.6) stratigraphy outcrops along a 1-km long Holocene landslide scar reactivated within an older landslide, and is located on the north side of the Tintina Trench, approximately 1.0 km west of the river (Figs. 49.2 u0015

and 49.6). The exposure reveals several older landsliding events, also seen at many other localities, and may relate to extensional faulting along the trench in the Late Miocene. Beds within the landslide have undergone minor rotation and lowering but have remained intact. The WFR stratigraphy exposes a 14 m sequence of tilted Miocene alluvial deposits, overlain by 26 m of conformable and horizontally stratified glacial deposits described at two sites (Fig. 49.6). The contact between these two depositional sequences forms an angular unconformity which is clearly visible along all landslide scars in the Trench. Approximately 200 m of partially exposed and poorly preserved Tertiary (and older) strata extend to creek level. The stratigraphy above the unconformity at WFR site consists of Pliocene preglacial gravel and laminated sand, overlain by till and loess units. This stratigraphical sequence is less complete than that seen at EFR site but is equivalent to the lower units at RC and EFR. Unit 1 has preglacial gravel and sand with minor laminated clay beds which overlie tilted alluvial Miocene deposits and are overlain by the first till (Fig. 49.6). A silty fine sand bed near the unconformity is reversely magnetised and probably belongs to either the Kaena (3.12–3.05 Ma) or the Mammoth (3.33–3.22 Ma) reversed subchrons within the Gauss Normal Chron (Late Pliocene). This age assignment is supported by the presence of *Polemonium*, *Polygonum* and *persicaria*-type pollen which is generally thought to have a maximum age of Late Miocene, and by recently dated sediments in the Klondike Plateau which are thought to be equivalent, and contain the Quartz Creek tephra (3.00 ± 0.33 Ma; Sandhu et al., 2000). The pollen indicates a cool/cold alpine climate. Unit 2 is exposed in a 16-m vertical outcrop where study was limited to the basal portion. The exposure may contain sediments from other glaciations, and additional polarity histories may also be present. Unit 2 is a till, which in places has incorporated blocks of underlying preglacial sediments. The fine sand and silty-clay beds at the base may be outwash deposits. The till appears to be capped by a palaeo-
Au6 sol ~~(?)~~ which ~~appears to be~~ discontinuously preserved. The normal polarity is assigned to the upper Normal Gauss Chron based on stratigraphical position and polarities recorded in units above and below (Figs. 49.3 and 49.6). Units 7–9 are loess deposits recording three polarities (N–R–N), suggesting a considerable time span. They are assigned (from bottom to top), to the Jaramillo subchron (N), latest Matuyama Chron (R) and early Brunhes Chron (N) and are correlated with units 8 and 9 at EFM and at RC. At EFR and WFR, these units are overlain by the middle Brunhes Reid till (MIS 8 or 6). The extensive loess sequence at WFR indicates that glaciers from the Ogilvie Mountains most likely did not reach this part of the Tintina Trench. The upper part of unit 9 exhibits cryoturbation indicating periglacial activity during this time. Unit 10 is a till with a basal glacio-lacustrine component. Both till and lacustrine sediments are normally magnetised and are assigned to the Brunhes Normal Chron. This till is most probably the late Middle Pleistocene (Reid age) till (MIS 6 or 8) and is correlated with the uppermost till at EFM. Unit 11 is a 40-cm-thick unoxidised regional loess cover, which lacks structure, suggesting little or no reworking. It is normally magnetised, overlies the assumed Reid age till, and is thought to be Late Pleistocene (<23 ka, (MIS) 2) McConnell loess.

49.2.2. Klondike Gold Fields s0020

The Lower Klondike River Valley has yielded an extensive p0065
late Neogene stratigraphy and chronology. Two sites (MD and Jackson Hill (JH), sites 4 and 5; Figs. 49.1–49.3, 49.7 and 49.8) have preserved a stratigraphical record that complements most of the late Neogene geologic record in the Tintina Trench (Duk-Rodkin et al., 2010).

1. *JH* (site 4, Figs. 49.3 and 49.7) records upper preglacial u0020
gravels (White Channel) and outwash gravels related to the first glaciation in west-central Yukon which occurred in the Late Pliocene (ca. 2.65 Ma; Froese et al., 2000). The White Channel Gravels are of local provenance (Klondike Plateau gold fields; Fig. 49.1), while the glacial outwash gravels are of Cordilleran origin. The lower part of the White Channel Gravels reveals a reversed/normal/reversed/normal magnetic polarity sequence assigned to the Gilbert/Gauss Epochs (4.18–3.05 Ma; Figs. 49.3 and 49.7). The upper reversed/normal sequence within the White Channel Gravels contains ice-wedge casts which provide clear evidence for the onset of a cold climate (Fig. 49.7). The upper White Channel Gravels interfinger with Cordilleran outwash, and sediments are normally magnetised throughout this zone of mixed sedimentation (Fig. 49.7). Elsewhere in the gold fields, two tephras were obtained from this strata (Dago Hill and Quartz Creek) which have fission-track ages of 3.18 and 2.97 Ma, respectively (Sandhu et al., 2000; Westgate et al., 2002).
2. *MD* (site 5; Figs. 49.3 and 49.8) preserves Middle–Early u0025
Pleistocene basal fluvial gravels, outwash gravels, and loess deposits along the north side of the lower Klondike River Valley. The loess sequence has a reversed/normal/reversed/normal magnetisation which intermittently spans the late Matuyama and Brunhes Chrons (1.45 Ma–present) and includes the Jaramillo normal subchron (0.99–1.05). This sequence contains two tephras, one in the lower reversed loess which was

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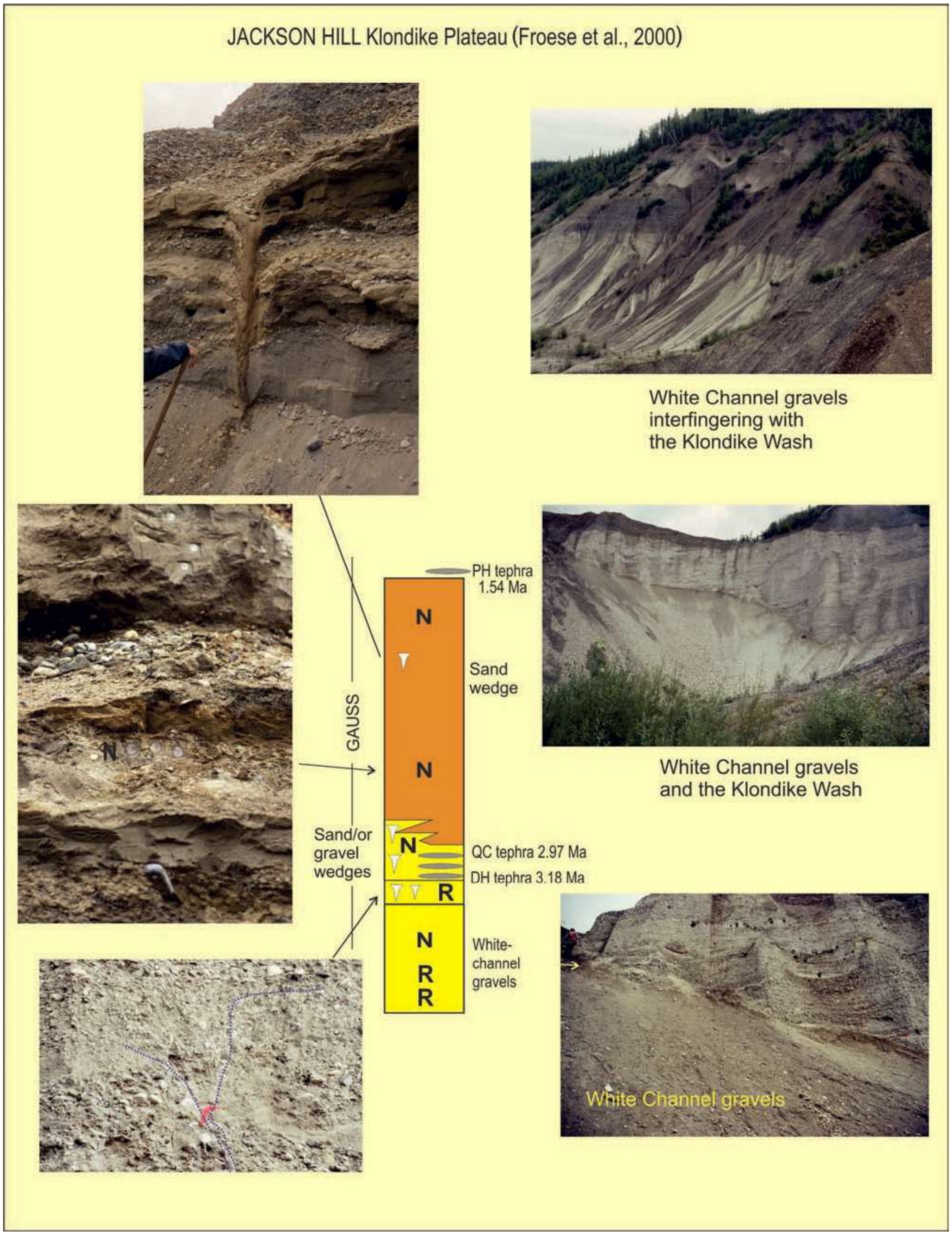

f0035 **FIGURE 49.7** Stratigraphy of Jackson Hill is exposed in a large placer mine outcrop near Dawson townsite in the Klondike Valley. The stratigraphy reveals preglacial White Channel gravels which interfinger with the Klondike outwash near the upper contact (MIS G10). Both preglacial gravels and outwash have sand and gravel ice-wedge casts developed at various palaeo-surfaces.

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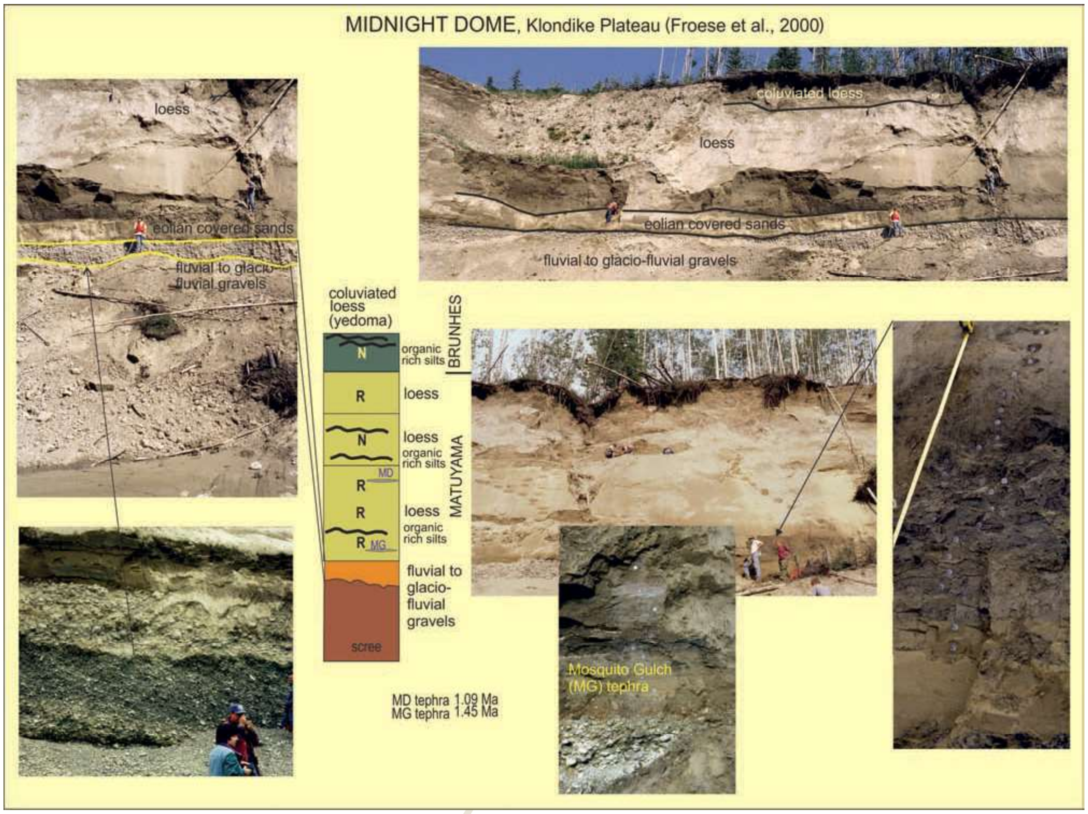

f0040 **FIGURE 49.8** Stratigraphy of Midnight Dome (MD) is exposed in a placer mine outcrop near Dawson townsite in the Klondike Valley. Late Matuyama to early Brunhes age deposits are exposed at MD. The stratigraphy reveals loesses developed under both glacial and interglacial conditions, and contains organic rich silt horizons (palaeosols) and ice-wedge casts.

deposited during a warm interval (1.4 Ma Mosquito Gulch tephra) and the other in the upper part of the same reversed unit deposited during a cold event (1.09 Ma, MD tephra; Froese et al., 2000; Froese and Westgate, 2001). This loess sequence reveals a short interval at its base containing pine pollen, followed by cold and very cold (glacial) conditions (colluviated loess, or ~~so-called~~ yedoma).

s0025 49.2.3. Fort Selkirk

p0080 Fort Selkirk sites in the west-central Yukon preserve an extensive late Neogene record of volcanic, glacial and interglacial events (Figs. 49.1–49.3). The stratigraphy outcrops along the Yukon River (Fig. 49.1) and is depicted in four composite sites (Figs. 49.9–49.12) labelled (from older to younger): (1) Wolverine sequence (Ne Ch'e Ddhawa north and Ne Ch'e Ddhawa tuya, Fig. 49.9); (2) Fort Selkirk Volcanic Complex: Lower Mushroom site (Fig. 49.10); (3) Fort Selkirk Volcanic Complex: composite of Mushroom, Cave and Fossil sites (Fig. 49.11) and (4) Fort Selkirk Volcanic Complex: Black Creek flows (Tip, Angel and Pillow Point sites, Fig. 49.12). In total, five glacial events are recorded from sediments which are only locally preserved beneath, within and above lava flows and hyaloclastite complexes. Four of these glaciations fall within the Matuyama Reversed Chron and one within the Brunhes Normal Chron. The ages of these events span from 1.83 to 0.30 Ma. The deposits have been dated by K–Ar, Ar–Ar, fission-track, palaeomagnetism and fossil evidence. In addition, geomorphological evidence of glaciations, such as striae on lava beds, exotic glacial pebbles within lavas, and the presence of pillow lavas as indicators of eruption through ice, have also been used (Jackson et al., 1996; Huscroft et al., 2004; Nelson et al., 2009).

Wolverine sequence (Ne Ch'e Ddhawa north and Ne p0085
Ch'e Ddhawa tuya, Figs. 49.3 and 49.9) is composed of three basalts flow (total thickness ~60 m). The lower flow (4.34 ± 0.06 Ma) is reversely magnetised and falls within the Upper Gilbert, the middle flow (3.21 ± 0.07 Ma) is also reversed and falls within the Mammoth subchron of the early

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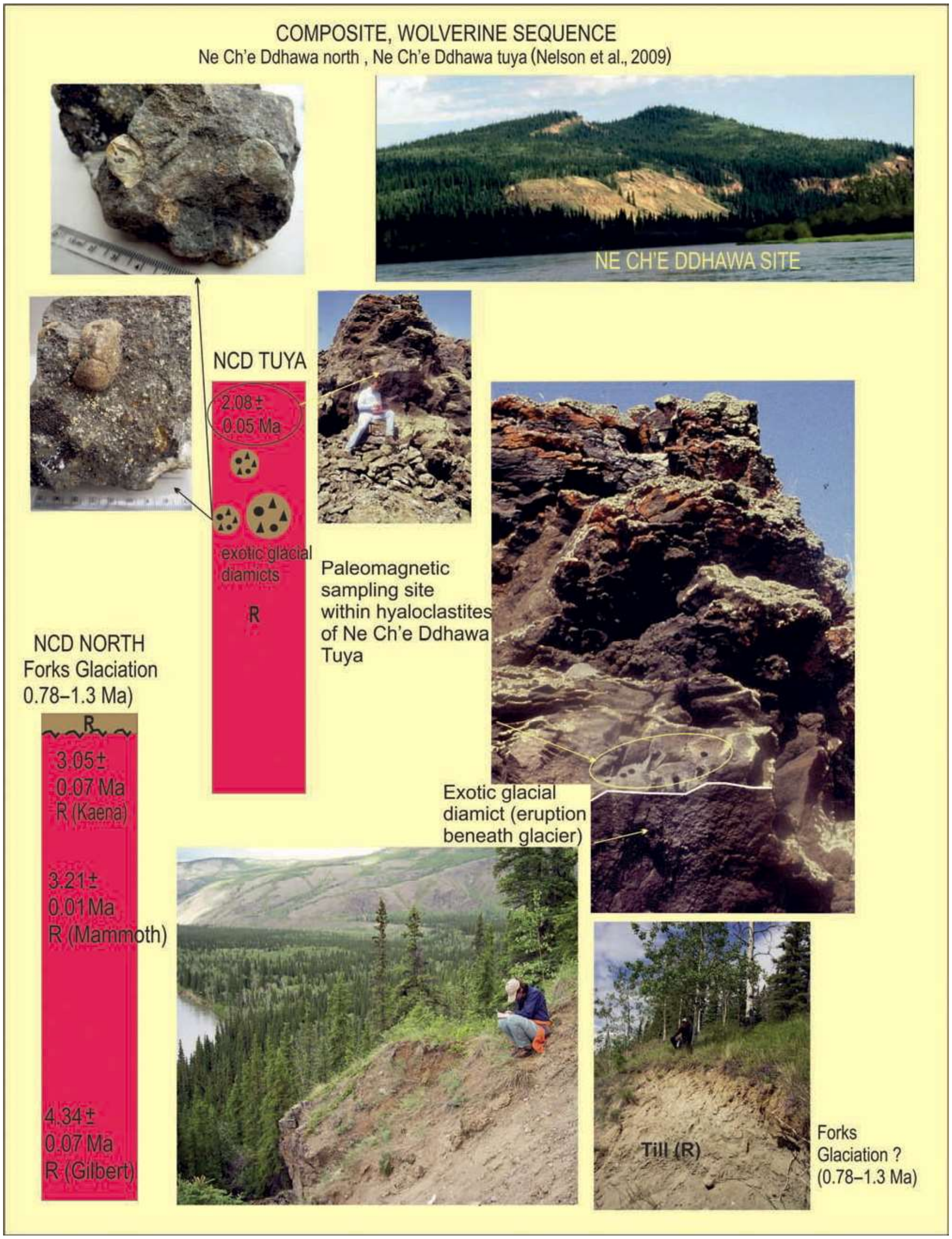

f0045 **FIGURE 49.9** Composite stratigraphy of the Wolverine sequence is described at two sites: NCD Tuya and NCD North. NCD Tuya exposes diamictites (till) incorporated into lava during a subglacial eruption and provides an accurate age for this glaciation (2.14 ± 0.14 Ma). NCD North exposes a till (latest Matuyama) overlying a 3.05 ± 0.07 Ma basalt.

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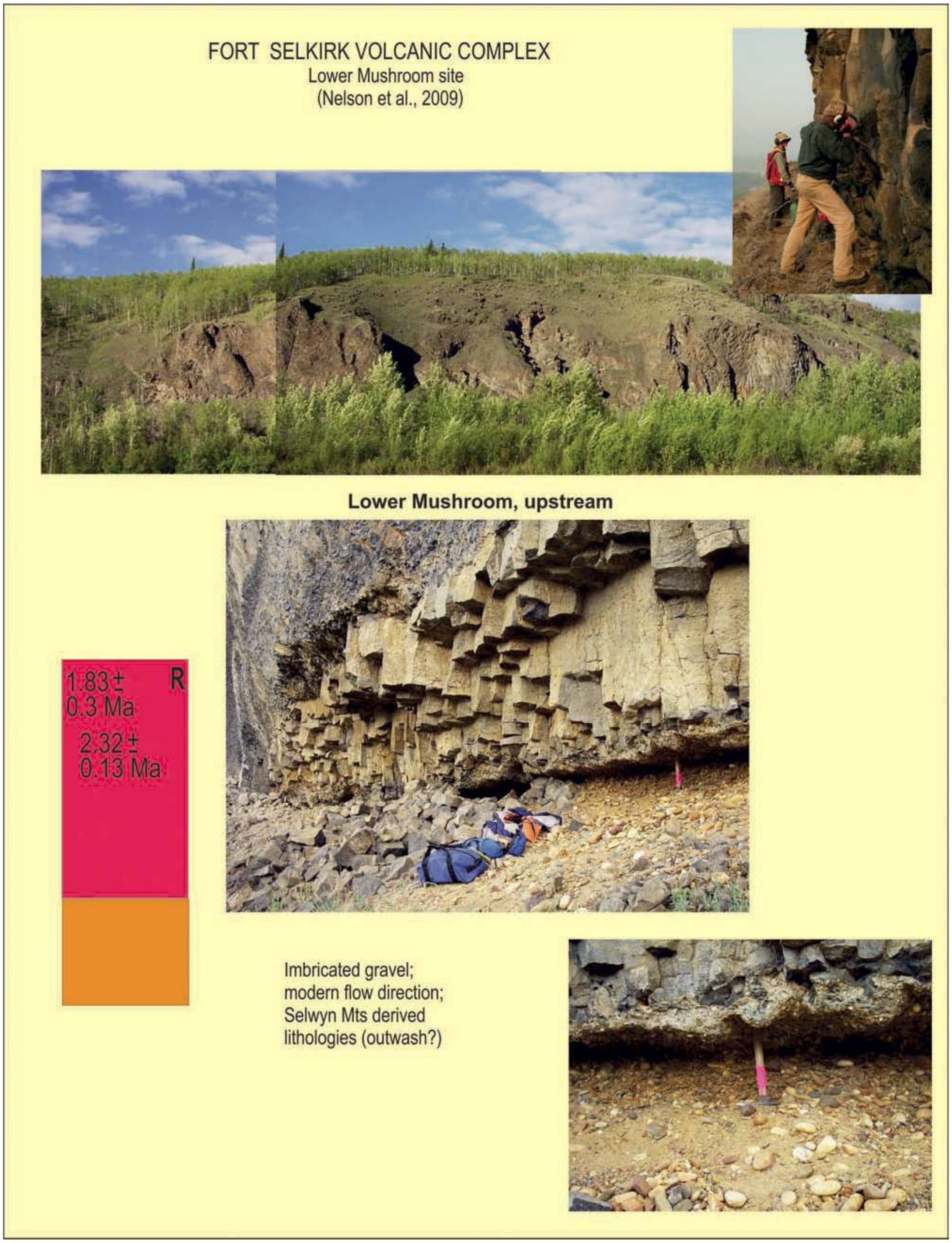
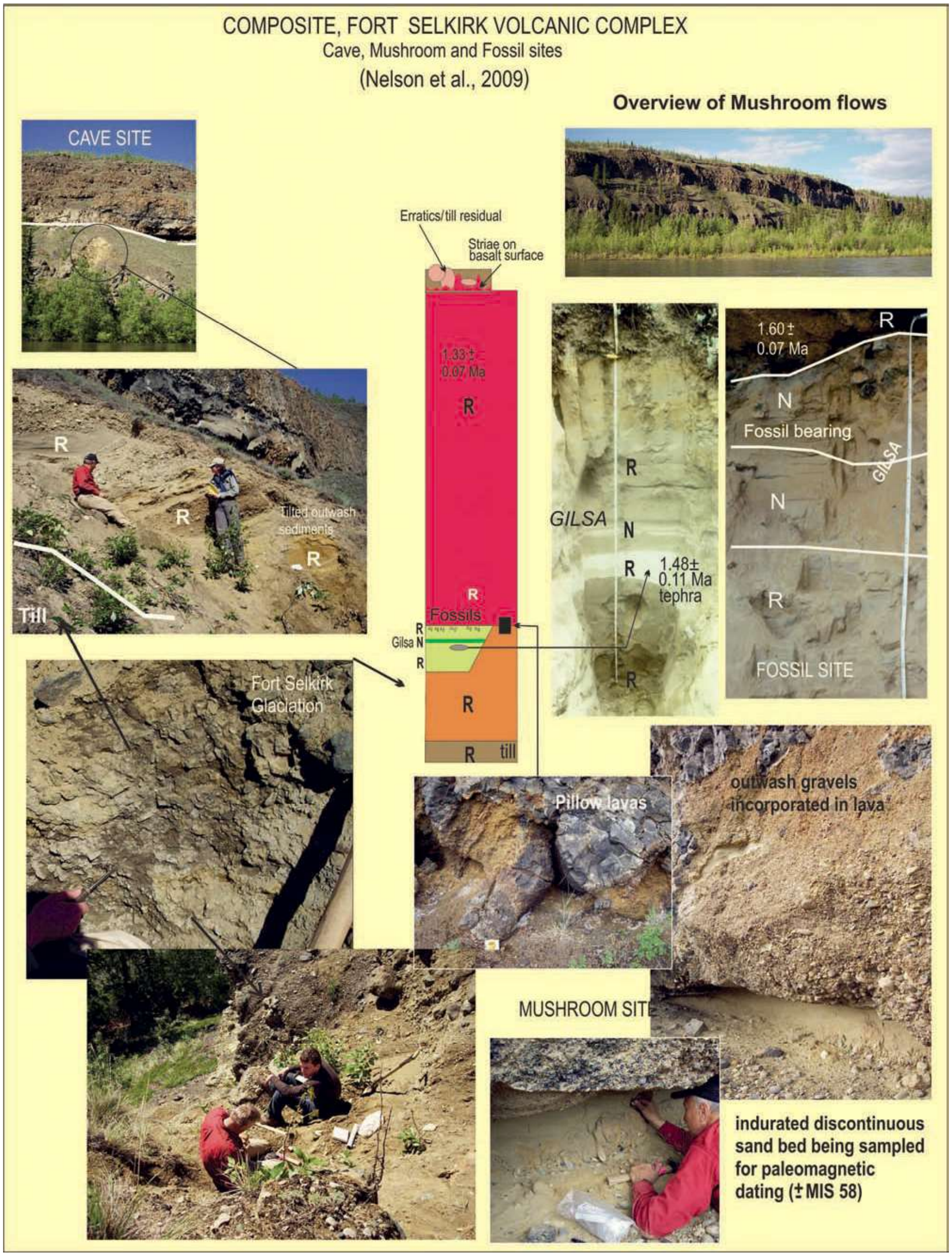
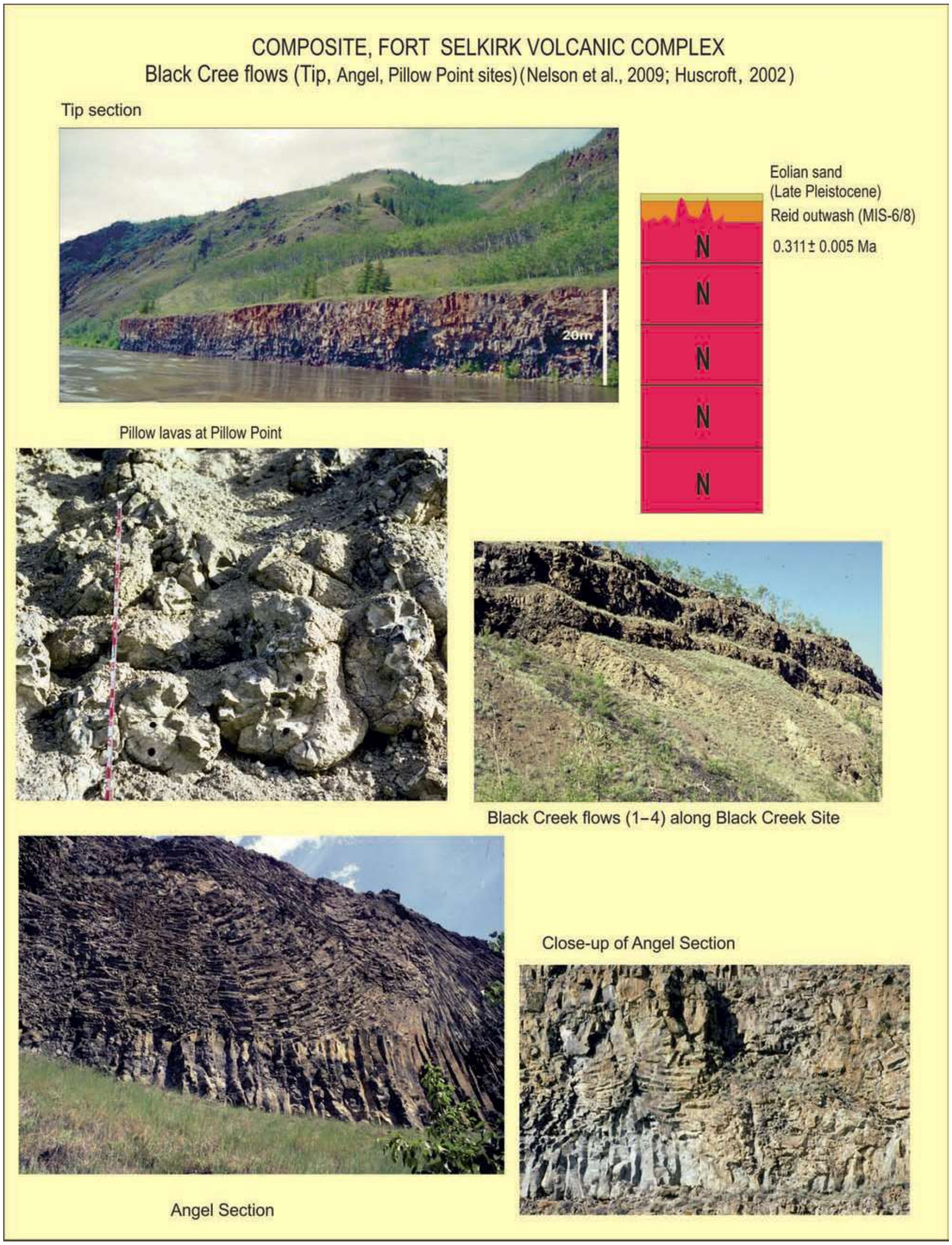


f0050 **FIGURE 49.10** Lower Mushroom site (Fort Selkirk volcanic complex) exposes a basalt (1.83 ± 0.3 and 2.32 ± 0.13 Ma) overlying outwash (?) gravels which were deposited during the Gauss (G10) or earliest Matuyama (MIS 100) Chrons.



f0055 **FIGURE 49.11** Cave, upper Mushroom and Fossil sites of the Fort Selkirk volcanic complex expose glacial and interglacial deposits underlying a reversed basalt (1.33 ± 0.07 Ma). The basalt has been overridden by ice, as evidenced by glacial striae and residual erratics. Reversed till and outwash deposits at the base of the exposure are post-Olduvai (< 1.78 Ma) but younger that the Gilsa subchron (1.6–1.55 Ma). Interglacial deposits above the till and outwash contain a reversed–normal–reversed polarity sequence and a tephra (1.48 ± 0.11 Ma). The normal sediments are assigned to the Gilsa subchron and are overlain by reversely magnetised sediments containing Blancan fossils.



f0060 **FIGURE 49.12** Black Creek outcrop (Fort Selkirk volcanic complex) exposes five basalt flows, and the upper flow (0.311 ± 0.005 Ma) is overlain by outwash of the Reid glaciation (MIS 6/8).

Gauss, while the third flow (3.05 ± 0.07 Ma) is reversed and falls within the Kaena subchron of the early Gauss. The upper flow is overlain by a reversely magnetised till (Forks Glaciation, Jackson et al., 2010) considered to be of late Matuyama age (Fig. 49.3). Stratigraphically above, and some 300 m to the south of Ne Ch'e Ddhawa north is the *Ne Ch'e Ddhawa tuya site* (Figs. 49.3 and 49.9). The tuya is the product of subglacial eruption and contains blocks of exotic glacial diamicts (Fig. 49.9). The upper part of the Tuya has an age of 2.08 ± 0.05 Ma and is reversely magnetised, and therefore this glaciation falls within the early Matuyama (Jackson et al., 2008, ~~2010~~; Nelson et al., 2009).

p0090 *Fort Selkirk Volcanic Complex: Lower Mushroom site* (Figs. 49.3 and 49.10) consists of a basalt flow underlain by outwash gravel. Two Ar/Ar ages for the reversely magnetised basalt (2.32 ± 0.13 and 1.83 ± 0.3 Ma) provide a minimum age for the underlying outwash. This glaciation may correspond to the one which produced the NCD Tuya, or may be an earlier glaciation.

p0095 *Fort Selkirk Volcanic Complex: omposite of Mushroom, Cave and Fossil sites* (Figs. 49.3 and 49.11) is a sedimentary and volcanic sequence occurring between two glacial events (Fort Selkirk Glaciation and an unnamed glaciation). The Fort Selkirk Glaciation consists of till overlain by outwash, both reversely magnetised, and both considered to belong to the same glaciation, based on their nearly identical palaeomagnetic directions. Reversely magnetised interglacial deposits overlie the outwash and contain a tephra (1.48 ± 0.11 Ma, also reversed), and a short interval of normally magnetised silt (Gilsa subchron, Froese and Westgate, 2001). A 14-m-thick basalt (1.33 ± 0.07 Ma) overlies the interglacial deposits, reveals striations at its upper surface, and is overlain by discontinuous drift of a younger glaciation (< 1.33 Ma), perhaps equivalent to the Forks Glaciation at NCD North.

p0100 *Fort Selkirk Volcanic Complex: Black Creek flows (Tip, Angel and Pillow Point sites*; Figs. 49.3 and 49.12) consist of a series of five lava flows exposed along the Yukon River downstream from Fort Selkirk and are discontinuously overlain by outwash and loess. The uppermost basalt has an Ar/Ar age of 0.311 ± 0.005 Ma, and all flows are normally magnetised. The outwash deposit is assumed to be the late Middle Pleistocene Reid glaciation (MIS 8/6) and is overlain by loess of the latest Pleistocene (McConnell Glaciation, MIS 2; Huscroft, 2002; Huscroft et al., 2004; Nelson et al., 2009).

s0030 49.3. NORTHWEST TERRITORIES

s0035 49.3.1. Mackenzie Mountains

p0105 *Katherine Creek (KC) section* (Fig. 49.13) consists of five montane tills, capped by one Laurentide till. These tills overlie 8 m of colluvium developed above a bedrock pediment. It is difficult to differentiate between the colluvium and the lowest montane till because the till clasts are subangular and glaciers travelled only short distances from their mountain sources. This colluvial unit is also present at the Little Bear (LB) site where it reaches thicknesses of over 20 m. In Duk-Rodkin et al. (1996), this first deposit overlying the bedrock pediment was considered to be a colluvium. At both the KC and LB sections, this lowest unit is normally magnetised, and if this unit is in fact a till it may correlate with the earliest glacial deposits in the Yukon, which are also normally magnetised, and assigned to the latest Gauss Normal Chron. Above the normally magnetised colluvial unit are two reversed tills (pre-Olduvai), thought to be laid down by a single glaciation, as there is no sharp contact or palaeosol between the two. A luvisol is developed on the upper reversed till. The overlying till is normally magnetised and assigned to the Olduvai (1.95–175 Ma). It contains ice cast pseudomorphs developed at its surface, as well as a luvisolic B horizon. Two normally magnetised tills were deposited above the Olduvai till, and these are assigned to the Brunhes Normal Chron (< 0.78 Ma; MIS 16?, 12? or 8?). The surface till is continental (Laurentide) and considered to be Late Pleistocene (MIS 2). Chlorine 36 ages of 28–26 ka obtained from boulders near LB site indicate that the glacier had receded from its maximum position by that time (Duk-Rodkin et al., 1996).

LB River section (Fig. 49.14) comprises five montane tills overlying a colluvial deposit. The entire sequence is overlain by a till of Laurentide origin (Fig. 49.14). As in the KC section, three tills (normal/reversed/normal polarity) in the lower half of the outcrop span the late Gauss (2.70–2.58 Ma) to early Matuyama (2.58–1.98 Ma). The three overlying montane tills are coarse-textured, and only the last till provided a (normal) polarity. The tills are assigned to the Brunhes Normal Chron, and the uppermost Montane till is assumed to have been deposited by a Reid equivalent MIS 8/6 glaciation. The palaeosols at LB indicate a progressive deterioration of climate. The palaeosol developed on the lowermost colluvium exhibits a thick weathering horizon, while at the top of the section, a thin Eutric Brunisol is identified (Fig. 49.14). p0110

Inlin Brook (IB) section (Fig. 49.14) has a less complete stratigraphy than the KC and LB sites and is considered as a complimentary section. It consists of a preglacial gravel deposit of Tertiary age at the base, overlain by tills and outwash deposits capped by a single continental (Laurentide) till. There are five distinctive glacial units (Fig. 49.14), four of which have a palaeosol developed at their upper contact (detailed study of the palaeosols has not been carried out at this locality). Two tills and outwash at the base of the section are reversely magnetised and are assigned to the early Matuyama (2.58–1.98 Ma). These are overlain by a till and palaeosol of normal polarity (Olduvai 1.95–177 Ma), which in turn are p0115

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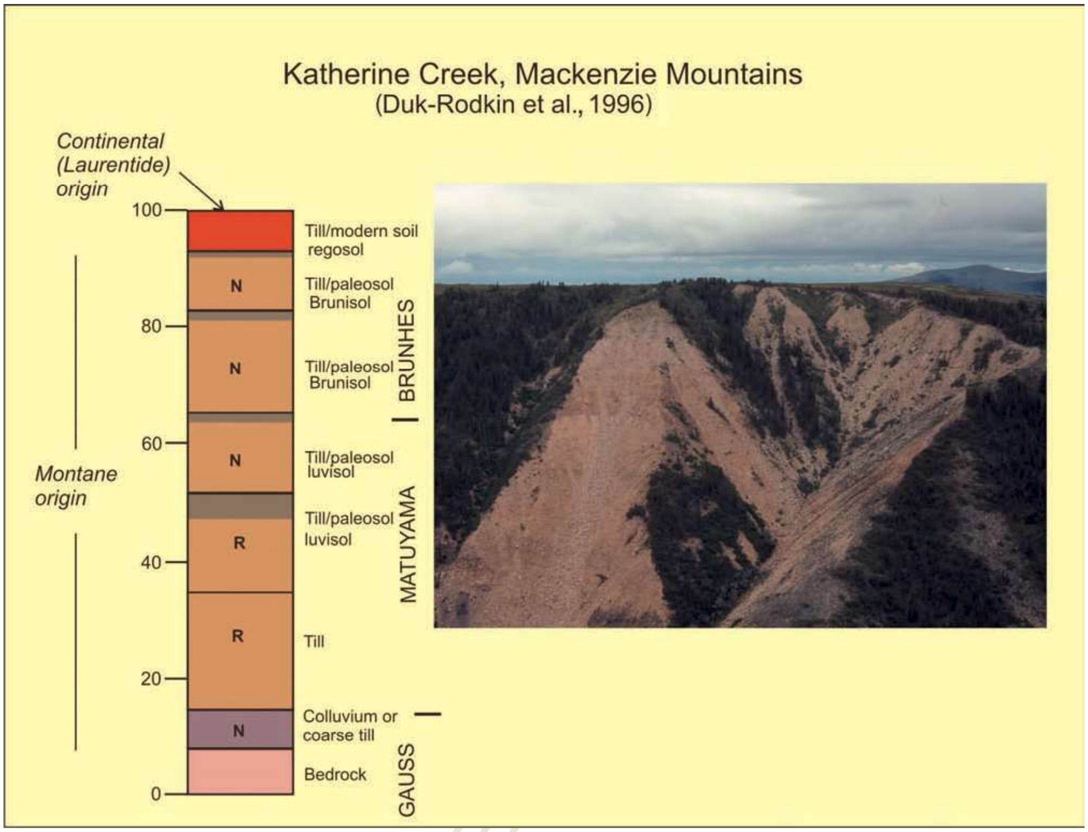

f0065 **FIGURE 49.13** Katherine Creek (KC) site exposes a series of montane (local) tills of both Matuyama and Brunhes age. These tills are underlain by normally magnetised colluvium over bedrock and are overlain by a Late Wisconsin (Laurentide) glacial till at the surface.

overlain by two tills and palaeosols for which no polarity was obtained. However, they are assumed to be correlative with the Brunhes age tills at the KC and LB sites. The three sections were correlated on the basis of lithology, palaeomagnetism and palaeosol properties. For the younger strata, chlorine dates obtained from surface boulder erratics were used in the correlation. A formal stratigraphical nomenclature has been developed for the deposits of this region (Duk-Rodkin et al., 1996). The sequence of glacial tills and palaeosols marks a long record of glacial–interglacial cycles, while soil properties for the two oldest palaeosols point to climatic conditions much warmer and wetter than today.

s0040 49.3.2. Mackenzie Delta

p0120 Glacial and non-glacial deposits have been recorded in the Mackenzie Delta area from the Taglu, Kumak and Unipkat boreholes, which extend to 450, 250 and 95 m depth, respectively (Figs. 49.3 and 49.15). Only the Taglu and Kumak boreholes contain diamictons thought to be of glacial origin and fall within the early Matuyama Reversed Chron (Dallimore and Matthews, 1997). The cores represent mostly fluvial, glaciofluvial and marine deposits consisting of intercalated sands/silts/clays and lesser amounts of gravels. Cross-beds and foresets are common, indicating deltaic deposition. The diamictons are located at the base of the cores and are non-glacial in origin below the Gauss/Matuyama boundary (2.58 Ma), and Pleistocene in age above the boundary, based on the presence of *Artemisia* (Dallimore and Matthews, 1997). Detailed palaeomagnetic measurements of all three cores were carried out by Wang and Evans (1997). Pollen analysis of the Kumak borecore was carried out by Jette, and macrofossils were studied by Matthews and are reported in Dallimore and Matthews (1997).

Au7

p0125 *The Taglu borecore* (Fig. 49.15) reveals a sequence of 35 m (450–415 m) of interbedded clay and silt with occasional gravel zones interbedded with silty sand beds. It is overlain by a diamicton of about 25 m thickness, with some

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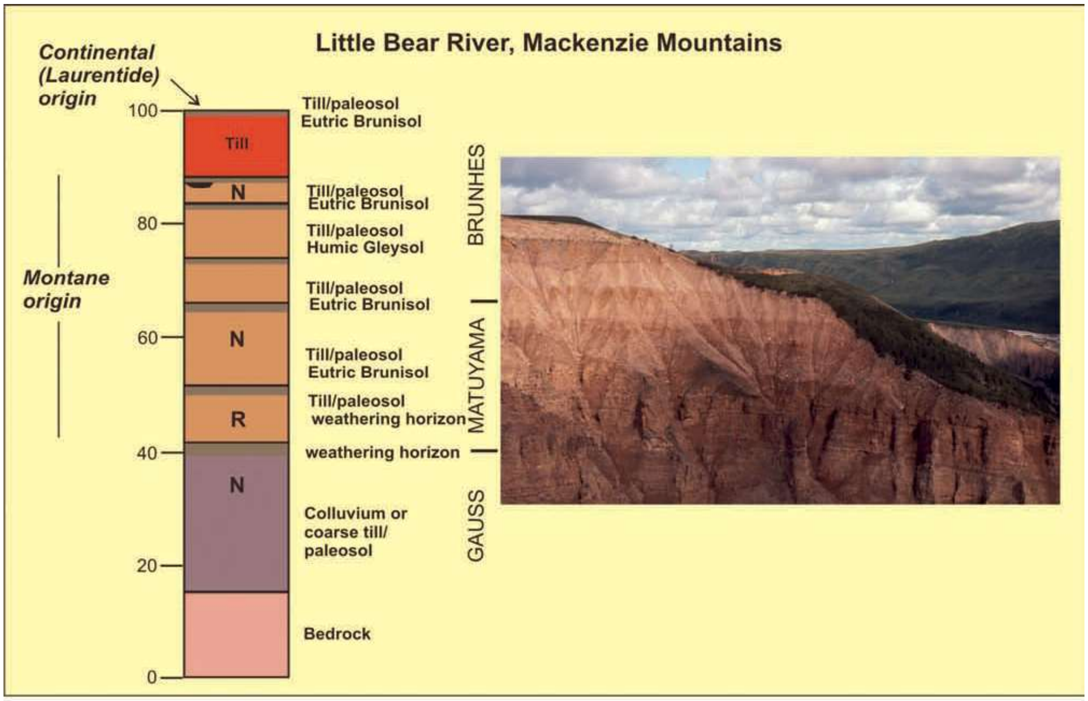

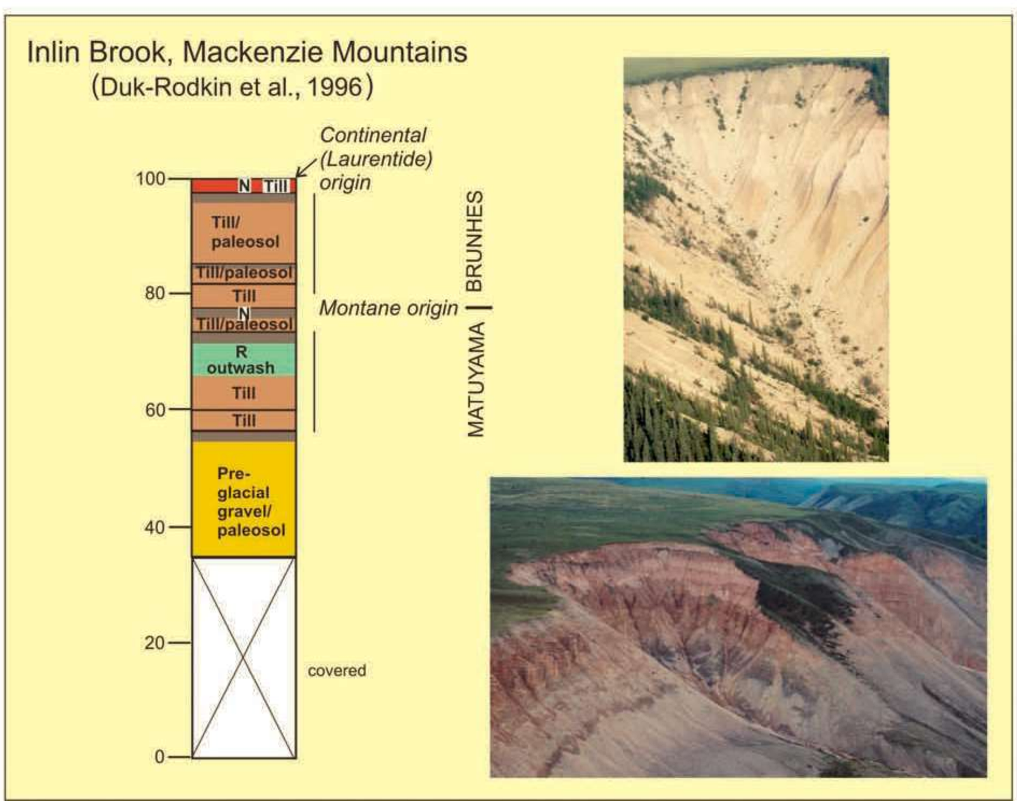

f0070 **FIGURE 49.14** Little Bear (LB) and Inlin Brook (IB) are two exposures near the KC site and reveal a similar stratigraphy to that of KC.

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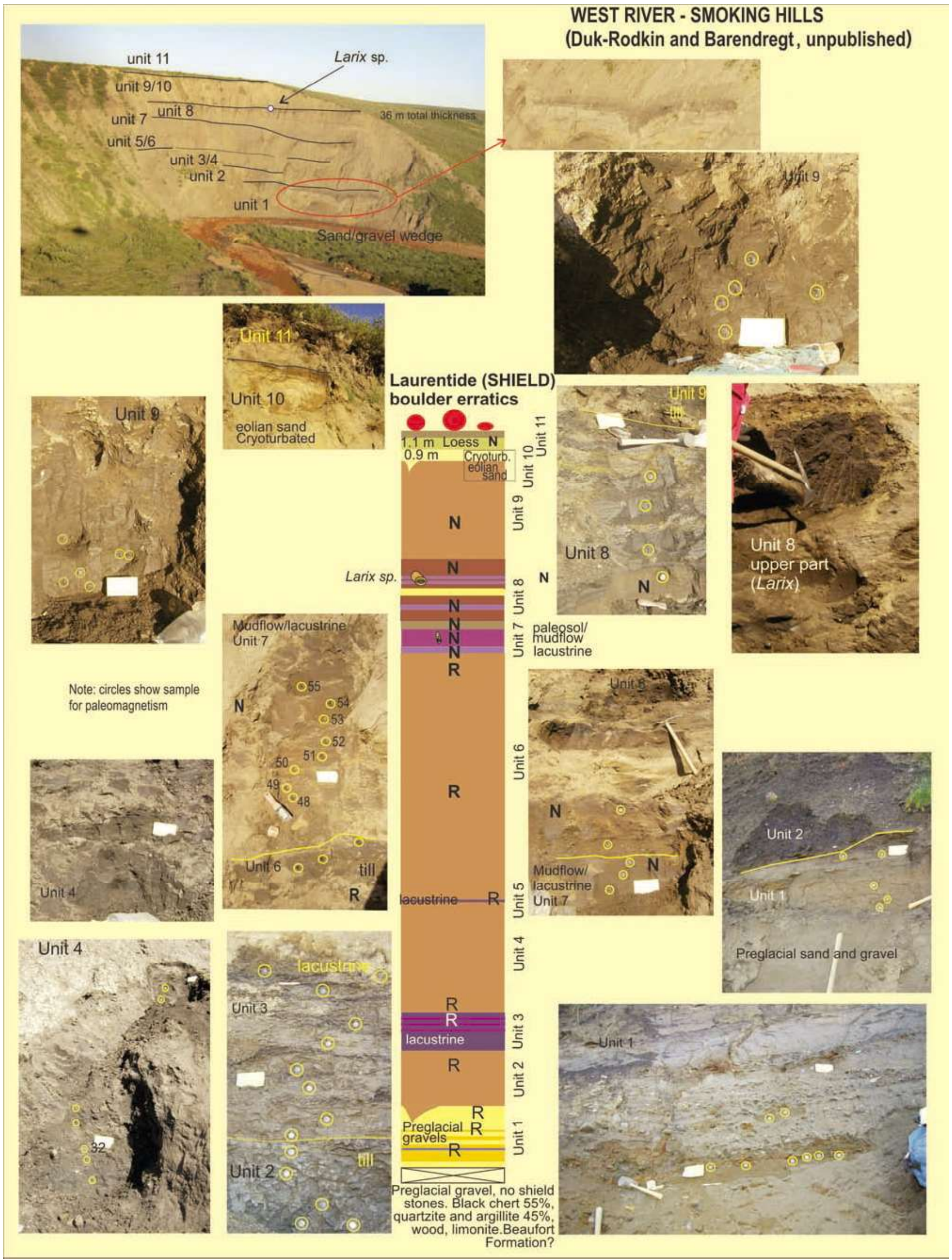


f0075 **FIGURE 49.15** West River (tributary of Horton River) in the Smoking Hills provides an extensive exposure of Matuyama and Brunhes age glacial and interglacial deposits, overlying reversely magnetised preglacial deposits which may be late Beaufort Formation or younger (possibly Worth Point equivalent?). The preglacial sediments contain ice-wedge casts suggesting cold conditions, and these were preserved by a glacial till which was deposited shortly after their formation. Only the surface till (Late Wisconsin) contains Shield erratics. Pollen analysis of interglacial deposits is currently in progress.

core gaps above and below the diamicton. The diamicton extends from 415 to 390 m depth and is normally magnetised (Gauss) (Dallimore, 1992). The samples are rich in reworked pollen, indicating floral characteristics of a climate warmer than today. However, one sample contains pollen which suggests a climate as cold as today. The diamicton also contains reworked pollen which was derived from Eocene to Jurassic bedrock. This diamicton is clearly associated with non-glacial conditions. Above this diamicton is a 15 m (390–375 m) thick silty/clay bed contain~~s~~ recycled pollen from Eocene to Jurassic rocks. It is reversely magnetised and assigned to the Kaena or Mammoth subchron. This silty/clay bed is overlain by a 35-m-thick diamicton and sand unit with normal polarity (Gauss) at its base, and reversed polarity (earliest Matuyama) at the top of the unit. This diamicton extends from 375 to 340 m with the reversely magnetised sediments extending from 351 to 360.5 m. These sediments contain no plant macrofossils but do contain shells. This second diamicton, which spans the Gauss–Matuyama boundary, contains a great admixture of pollen types revealing herbaceous-shrub tundra vegetation. This mix suggests cold (glacial?) conditions for the second diamicton (Dallimore and Matthews, 1997). Both diamicton units are predominantly clay-textured, with Au8 varying amounts of granules and pebbles. ~~The mineralogical and lithological provenance of the pebbles has not been determined.~~ This second diamicton (reversed) is underlain and overlain by normally magnetised sediments which are assigned to the Gauss Normal Chron and the Olduvai normal subchron, respectively (Fig. 49.15). Overlying this second diamicton are 80 m (340–260 m) of conglomerate with silty sand beds and sandy gravel beds containing organic debris, wood and occasional shells (to the top). Several oxidised horizons in the upper segment of this core interval may represent palaeowater table ~~positions.~~ Polarity for this interval indicates a reversed/normal/reversed/normal/reversed sequence, where the normal intervals are assigned to the Reunion and Olduvai, respectively (Fig. 49.15). This interval is overlain by about 115 m (260–145) of sandy/silt to silty/sand beds some with organic detritus, wood and occasional shells. This core interval records, from bottom to top, an R–N–R polarity sequence which is assigned to the late Matuyama (post-Olduvai), Jaramillo and latest Matuyama, respectively. The overlying sediments (145–0 m) are all normally magnetised (Brunhes Normal Chron) and from bottom to top consist of massive sand with organic detritus, silty beds grading to sand with minor laminations, clayey silt and ice-rich organic silt of terrestrial and marine origin to the top of the core.

p0130 *The Kumak borecore*, at its base, reveals a normally magnetised diamicton (262–225 m) consisting of massive pebbly/silty/clay (Fig. 49.15). This lowest segment of the core (Late Pliocene) contains abundant pine, spruce, fir and hemlock pollen (Dallimore and Matthews, 1997) which is typical of Pliocene deposits in this region and points to a climate warmer than present. A sharp contact separates this lower normally magnetised (Gauss age) diamict from the pebbly reversely magnetised (earliest Matuyama) upper diamict. The pebbly diamicton changes to sand interbedded with clayey silt beds containing little or no organic detritus (250–225 m)~~ containing~~ reworked pollen. This pollen mix derived from the upper diamicton contains a high percentage of spruce and Polypodiaceae, a good indicator of poorly preserved, rebedded pollen. The low quantity of pollen and organics detritus in addition to the sedimentological characteristics of the diamicton suggests glacial conditions or the initial stages of a cooling episode (earliest Matuyama, MIS 100?) (Dallimore and Matthews, 1997). Pebble lithologies were not available, precluding an estimate of the provenance of the diamicts. The next core segment (225–215 m) reveals silt interbedded with sand and clay, and has no record of organic detritus. The pollen record near the base of this core segment shows a decrease of spruce and alder with fluctuations of Cupressaceae (juniper, *Thuya*, etc.), *Abies* (fir), and pine, a low percentage of herbs, and an increase of grasses and sedges. Further up the core segment, pollen indicates a change to colder climate, with increasing spruce, grasses, sedges and birch, and a decrease of pine pollen. The lower part of the core (262–215 m) records an N–R–N polarity sequence assigned to the late Gauss, early Matuyama and Olduvai (Late Pliocene to Early Pleistocene), respectively. The core segment between 215 and 174 m is predominantly reversely magnetised but contains a short interval of normally magnetised sediments assigned to the Gilsa subchron (1.5–1.55 Ma). This core segment consists of sand with laminations and gravel at the base. At a depth of 183 m, these sediments are high in *Picea* (spruce) pollen but contain low amounts of pollen from shrubs and herbs, indicating generally cool conditions, with temperatures similar to today. The next core segment (175–149 m) consists of reversely magnetised massive sands, which have a generally low pollen count, and contain three oxidised horizons which may indicate palaeowater table conditions. Above these horizons, a sample rich in pollen (*Picea*, *Abies*, *Sambucus*) indicates conditions warmer that today. The core segment extending from 149 Au9 to 99 m consists of sandy/silt deposits with laminations, rip-up clasts and wood detritus at the base, organic silt beds increasing to the top ~~and~~ contain~~s~~ reworked pollen. The sediments reveal a reversed/normal (Jaramillo)/reversed/normal polarity sequence (assigned to the late Matuyama, Jaramillo, latest Matuyama and early Brunhes). Between 99 and 74 m, the core sediments are composed of massive sand with wood detritus and an oxidised horizon changing to clayey sandy/silt with organics. They are normally magnetised (Brunhes). Pollen here consists of a high percentage of *Picea*, little *Pinus*, and some reworked Cupressaceae. From 75 to 49 m, sediments are clayey sandy silt, and contain organics. They are normally magnetised (Brunhes) and contain mostly spruce pollen, very little pine, and about 10% *Betula*, and *Alnus*. The uppermost part of the Kumak core (49–0 m) consists of silty clay to clayey silt with some massive sandy beds containing wood detritus and shells, and abundant spruce pollen.

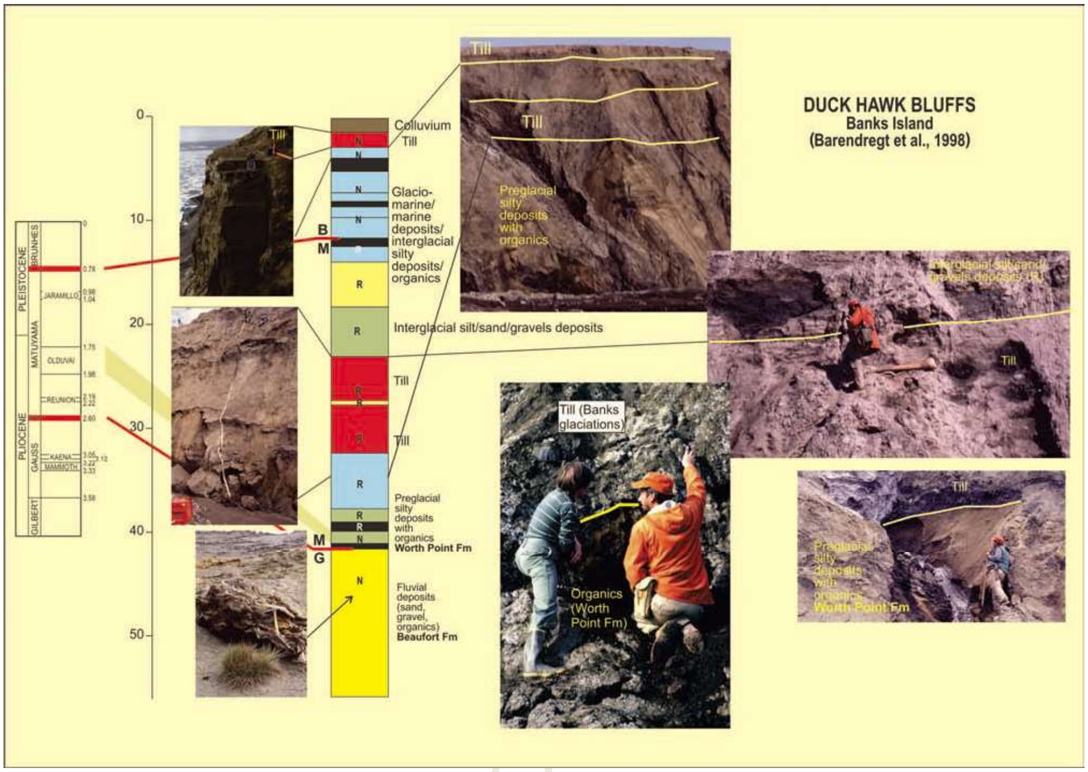
s0045 49.3.3. Smoking Hills

p0135 An exposure along the West River, a tributary to the Horton River near the coast of the northern mainland (Figs. 49.1–49.3, 49.15), reveals a sequence of multiple tills separated by silty clay deposits, some of which contain organic material. The surface till was deposited by continental (Laurentide) ice, and a lag of boulders and cobbles of Canadian Shield (Keewatin) provenance litter the landscape. The Laurentide till is covered discontinuously by massive loess (Duk-Rodkin and Barendregt, field notes 2004; Fig. 49.15). The glacial sequence overlies preglacial sands and gravels probably correlative with the Late Tertiary (Pliocene) Beaufort Formation or the Olduvai age Worth Point Formation (Vincent, 1990). The preglacial deposits are underlain by Upper Cretaceous shales. The glacial sequence consists of three reversely magnetised tills separated by two silty clay deposits (also reversed). The tills contain predominantly chert and quartzite pebble lithologies and minor conglomerate (< 1%). The silty/clay deposits may be remnants of interglacial deposits. Pollen analysis is currently being carried out for these units. The upper reversed till is truncated by two silty/clay to clayey/silt and minor sand deposits and is overlain by a thin lacustrine unit containing minor mudflow lenses and minor organics. The lacustrine unit has a palaeosol developed at its surface which is overlain by overbank deposits containing organic and wood detritus. The units above the upper reversed till are all normally magnetised. A 13-cm diameter log (*Larix* sp.) was found within the upper unit, suggesting that climatic conditions at the time of deposition of this unit were similar to those presently seen some 500 km to the south. Overlying the organic rich interglacial deposits is a till which is normally magnetised and contains pebble lithologies of a much greater variety than lower units. These include dolomite, siltstone, sandstone, chert, quartzite and gneiss. The till is overlain by cryoturbated aeolian sand and loess with a well-developed soil and scattered Laurentide glacial erratics. Pebble lithologies of all the subsurface tills are of local origin only, supporting the hypothesis that the Horton ice cap (Duk-Rodkin et al., 2004; Barendregt and Au10 Duk-Rodkin, 2010) was restricted to the local uplands only. The normally magnetised till exhibits a larger variety of lithologies which may indicate ice provenance from a greater region, including perhaps Banks Island. It is important to note that no shield lithologies were found in any of the subsurface tills.

49.3.4. Banks Island s0050

Evidence of older glacial deposits is recorded in sections along the southern, western and eastern coasts of Banks Island (Figs. 49.3 and 49.16–49.19). These deposits extend back to the Early Pleistocene (Vincent et al., 1984; Barendregt and Vincent, 1990; Vincent, 1990; Barendregt and Irving, 1998). Preglacial (Worth Point Formation) sediments are found above the Beaufort Formation which occurs at the base of two sections (Figs. 49.16 and 49.17) and are assigned to the Olduvai Subchron (1.95–1.77 Ma). These fluvial, aeolian and colluvial deposits contain buried peat and a palynological record indicating open larch-dominated forest-tundra vegetation (Matthews et al., 1986; Vincent, 1990). Overlying the preglacial Worth Point Formation is a series of tills, collectively referred to the Banks Glaciation(s), which may represent as many as four separate glaciations during the interval 1.77–1.05 Ma. They are overlain by interglacial deposits, including peat and soil, which contain the Jaramillo Subchron (1.05–0.99 Ma at the Morgan Bluffs Site; Fig. 49.19). These deposits in turn are overlain by a reversely magnetised till of late Matuyama age (unnamed glaciation), and interglacial silt deposits and soil developed during the Brunhes/Matuyama transition. The Early Pleistocene glacial limit is marked by deposits of the Banks Glaciation(s), which covered most of the terrain except for the NW part of the island (Vincent, 1983). During this time, the Bernard and Plateau Tills of northeastern Banks Island were also deposited. During the Matuyama Reversed Chron, sediments on Banks Island provide a record of at least two and probably as many as five glaciations and two interglaciations. p0140

Evidence for two middle Pleistocene glaciations is found on Banks Island, an unnamed glaciation, and the Thomsen Glaciation, separated by an extensive suite of interglacial sediments (unnamed interglaciation). These two glaciations occurred between the Brunhes/Matuyama boundary (0.78 Ma) and 0.13 Ma (Vincent, 1983; Barendregt et al., 1998). They are underlain by deposits of an unnamed interglacial which spans the Brunhes/Matuyama boundary (Fig. 49.3), and is overlain by marine transgressive sediments and organic beds of the interglacial Cape Collinson Formation (Vincent, 1992). These glacio-marine sediments contain *in situ* shells which yielded dates of > 37 ka (GSC-3698) and a U/Th age estimate of 85.9–130.0 ± 11.9 ka (UQT-143) (Vincent, 1992). These deposits are therefore considered to be of Sangamonian age (80–130 ka) and the underlying till of the Thomsen Glaciation is pre-Sangamonian, and most likely of Middle Pleistocene age (250 ka (MIS) 8?). Apart from the stratigraphy, there is no geomorphological evidence for these two Middle Pleistocene glaciations. However, it is thought that the Thomsen Glaciation marks the northern extent of Middle Pleistocene-ice in NW Canada. It reached the south-central part of the island p0145



f0080 **FIGURE 49.16** Composite stratigraphy at Duck Hawk Bluffs sections indicates preglacial (Olduvai) sediments overlain by a sequence of two reversed tills and one normal till, as well as glacio-marine and interglacial deposits.

and must have travelled along the eastern coast, cutting across the north-east of the island, and bordered along the Plateau Hills to the west, south and east. Thomsen Glaciation deposits were over-ridden along their middle-eastern extent by Late Pleistocene ice (Early Wisconsinan Amundsen Glaciation; Vincent, 1983). This limit was considered to be of Late Wisconsinan age by various authors, and this age has recently been verified by England et al., 2009.

u0030 **1.** *Duck Hawk Bluffs*. These sites contain 11 lithostratigraphical units (Figs. 49.3 and 49.16; Matthews et al., 1986; Vincent, 1990). Reversely magnetised aeolian sediments and associated pond deposits assigned to the Worth Point Formation overlie fluvial facies of the Pliocene (Gauss Normal Chron) Beaufort Formation. These are overlain by marine sediments, and two tills (pre-Jaramillo age Banks Glaciations), all of which are reversed. Above these deposits are reversely magnetised interglacial colluvial, fluvial and aeolian deposits (Late Matuyama) (Vincent, 1992). These are overlain by marine and woody peat deposits which record periglacial and interglacial conditions, and at their base record the Brunhes/Matuyama boundary, and at their upper contact are overlain by Late Pleistocene till (Amundson Glaciation) and Holocene deposits.

2. *Worth Point Bluffs*. At Worth Point (Figs. 49.3 and 49.17), three units occur above Pliocene fluvial coastal plain sediments of the Beaufort Formation. The lowest unit is composed of preglacial colluvium and paludal deposits which contain a rich palaeoflora and fauna (Matthews et al., 1986; Vincent, 1990), indicating that climatic conditions were sufficiently warm to allow conifer growth. The unit is reversely magnetised, except for a 2-m-thick subunit comprising paludal (pond) deposits, which is normally magnetised and assigned to the Olduvai subchron, based on an extensive sequence of reversely magnetised sediments which overlie this unit at other localities, and the generally warmer than modern conditions which prevailed during the Early Pleistocene. This unit is overlain by periglacially reworked till (normal), which in turn is overlain u0035

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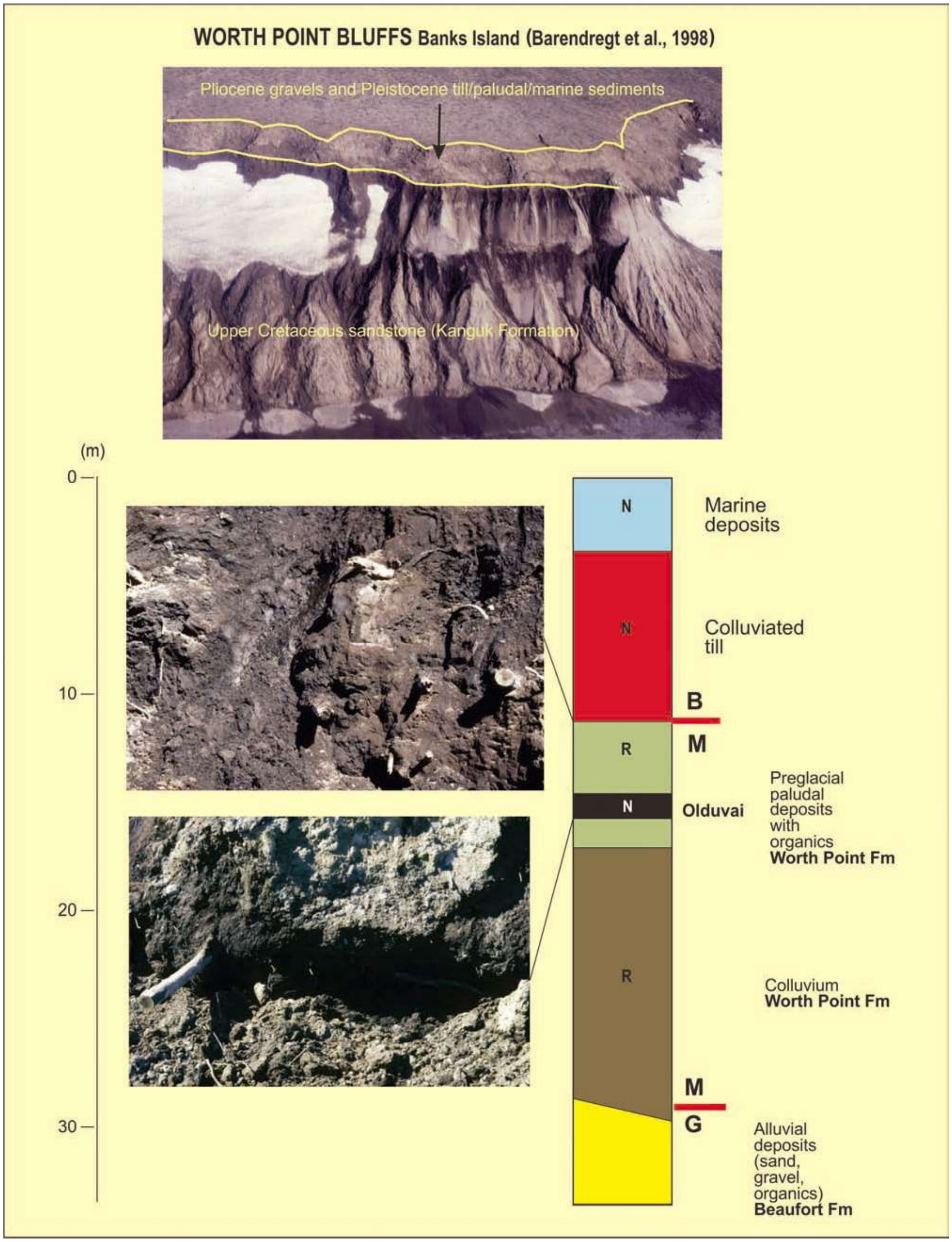

f0085 **FIGURE 49.17** Worth Point stratigraphy exposes (at its base) an extensive sequence of reversely magnetised preglacial sediments which contain the Olduvai subchron (1.97–1.78 Ma) which is overlain by a Brunhes age till and marine deposits.

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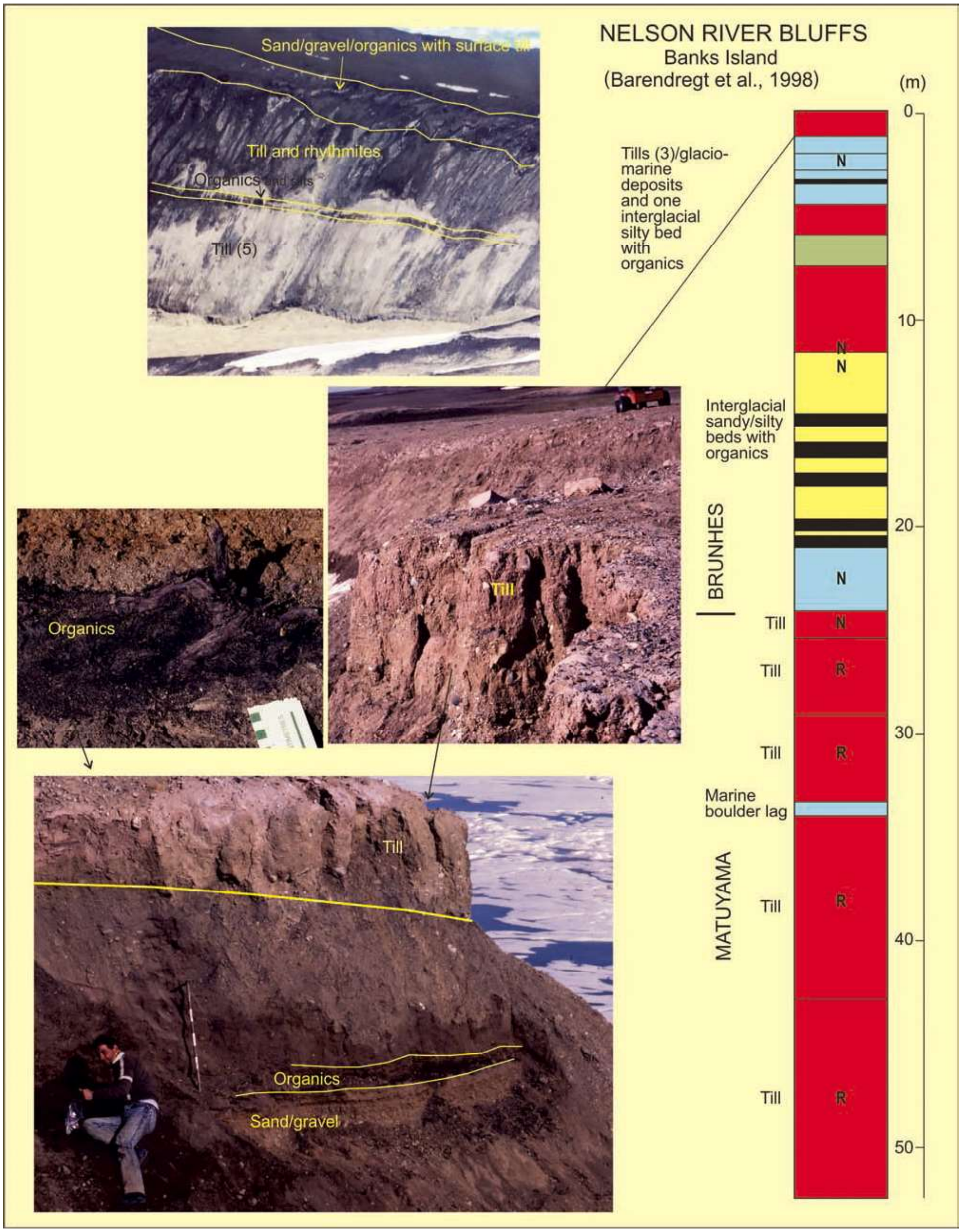

f0090 **FIGURE 49.18** Nelson River Bluffs expose an extensive sequence of reversely magnetised tills overlain by normally magnetised interglacial deposits and three tills.

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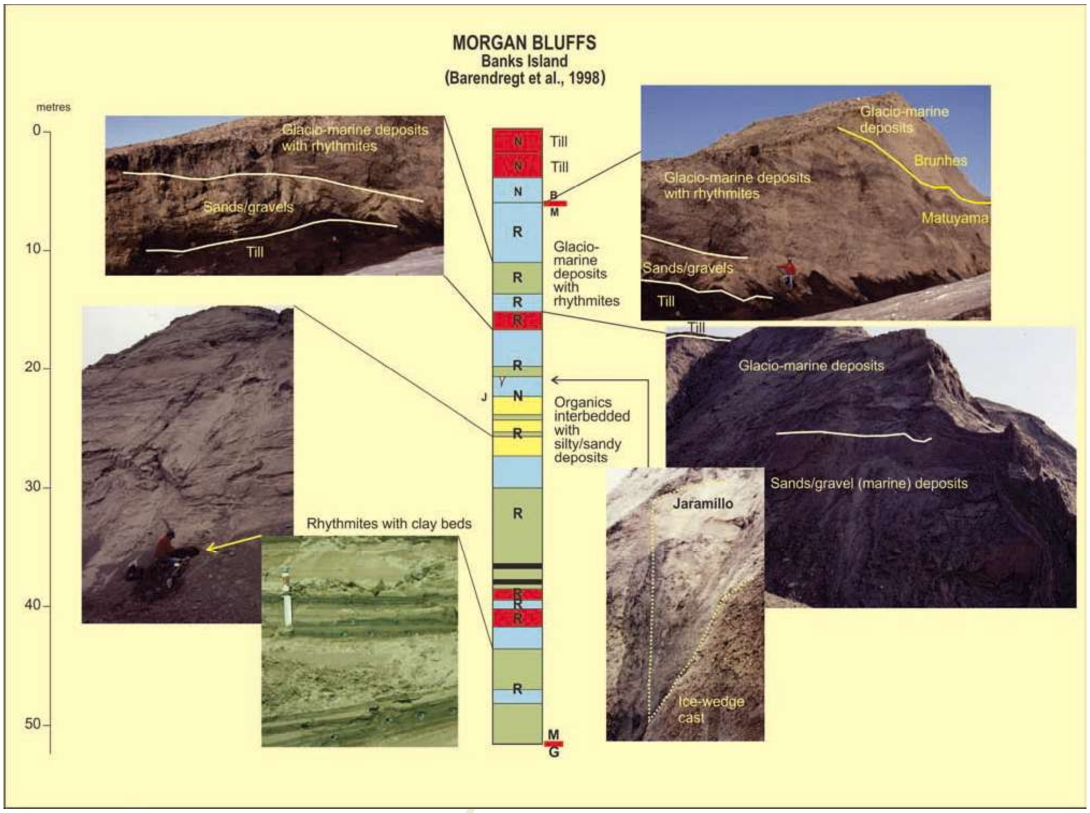

f0095 **FIGURE 49.19** The composite stratigraphy at Morgan Bluffs exposes a long sequence of marine and paludal sediments and three tills (all reversed). A short normal interval occurs near the middle of the section and is assigned to the Jaramillo. The two upper tills are normally magnetised and assigned to the Brunhes.

by sands and gravels (normal) laid down during a marine transgression associated with the pre-Sangamon Thomsen Glaciation.

u0040 **3.** *Nelson River Bluffs*. The Nelson River Bluffs (Fig. 49.18) expose 13 lithostratigraphical units which are assigned to the Matuyama (post-Olduvai) and Brunhes Chrons (Barendregt et al., 1998). At their base, the sequence consists of two reversed tills and a marine boulder lag, which in turn is overlain by two additional reversed tills. The four tills were deposited by the Banks Glaciations, and all are post-Olduvai–pre-Jaramillo in age. These tills are overlain by a Brunhes sequence, comprising a till, marine sands, thick interglacial sediments, and *in situ* peat units interbedded in a perimarine delta sequence. It is overlain by two tills (Thomsen Glaciation) separated by a silt bed containing organics (interglacial). Overlying these tills are a few metres of rythmites and deltaic sands and gravels associated with deglaciation, which in turn are overlain by the Amundsen till of Latest Pleistocene age (Late Wisconsinan).

4. *Morgan Bluffs Site (composite)*. At these bluffs, 13 lithostratigraphic units have been recognised from outcrops at many sections (Fig. 49.19). The first five units record the first glaciation(s) (Banks Glaciations including the Bernard Till) and associated high and low sea-stand deposits. They are reversely magnetised and predate the Jaramillo (1.05–0.99 Ma). These units are overlain by interglacial deposits, which are also reversely magnetised, but contain a normally magnetised large ice-wedge cast near its upper contact, which is assigned to the Jaramillo (Barendregt et al., 1998). These units are in turn overlain by reversely magnetised till and associated high and low sea-stand deposits (post-Jaramillo, Latest Matuyama). The three upper units are normally magnetised tills associated with the Thomsen and Amundsen Glaciations. u0045

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s0055 ## 49.4. NORTHERN BRITISH COLUMBIA

u0050 **1.** *Sezill Creek*. This site is located in a Plio–Pleistocene volcanic complex (Fig. 49.20). A basalt unit forming the base of this section is dated between 6.1 and 7.1 Ma. It is overlain by a diamicton (till?) and sandy sediments which have a reversed polarity (Gilbert–Gauss? early Matuyama?). These are overlain by a boulder lag, followed by a diamict and overlying rythmites. Up section is a coarse to medium diamict (MIS 34?) containing striated clasts (intrusive and metamorphic megaclasts), and isolated pockets of openwork gravels (till). The glacial event that deposited this till was regional in scope, based on clast lithologies. Continuing up section, two tills are preserved between three basalt flows bracketed between a 1.1 Ma (Pyramid Formation) and a 1.0 Ma (Ice Peak Formation(s); Souther, 1992; Spooner et al., 1995). The lower till contains exotic megaclasts, rare pyroclastic debris, and several erosional contacts which may represent several glacial events. The upper till (MIS 30) interfingers with lacustrine tuff at a section approximately 5 km to the east of Sezill Creek section, indicating that the Pyramid Formation basalt is coeval with the glacial event that deposited this lower till. The top of the section is covered by a thick colluvial unit which is overlain by a reversed (post-Jaramillo) basalt.

u0055 **2.** *Tahltan/Stikine River*. The sediments recorded at the Tahltan Canyon and Stikine River sites are glacial and non-glacial in origin. They overlie bedrock of Triassic age. A composite stratigraphy of the two sites is presented in Fig. 49.21. The deposits have been preserved beneath Pleistocene basalt flows from Mount Edziza and have yielded normal polarity (Brunhes Chron) (Spooner et al., 1996). These sediments record a regional glaciation from the Coast Mountains of British Columbia. The initial ice blocked the Stikine River, forming a glacial lake and glaciofluvial delta. Basalts were deposited on fluvial as well as glaciofluvial sediments. The basalt flow (K–Ar age of 0.30 ± 0.03 Ma) at the top of the section contains hyaloclastic/palagonite minerals indicating that it was deposited in water, or in association with ice. The deposits beneath the basalt consist of horizontally bedded, cross-bedded, massive and laminated sands interbedded with thin diamictons.

s0060 ## 49.5. SOUTHERN BRITISH COLUMBIA

s0065 ### 49.5.1. Merritt Sections (Composite)

p0185 Deposits exposed along Lily Lake Road, and the Coldwater River in the vicinity of Merrit, British Columbia (Fulton et al., 1992), contains evidence of five glaciations and six interglaciations (Fig. 49.22). At the base of the sequence, proglacial lacustrine sediments and overlying glacio-lacustrine sediments are separated by a Chernozemic palaeosol and are reversely magnetised. The intervening soil indicates that these lacustrine sediments represent two separate glaciations. These units are unconformably overlain by interglacial sediments containing a tephra (>670 ka) at its base and a palaeosol near the top. The Brunhes/Matuyama boundary occurs directly above the palaeosol. The palaeosol and underlying sediments are reversely magnetised, while the uppermost interglacial sediments are normally magnetised. The latter are overlain by a suite of glacial deposits and are normally magnetised. The age of these glacial deposits cannot be further constrained at this time, but it is possible that this glaciation occurred relatively soon after the eruption of a 0.6 ± 0.4 Ma normally magnetised valley basalt in the Merrit basin because the boulder lag (Fig. 49.22) is made up of material derived from this basalt, and the basalt is striated. The basalt was deposited during an interglacial period. The suite of glacial sediments containing the basalt boulder lag was succeeded by at least two more glaciations, a penultimate glaciation, and the Late Pleistocene (Wisconsin) Fraser Glaciation.

49.6. REGIONAL CORRELATIONS s0070

The NW Canadian glacial/interglacial record of the Late Cenozoic is preserved in a large number of sites which have been studied by various authors. The most complete stratigraphical record has been obtained from sites in the Yukon, northern Interior Plains and British Columbia. These sites (Fig. 49.1, sites 1–5 and 8–10) record multiple Cordilleran and/or montane glaciations, as well as periods of soil formation and loess deposition. The glacial/interglacial deposits overlie a preglacial stratigraphy, which in most cases is marked by a regional unconformity. Other sites record multiple plateau and/or continental glacial deposits overlying preglacial fluvial stratigraphy, and these records are less extensive than that seen in the cordillera (Fig. 49.1, sites 11–17). A third group of sites (Fig. 49.1, sites 6, 7, 18–20) provides a record of glaciations (tills) preserved between lava flows. p0190

Sites within the Tintina Trench (Figs. 49.3–49.6) contain the most complete Late Cenozoic stratigraphy, and other study sites are compared to this group. The Tintina Trench sites provide a robust magnetostratigraphy with clear polarity chrons and subchrons which can be reliably correlated with the global Geomagnetic Polarity Timescale (Fig. 49.23). Other sites provide radiometric ages (tephra, basalt, organics) and exposure dates (^{36}Cl) that have further refined the ages of these deposits. When this magnetostratigraphy is combined with sites throughout NW Canada, an extensive lithostratigraphy is developed which can be correlated with the marine isotope record and provides mappable evidence of the extent and timing of glaciations. p0195

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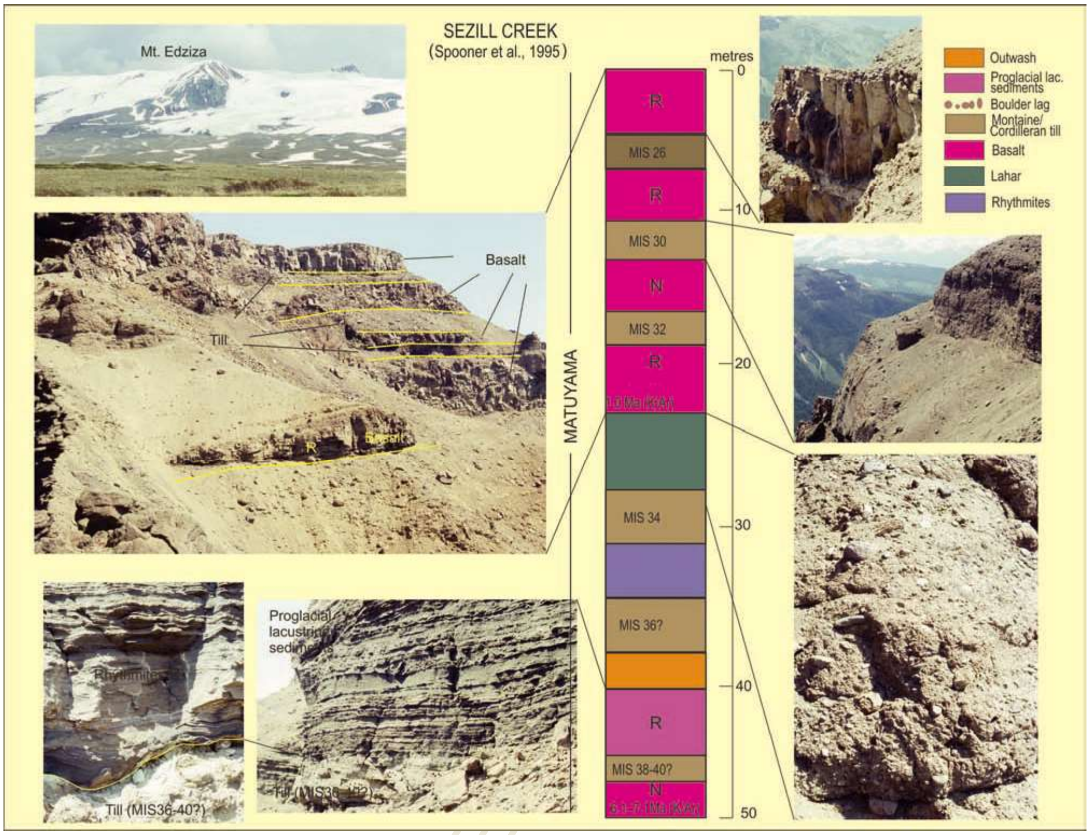


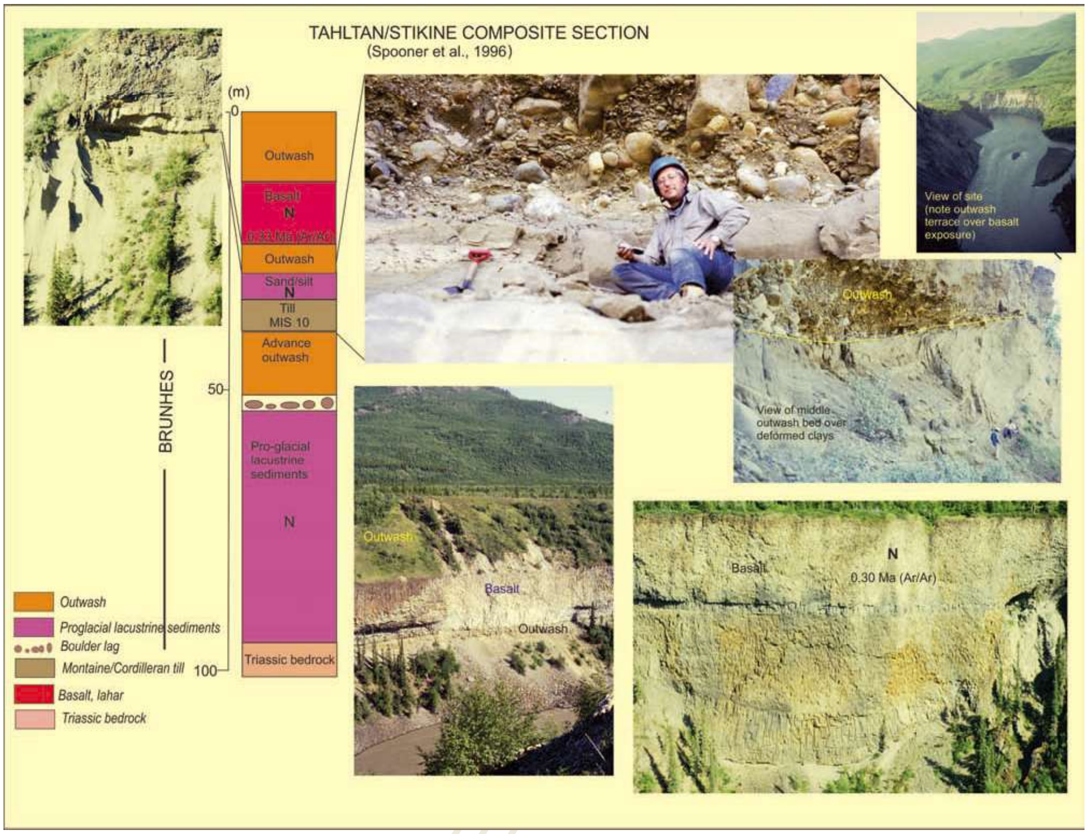
f0100 **FIGURE 49.20** Sezill Creek section near Mount Edziza, northern B.C. exposes a sequence of basalts and interbedded glacial sediments. The base of the section exposes a normally magnetised basalt (6.1–7.1 Ma) overlain by three tills separated by glaciofluvial and glacio-lacustrine deposits. These sequences are overlain by four basalts units and interbedded tills spanning the Jaramillo and latest Matuyama.

p0200 In the Tintina Trench, 10 glacial units and seven non-glacial units span a substantial portion of the Quaternary record, and this record is evidently more extensive than those found at other sites in NW Canada. Data from the Mackenzie Mountains and Banks Island in the NWT reveals two additional glaciations within the Brunhes Chron which are not found elsewhere (Fig. 49.3; Duk-Rodkin and Barendregt, 2010).

s0075 49.7. LATE PLIOCENE PREGLACIAL SEDIMENTS AND THE FIRST GLACIATION (MIS G6)

s0080 49.7.1. The Cordillera

p0205 Pliocene and older Tertiary unconsolidated preglacial sediments are found in many sections in the Northern Cordillera, but few of these sediments have been dated. Along the Tintina Trench and on the northern slopes of the Klondike Plateau (upper White Channel Gravels), excellent exposures of preglacial gravels occur. They are largely composed of sands and gravels deposited as alluvial fans, and in places occur as mudflow deposits and ponded silts, clays Au11 and minor sands. In the Tintina Trench, they occur above a major Miocene–Pliocene unconformity which separates tilted Miocene sands and conglomerates from horizontal Pliocene preglacial fluvial deposits. The tilted beds contain *Pterocarya* and *Tsuga* pollen grains which argues for a Miocene and older age for the sediments and indicates warm climatic conditions (Duk-Rodkin et al., 2001) while the preglacial conformable beds above have an assemblage with *Polemonium* pollen grains indicative of cooler conditions. The preglacial deposits in the Tintina Trench have been assigned to MIS G19 because the *Polemonium* assemblage argues for a cool climate, and after stage G19 the isotopic record reveals a strong cooling trend leading to the



f0105 **FIGURE 49.21** The composite of the Tahltan and Stikine sections reveals a sequence of Brunhes age glacial sediments: glacio-lacustrine and glacio-fluvial beds and a till. In addition, one basalt (0.30 Ma) bed occurs between outwash units near the surface of the outcrop.

first glaciation (G18) in the area (Fig. 49.3). These deposits are correlated with the nearby Klondike Wash stratigraphy (22 km to the south) reported by Froese et al. (2000) who provided evidence for the interfingering of White Channel gravels and the first glacial outwash in the region (Klondike Wash) during the late Gauss. These beds are considered to be equivalent to the preglacial White Channel gravels based on the presence there of the 3.0 ± 0.33 Ma Quartz Creek tephra (Sandhu et al., 2000), pollen (late Miocene or younger) and normal polarity sediments (of probable Gauss age, Froese et al., 2000; Duk-Rodkin et al., 2001).

p0210 In the absence of tephra dates in the Tintina Trench, the reversed polarity of unit 1a at WFR cannot be assigned with confidence to Kaena, Mammoth or Gilbert, but may be equivalent to the Kaena age upper White Channel gravels reported in Froese et al. (2000). The sediments are older than 3.18 Ma (base of upper Gauss normal) and older than the preglacially ponded deposits at RC which contain *Polemonium* pollen and a normal Gauss polarity and therefore are broadly correlative to the upper White Channel gravels.

At the Fort Selkirk volcanic complex, the Lower Mushroom site contains gravels which may be associated with the first glaciation and is overlain by basalt dated at 2.32 ± 0.13 Ma (Westgate et al., 2001). This gravel deposit is thought to be glacial in origin, based on clast lithologies, although this cannot be said with certainty. If it is glacial in origin, then this first glaciation in the area likely occurred around or before 2.3 Ma (Fig. 49.10). p0215

In the Mackenzie Mountains, preglacial deposits are found at the LB and KC sections (Figs. 49.3, 49.13 and 49.14). At these sites, the preglacial deposits are mostly coarse subangular gravel with minor fine sand and silt developed on bedrock pediments (Duk-Rodkin et al., 1996). These deposits (colluvium/diamicton/till?) have a weathering horizon at its upper contact and are normally p0220

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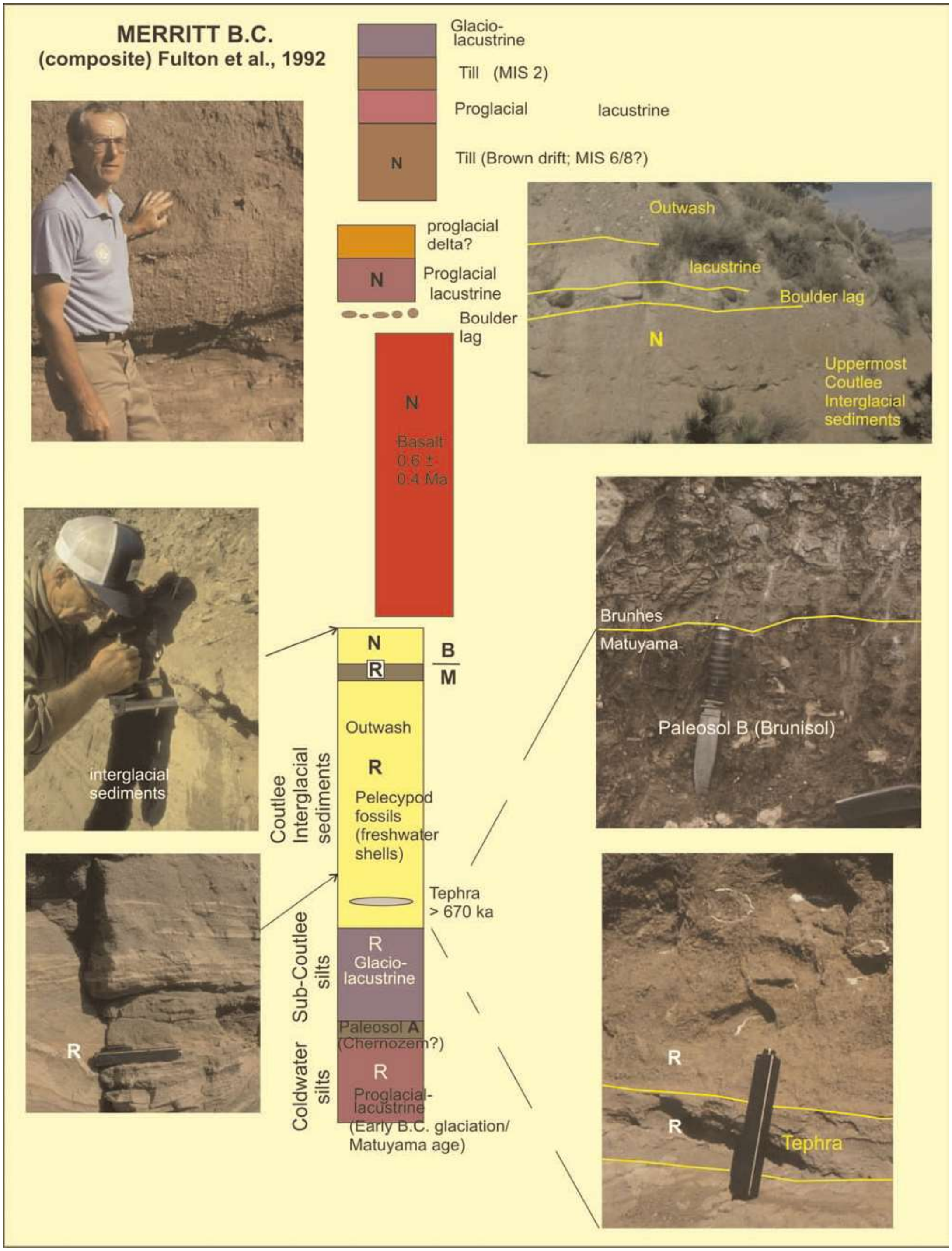
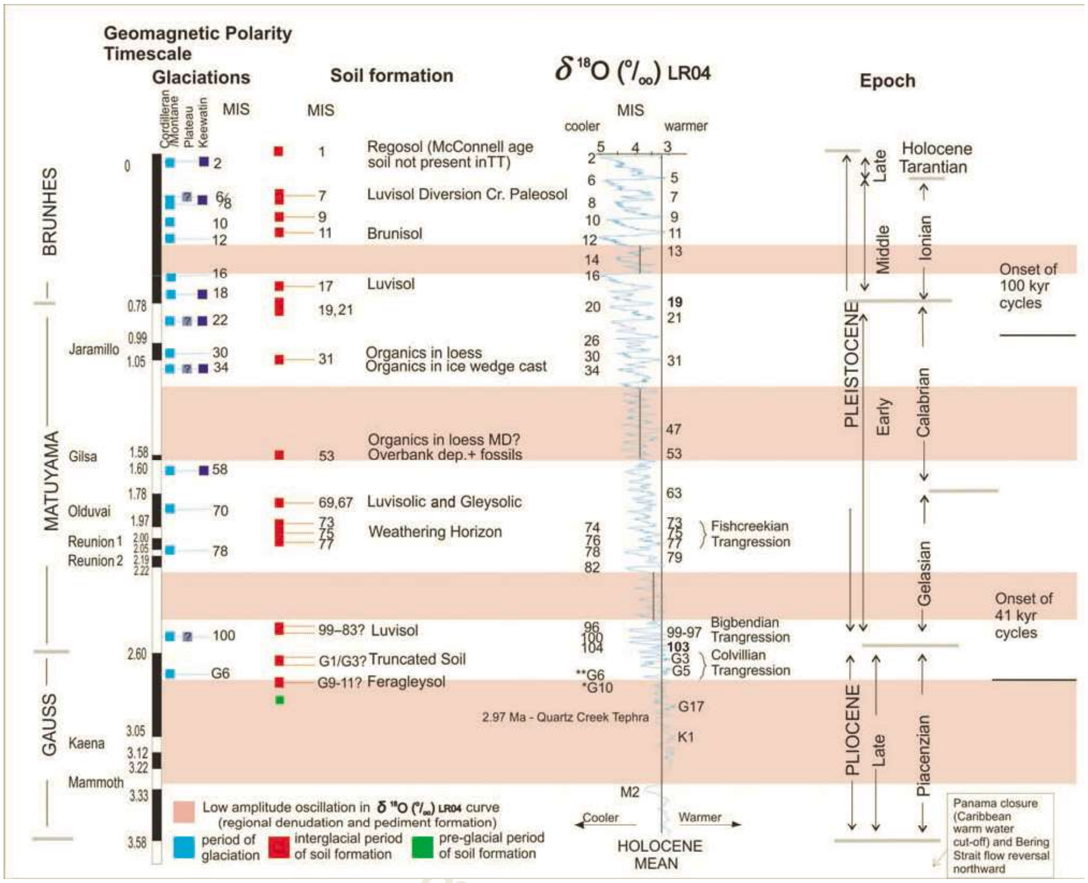


f0110 **FIGURE 49.22** The composite of the sections near Merritt, in southern B.C. expose from bottom to top, a sequence of reversely magnetised glacio-lacustrine and interglacial sediments containing a tephra (>0.670 Ma) and palaeosol. Above these deposits is a normal basalt (0.60 ± 0.4 Ma) which is overlain by outwash deposits and two tills (all normal) representing up to three glaciations.



f0115 **FIGURE 49.23** Zones of low amplitude oscillation in the LR04 composite δ^{18}O record during the Late Pliocene and Pleistocene are considered to be periods of regional denudation and pediment formation, and are compared to the glacial/interglacial record of NW Canada. Geomagnetic polarity timescale is based on (Cande and Kent, 1995; Gradstein et al., 2004) and composite δ^{18}O LR04 marine isotopic record (relative palaeotemperature) is obtained from multiple deep ocean cores (Lisiecki and Raymo, 2005). The base of the Pleistocene (2.58 Ma) and new subdivisions of the Pliocene and Pleistocene follow the recently ratified convention described in Gibbard et al. (2010). Black and white areas are normal and reversed polarity, respectively. Marine Isotope Stages (MISs) are labelled on LR04 (even numbers represent colder (glacial) and odd numbers warmer (interglacial) conditions). MIS numbering scheme
Au1 follows Ruddiman et al. (1986, 1989), Raymo et al. (1989) and Raymo (1992) from present to MIS 104, and Shackleton et al. (1995) in the Gauss Chron. Vertical line marks Holocene mean δ^{18}O (Raymo 1992). Suggested correlation of glacial deposits to cold stages in the marine isotopic record (blue squares) is shown to the right of Geomagnetic Polarity Timescale. There are three types of glacial regimes shown (Cordilleran/montane, Plateau and Keewatin glaciations). Suggested correlation of soil forming periods to warm stages in the marine isotopic record is shown with red squares. G18 (2.97 Ma)—First Cordilleran glaciation in Yukon; *G10—Worldwide cooling commences; **G6—First global glacial event coincides with final closure of Panama Isthmus, start of Chinese loess/palaeosol sequences, and appearance of genus Homo; MIS 25–21—Marks onset of pronounced glacial/interglacial cyclicity. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this chapter.)

magnetised (Gauss Normal Chron) and may be equivalent to the preglacial sediments at the base of RC (unit 1b). Alternatively, it may be correlated to the till at RC (RC unit 2). At the IB section, the preglacial gravels are thick alluvial fan deposits (Palaeocene, Summit Creek Formation) which overlie bedrock.

49.7.2. Northern Interior Plains s0085

In the northern Interior Plains of Canada, three separate regions, each with multiple sites, record glacial deposits laid down by local ice caps. The glacial history of the Mackenzie Delta region is characterised on the basis of p0225

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two long cores (Taglu and Kumak). In the Taglu core, silty sand sediments (normal) at the base of the core are considered to be preglacial fluvial deposits. They are followed by a sequence of mudflow, lacustrine, fluvial sand and diamicton deposits. This diamict is non-glacial in origin and is normally magnetised (Gauss Chron). At the base of the Kumak core, normally magnetised silty clay diamicton (mudflow) contains pollen of warmer/preglacial conditions, and is therefore assigned to the late Gauss Chron. This non-glacial diamicton grades to a glacial diamicton at the Gauss/Matuyama boundary (Fig. 49.24).

p0230 In sharp contrast to the Late Pliocene preglacial sediments described for the Mackenzie Delta cores and the Smoking Hills, the Banks Island record reveals an Early Pleistocene age for the preglacial sediments underlying the first till (Worth Point, Fig. 49.17), based on a suite of normally magnetised paludal deposits contained within a much more extensive silt, sand and aeolian sequence, which is reversed. The first glaciation on Banks Island (Barendregt et al., 1998) is post-Olduvai (late Matuyama, MIS 58?).

s0090 49.8. EARLIEST MATUYAMA GLACIATIONS (2.2–2.6 MA, MIS 100 OR 98 OR 96)

s0095 49.8.1. The Cordillera

p0235 At the Tintina Trench RC and EFR sites, a reversely magnetised till (unit 3) represents an early Matuyama glaciation (the second glaciation to affect this region). Morphologic evidence of this early Matuyama glaciation is recorded on two terrace outwash remnants in the lower Klondike Valley which are loess covered, and these loesses are reversely magnetised (Froese et al., 2000) (see Dawson map, Duk-Rodkin, 1996). The till of this second glaciation is overlain by thin beds of fine sands and silts and a well-developed luvisol from which palaeomagnetic samples were collected. Like the till parent material below, the soil yielded a reversed polarity. The soil forming period has been tentatively correlated with the Bigbendian marine transgression (Fig. 49.23) in Alaska, and with isotope stage 97. At the WFR section, unit 3 may or may not be present. The extensive vertical outcrop precluded detailed assessment.

p0240 This early Matuyama glaciation may or may not be present in the Mackenzie Mountains as there is only one pre-Olduvai reversed till recorded there (Figs. 49.3, 49.13 and 49.14). Deposits of this glaciation may also be present at the base of Sezill Creek section in northern British Columbia, but this cannot be stated with certainty (Figs. 49.3 and 49.21).

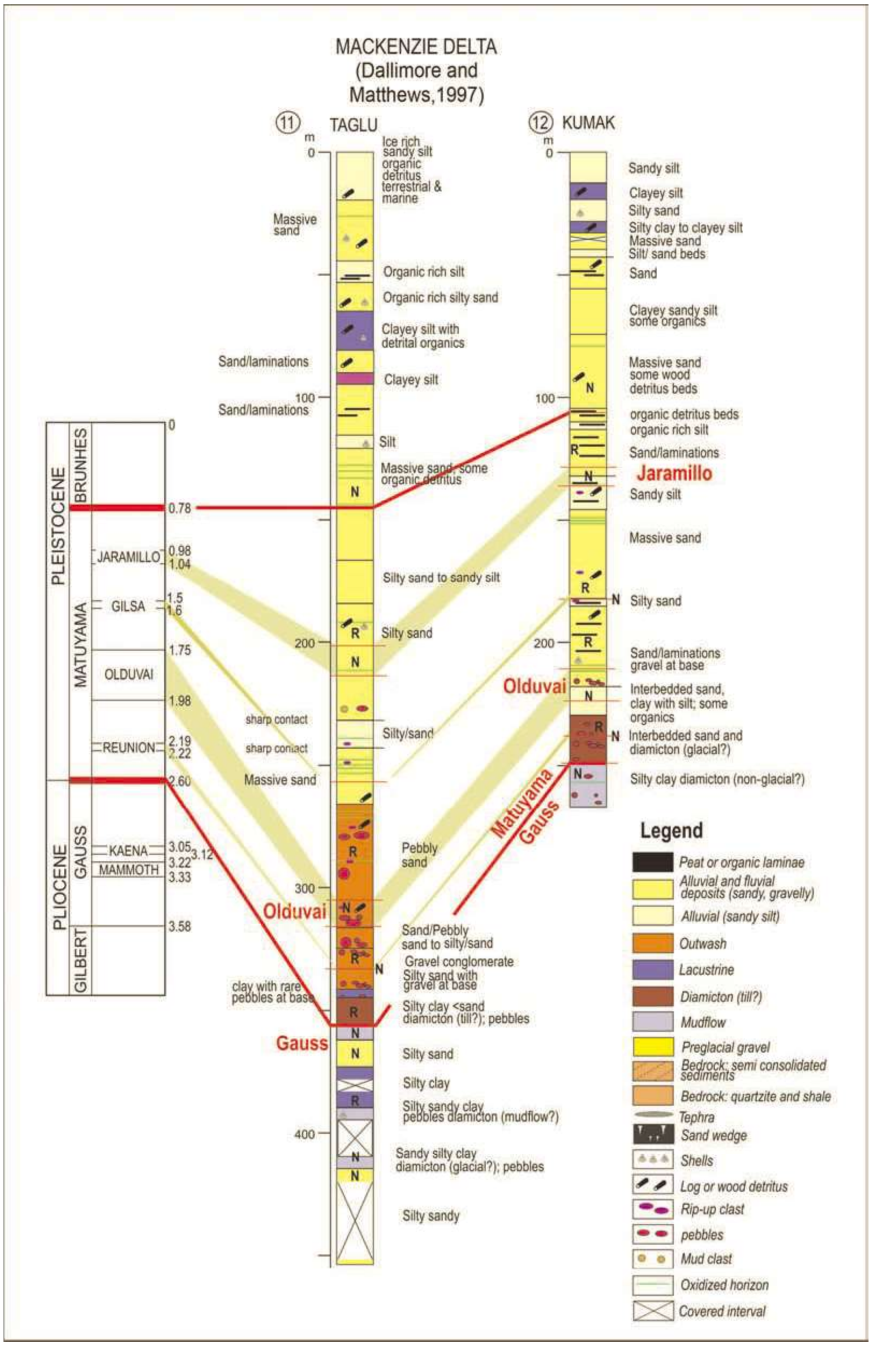
s0100 49.8.2. Northern Interior Plains

p0245 In the northern Interior Plains (Fig. 49.3), evidence for an early Matuyama glaciation is found in the Mackenzie Delta (reversely magnetised diamicts in the lower part of the Taglu and Kumak cores, below the Reunion normal subchron, Fig. 49.24). In the Mackenzie Delta cores, the diamicton marking the first glaciation in this region extends across the Gauss/Matuyama boundary, changing its characteristics from non-glacial to glacial, and from normal to reversed polarity. In the Smoking Hills area, along the West River, one of the three exposures described in Duk-Rodkin et al. (2004) has yielded much additional information. The West River exposure reveals preglacial gravels with wood detritus and other organic debris at the base. These gravels may be the Late Pliocene Beaufort, or may be considerably younger (Worth Point equivalent). The gravels yield a reversed polarity, most likely the Mammoth or Kaena subchron within the Gauss Chron. This preglacial deposit contains sand-wedges developed at its upper contact indicating cold (periglacial/cryogenic) conditions following deposition of the host sediments. The same ice-wedges are, in places, filled with diamicton (till) (Fig. 49.15) which is reversely magnetised. The preservation of the underlying ice-wedge cast argues for till deposition fairly soon after the formation of the ice wedge, which otherwise would probably have been destroyed by subaerial processes. This event likely records the first glaciation on the northwest continental Arctic coast. This event may be correlative with the first glacial event in the Mackenzie Delta cores, and with sediments of the second glaciation in the Cordilleran stratigraphy (MIS 100?, Fig. 49.3). It is unlikely that ice from the Horton Plateau Icecap (Smoking Hills; Duk-Rodkin et al., 2004) reached the Mackenzie Delta because of the distance between the two sites (>400 km) and the very low ice gradient which would have existed. Further, the presence of the Horton Plateau Ice cap would preclude continental (Laurentide) ice from reaching the Mackenzie Delta region, and therefore the glacial diamicts at the bottom of Taglu and Kumak cores are almost certainly of local origin. The only possible local source would be the Aklavik Range, where geomorphologic evidence suggests the presence of pre-Late Pleistocene piedmont glaciers (Duk-Rodkin and Hughes, 1992).

49.9. EARLY MATUYAMA GLACIATION (1.98–2.15 MA, MIS 78) s0105

49.9.1. The Cordillera s0110

At the Tintina Trench RC site, an extensive mudflow deposit of glacial origin (unit 4; Fig. 49.4) overlies deposits of two older glaciations. The mudflow has a silty clay matrix and was further enriched in clays as a result of a prolonged period of moderate weathering and translocation of surface clays from a >2-m-thick regosolic soil developed at its surface. No polarity was obtained from these sediments, but it is overlain by a normally magnetised outwash p0250



f0120 **FIGURE 49.24** Taglu (450 m) and Kumak (260 m) cores collected from the Mackenzie Delta expose a continuous sequence of sediments which span the late Gauss, Matuyama and Brunhes Chrons and include most, if not all, of the subchrons. While the sedimentology of the cores has not been fully studied, a rich pollen assemblage has been obtained, which suggests that the Mackenzie Delta may have been impacted by early glaciations only (earliest Matuyama to Gilsa; 2.58–1.6 Ma). Sandy pebbly diamicts and reworked pollen near the base of the cores are thought to mark glacial conditions.

(Olduvai subchron, unit 5) and underlain by a reversely magnetised (early Matuyama) till/luvisolic palaeosol (unit 3, MIS 100 and Bigbendian marine transgression). The mudflow (unit 4) is tentatively correlated with the Fishcreekian marine transgression in Alaska (MIS 78). This unit may be equivalent to the pre-Olduvai reversely magnetised till present at any of the Mackenzie Mountains sites: KC, LB, IB.

s0115 49.9.2. Northern Interior Plains

p0255 The early Matuyama glaciation is represented in the Taglu core by reversely magnetised sediments composed predominantly of coarse gravel conglomerate (outwash?) which are underlain by normally magnetised sediments assigned to the Reunion normal subchron. In the Kumak core, this unit is a diamicton occurring between normally magnetised sediments of the Reunion and Olduvai. There were no macrofossils recovered from this core interval, and it was not possible to determine whether these sediments are glacial or non-glacial in nature.

p0260 At the Smoking Hills section, this unit may be equivalent to one of the upper two reversely magnetised tills (Fig. 49.15).

s0120 49.10. OLDUVAI GLACIATION (1.75–1.98 MA, MIS 70?)

s0125 49.10.1. The Cordillera

p0265 At the Tintina Trench RC and EFR sites, a suite of normally magnetised glacial sediments and overlying palaeosol (unit 5) occur between the underlying glacial mudflow (unit 4) and an overlying outwash (unit 6) which is reversely magnetised and thus limits the age of unit 5 to the Olduvai subchron. Unit 5 consists of an outwash overlain by a till on which a weathering horizon was developed. The sharp unconformity between the weathering horizon and the overlying outwash may suggest truncation of what was at one time a fully developed palaeosol. Evidence also exists in the Mackenzie Mountains for a probable Olduvai age glaciation (Duk-Rodkin et al., 1996) on which a well-developed luvisol is found; both till and soil are normally magnetised.

s0130 49.10.2. Northern Interior Plains

p0270 In the Mackenzie Delta cores, deposits of Olduvai age include fluvial sediments (Taglu core) and marine clays (Kumak core) indicating interglacial conditions. In the Smoking Hills, normally magnetised interglacial lacustrine deposits with a palaeosol overlain reversed tills may be of Olduvai age. Likewise, paludal (preglacial Worth Point) deposits on Banks Island (Fig. 49.17) are normally magnetised and assigned to the Olduvai subchron (Barendregt et al., 1998). Macrofossils and pollen of these deposits indicate non-glacial conditions. The first glaciation to affect Banks Island developed shortly after the end of the Olduvai normal subchron.

49.11. LATE MATUYAMA GLACIATIONS (1.06–1.78 MA, MIS 58, 34) s0135

49.11.1. The Cordillera s0140

Reversely magnetised outwash and diamicton (till) deposits occurring between the Olduvai and Jaramillo subchrons are found at the RC and EFR sites, respectively (unit 6; Figs. 49.3–49.6). The palaeosol developed on the till at EFR is a gleysol and is also reversely magnetised. Both units are post-Olduvai in age. The age between 1.78 and 1.06 Ma represents one of the MISs in the range of 60–58 or 38–34. The most likely candidate is MIS 58 because the till in all likelihood correlates with a reversely magnetised till and outwash at Fort Selkirk occurring directly below the Gilsa subchron (an interglacial, falling somewhere between MIS 55 and 51; Fig. 49.11). p0275

At the MD site on the Klondike Plateau, the upper Matuyama is represented by an extensive loess stratigraphy deposited under both glacial and interglacial conditions (at least three separate interglaciations; Fig. 49.8). The lower part of the exposure contains reversely magnetised loess with interglacial pollen, the Mosquito Gulch tephra (1.45 Ma), loesses deposited under glacial conditions (MIS 34?), another tephra (MD, 1.09 Ma), and ice-wedge casts in which a palaeosol (cryosol) is developed. In the upper half of the MD section is a unit of normally magnetised loess (Jaramillo, MIS 29?) in which a luvisol is developed, and is overlain by reversed loess, normal loess (B/M boundary marked by colluvial organic silt or yedoma), and finally by colluviated loess (yedoma) at the top (normal, Brunhes age) (Froese et al., 2000). p0280

At Fort Selkirk Cave, Mushroom and Fossil sites reversely magnetised outwash and till (Fig. 49.11) were deposited during MIS 58, and overlying reversely magnetised interglacial deposits (MIS 57) contain the Fort Selkirk tephra (1.48 ± 0.11 Ma) which in turn are overlain by normally magnetised silts (Gilsa subchron, 1.58–1.60 Ma), in turn overlain by reversely magnetised post-Gilsa interglacial paludal deposits containing fossils (MIS 55?) (Jackson et al., 1996; Nelson et al., 2009). p0285

At the Sezill Creek site (Mount Edziza, B.C., Fig. 49.20), reversely magnetised glacial deposits at the base of the exposure are underlain by a diamicton (till?), which in turn is underlain by 6.1–7.1 Ma basalt. The glacial deposits and diamict are overlain by a series of undated deposits (glaciolacustrine, outwash gravels, diamicton (till?), glacio-lacustrine and two further diamicts (tills?)). This sequence is p0290 capped by a reversely magnetised basalt (1.0 Ma), and three interbedded tills and basalts for which only polarity data is available. Each basalt and till pair is assumed to be of similar age, and the pairs are assigned to MIS 32, 30 and 26, respectively. At the Sezill Creek site, there are two additional glacial packages beneath the reversely magnetised basalt (1.0 Ma) and above the lowermost till. There are no records of more than two glaciations between the Olduvai and Jaramillo subchrons in the stratigraphy of northwest Canada, possibly due to the low amplitude and uniform fluctuation of climate during the time interval between MIS 56–37 (Fig. 49.23), and therefore these two glaciations probably occurred after MIS 37 (1.22 Ma) and before 1.0 Ma and are most likely MIS 36 and 34 cold events. The lower most diamicton (till?) at the Sezill Creek section may be correlative to MIS 58 or may correspond to a much older (pre-Olduvai) glacial event.

p0295 Finally, at the Merrit section in British Columbia (Fig. 49.22), there are two sets of glacio-lacustrine deposits separated by a palaeosol (all reversed) which may be Late Matuyama, based on a minimum age of 0.670 Ma on an overlying tephra, and may therefore have been deposited by glaciations which occurred between the Olduvai and Jaramillo (MIS 78?, 70?, 58?, 34?).

s0145 49.11.2. Interior Plains

p0300 Post-Olduvai–pre-Jaramillo age sediments are present in the cores of the Mackenzie Delta (Fig. 49.24). However, it is not possible to determine with certainty whether these sediments are glacial or non-glacial in nature. The bulk of the evidence ~~(Fig. 49.24)~~ would suggest that the sediments are non-glacial. In the Smoking Hills, two reversed upper tills underlain by reversed glacio-lacustrine (?) sediments and overlain by a normal polarity sequence may correspond to MIS 58 and/or MIS 34 (Fig. 49.15).

p0305 On Banks Island, reversely magnetised preglacial paludal deposits containing the Olduvai subchron (Worth Point Formation at the Worth Point site, Fig. 49.17) are assigned to the late Matuyama. One of the two reversed tills at Duck Hawk Bluffs, one of the four reversed tills at Nelson River and one of the two reversed tills at Morgan Bluffs may correspond to MIS 58 and/or 34 (Fig. 49.9).

s0150 49.12. JARAMILLO SUBCHRON GLACIATION (0.99–1.05 MA, MIS 30)

s0155 49.12.1. The Cordillera

p0310 At the Tintina Trench RC site, a normally magnetised outwash (unit 7; Fig. 49.4) is underlain by reversely magnetised sediments. The upper contact of the outwash forms an unconformity with blocks of sediment that are reversed (unit 8). At WFR, this period of time is represented by loess (unit 7) which is not found at EFR.

Normally magnetised loess deposits of Jaramillo age occur in the Klondike Plateau at the MD site (Fig. 49.8). The loess deposits contain pollen and a palaeosol (luvisol) in the middle part of the loess unit. They are overlain by a diamict containing reworked pockets of the palaeosol and are also considered to be of Jaramillo age. Both loess and diamict are thought to have been deposited during interglacial conditions (MIS 31?). Above the diamict is a massive loess, which is reversely magnetised (Froese et al., 2000). p0315

Within the Fort Selkirk Volcanic complex, Cave, Mushroom and Fossil sites contain glacial erratics and striae over a basalt surface (1.33 ± 0.07 Ma). It is assumed that the glacial event that left the erratics and the striae on this surface basalt corresponds to one of MIS 36, 34, 30? p0320

At the Mount Edziza Sezill Creek site (Fig. 49.20), Jaramillo age deposits are thought to be represented by a diamicton (till?) (MIS 30?) overlain by a normal basalt (undated) occurring within a sequence of reversed basalts and interbedded diamictons (tills?). p0325

49.12.2. Interior Plains s0160

The Jaramillo subchron occurs in interglacial massive sand and silt with reworked organics, wood detritus and shells, in the Taglu and Kumak cores in the Mackenzie Delta. p0330

The West River site in the Smoking Hills has several metres of interglacial sediments separated by a palaeosol, all of which are normally magnetised. It is not certain whether this normal interval is of Jaramillo age or is entirely within the Brunhes Normal Chron. Pollen analysis of this unit is still ongoing. p0335

On Banks Island, Jaramillo age deposits occur only at the Morgan Bluffs Sites (Barendregt et al., 1998) where normal sediments occur within ice-wedge casts. The cryogenic polygons formed in reversely magnetised interglacial sediments deposited immediately before the Jaramillo (MIS 32) and the infilling occurred during the Jaramillo (MIS 31). p0340

49.13. LATEST MATUYAMA GLACIATION (0.99–0.78 MA, MIS 20 OR 22) s0165

49.13.1. The Cordillera s0170

At the Tintina Trench RC site, post-Jaramillo outwash gravels (unit 8) and loess at both EFR and WFR (unit 8) are reversely magnetised and are overlain by normally magnetised (Brunhes) loess (unit 9) containing pollen. At RC, unit 8 is a remnant of glacial deposits (pockets of outwash sediment) preserved intermittently along an erosional and discontinuous contact. On the Klondike Plateau at the MD site, reversely magnetised sediments overlie Jaramillo age interglacial deposits (Froese et al., 2000). These p0345

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deposits are discontinuous organic silts and diamicts with interbedded organics. They are interglacial and were probably deposited during (MIS 21?).

p0350 At the Sezill Creek site near Mount Edziza, post-Jaramillo reversed basalt and interbedded diamicton (till?) extend to the top of the section.

p0355 At the Merritt sites in southern British Columbia, there are reversely magnetised proglacial lacustrine and glacio-lacustrine deposits separated by a palaeosol (Chernozem). They are stratigraphically below reversely magnetised interglacial sediments containing a tephra dated at >0.67 Ma. These interglacial deposits have a palaeosol at their upper contact which is also reversed, and are overlain by normally magnetised interglacial deposits marking the Brunhes/Matuyama boundary. The reversely magnetised interglacial sediments are thought to be latest Matuyama, while the age of the underlying reversely magnetised glacio-lacustrine deposits are less well constrained.

s0175 49.13.2. Interior Plains

p0360 In the Mackenzie Delta cores, the latest Matuyama is represented by silty sand in the Taglu core and by organic rich silt interbedded with clay laminations in the Kumak core (Fig. 49.24).

p0365 The West River site in the Smoking Hills contains three reversed tills which could be assigned to any of the glacial intervals within the Matuyama Chron (Fig. 49.15), and it may be that the top reversed till is late Matuyama in age.

p0370 On Banks Island, the Morgan Bluffs Sites are the only sites with Jaramillo age deposits and also reveal post-Jaramillo (reversed) glacial sediments which can confidently be assigned to the latest Matuyama. This latest Matuyama sequence contains a till which is underlain and overlain by glacio-marine sediments (all reversed). The till was most probably deposited during MIS 22 or 20?

s0180 49.14. EARLY BRUNHES GLACIATIONS (0.78–0.40 MA, MIS 18, 16 AND 12?)

s0185 49.14.1. The Cordillera

p0375 The Brunhes–Matuyama boundary is present in most stratigraphical records in NW Canada. In the Tintina Trench at the RC site, the top normally magnetised outwash (unit 9, Fig. 49.4) unconformably overlies reversely magnetised outwash (latest Matuyama). Loess of equivalent age occurs at EFR and WFR sections. Significant cold periods are recorded worldwide for MIS 16 and 12, and it is likely that the outwash and loess was deposited at this time. The loess deposits of unit 9 do not reveal any clear sedimentary break with unit 8. Polarity changes which are not accompanied by stratigraphical boundaries are commonly reported for loess.

Stratigraphically, these early Brunhes deposits (unit 9) are bracketed between two interglacials, a lower one which is represented by the pollen assemblage found at EFR site and an upper one which is represented by a palaeosol ("Wounded Moose" type luvisol). The lower contact occurs at MIS 19 (the Brunhes/Matuyama boundary) and the upper contact falls somewhere in the range of MIS 17–11 (strong warm spikes in the oceanic δO^{18} record). The 1.2-m-thick luvisol which was developed on the outwash at RC is a typical Wounded Moose type palaeosol described by Tarnocai and Schweger (1991). The pollen record in unit 9 reflects interglacial conditions (MIS 19; Fig. 49.5). The assemblage includes *Ambrosia*-type, *Betula*, *Pinus*, *Alnus*, *Salix*, *Picea* and *Botrychium*. p0380

The Brunhes/Matuyama boundary (MIS 19) thus occurs within a thick loess sequence at both the EFR and WFR sites, while at RC site, the boundary is marked by an unconformity which presumably indicates that interglacial conditions prevailed here, as elsewhere. The Brunhes/Matuyama boundary occurs worldwide at MIS 19, an interglacial period. p0385

At the MD site in the Klondike Plateau, the Brunhes/Matuyama boundary occurs within colluviated organic silt (Froese et al., 2000). p0390

In the Mackenzie Mountains, several normally magnetised tills may represent glaciations during MIS 18 or 16. p0395

At the Merrit site in British Columbia, normally magnetised proglacial lacustrine and outwash sediments, and a boulder lag composed of the same lithology as the underlying flow (0.6±0.4 Ma) suggest that at least one early Brunhes glaciation may be present. p0400

49.14.2. Interior Plains s0190

In the Mackenzie Delta cores, the early Brunhes is marked by fluvial deposits containing much organic detritus (Fig. 49.24). p0405

At West River site in the Smoking Hills, the normally magnetised upper suite of sediments awaits further pollen analysis. On Banks Island, the Brunhes/Matuyama boundary occurs in interglacial deposits, while at the Nelson River site, this boundary is marked by an unconformity between two till units. p0410

49.15. LATE BRUNHES GLACIATIONS (0.40–0.015 MA, MIS 10–2) s0195

The normally magnetised surface till at the EFR and WFR sites (unit 10) forms a generally thin veneer and is of local provenance. During the Reid Glaciation (MIS 6 or 8) and subsequent glaciations, neither local nor Cordilleran ice reached the RC area. The normally magnetised palaeosol (brunisol) developed on this till is thinner than that seen at the Reid type locality, and also thinner than the underlying palaeosols at these sections. The Reid glaciation was as p0415

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extensive as the first local glaciation in the area, and in both cases these glaciers extended from the Fifteenmile Valley and reached the Yukon River, blocking it and forming a glacial lake (Duk-Rodkin, 1996; Fig. 49.4). The Late Pleistocene glaciations (MIS 2) in this area were not as extensive as earlier glaciations, and did not reach the Tintina Trench.

p0420 Recent exposure dating in the Aishek map area (Ward et al., 2008) has yielded ca. 50 ka ages for glacial erratics that were previously estimated to be "pre-Reid" (pre-Middle Pleistocene). This opens the possibility that a "Reid" designation may include more than a single glaciation. These young ages suggest a later advance of local ice. Therefore, while the Tintina Trench unit 10 (Reid) glaciation is assigned to MIS 8/6, some of the so-called Reid deposits may be as young as MIS 4 (Ward et al., 2008).

p0425 At the Fort Selkirk Volcanic complex, the Black Creek flows comprise a series of five basalt flows for which the upper flow has a date of 0.311 ± 0.005 Ma. They are overlain by Reid Glaciation outwash (MIS 6 or 8) and Latest Pleistocene loess.

p0430 Equivalents to the MIS 6 or 8 glaciations are almost certainly present in the Mackenzie Mountains, where up to 3
Au12 normal tills occur beneath the Late Pleistocene Laurentide glacial deposits at the surface.

p0435 At the Mount Edziza, Tahltan/Stikine sites, a sequence of normally magnetised glacial sediments are overlain by basalt dated by Ar–Ar at 0.30 Ma. The till has been assigned to MIS 10 (Spooner et al., 1996).

p0440 At the Merrit site, a normally magnetised till and proglacial lacustrine sediment sequence has tentatively been interpreted as being MIS 6 or 8 (Fulton et al., 1992). These deposits are overlain by glacial deposits of the Late Pleistocene (Wisconsin) Fraser glaciation.

s0200 49.15.1. Interior Plains

p0445 In the West River site, in the Smoking Hills, there is one normally magnetised till beneath the Late Pleistocene (Wisconsin) Laurentide till (Fig. 49.15). At the Banks Island sites up to two tills occur beneath the Late Pleistocene deposits (Fig. 49.3).

s0205 49.16. LATEST BRUNHES GLACIATIONS (32–12 KA, MIS 2)

s0210 49.16.1. The Cordillera

p0450 Late Pleistocene loess deposits are found at the Tintina Trench sites, Klondike Plateau sites and Fort Selkirk sites (Fig. 49.3). The Mackenzie Mountain sites are all capped by Late Wisconsin continental (Laurentide) tills containing glacial erratics transported from the Shield terrain of Canada.

49.16.2. Interior Plains s0215

The Smoking Hills are covered by a discontinuous lag of pebbles, cobbles and boulders of Shield origin, as well as by loess (Late Wisconsin). All glacial sediments beneath the late Wisconsin loess in the Smoking Hills are of local origin, indicating that only the Latest Pleistocene Laurentide Ice Sheet reached the northern Interior Plains. The Late Pleistocene (Wisconsin) Laurentide Ice Sheet had a very profound effect upon the Canadian landscape, including the reversal of flow of major rivers and/or the rerouting of many of the major rivers and their tributaries during retreat of the ice sheet (Duk-Rodkin and Hughes, 1992, 1994; Duk-Rodkin et al., 2004). p0455

49.17. CONCLUSIONS s0220

The Tintina Trench stratigraphy (RC, EFR and WFR) contains one of the most extensive records of preglacial, glacial and interglacial sediments in northwest Canada. Perhaps its most notable attribute is the large number of glaciations which occurred within the Latest Pliocene and Early Pleistocene. Seven of the eight glaciations documented here fall within the Matuyama Reversed Chron and provide a snapshot of deteriorating Late Pliocene climate conditions and the series of regional glaciations which followed. In addition to the nine glaciations and six interglaciations defined for the Tintina Trench sites, the trench contains an overlying till and loess sequence which are assigned to the late Brunhes. Other Cordilleran sites (sites 4–10, 18–20, Fig. 49.1) exposing a less complete Plio–Pleistocene stratigraphical record have been correlated to the sites described in the Tintina Trench. The large moisture supply from the north Pacific and Arctic Ocean and the onset of global cooling around 3.0 Ma (Figs. 49.1, 49.2 and 49.23) were key elements in the formation of the largest Cordilleran ice sheets in early Late Pliocene, in the Tintina Trench and Klondike areas, as well as in parts of Alaska. During cold conditions (glacial periods), the region experienced the build-up of both local and regional ice sheets and saw the deposition of extensive loess sheets beyond glacier margins. The extent of regional and local ice varied temporally and spatially. During warmer conditions (interglacial periods) fluvial, alluvial and colluvial processes predominated, and weathering of landscape surfaces produced a variety of soils which today are preserved as palaeosols (G10, Fig. 49.23). p0460

In the topographically lower regions of NW Canada, the first glaciations appear to have occurred somewhat later. Rising sea level led to the opening of the Bering Strait around about 3.0–3.5 Ma (Dowsett et al., 1994; Robinson, 2009), and heat transfer across the Bering Strait and into the Arctic Ocean may have warmed and moderated the climate along the continental Arctic and southern Arctic Islands. p0465

The build-up of ice on the ocean surface was probably quite restricted and seasonal (Dowsett et al., 1994). Recent work (Spielhagen et al., 1997; Marincovich, 2000; Gusev et al., 2009) has suggested a relatively warm and largely ice-free Arctic in the earliest Pleistocene and this probably accounts for the somewhat later development of ice in the Mackenzie Delta and Mackenzie Mountains (<2.6 Ma) as well as in the Smoking Hills (<2.6–1.6? Ma). Initiation of glaciation appears to have been considerably later (<1.8 Ma, post-Olduvai) on Banks Island.

p0470 Magnetostratigraphy has been used extensively to establish a correlation both within and between study sites reported here. Chronological data obtained from tephrochronology, Ar/Ar, K/Ar, ^{14}C and ^{36}Cl, as well as fossils, pollen and palaeosols, have been used where available. This has greatly facilitated the assignment of glacial and interglacial sedimentary units found at the 20 major study sites (Fig. 49.1) to the Geomagnetic Polarity Timescale and, where possible, to the $\delta^{18}O$ marine isotopic record. In this manner, a systematic comparison was made with records from the Cordilleran (Klondike Plateau, Fort Selkirk, Mackenzie Mountains, British Columbia) and Northern Interior Plains sites (Mackenzie Delta, Smoking Hills and Banks Island).

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Abstract

This chapter deals with stratigraphical correlations of glacial and interglacial deposits found in the northern Canadian Cordillera and in the northern Interior Plains of Canada. The sequences described here record multiple glacial events commencing at 2.7 Ma in the mountains and 1.6 Ma in ~~the northern plains~~. Extent and timing of these glaciations are based on magnetostratigraphy, tephrochronology, radiometric dating, paleosols and pollen.

Keywords: Cordilleran glaciations, paleomagnetism, paleosols, pollen, glacial tills

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