

An extensive late Cenozoic terrestrial record of multiple glaciations preserved in the Tintina Trench of west-central Yukon: stratigraphy, paleomagnetism, paleosols, and pollen¹

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Abstract: The Tintina Trench in west-central Yukon is a late Miocene graben formed along the antecedent early Tertiary Tintina fault. Since its formation the trench has served as a sediment trap for alluvial and glacial deposits. An extensive record of preglacial, glacial, and interglacial sediments spanning the late Pliocene to late Pleistocene has been preserved and is exposed today in modern landslide scars. This sedimentary record comprises multiple sequences of tills, outwash, mudflows, loess, and paleosols. The glacial sediments are the product of both local (montane) and regional (Cordilleran) ice advances that channeled into the trench, while loess and well-developed paleosols (brunisol and luvisol) reflect nonglacial and interglacial conditions, respectively. The Tintina Trench exposures provide the most complete record of glaciations for the region. Paleomagnetism, paleosols, and palynology provide age constraints for the geological events. A formal stratigraphic nomenclature is proposed for this region. The name West Tintina Trench Allogroup is assigned to the glacial–interglacial and nonglacial strata that occurs above a major regional Miocene–Pliocene unconformity. The allogroup spans the late Pliocene (3.6 Ma) to middle Pleistocene (0.126 Ma), based on magnetostratigraphy and pollen data. The sequence includes an alluvial deposit at the base, overlain by an extensive sequence of tills and outwash, and capped by loess. Paleosols and weathering horizons occur throughout the sequence. Tintina Trench; Beringia; glacial chronology; magnetostratigraphy; early and middle Pleistocene; Yukon paleoenvironments; Yukon paleosols; Yukon pollen; North American glaciations; West Tintina Trench Allogroup.

Résumé : Le sillon de Tintina dans le centre ouest du Yukon est un graben du Miocène tardif, formé le long de l'ancienne faille de Tintina (Tertiaire précoce). Depuis sa formation, le sillon a servi de piège à sédiments pour les dépôts alluvionnaires et glaciaires. Un enregistrement complet de sédiments préglaciaires, glaciaires et interglaciaires datant du Pliocène tardif au Pléistocène tardif a été préservé et affleure maintenant dans des cicatrices de glissements modernes. Ces dépôts sédimentaires comprennent de multiples séquences de tills, de dépôts fluvio-glaciaires, de loess et de paléosols. Les sédiments glaciaires proviennent d'avancées glaciaires locales (subalpines) et régionales (de la Cordillère) qui ont été dirigées dans le sillon alors que le loess et les paléosols bien développés (brunisol et luvisol) reflètent respectivement des conditions non glaciaires et interglaciaires. Les affleurements du sillon de Tintina fournissent les données les plus complètes des glaciations pour la région. Le paléomagnétisme, les paléosols et la palynologie fournissent des cadres pour l'âge des événements géologiques. Nous proposons une nomenclature stratigraphique formelle pour cette région. Le nom West Tintina Trench Allogroup [Allogroupe du sillon de Tintina occidentale] est assigné aux strates glaciaires–interglaciaires et non glaciaires qui se trouvent au-dessus d'une discordance majeure régionale entre le Miocène et le Pliocène. Selon la magnétostratigraphie et les données sur le pollen, l'allogroupe couvre la période du Pliocène tardif (3,6 Ma) au Pléistocène moyen (0,126 Ma). La séquence comprend un dépôt d'alluvions à la base, recouvert d'une importante séquence de tills et de dépôts fluvio-glaciaires, chapeauté par du loess. Des horizons de paléosols et d'altération se retrouvent à travers toute la séquence.

[Traduit par la Rédaction]

Introduction

The southwestern Yukon and southeastern Alaska region of northwestern North America (Fig. 1) contains an extensive glacial record dating back to the late Miocene – early Pliocene (Denton and Armstrong 1969). Coastal mountain uplift commenced ca.14 million years ago (O'Sullivan and Currie 1996) followed by progressively colder conditions that lead to the initial glaciation of this region ca.10 million years ago (Denton and Armstrong 1969). These events were followed by regional erosion and renewed uplift ca. 4 million years ago, followed by intensified cold conditions and the late Cenozoic ice age (Haug et al. 2005; Raymo 1992;

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Fig. 1. Location of stratigraphic sections in the Tintina Trench and sites correlated with the West Tintina Trench Allogroup. Map shows relationship of sites to major topographic features (mountain ranges) and proximity to oceanic moisture sources for glaciations.

White et al. 1999). The Yukon Territory has been impacted by Cordilleran and montane glaciers at various times throughout the late Cenozoic, as well as by continental ice of Keewatin provenance during the latest Pleistocene. The earliest glaciation in northwestern Canada occurred in west-central Yukon during the late Pliocene, between 3.0 and 2.58 Ma (Duk-Rodkin and Barendregt 1997; Froese et al. 2000). This glaciation was the most extensive and formed a continuous carapace of ice covering all mountain ranges, except for a small area in the Dawson Range and a somewhat more extensive region in the northern Yukon.

All glaciations in the region impacted drainage systems to a greater or lesser extent (Fig. 2). The earliest Cordilleran glaciation diverted the Yukon River to the northwest into Alaska forming a proglacial lake which drained to the west and incorporated Yukon River drainage into the Alaskan Kwikpak River (Duk-Rodkin et al. 2001). Today, these two river systems are collectively referred to as the Yukon River. Glaciations resulted in numerous other drainage diversions in northwest Canada (Fig. 2). While preglacial rivers flowed into the Arctic (Peel and Porcupine rivers), Atlantic (Bell River), and Pacific oceans (Kwikpak and paleo Yukon rivers), present-day rivers drain only to the Pacific (Yukon River) and Arctic oceans (Mackenzie River). It is estimated that glaciations have altered ~95% of the ancestral drainage systems in northwest Canada (Duk-Rodkin and Barendregt 1997; Duk-Rodkin et al. 2004). Laurentide ice (Marine Isotope Stage (MIS) 2) in the Mackenzie River basin integrated all drainage east of the northern Cordillera into the Mackenzie River basin (Duk-Rodkin and Hughes 1994; Lemmen et al. 1994), while all drainage west of the northern Cordillera, including the Porcupine River basin, was integrated into the Yukon River system.

Preglacial and glacial deposits of late Cenozoic age are documented from outcrops in the Tintina Trench graben (Figs. 3, 4). These deposits represent an extensive sequence that is separated by a major unconformity that resulted from late Miocene extensional faulting within the Tintina fault zone. The Tintina Trench has preserved preglacial Eocene to Miocene stratigraphy, which was later deformed, and subsequently overlain by fluvial and glacial deposits. Miocene and older sediments below the unconformity are reported in Duk-Rodkin et al. 2001. Detailed stratigraphic studies (this paper) are carried out as part of an extensive and ongoing systematic surficial geologic and glacial limits mapping program (1:100 000 to 1:250 000 scale) in northwest Canada (Duk-Rodkin et al. 2008, and Duk-Rodkin and Barendregt 2010). An accompanying paper in this issue (Barendregt et al. 2010) describes detailed studies of paleomagnetism carried out to determine ages for these sediments.

Stratigraphy

The extensive succession of late Pliocene to middle Pleistocene strata deposited by preglacial fluvial streams, piedmont and cordilleran glaciers (Figs. 4, 5), and ice marginal winds form a unique sequence of stratified beds, which can be characterized as an allogroup (North American Commis-

sion on Stratigraphic Nomenclature 1983). This allogroup is defined by bounding areal (lateral) discontinuities and comprises a series of tills and (or) outwash deposits of Cordilleran and (or) local montane glacial provenance, and loess deposits, separated in places by paleosols. These deposits are found in sections that expose units of correlative age (Figs. 5, 6). Of the three sites described here, the Rock Creek (RC) site at 830 m above sea level (asl) (64°13'N, 139°07'W) forms the type section. Two nearby sites reveal correlative stratigraphy and serve as useful comparative sections: one located along the east side of the Fifteenmile River (EFR site) at an elevation of 762 m asl (64°23'N, 139°48'W), and the other along a western tributary of Fifteenmile River (WFR site) at 765 m asl (64°29'N, 139°55'W). These three sites are located near the northern margin of the Tintina Trench (Fig. 4). Several exposures along the southern margin of the trench reveal a similar stratigraphy (Duk-Rodkin et al. 2001), as do exposures along the northern slopes (Fig. 4) of the Klondike Plateau (Froese et al. 2000).

West Tintina Trench Allogroup

The name West Tintina Trench Allogroup has been assigned to glacial and nonglacial strata located at its type section (Rock Creek site, Figs. 4, 5, 6, 7). These deposits extend from early Pliocene (5.33 Ma) to middle Pleistocene (0.126 Ma). They include alluvial deposits at the base, overlain by a succession of tills and outwash deposits with paleosols or weathering horizons at the upper contacts. This sequence is located above a regional unconformity of late Miocene age. In this study, we consider only the stratigraphy above the unconformity, which represents geologic events spanning ~3.0 Ma. All units within the West Tintina Trench Allogroup are horizontally bedded and, thus, easily distinguished from the tilted underlying late Miocene beds. The uppermost boundary of the allogroup is defined by several metres of loess (typically affected by groundwater), or by a Wounded Moose-type paleosol developed on till or outwash (Smith et al. 1986). Deposits contain abundant striated and weathered clasts throughout. In general, the sediments are highly compact. Their provenance can be of either local and (or) Cordilleran origin (Fig. 4). This allogroup records nine glacial, five interglacial (paleosols), and one nonglacial event(s) (preceding the first glaciation). The stratigraphy forming this allogroup ranges in thickness from 60 to 80 m. It extends more or less continuously along the Tintina Trench for 120 km and discontinuously for another 40 km, and extends west of the trench for about 150 km, crossing the Canada–USA border. These distances have been established from areas of continuous glacial drift cover exposed along the trench (120 km), and less commonly from isolated terraces and drift surfaces (40 km; upper–middle Klondike Valley), separated in places by large gaps. Large drift surfaces extend west into Alaska for 150 km before disappearing west of Circle, Alaska (Duk-Rodkin et al. 2004; Froese et al. 2003).

Sites

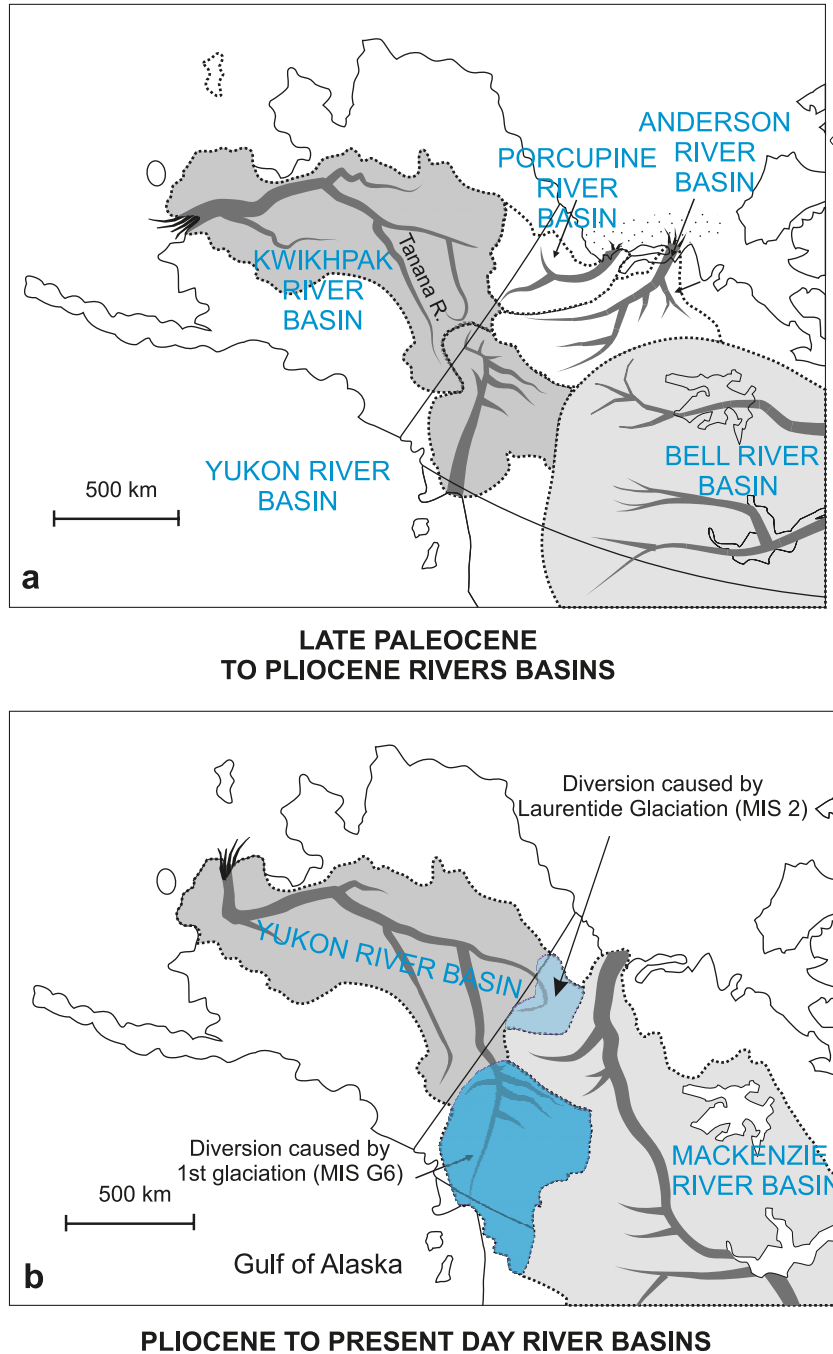
Tintina Trench sites
Klondike Plateau

Mackenzie Mountains

Macke



Fig. 2. Drainage diversions in northwestern Canada triggered by glaciations (Duk-Rodkin et al. 2001).



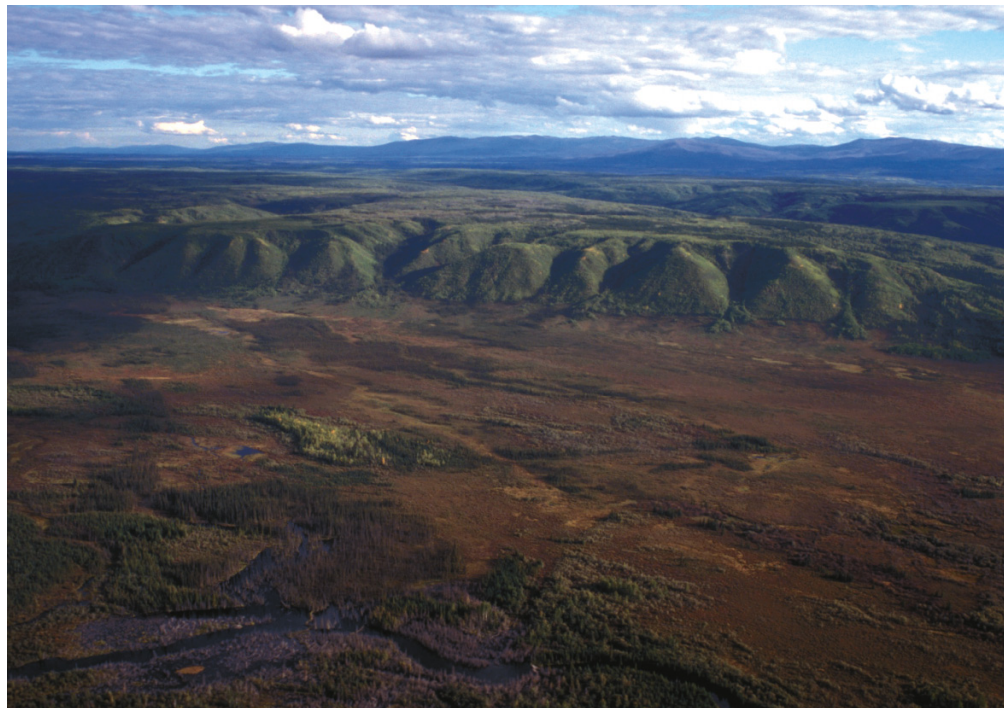
Provenance of glacial deposits

Clast lithologies (%) for RC, EFR, and WFR sites were determined for all preglacial gravel, till, outwash, and mud-flow units (Fig. 8). For each of these units ~100–150 pebbles were identified, generally from two subsites. At RC, quartzite pebbles are the dominant lithology, and they together with slate, siltstone, argillite, and gabbro are derived from the northern trench area. There are four particular lithologies that characterize the RC site (units 2–9), namely basalt, aplite, granodiorite, and syenite (felsic granitoids). Basalt in this part of the Tintina Trench is derived from the Klondike Plateau to the southeast (Green and Roddick 1961; Mortensen 1988). This indicates a Cordilleran ice source,

with ice advancing to the west-northwest from the Stewart River area to the southeast. The ice, thus, bordered the eastern slopes of the Klondike Plateau on its way to the Tintina Trench. The felsic granitoids at RC are probably derived from the same source in the Stewart River area (middle Cretaceous Cassiar Suite; Gordey and Makepeace 1999) because none of the valley glaciers in the southern Ogilvie Mountains could have deposited these clasts at the RC site (Fig. 4).

Pebble lithologies from EFR and WFR sites (Fig. 8) are dominated by argillites (40.5%) and quartzites (26.7%) and are very similar for both sites, with the exception of rhyolite (5.4%), which is present only at EFR, and shale (13.7%) and

Fig. 3. Overview of Tintina Trench, view is to the north. Note south-facing scarp of graben.



limestone (9%), which are present only at WFR. All lithologies for EFR and WFR indicate a southern Ogilvie Mountains or northern trench source and point to local ice movement only (Figs. 4, 6).

Stratigraphy of Rock Creek site: type locality

The type locality (Figs. 4–7) is located along the north side of a western tributary to Rock Creek, is south facing, and lies ~25 km northeast of Dawson. The tributary creek drains along a structural lineament (fault) that marks the north side of the Tintina Trench (Figs. 4, 6). The type section consists of three sites (labeled a, b, and c), all located along the northern side of the trench (Fig. 7).

Unit 1 (site a)

Description

Unit 1 consists of two subunits: unit 1a and unit 1b. Unit 1a is a 7.9 m thick diamict containing two subunits: (i) a 5.5 m diamict with 40% clast content, and a weathered, oxidized, compact, cemented coarse sandy matrix. Clasts (average size 11 cm, maximum 8 cm) reveal crude imbrication to the west, and (ii) a 2.4 m thick diamict containing about 20% clasts and silty fine sand matrix, which has been diagenetically altered to a light grey colour. Clasts (average size 4–5 cm, maximum 15 cm) have a crude fabric (from west), are subrounded to angular with rare well-rounded clasts, are matrix supported, and form a sharp contact with overlying lacustrine sediments. Unit 1b is a lacustrine deposit (0.10 m) consisting of compact clay containing uniformly dispersed pebble-sized dropstones, and *Polemonium* sp. pollen.

Interpretation

Unit 1 (Fig. 7) is a debris flow deposit overlain by a thin

lacustrine unit. The debris flow was likely produced by local stream adjustment (aggradation) triggered by a period of major extensional faulting in the Tintina Trench. Subunit 1b is a local shallow-lacustrine deposit, containing *Polemonium* sp. pollen, and is normally magnetized. *Polemonium* sp. first appears in the upper Miocene (Muller 1981) and is thought to have persisted in this region until the latest Pliocene. It is present in the Lost Chicken beds (ca. 2.9 Ma) of the Yukon and Alaska (White et al. 1999; Matthews et al. 1990), which are thought to be correlative with unit 1. Its presence in the Tintina Trench identifies sediments deposited before the onset of the first glaciation in the region and is diagnostic of a late Pliocene climate.

The assignment of a late Gauss age for this preglacial unit is based on its stratigraphic position, polarity, and pollen. It occurs above the Miocene–Pliocene unconformity and below normally magnetized outwash gravels of the first glaciation (table 1 of Barendregt et al. 2010). A normal polarity for sediments of the first glaciation is also documented at nearby sites (Froese et al. 2000; Duk-Rodkin et al. 2004).

Unit 2 (site a)

Description

Unit 2 comprises 39.3 m of iron stained gravel, intercalated with grey gravels, and is relatively well stratified. The stratification is marked by fine sand beds up to 0.4 m thick, which grade to silty clay and medium fine sands. Coarse gravels show a weak imbrication to the northwest and are composed of subrounded clasts, cobbles, and pebbles, some of which are striated. Coarsening upward beds repeat every 3–4 m through the gravel deposits. The average clast size is 5–6 cm near the base, and 20 cm near the top of a bed. The upper 4.5 m of unit 2 consist of 4 m of cobble gravel overlain by 0.5 m of diamict, mainly massive, containing a

Fig. 4. Location of sites in relation to glacier extent and provenance (Cordilleran and local Ogilvie Mountain ice) and Yukon glacial limits map (inset).

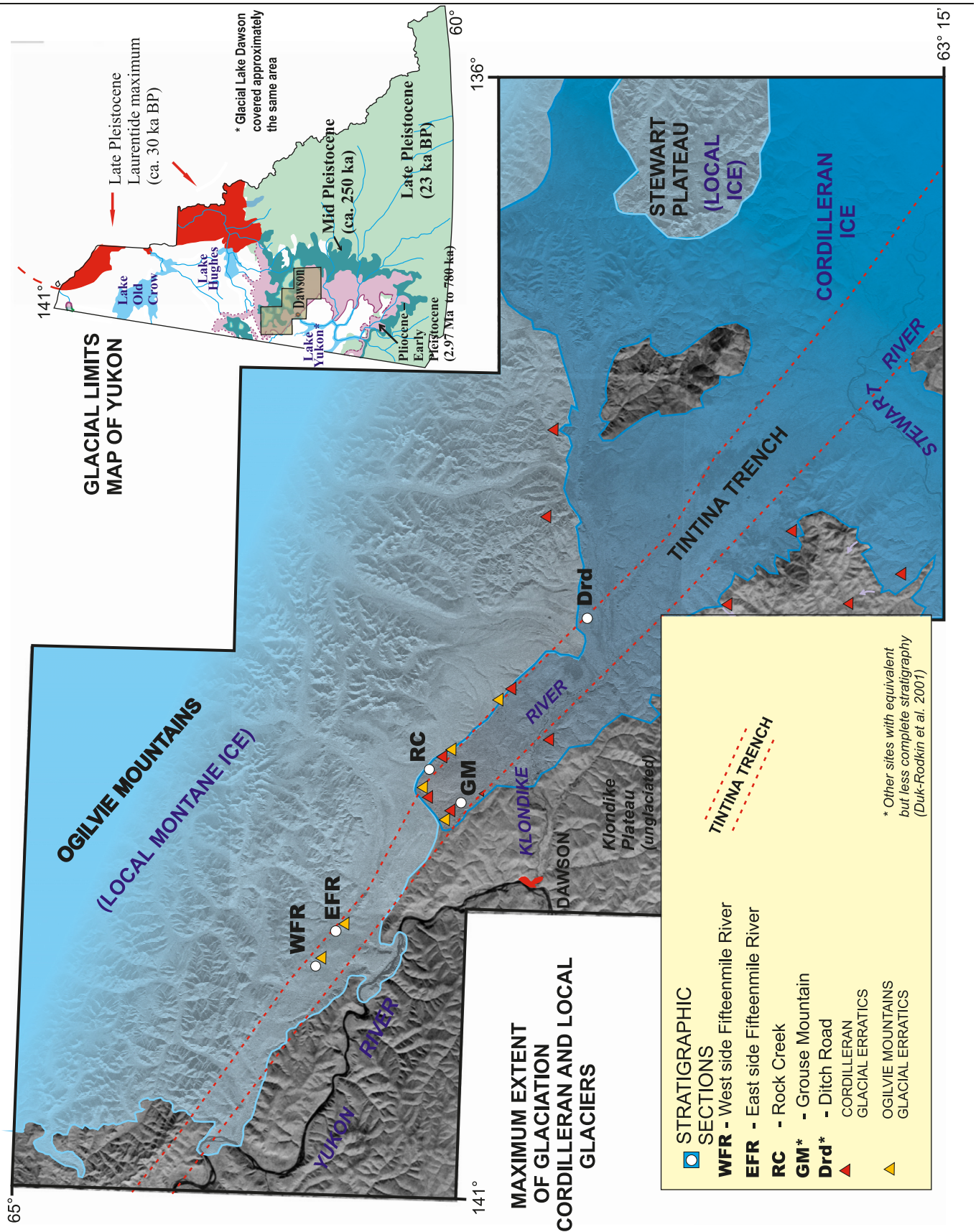


Fig. 5. Stratigraphic correlation of type locality at Rock Creek (RC) site and complementary sites at east side of Fifteenmile River (EFR) and west side of Fifteenmile River (WFR). Geomagnetic Polarity Time Scale is based on (Cande and Kent 1995) and composite $\delta^{18}\text{O}$ LR04 marine isotopic record (relative paleotemperature) 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. Even numbers to left of curve are cold isotope stages, and odd numbers to right are warm stages (MIS). Letters and numbers used before isotope stage 104 (Matuyama–Gauss boundary) follow Shackleton et al. (1995). Arrow at bottom is mean Holocene $\delta^{18}\text{O}$ value. Bold numbers in open squares correspond to stratigraphic units discussed in the text and, also, to units shown in Figs. 7–10. Suggested correlation of glacial deposits (bold letters) to cold stages in the marine isotopic record (blue squares) is shown to the right of Geomagnetic Polarity Time Scale. N, normal polarity; R, reverse polarity; sh, shale; ss, sandstone; congl, conglomerate; gr., gravel.

boulder lag, with average boulder diameter of 0.3–0.4 m. Pebble lithologies reveal mainly quartzite, felsic granitoids, slate, granodiorite, chert, basalt, gabbro, and syenite (Fig. 8).

Interpretation

Unit 2 is an outwash gravel containing several fine sandy subunits. These sub units are normally magnetized (assigned to the Gauss Chron, Fig. 7) and do not contain pollen. These deposits mark the first entry of local and Cordilleran ice (Figs. 4, 8) into the Tintina Trench region and are the oldest identifiable sediments of glacial origin.

Unit 3 (site b)

Description

Unit 3 contains 12 m of stony diamict, of which 4 m are well exposed. The diamict exhibits a northwest to north-northeast fabric and is capped by 0.2 m of silty fine sand and a 2 m thick paleosol. Clast lithologies reveal quartzite, siltstone, basalt, granodiorite, argillite, and syenite (Fig. 8).

Interpretation

Unit 3 is interpreted as a till capped by a fluvial silty sand bed, in which a paleosol was developed. The paleosol is a luvisol with characteristics generally associated with the southern limit of boreal forest vegetation today. Luvisols are characterized by the accumulation of translocated clays in the B horizon (Dampier et al. 2009) The paleosol is reversely magnetized and is assigned to the earliest Matuyama Chron, based on the underlying normal Gauss Chron polarity (unit 2) and the overlying normally magnetized unit 5, assigned to the Olduvai subchron (Figs. 5, 7, and table 1 of Barendregt et al. 2010). Sites a and b are 0.5 km apart, and between the outwash (unit 2, site a) and diamict (unit 3, site b) an 8 m section is obscured by colluvium. Within this 8 m section polarity changes from normal to reversed (Figs. 5, 7).

Unit 4 (site c)

Description

Unit 4 comprises 12 m of clast-supported diamict (about 80% clasts) with a minor amount of silty clay and granule matrix. It is for the most part massive but exhibits faint stratification in places. Clusters of pebbles are visible in the lower 3 m. Clasts are commonly about 8–10 cm, but boulders up to 40 cm, as well as tightly packed and indurated granules, occur within this deposit. Clasts are commonly weathered throughout, and the majority are completely weathered, especially near the top of the unit. Fabric measurements do not indicate a clear trend, but a faint south-

southeastern direction suggests a Cordilleran ice source. A boulder lag occurs about 7 m from top of unit. Pebble lithologies for this unit reveal mainly quartzite, siltstone, slate, basalt, and sandstone (Fig. 8).

Interpretation

The unit 4 diamict is interpreted as a glacial mudflow. The north-northwest fabric may suggest a Cordilleran glacial source. A weathering horizon at the upper contact is enriched in clay content as a result of a prolonged period of moderate weathering and translocation of surface clays. These sediments are too coarse for paleomagnetic sampling; however, they are underlain by a reversely magnetized diamict (unit 3) and overlain by a normally magnetized outwash (unit 5), and therefore unit 4 must fall within the early Matuyama Chron (table 1 of Barendregt et al. 2010).

Unit 5 (site c)

Description

Unit 5 comprises an 8m basal subunit of crudely to well-stratified gravels and sands, with sand beds up to 12 cm thick. Gravel (cobbles up to 20 cm diameter) is well sorted and has a coarse sand matrix. A fine sandy bed within the gravels is normally magnetized.

Gravels and sands are overlain by 5 m of stony diamict containing 40% clasts, rounded to subrounded, average size 4 cm, some up to 8 cm and occasionally to 20 cm diameter. Most clasts are weathered throughout and reside in a massive sandy–clayey – minor silt matrix. A 1.2 m weathering horizon occurs at the top of the unit and contains gravels coated with clay skins. Diamict fabrics indicate a southeast provenance. Pebble lithologies for unit 5 are mainly quartzite, aplite, argillite, basalt, chert, felsic granitoids, syenite, and slate (Fig. 8).

Interpretation

Unit 5 is outwash overlain by till. The till has a weathering horizon 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. The normal polarity measured in the outwash has been assigned to the Olduvai subchron (the first major normal polarity subchron within the Matuyama) based on its stratigraphic position between a reversed–normal–reversed–normal (R–N–R–N) polarity sequence above and a reversed–normal–normal (R–N–N) sequence below (table 1 of Barendregt et al. 2010).

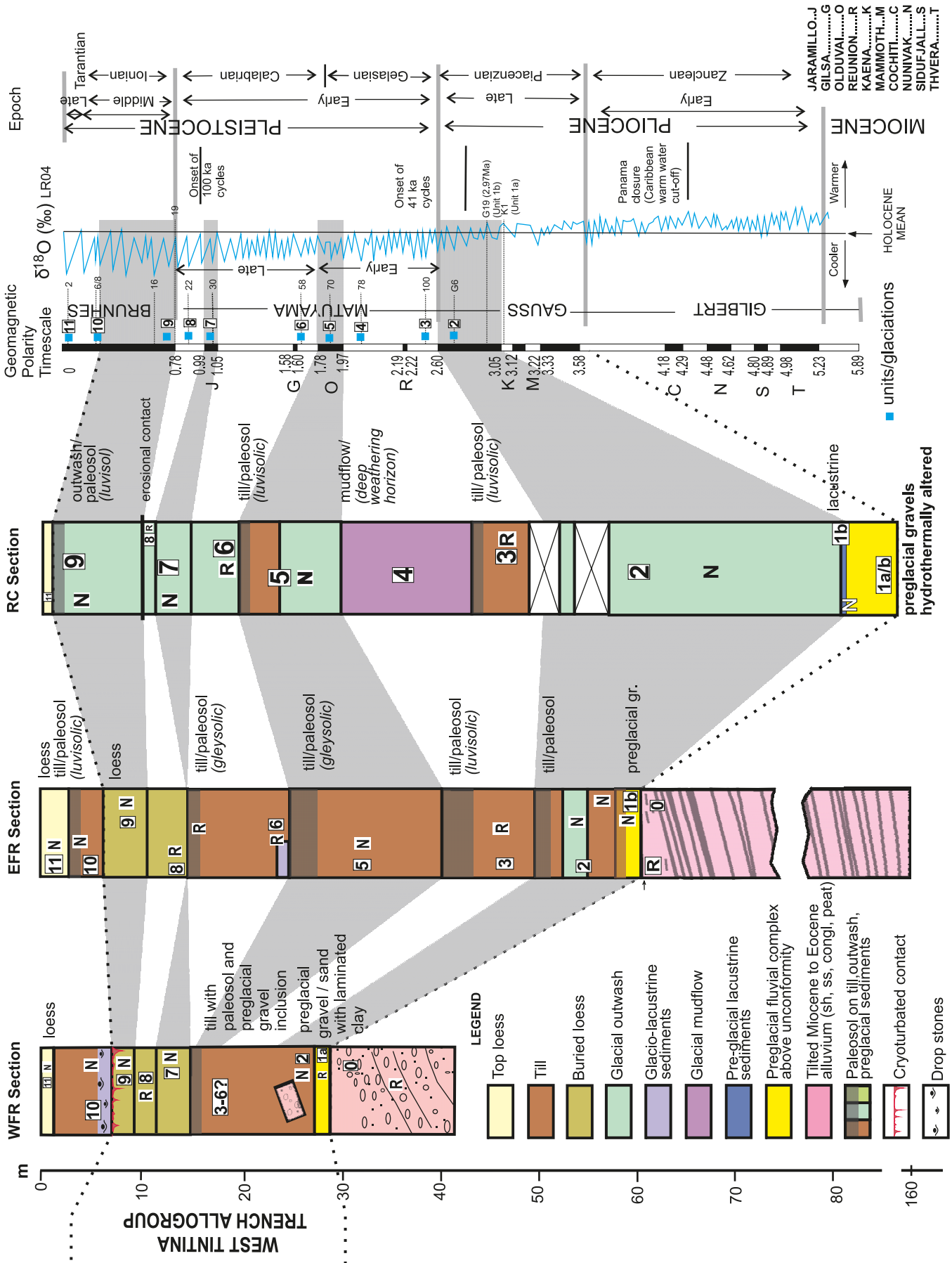
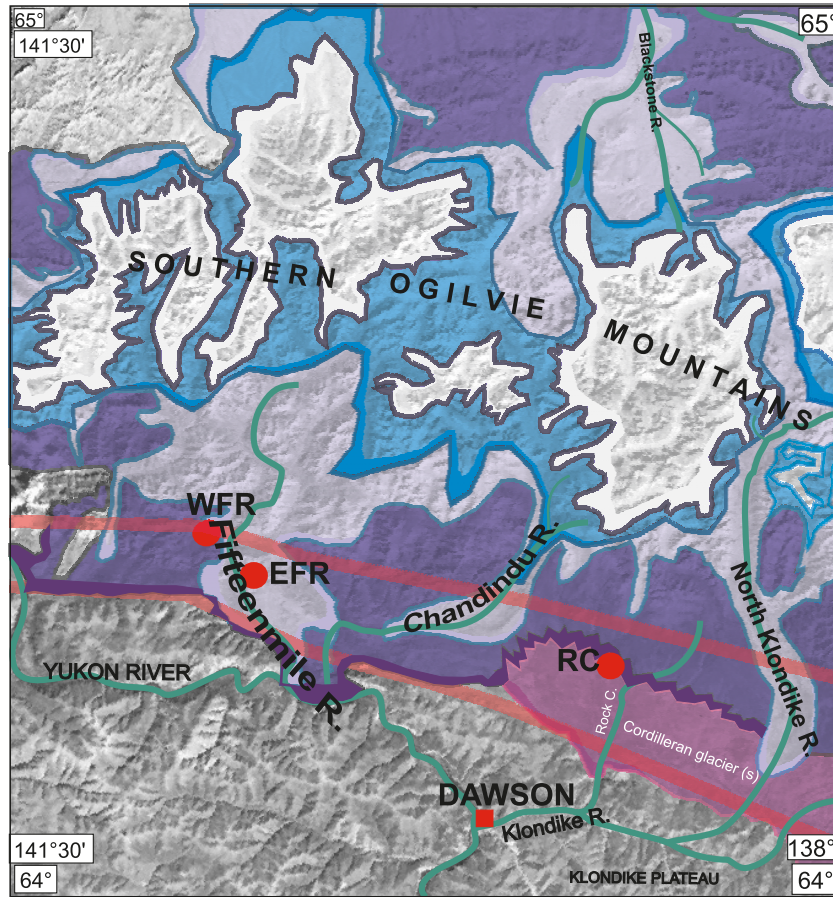







Fig. 6. Extent of Gauss, Matuyama, and Brunhes age glaciations in the Ogilvie Mountains. Unit numbers correspond to the stratigraphic units identified in text. RC, Rock Creek; EFR, East Fifteenmile River; WFR, West Fifteenmile River.



LEGEND

Coalescing Cordilleran (continental divide) and/or montane (Southern Ogilvie Mountains) glaciations

- 

approx. boundaries of the Tintina Trench
- Gauss/Matuyama/Brunhes

rivers, streams
- 

stratigraphic sites
- unglaciated terrain

Local montane valley glaciers (Southern Ogilvie Mountains)

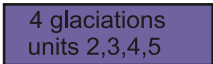
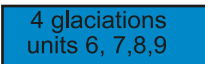
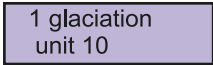
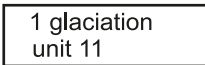
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- Gauss/Early Matuyama
Late Matuyama/Early Brunhes
- 

- Early Late Brunhes
Late Brunhes

Fig. 7. Composite stratigraphy of type locality at Rock Creek. This stratigraphic column was assembled from three transects along the same slope, labeled as sites a, b, and c. Note hydrothermally altered gravels overlain by outwash at site a. Unit 4 gravels dip gently into slope. N, normal polarity; R, reverse polarity.

Unit 6 (site c)

Description

Unit 6 comprises 5.25 m crudely to well-stratified gravels with intercalated matrix-supported and open work gravel beds, and beds of fine sands. Matrix supported gravels contain cobbles up to 50 cm in diameter. Partially weathered clasts exhibiting weathering rinds are common, while fully weathered clasts are rare. Open work gravels are smaller in size and better sorted. Fine sandy beds have reversed polarity. The lower contact is erosional, based on a truncated paleosol at its lower contact (unit 5). Pebble lithologies of units 6–9 reveal mainly quartzite, basalt, and granodiorite (Fig. 8).

Interpretation

Unit 6 is an outwash gravel assigned to the middle Matuyama, based on its stratigraphic position between the Olduvai and Jaramillo subchrons (table 1 of Barendregt et al. 2010).

Unit 7 (site c)

Description

Unit 7 (bottom to top) comprises 3 m of poorly to well-stratified gravels with intercalated beds of matrix-supported and open work gravels, a 0.2 m silty sand bed, a 0.5 m coarse sand with minor clay matrix-supported gravel bed with clasts up to 26 cm (often in clusters), a 0.15 m well-sorted open work gravel (2 cm), and a 0.19 m silty sand bed. The matrix-supported beds have cobbles up to 50 cm diameter. Partially weathered clasts are common, fully weathered clasts are rare. Open work gravels are smaller in size and better sorted. Lower contact with unit 6 is sharp and is defined by silty fine sands and clay beds.

Interpretation

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 magnetized units above and below, assigned to the late Matuyama Chron.

Unit 8 (site c)

Description

Unit 8 comprises discontinuous pockets (1.5 m × 0.6 m) of weakly bedded (north-dipping) coarse sands (at base) within and overlain by clast-rich sands and silts (Fig. 7). The discontinuous pockets extend laterally over 40 m of the exposure. The lower erosional contact is irregular.

Interpretation

Unit 8 sediments are outwash sands and silts containing pockets of entrained material that may have been frozen during transport. Silts have reversed polarity, are underlain by normally magnetized outwash deposits (Jaramillo) and overlain by normal sediments (Brunhes Chron), and can therefore be assigned to the latest Matuyama Chron.

Unit 9 (site c)

Description

Unit 9 (from bottom to top) comprises 7.75 m crudely stratified, poorly sorted gravels and poorly sorted sand lenses up to 60 cm thickness with clasts imbedded throughout; 0.8 m coarse sand and granule matrix-supported gravels, well sorted, with clay skins, cobbles up to 60 cm, subrounded to subangular, some frost shattered, and some weathered throughout; 0.4 m oxidized coarse gravels with clay skin coatings, cobbles up to 50 cm, frost shattered, massive silty fine sand matrix. Fine sand lenses at base, middle, and upper portions of unit 9 have normal polarity. This unit is discontinuously covered with colluvium and loess on which a 90 cm thick paleosol (luvisol) was developed.

Interpretation

Unit 9 is the uppermost glacial outwash at the Rock Creek site and has a luvisolic paleosol developed at its surface (comparable to a Wounded Moose paleosol). Unit 9 is overlain by loess (unit 11, described later) and underlain by outwash (unit 8). Clasts within the soil exhibit clay skin coatings. The normal polarity recorded in fine grained sand lenses is assigned to the Brunhes Normal Chron (table 1). This deposit is assumed to be equivalent to a normally magnetized loess bed at West and East Fifteenmile River sites (Fig. 5).

Unit 10 (units 10 and 11 are not included in West Tintina Trench Allogroup)

Unit 10 is missing at the RC site because Cordilleran and (or) local montane glaciers did not reach this location during the late Pleistocene. However, local ice from the Ogilvie Mountains advancing out of Chandindu valley came to within a few kilometres of the RC site (Duk-Rodkin 1996), and unit is described for the East Fifteenmile River site (as follows).

Unit 11 (site c)

Unit 11 forms the uppermost loess unit (20 cm) at RC. This regionally extensive unoxidized surface loess lacks structure, suggesting little or no reworking. It is normally magnetized and overlies Reid till (MIS 6–8) and is, therefore, younger than 126 ka, probably of McConnell age (<23 ka BP).

Stratigraphy of Fifteenmile River, east site

Stratigraphy described at the East Fifteenmile River site outcrops in a Holocene landslide scar on the north side of the Tintina Trench, 4.0 km east of Fifteenmile River (Figs. 4, 6, 9). About 30% of the slopes along the trench have been affected by landsliding. The exposure itself reveals several older episodes of landsliding that may extend back to the period of extensional faulting in the late Miocene. Beds within the landslide have been rotated and lowered, but they remain intact. At all horizons where beds

**West Tintina Trench Allogroup type section:
Rock Creek sites**

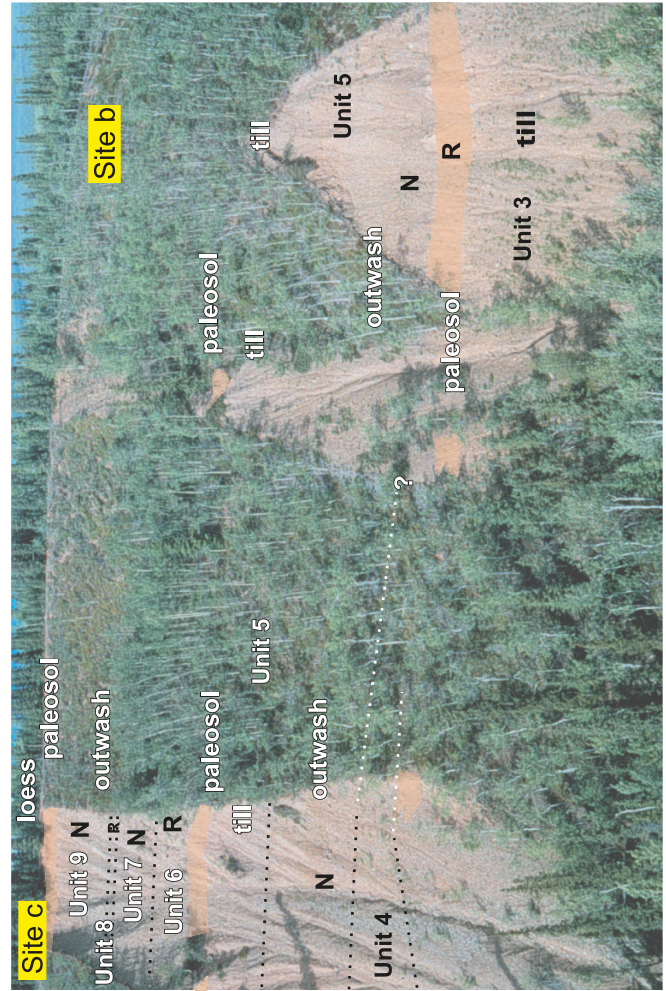
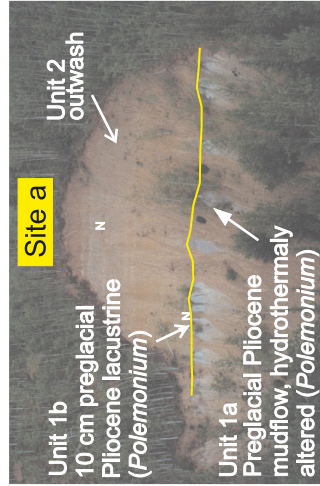
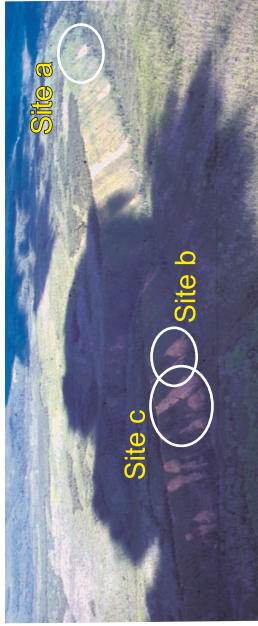
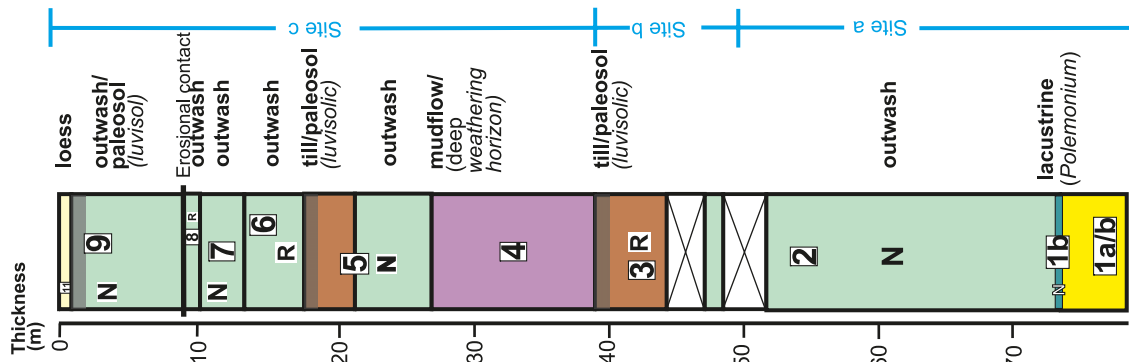
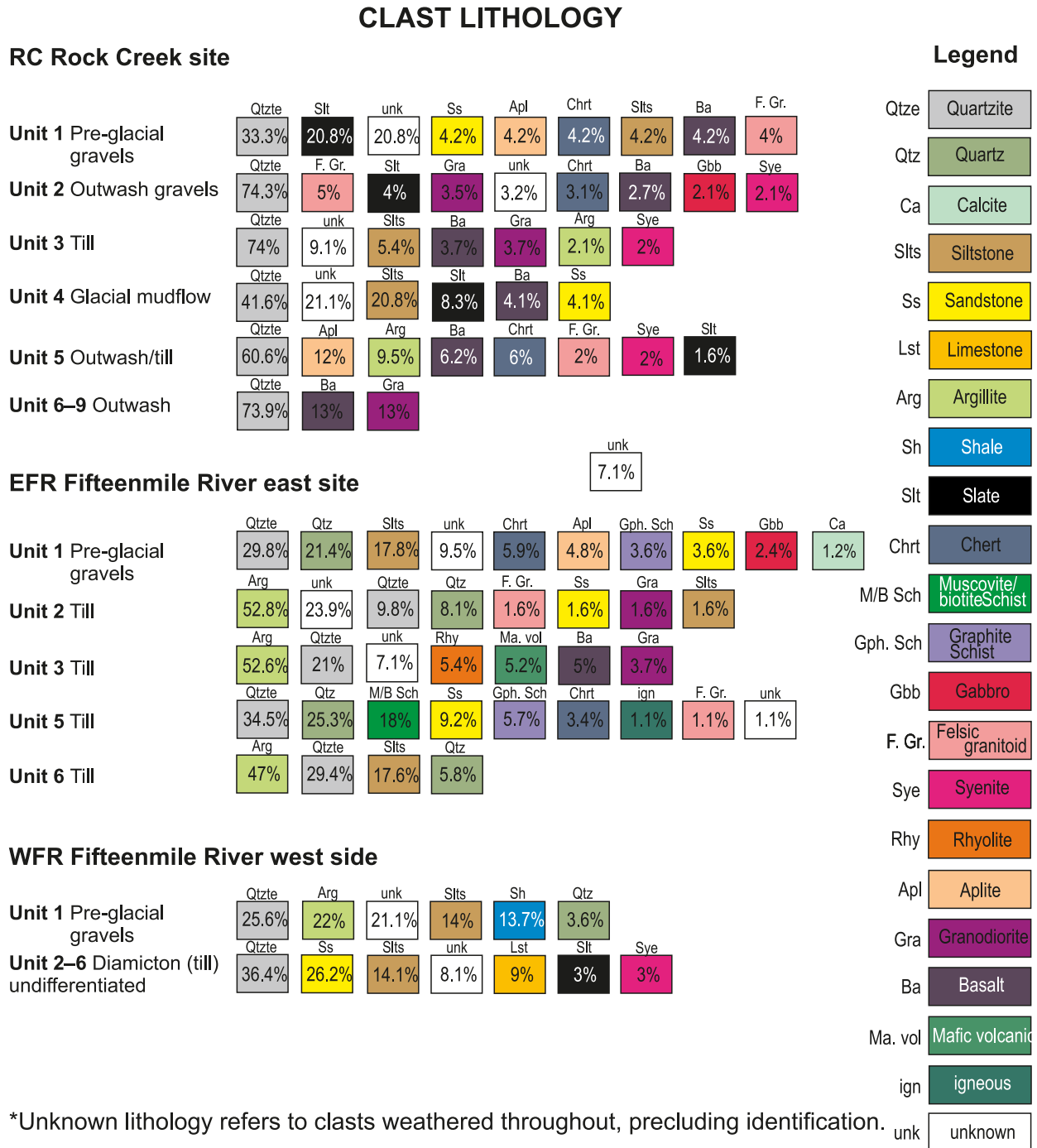


Fig. 8. Clast lithologies for the three sites of the West Tintina Trench Allogroup given in percentages for each lithology, and for each stratigraphic unit. The presence of Tertiary basalt from the east part of Klondike Plateau, seen in units 2–9 at RC indicates an eastern (Cordilleran) source of ice for these clasts. Lithologies at EFR and WFR indicate only ice of local provenance.



were not horizontal, appropriate dip corrections have been applied to samples collected for paleomagnetic analysis. Till fabrics at this site were not measured because of the landsliding, but in general, fabric reveals a north-northwest iceflow.

The EFR outcrops expose a package of Plio-Pleistocene preglacial and glacial sediments separated unconformably from dipping Miocene beds (Fig. 9). 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 from local ice out of the Ogilvie Mountains are present. Nevertheless, a sequence of glacial, interglacial, and nonglacial events similar to that seen at RC is described at EFR and can be considered as a complementary section for the West Tintina Trench Allogroup. The EFR stratigraphy is a composite of sites a, b, and c (Fig. 9).

Fig. 9. Composite stratigraphy of East Fifteenmile River (EFR) site. This stratigraphic column was assembled from three transects along the same slope, labeled sites a, b, and c. Note exposure of preglacial alluvial deposits (unit 1b) and overlying first till (unit 2). Both units are normally magnetized and of Gauss age. Contact is highly oxidized. Till includes minor rip-up clasts from underlying preglacial alluvium.

Unit 1b (site a)

Description

Unit 1b consists of 2.5 m of massive gravelly sand with subhorizontal thin beds (2 cm) of silty-clay and sand. Subrounded pebbles (6 cm average size) exhibit manganese staining. A 1 m thick weathering horizon (gleysol) containing abundant weathered clasts, occurs at the upper contact with unit 2 and fades down profile. Glacial overriding of these deposits has incorporated soil and silty-clay beds, 5–20 cm thick, into the base of the overlying diamict (unit 2, Fig. 9).

Interpretation

Preglacial alluvial sand and gravel overlie tilted alluvial Miocene deposits. These preglacial sediments contain a partially truncated paleosol at their upper contact. The paleosol is a feragleysol probably formed under high water table conditions associated with periodic ponding of surface waters. The soil is truncated and deformed (Fig. 9) and in places incorporated into the overlying till, forming a wavy upper contact. Fine-grained beds are normally magnetized and correlated to the Gauss Normal Chron. Unit 1b overlies the Miocene–Pliocene unconformity and reveals the same polarity (and paleomagnetic directions) as the overlying (unit 2) glacial deposits. This relationship is also seen at the RC site (table 1 of Barendregt et al. 2010).

Unit 2 (site a)

Description

Unit 2 comprises 5 m of subhorizontally stratified diamict with sand lenses, overlain by 3 m of silty fine sand, which in turn is overlain by 4 m of massive sandy-clay matrix diamict, containing pockets of silty clay, and a weathering horizon at its surface. The basal diamict subunit forms an irregular contact with the underlying preglacial gravels and contains sheared components of these gravels at its base. The basal diamict contains 35% pebbles that are subrounded, with 80% < 6 cm in size and occasional larger clasts up to 70 cm, and 25% of all clasts are highly oxidized. The upper diamict subunit contains 40% pebbles that are subrounded, with 80% < 6 cm in size and occasional larger clasts up to 70 cm, and 25% of all clasts are highly oxidized, and most are weathered throughout. Clast lithologies are mainly argillite, quartzite, quartz, felsic granitoids, sandstone, granodiorite, and siltstone (Fig. 8).

Interpretation

Unit 2 is interpreted as a till with an interbed of silty fine sand, which is normally magnetized and correlated to the latest Gauss Normal Chron (2.7–2.58 Ma) based on its stratigraphic location above alluvial deposits of unit 1, and its comparable polarity and paleomagnetic directions. The weathering horizon at the top of the unit has characteristics of a truncated luvisol.

Unit 3 (site b)

Description

Unit 3 comprises a diamict (7 m) with clayey silt, minor sand and granule matrix, 25% clasts (up to 25 cm), which are subangular to subrounded and weathered throughout. The diamict contains inclusions of shale from underlying bedrock. A luvisol (1.2 m) at the top of the unit has thick clay skins in the B horizon that become less prominent down profile. The profile has been affected by ground water, which imparted a banded (oxidized) colouring to the diamict. Unit 3 has an erosional contact at the base. Clast lithologies reveal mainly argillite, quartzite, rhyolite, mafic volcanic, basalt, and granodiorite (Fig. 8).

Interpretation

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 4 (site b)

Unit 4 is not present, presumably because the valley glacier sourced in the southern Ogilvie Mountains did not reach the EFR site at this time.

Unit 5 (site b)

Description

Unit 5 is mostly a diamict (9 m), in which the matrix changes from sand to silty clay with minor sand, from bottom to top. The base of the unit has a sharp contact with unit 3. Above this contact very thin sandy and granular beds and a 10–15 cm thick silty-clay bed are found. The overlying diamict has about a 30% clast content, ranging from pebbly to bouldery (20–100 cm), and these are subangular to subrounded in shape. A paleosol (1.5 m) is developed at the surface of the diamict and is groundwater affected. Clast lithologies of this unit reveal mainly quartzite, quartz, muscovite/biotite schist, sandstone, graphite schist, chert, and igneous and felsic granitoids (Fig. 8).

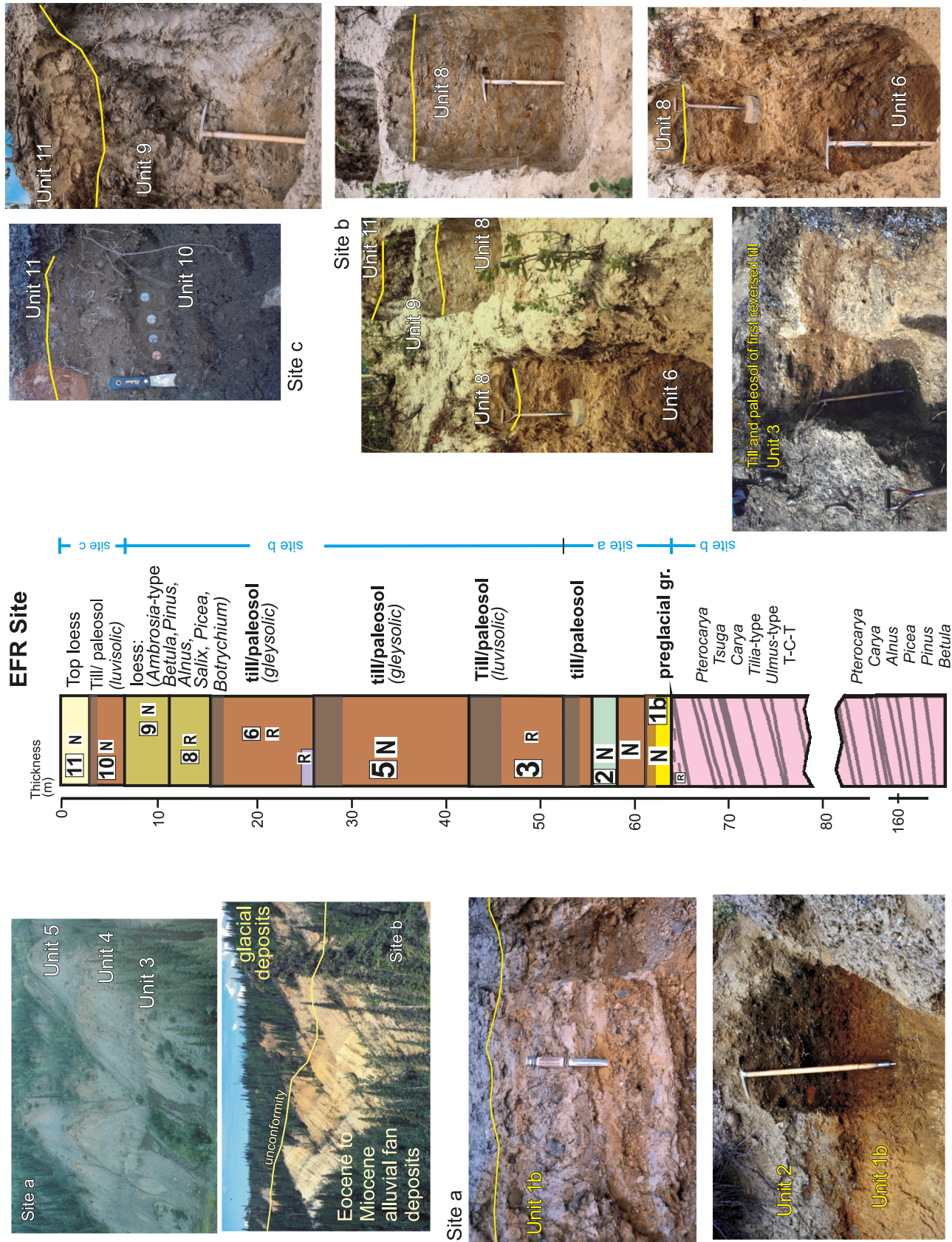
Interpretation

Unit 5 is interpreted as a till, overlying thin water-lain sediments, with a gleysolic paleosol 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 magnetized sediments of the early Matuyama (unit 3) and a pre-Jaramillo reversed till (unit 6), it is assigned to the Olduvai subchron (1.97–1.78 Ma).

Unit 6 (site b)

Description

Unit 6 contains a discontinuous bed of laminated silty clay and dense purplish clay (0.7 m) at its base (Figs. 5, 9).



This clay subunit forms a sharp contact with underlying till (unit 5) and is overlain by a (10.3 m) diamict. The diamict contains a few striated boulders (up to 1.5 m) at its base,

with cavities between boulders filled with medium to coarse sand and granules. The middle part of the diamict grades from 30% to >50% clast content in a silty-clay and minor

fine sand matrix. The upper part of the diamict consists of intercalated beds of variegated colour with very few clasts. All clasts are weathered throughout. In the upper part of the diamict, concentric sandy silt lenses are formed around clasts, and stratified channel fills up to 70 cm thickness are present. The upper metre of the unit 6 diamict is highly oxidized, with a mottled and cryoturbated appearance, and contains ventifacts exhibiting desert varnish. Clast lithologies of this unit reveal mainly argillite, quartzite, siltstone, and quartz (Fig. 8).

Interpretation

Unit 6 comprises a basal lacustrine clay subunit, overlain by till with melt-out characteristics. The top of the unit exhibits a gleysolic weathering horizon that formed under poorly drained conditions and is highly disturbed, probably owing to cryoturbation. The lacustrine subunit and till are reversely magnetized, 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 (Fig. 5).

Unit 7

Unit 7 is not present at the EFR site.

Unit 8 (site b)

Description

Unit 8 is a 3.6 m thick silt and fine sand deposit with mottled appearance and exhibiting minor stratification marked by fine clay beds. The lower contact is sharp. Samples collected for paleomagnetic determination were also used for pollen identification. Only one sample yielded some identifiable pollen grains, which contained 51 grains: *Ambrosia*-type 33%, *Betula* 29.4%, *Pinus* 19.6%, *Alnus* 5.9%, *Salix* 5.9%, *Picea* 3.9%, and *Botrychium* 2%.

Interpretation

Unit 8 is reversely magnetized loess and is assigned to the latest Matuyama. This assignment is based on its stratigraphic position between Jarmillo and Brunhes age deposits, and comparable paleomagnetic directions for unit 8 at RC and WFM sites (table 1 of Barendregt et al. 2010). The pollen results from this sample must be seen in light of the small sample size and are presented without much certainty (normally, the minimum acceptable sample size is about 200 identifiable pollen grains). *Ambrosia*-type pollen represents the genera *Ambrosia*, *Iva*, and *Franseria* of the Compositae. As these are herbaceous heliophytes, their presence suggests local open habitat. *Betula* may be sourced as arboreal or shrub, the latter representing shrub tundra. *Pinus* is the most interesting of the taxa in this sample. It is known that pine, at least to the species level, and based on megafossils, was widespread in the Yukon and Alaska during the Pliocene, probably before 3 Ma. However, pine pollen does occur in younger interglacials but usually at <1%–2%. Of greater significance is the 3.4% pine pollen recovered from Midnight Dome Organics (the third interglacial), which Schweger et al. 1999 and Froese et al. 2001 placed at the base of the Brunhes Chron (Fig. 1). It is possible that restricted pine stands did exist in central Yukon during Pleistocene interglacials. This would support the placement of this sample

within the time period of the Brunhes–Matuyama boundary. The relatively low amount of alder (*Alnus*, 5.9%) is typical of past interglacials (<1%–20% range and 7.6% average), suggesting limited permafrost. Willow (*Salix*) pollen occurs with forest and tundra vegetation, and so its occurrence here is expected. Spruce (*Picea*) pollen reaches only 3.9%, low for a spruce-dominated boreal forest, where modern frequencies usually range from 20%–40%, suggesting that spruce was not a major component of the regional forests during this interglacial. Spruce pollen counts reach 47%–92% in interglacial records from central Yukon (Schweger et al. 1999). The pteridophyte, *Botrychium*, is also present and is a herbaceous component of the local vegetation. Based on the pollen spectra, an open mixed deciduous–conifer vegetation is suggested.

Unit 9 (site b)

Description

Unit 9 is a 5.4 m thick silt and fine sand deposit with mottled appearance and minor stratification marked by fine clay beds. It is normally magnetized.

Interpretation

Unit 9 is a normally magnetized loess, assigned to the early Brunhes based on stratigraphic position (Fig. 5) and similarities to the record found at WFR (table 1 of Barendregt et al. 2010). The lower contact is gradational. 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 the Klondike Midnight Dome (Froese et al. 2000) and that this stratigraphic contact marks the Brunhes–Matuyama boundary. The Brunhes–Matuyama boundary (0.78 Ma) falls within marine oxygen isotope stage (MIS) 19, an interglacial period (Fig. 5). Pollen obtained from the base of unit 9 reveals the first occurrence of pine pollen, together with other pollen types (*Ambrosia* type, *Betula*, *Alnus*, *Salix*, *Picea*) and suggests deposition during an interglacial. This further supports an early Pleistocene (late Matuyama) age for the underlying unit 8 (loess) at EFR.

Unit 10 (site c)

Description

Unit 10 is a 1 m thick diamict with a silty-clay matrix and 20% clasts up to 15 cm in size. It forms a sharp contact with underlying unit 9.

Interpretation

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. 5).

Unit 11 (site c)

Description

Unit 11 is a 2 m thick, massive silt and fine sand bed.

Interpretation

Unit 11 is loess, which corresponds to the regionally extensive unoxidized surface loess that discontinuously covers much of the western Yukon. Its massive characteristic sug-

gests little or no reworking. It is normally magnetized, overlies unit 10 at EFR and WFR sites, and is therefore considered to be the late Pleistocene (<23 ka BP) McConnell loess.

Stratigraphy of Fifteenmile River, west site

The stratigraphy described at West Fifteenmile River outcrops along a 1 km long Holocene landslide scar reactivated within an older landslide, and it is located on the north side of the Tintina Trench, ~1.0 km west of the river (Figs. 4, 6). The recent landslide was created by the down cutting and lateral erosion of a small creek that was diverted by glaciers during the Reid glaciation (MIS 6–8). 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 they have remained intact.

The WFR stratigraphy (Figs. 5, 10) 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 (a, b in Fig. 10). The contact between these two depositional sequences forms an angular unconformity that is clearly visible along all landslide scars in the Tintina 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 stratigraphic sequence is less complete than that seen at EFR site, but it is equivalent to the lower units at RC and EFR. The WFR site exposes a stratigraphic unit (unit 7), which is not present at EFR, and therefore WFR is considered a complementary section to the West Tintina Trench Allogroup (Fig. 5).

Unit 1 (site a)

Description

Unit 1 is composed of 3 subunits (bottom to top). Subunit 1 (30 cm) comprises subangular to rounded gravels, averaging 5 cm, with a few up to 12 cm, and is matrix supported (massive silty-fine sand). The matrix contains herbaceous pollen (*Polemonium* sp. together with *Polygonum* and *persicaria*-type, Fig. 10). Subunit 2 comprises 35 cm of gravel with an average clast size of 2 cm and a maximum of 12 cm. Clasts are strongly imbricated (to northwest). Matrix is silty fine sand with lesser amounts of clay. Subunit 3 comprises 2 m of massive clast-supported medium coarse gravel with sand lenses at the top of the unit. Clasts are subangular to subrounded and average 10 cm. The matrix consists of silty fine sand and thin laminated clay beds.

Interpretation

Unit 1 is a 2.7 m preglacial gravel and sand with minor laminated clay beds that overlie tilted alluvial Miocene deposits and are overlain by the first till (Figs. 5, 10).

A silty-fine sand bed near the unconformity is reversely magnetized and probably belongs to either the Kaena (3.12–3.05 Ma) or 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* pollen, which is generally thought to have a minimum age of

latest Pliocene, 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 to cold alpine climate.

Unit 2 (site a)

Description

The basal part of unit 2 is the only accessible part of a 16 m thick diamict with silty clay and minor fine sand matrix, containing 35% clasts that are subangular to subrounded, up to 1 m in diameter, and have an average size of 5 cm. Observation with binoculars indicates the presence of several lenses of fine-grained sediments in an otherwise massive till (Fig. 10). Most of the accessible clasts are weathered through. The diamict is massive, but thin sand and silty-clay lenses are present near its base, and these are normally magnetized. The diamict also contains blocks of preglacial gravels and sands at its base, forming a sharp, wavy, and erosional lower contact. Clast lithologies reveal mainly quartzite, sandstone, siltstone, shale, and quartz (Fig. 8).

Interpretation

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 paleosol(?), which appears to be discontinuously preserved. The normal polarity is assigned to the upper Normal Gauss Chron based on stratigraphic position (Fig. 5) and polarities recorded in units above and below (table 1 of Barendregt et al. 2010).

Units 7, 8, 9 (site a)

Description

Units 7–9 are fine-grained deposits (10 m total thickness) composed predominantly of fine sandy silts with numerous thin, stratified, oxidized fine sandy silt beds (1.5–3.0 cm), separated in places by thin lenses of gray clayey-silt. The top of unit 9 has a 1 m thick cryoturbated zone.

Interpretation

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 EFR and at RC. At EFR and WFR, these units are overlain by the middle Brunhes Reid till (MIS 6–8). The extensive loess sequence at WFR indicates that glaciers from the Ogilvie Mountains most likely did not reach this part of the Tintina Trench.

Unit 8 (site b)

Description

Unit 8 comprises 4 m of colluviated silt and fine sand, with some laminated clay beds (2.5 cm) predominantly in the middle part of this unit. A massive and mottled silt bed

Fig. 10. Composite stratigraphy of West Fifteenmile River (WFR) site. This stratigraphic column was assembled from two transects described along the same slope, sites a and b. Site a exposes the highly oxidized planar to contorted contact between preglacial gravels (unit 1a) and first till (unit 2). The till includes large blocks of highly compact (oxidized) preglacial gravels.

(1.5 m) occurs below the laminations. A silty clay bed (10 cm) with occasional very fine pebbles, occurs near its base.

Interpretation

Unit 8 is a reversely magnetized colluviated loess, underlain by colluviated till of Jaramillo age and overlain by modern or Reid age loess. Unit 8 is assigned to the latest part of the Matuyama Reversed Chron.

Unit 9 (site b)

Description

Unit 9 comprises 1.3 m of colluviated silt and fine sand with fine beds of laminated silts. It is overlain by colluviated slope wash. The sediments are oxidized and affected by groundwater. Unit 9 forms a gradational contact with unit 8.

Interpretation

Unit 9 is a normally magnetized colluviated loess. The reverse to normal loess deposits (units 8 and 9 at site b) are assigned to the latest Matuyama and earliest Brunhes, respectively, and thus span the Brunhes–Matuyama boundary (0.78 Ma).

Unit 10 (site a)

Description (unit 10 is not part of the Allogroup)

Unit 10 is a massive diamict (4.5 m) with fabric indicating ice flow from the northeast. It overlies 1 m thick interstratified silty-clay and clay beds (up to 3 cm thick) with occasional drop stones up to 3 cm in size, which form a sharp lower contact with unit 9. The diamict has a clayey-silty matrix, with 20%–30% clasts, diameters ranging up to 40–50 cm, averaging 6 cm. Clasts are subangular to subrounded, and aggregated in places. Many clasts (up to 25%) are incorporated from older sediments and are weathered throughout.

Interpretation

Unit 10 is a till with a basal glaciolacustrine component. Both till and lacustrine sediments are normally magnetized and are assigned to the Brunhes Normal Chron. This till is most probably the middle Pleistocene Reid till (MIS 6–8) and is correlated with the uppermost till at EFR.

Unit 11 (site a)

Description and interpretation (unit 11 is not part of the Allogroup)

Unit 11 is a 40 cm thick unoxidized regional loess cover that lacks structure, suggesting little or no reworking. It is normally magnetized, overlies the assumed Reid age till, and is thought to be late Pleistocene (<23 ka) McConnell loess.

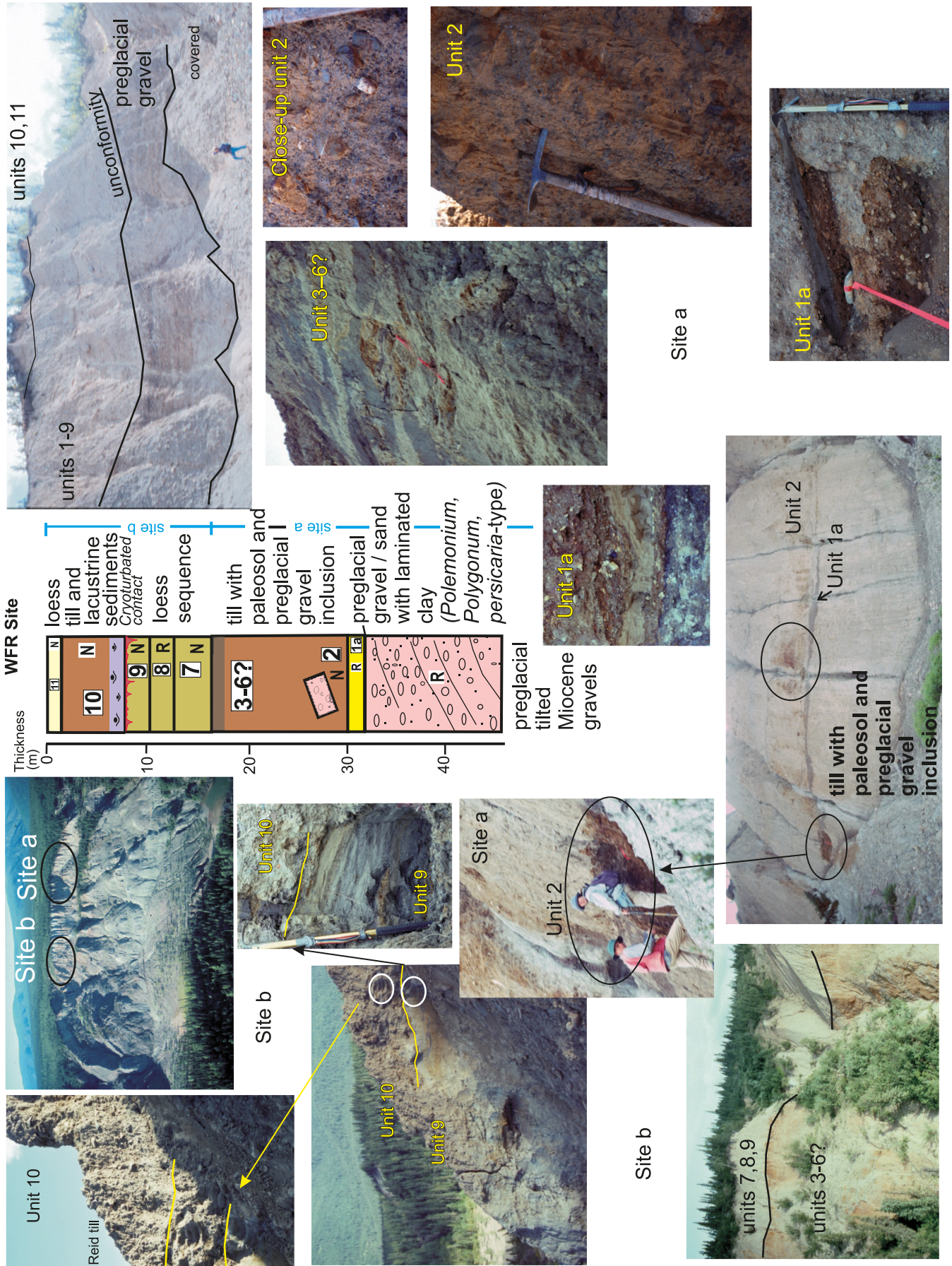
Discussion of results

Glacial record

The record of local (southern Ogilvie Mountains) and regional (Cordilleran) glaciations (Fig. 4, 6, 8) and interglaciations in west-central Yukon is developed from stratigraphy, paleomagnetism, paleosols, and pollen data reported from exposures in the Tintina Trench. The type section of the West Tintina Trench Allogroup (WTTA) at RC correlates well with complementary sections at EFR and WFR, and records one pre-Pleistocene (unit 2) glaciation, six early Pleistocene glaciations (units 3–8), and one late Pleistocene glaciation (unit 9). The magnetostratigraphy at the three sites documents six polarity reversals, which are recorded in glacial, interglacial, and preglacial sediments that span over 2 Ma. These sediments can be correlated to all major polarity chrons and subchrons within the late Gauss to late Brunhes timespan of the Geomagnetic Polarity Time Scale (Fig. 5). The eight glaciations are here assigned to the WTTA. Preglacial alluvial deposits (unit 1a and 1b) above a Miocene–Pliocene unconformity and underlying the first glacial sediments document the onset of colder conditions. They exhibit the same polarity as the first till and are included in the WTTA, forming its basal unit. The eight tills are for the most part indurated and affected by groundwater. Their drift surfaces are found within an area impacted by pre-middle Pleistocene glaciations in west-central Yukon (Fig. 6) and outcrop within the Tintina Trench (Fig. 4, 6). Extensive paleosols (>1 m thick) have developed at the upper contact of most tills.

The Tintina Trench contains no evidence for an equivalent to the Miocene–Pliocene glaciation reported in Alaska (Yakataga Formation, Lagoe et al. 1993; Plafker et al. 1991). Those deposits are thought to be local in nature and are probably related to uplift in the Alaska Range and St. Elias Mountains (O’Sullivan and Currie 1996).

Glacial events in central Yukon followed periods of major tectonic activity, most notably extensional faulting along the Tintina Trench, uplift of the southern Ogilvie Mountains, uplift of the St. Elias Mountains, and deformation along the Shakwak Trench, which extends along the foothills of the St. Elias Mountains and Alaska Range. Elsewhere in the Richardson Mountains, there is evidence of deformation of preglacial fluvial terraces (Duk-Rodkin and Hughes 1994; McNeil et al. 2001). Regional tectonic processes led to major readjustment of the drainage system in the Tintina Trench, reflected in periods of stream incision and aggradation of sediments downstream. This ongoing adjustment was interrupted by the first entry of ice into the region, resulting in the reversal of flow of the upper Yukon River to the west and its incorporation to the Kwikpak River, and led to other drainage basin adjustments as well (Fig. 2; Duk-Rodkin and Barendregt 2001). The most significant changes to the landscape resulted from the first glaciation in the area, while subsequent glaciations modified the landscape to a lesser extent.



Interglacial and paleosol record

During interglacial periods, pedogenesis in the Tintina Trench region produced deeply weathered sediments, altered clay minerals, and translocated weathering products to depths of several metres, often resulting in clay skin development on underlying gravels. Interglacial periods were lengthy and generally saw development of thick luvisols and brunisols, indicating somewhat warmer and (or) wetter conditions than today. Paleosol characteristics vary depending on length of soil development and climate. They developed predominantly during interglacial conditions and, to a lesser extent, during cold (ice-free) conditions. In most cases, luvisolic soils are found in the earliest and latest glacial deposits in the WTTA, while the middle units contain gleysols. The oldest paleosols do not exhibit the same degree of clay skin development seen in the youngest paleosol. Some soils contain cryogenic features, while others contain numerous ventifacts at their surface, presumably reflecting proximity to glacier margins (Froese and Schweger 1999).

The first paleosol in the WTTA developed on till of the first glaciation and is estimated to have formed over a period of about 100 ka (MIS G-3 to MIS 101, Fig. 5). It was later truncated, leaving only a weathered C horizon. Following the second glaciation, a luvisol formed (sometime between MIS 99 and MIS 79) at a time when conditions were warmer than today. The overlying unit 4 (glacial mudflow) occurs only at RC and marks a period during which local glaciers did not reach the trench. It exposes a deep weathering horizon at its surface. The succeeding 200 ka period was marked by low-amplitude climate fluctuations and probably allowed soil development to continue under conditions that were, on average, slightly cooler than the preceding period. The subsequent glacial deposits (till and outwash, unit 5) are overlain by a thick weathering horizon and gleysol, which may have continued to develop over a very long period of time (in the range of MIS 69 – MIS 37) and marked generally cooler conditions. A 0.5 m thick gleysol developed on till (unit 6) was formed over a relatively short period of time (~20 ka; MIS 31). Units 7 and 8 (loess and outwash) do not contain paleosols, and it may be that soil development was insignificant or that soils were eroded by subsequent glacial activity. The absence of paleosols is also noted at the Midnight Dome loess deposits south of the trench. Only the uppermost paleosol (unit 9) reveals characteristic “Wounded Moose” properties (Tarnocai and Schweger 1991; Tarnocai and Smith 1989; Smith et al. 1986). The “Wounded Moose” paleosol is a well-developed luvisol with complex soil properties, suggesting multiple weathering histories. It is developed on the Cordilleran outwash at RC (in the range of MIS 17 – MIS 13) and is not seen in the loess records at EFR and WFR, but compares well with paleosols south of the trench at Indian River and Barker Creek, also developed on Cordilleran outwash. The Diversion Creek paleosol (Reid age) is a luvisolic paleosol developed on till and outwash (unit 10) and marks warmer and wetter conditions than at present (126 ka, MIS 6–8; Smith 1986; Bond 1997).

In general, pedogenic development in the trench suggests a cooling trend throughout most of the Matuyama Chron (2.6–1.0 Ma). This trend was interrupted after the Jaramillo subchron by a return to warmer conditions and the formation

of luvisolic soils (1.0–0.78 Ma). In general, glacial conditions were less severe during this time and ice was restricted to the higher elevations within valleys (Figs. 6, 5, units 7–9). This was subsequently followed by a return to cooler conditions that saw the development of brunisols and regosols (<0.78 Ma). A detailed description of the Tintina Trench paleosols will be provided in a future publication.

Regional correlations

The Tintina Trench record complements a large number of magnetostratigraphic investigations carried out in northwestern Canada (Barendregt and Duk-Rodkin 2004). The Tintina Trench sediments display an extensive record of glaciations, loess deposition, and pedogenesis. While no absolute ages are presently available for this stratigraphy, paleomagnetic measurements provide clear polarity chrons and subchrons that can be reliably correlated with the global Geomagnetic Polarity Time Scale. When this magnetostratigraphy is combined with sites throughout northwestern Canada, where tephras and basalts provide absolute ages, an extensive lithostratigraphy is developed that can be correlated with the marine isotope record and that provides evidence for the timing and extent of glaciations (Figs. 11 and 12).

The Tintina Trench stratigraphy spans a substantial portion of the past 3.0 Ma and, in particular, contains a more extensive record of late Pliocene and Early Pleistocene glaciations, while the Mackenzie Mountains, eastern Alaska, and Banks Island record a greater number of glaciations that fall within the Brunhes Chron. (Fig. 11; Duk-Rodkin and Barendregt 2008).

Here, we make a first attempt at correlation of glacial deposits with cold peaks seen in the marine isotope record. In this correlation we use (1) magnetostratigraphy and chronologic data from study sites in northwestern Canada, (2) characteristics of cold peaks (magnitude and duration) from the LR04 composite paleotemperature curve derived from ocean cores (Lisiecki and Raymo 2005), and (3) paleosol and pollen data to estimate timing and duration of interglacial conditions before and after glacial events.

Late Gauss (late Pliocene) glaciation (first till and outwash, MIS G-6), and interglaciation (paleosol, G-5, G-3)

Pliocene preglacial sediments found in sections along the Tintina Trench (RC, EFR, WFR) are also found on the northern slopes of the Klondike Plateau. They are stratigraphically above the Miocene–Pliocene unconformity, which separates tilted Miocene beds (sands and conglomerates) from horizontal Pliocene fluvial deposits. They are for the most part composed of sands and gravels deposited as alluvial fans, and in places, they occur as mudflow deposits and silts, clays, and minor sands. The tilted beds below the unconformity contain *Pterocarya* and *Tsuga* pollen grains that are found in Miocene and older sediments only and argue for warmer climatic conditions (Duk-Rodkin et al. 2001). The overlying horizontal beds contain *Polemonium* sp. pollen grains, which occur in sediments of latest Miocene to latest Pliocene age. The absence of *Artemesia* in this pollen assemblage suggests an age older than Pleistocene (2.58 Ma) because arid conditions are needed for the

Fig. 11. Correlation of glacial–interglacial events based on a composite stratigraphy developed from multiple sites in the northern Cordillera, the northern Interior Plains, and Banks Island. The sites included here are discussed in the text, and identify glaciations (blue squares), as well as interglacial and preglacial sediments containing paleosols and (or) pollen (red squares). See Fig. 5 for legend of Geomagnetic Polarity Time Scale and composite $\delta^{18}\text{O}$ LR04 marine isotopic record. The Gauss and Brunhes normal chrons are highlighted in medium brown, and Olduvai and Jaramillo normal subchrons in light brown.

growth of this plant community. The preglacial deposits in the Tintina Trench have been assigned to MIS G-17 because *Polemonium* sp. is a cool climate flora, and, after stage G-19, the isotopic record reveals a strong cooling trend leading to the first glacial conditions in the area. At the Klondike Plateau, these Pliocene preglacial gravels (Upper White Channel gravels) contain the Quartz Creek (QC) tephra (3.0 ± 0.33 Ma; Sandhu et al. 2000) and, at their upper contact, interfinger with the Klondike outwash gravels that mark the first entry of ice into this region (Froese et al. 2000). Both gravels are normally magnetized, and, given the age of the QC tephra, these preglacial sediments and the first glaciation are clearly late Pliocene in age. White Channel gravels were laid down by tributaries to the ancestral south flowing Yukon River (Duk-Rodkin et al. 2001), while the Klondike gravels were laid down by tributaries associated with the north flowing Yukon River, documenting a reversal of drainage triggered by the first glaciation.

The first entry of ice into the area is recorded by till and outwash deposits (unit 2, Figs. 4, 6). In places, the deposits were laid down largely by small local ice tongues, while in other areas, the ice was derived directly from the Cordilleran ice sheet. Collectively, two general provenances of ice can be identified, based on clast lithologies: a southern Ogilvie Mountain source to the north and a Cordilleran ice source to the southeast, located in the general region of the continental divide (Selwyn Mountains) (Figs. 4, 6). At RC, this first evidence of glaciation is marked by ~30 m of outwash, while at EFR, it is marked by 12 m of sediments (till, outwash, till, and paleosol). At WFR, this event is represented by a thick till unit containing blocks of preglacial conglomerates (Fig. 10). In most areas of the western Yukon, evidence of these earlier glaciations is seen only from scattered erratics shown on the glacial limits map of Yukon (Duk-Rodkin 1999).

The sediments of this first glaciation are normally magnetized at all three localities, and because they are overlain by an extensive suite of reversely magnetized deposits, they have been assigned to the Gauss Normal Chron (MIS G-8). The paleomagnetic directions for the preglacial lacustrine unit (unit 1b at RC) compares well with the directions recorded in the overlying glacial outwash (unit 2 at RC; see table 1 in Barendregt et al. 2010). This first record of glaciation in the region is further supported by an extensive sediment and tephra record from the Klondike area (Sandhu et al. 2000). Corollary evidence for these age assignments comes from the Lost Chicken site in Alaska, where a 2.9 Ma. tephra is contained in sediments that contain *Polemonium* sp. pollen, indicating a Pliocene or older age (White et al. 1999). The age assignments for the first glaciation in the Tintina Trench region are more fully presented in Duk-Rodkin et al. (2001, 2004).

A weathering horizon is found at the upper contact of unit 2 at the EFR site and exhibits characteristics of a truncated

soil (Fig. 7). This soil is here correlated with the Colvillian transgression on Seward Peninsula in Alaska (MIS G-5 or G-3; Brigham-Grette and Carter 1992). Records of the first glaciation (Fig. 4) are also found at numerous localities south of the Tintina Trench area, within the Klondike Plateau (Figs. 1, 9, 11). Normal polarities for these deposits were obtained from the Klondike Wash at the goldfields in the Klondike Plateau (Fig. 1; Froese and Schweger 1999), at the mouth of Indian River, and at Barker Creek, a southern tributary to the Stewart River (Duk-Rodkin et al. 2004). At the last two sites, a luvisol (Wounded Moose-type) is found at the surface of the outwash deposits and probably also correlates with the Colvillian transgression (Fig. 1).

Across the continental divide in the Mackenzie Mountains (Figs. 1, 11) a normally magnetized colluvial unit (Gauss Normal Chron), containing solifluction lobes at its upper contact (Barendregt et al. 1996), may be equivalent to the preglacial sediments and till at RC (units 1b and 2). Further east, in the northern Interior Plains of Canada (Figs. 3, 10), evidence for the first glaciation is documented from the Mackenzie Delta (Kumak and Taglu) cores, where normally magnetized till and outwash is overlain by reversely magnetized tills. In the Smoking Hills, the occurrence of large sand and gravel wedges are all that remain of the first evidence of ice advance into the area. The till associated with this glaciation may have been eroded by ice that deposited the overlying reversely magnetized tills (Duk-Rodkin et al. 2004).

Early Matuyama glaciation (MIS 100?) and interglaciation (paleosol, MIS 99 or MIS 97?)

At RC and EFR sites, a reversely magnetized till (unit 3) records an early Matuyama glaciation (Fig. 5), the second to affect this region. The till is overlain by thin beds of fine sands and silts, on which a luvisolic soil has developed, that is also reversely magnetized. The soil forming period has been tentatively correlated with the Bigbendian marine transgression in Alaska, and with MIS 99 or MIS 97 (Figs. 1, 11; Brigham-Grette and Carter 1992). Morphologic evidence of this early Matuyama glaciation is also recorded on two terrace outwash remnants in the lower Klondike valley (Duk-Rodkin 1996). The outwash is covered with a reversely magnetized loess (Froese et al. 2000). This second glaciation is also recorded at Fort Selkirk (along the Yukon River) and in the Mackenzie Mountains (Figs. 1, 11). In the northern Interior Plains (Figs. 1, 11) it is found in the Mackenzie Delta Taglu and Kumak cores (reversely magnetized diamicts near base of cores), and in the Smoking Hills along West River, it includes the lowermost reversely magnetized till.

Early Matuyama mudflow and weathering horizon (MIS 78? and MIS 75?)

Thick mudflow deposits of glacial origin (unit 4), on

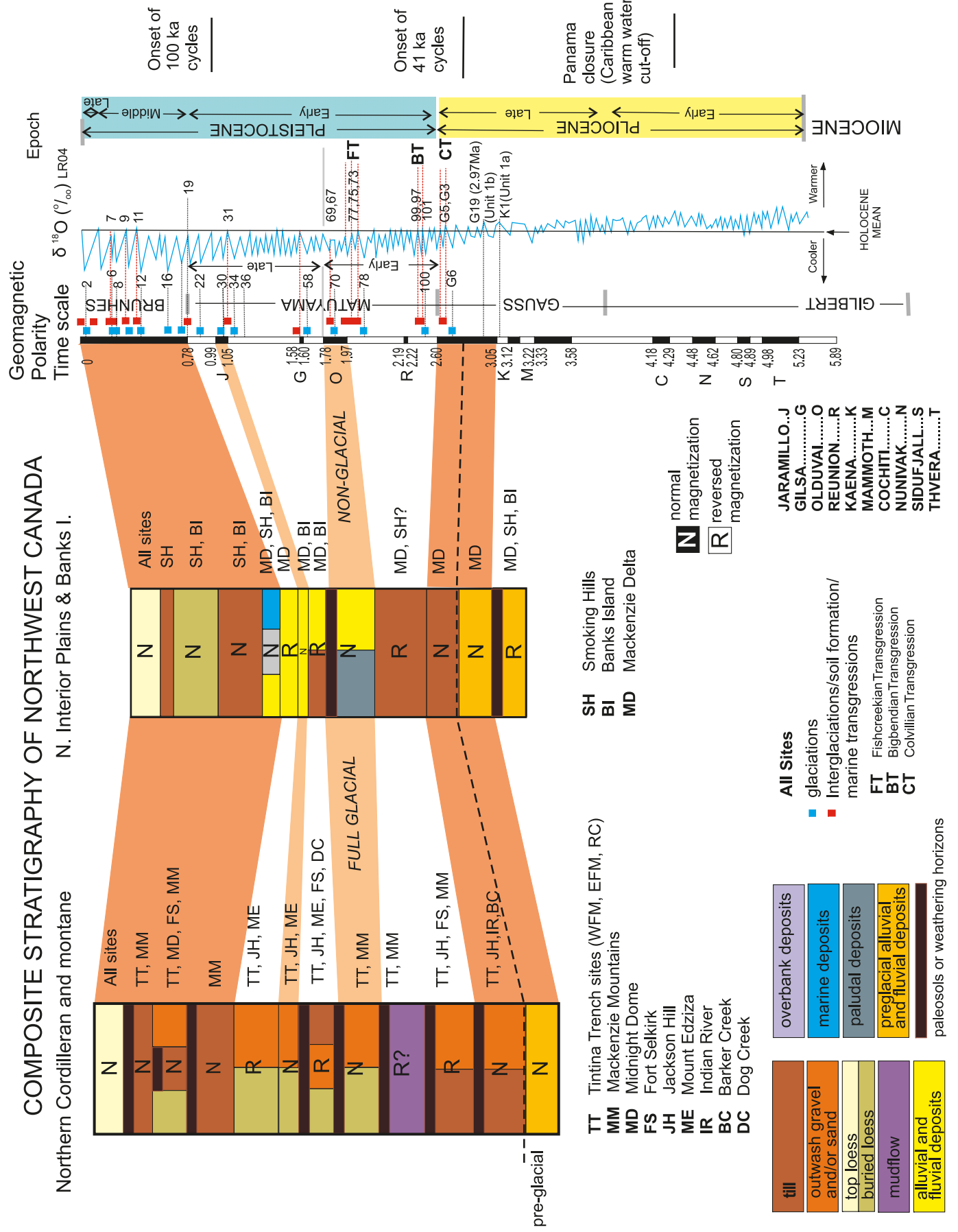
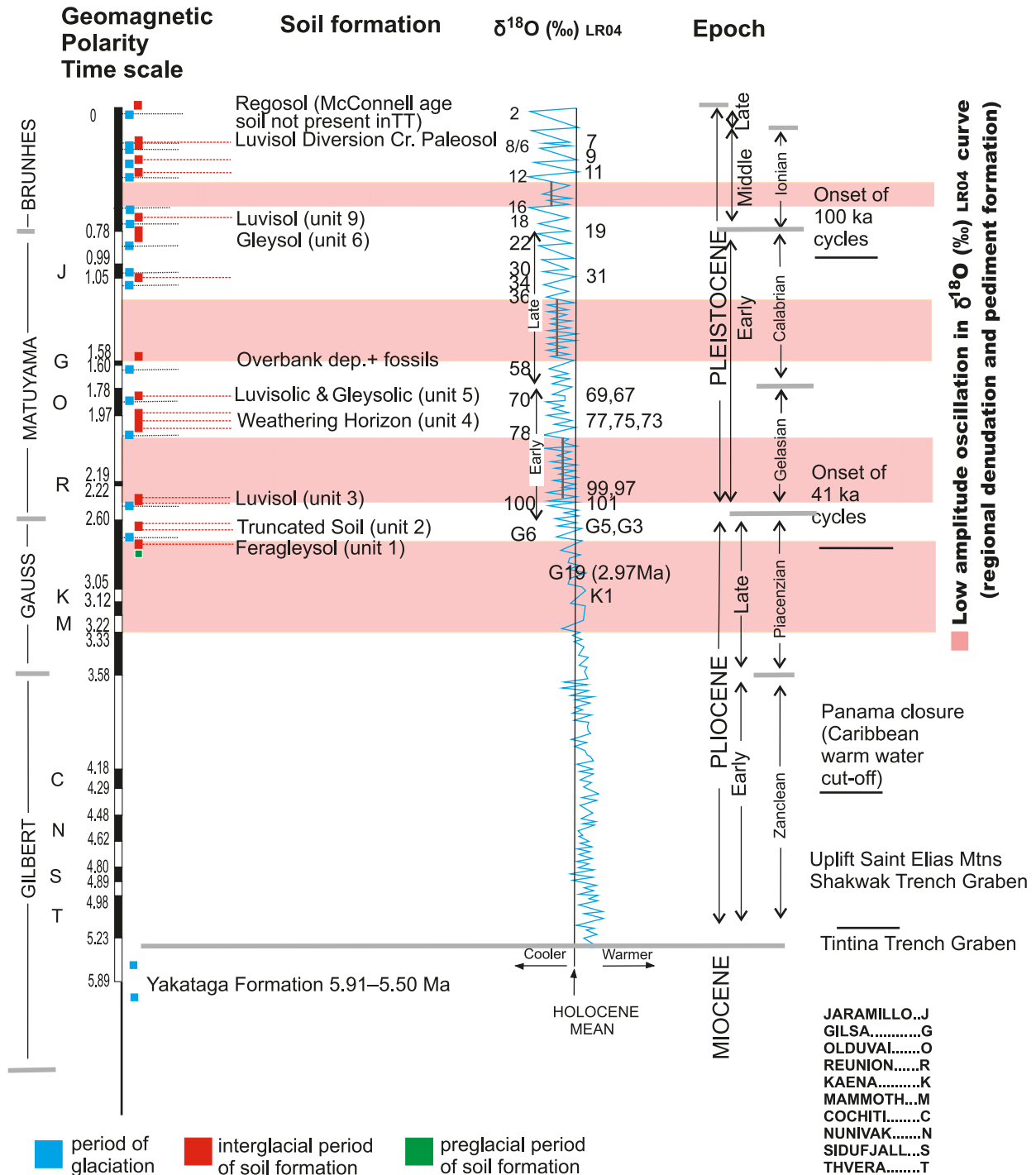


Fig. 12. Zones of low-amplitude oscillation in the LR04 composite $\delta^{18}\text{O}$ record during the late Pliocene and Pleistocene are correlated to the glacial-interglacial record of northwestern Canada and are considered to be periods of regional denudation and pediment formation. See Fig. 5 for legend of Geomagnetic Polarity Time Scale and composite $\delta^{18}\text{O}$ LR04 marine isotopic record.



which a thick weathering horizon was developed, are found only at RC site (Fig. 5) and overlie the soil and till of the second glaciation. A polarity record was not obtained from these sediments, but it is overlain by a normally magnetized outwash (Olduvai subchron) and underlain by a reversely magnetized till and luvisolic paleosol (early Matuyama). The weathering horizon of unit 4 is, therefore, tentatively correlated with the Fishcreekian marine transgression in

Alaska (MIS 77?, MIS 75?, MIS 73?; Brigham-Grette and Carter 1992). The unit 4 mudflow at RC may be equivalent to one of the three reversely magnetized tills outcropping along the banks of the West River in the Smoking Hills (Figs. 1, 11).

Olduvai glaciation (outwash and till, MIS 70?) and interglaciation (gleysol – weathering horizon, MIS 69 or MIS 67?)

At RC and EFR, normally magnetized outwash, till, and luvisolic soil (unit 5) occur between the underlying glacial mudflow (unit 4) and an overlying reversely magnetized outwash (unit 6), and these are assigned to the Olduvai subchron (Fig. 5). Normally magnetized till and luvisol in the Mackenzie Mountains, likewise, are assigned to the Olduvai (Barendregt et al. 1996). In the Mackenzie Delta, Olduvai age sediments are of fluvial (Taglu core) and marine (Kumak core) origin, indicating interglacial conditions. On Banks Island, paludal sediments of Olduvai age are nonglacial (Figs. 1, 11) and predate the first glaciation there (Barendregt et al. 1998).

Upper Matuyama glaciations (till and outwash, MIS 58; till, MIS 34) and interglaciation (paleosol, MIS 57)

At the RC site, a reversely magnetized outwash (unit 6) was deposited by Cordilleran ice (MIS 58) and forms an erosional contact with the overlying unit 7. It is correlated with a till at the EFR site, which was deposited by local ice, and has a gleysolic soil developed at its upper contact (MIS 57). Both till and paleosol are reversely magnetized (Figs. 5, 7). This upper Matuyama glaciation may correspond to a glaciation reported in the Fort Selkirk area (Nelson et al. 2009), where a reversely magnetized glacial diamict occurs directly beneath deglacial and interglacial sediments recording the Gilsa normal subchron (1.6 Ma). At the Smoking Hills in the northern Interior Plains, one of the two reversed tills, underlain by reversed glaciolacustrine sediments and overlain by a Brunhes sequence, may correlate with unit 6 in the Tintina Trench (Fig. 11). On Banks Island, reversely magnetized paludal deposits containing the Olduvai subchron (Worth Point Formation) are overlain by reversely magnetized tills (Barendregt et al. 1998) that occur below the Jaramillo-age deposits, and therefore, the unit 6 glaciation in the Tintina Trench may correspond to one of the upper Matuyama tills on Banks Island (Fig. 11).

An upper Matuyama (pre-Jaramillo) glaciation (MIS 34?) is also reported in south-central British Columbia at the Dog Creek site (Figs. 1, 11). Here, the glacial deposits (till and outwash) are interbedded between basalts dated at 1.1 and 1.3 Ma (Mathews and Rouse 1986). A MIS 34? glaciation may be present in the middle loess units at Midnight Dome as well (Froese et al. 2000).

Jaramillo glaciation (outwash and loess, MIS 30)

The outwash at the RC site (unit 7) is of Cordilleran and (or) local provenance. It is normally magnetized and is overlain by reversely magnetized sediments. The upper contact of the outwash forms an unconformity with discontinuous pockets of sediment that yield a reversed polarity (unit 8). At WFR, this period of time is represented by a loess (unit 7) that is not found at EFR.

Loess deposits of Jaramillo age (MIS 30) occur in the Klondike as well and contain the Midnight Dome tephra (1.09 ± 0.18 Ma, Froese et al. 2001). The Jaramillo sediments occur in fluvial deposits in the Taglu and Kumak cores in the Mackenzie Delta. Jaramillo equivalents have not been found in the Smoking Hills or the Mackenzie

Mountains. On Banks Island interglacial fluvial and marine deposits of Jaramillo age occur at the Morgan Bluffs section. At Mt. Edziza (Figs. 1, 11), a glacial till (MIS 30) associated with a lava flow (normal) is dated at 1.0 Ma (Spooner et al. 1995).

Latest Matuyama (outwash and loess, MIS 22 or MIS 20)

Cordilleran outwash at the RC site (unit 8) and loess at both the EFR and WFR sites (unit 8) are reversely magnetized and overlain by normally magnetized loess (unit 9) deposited after the Brunhes–Matuyama (B–M) polarity reversal at 0.78 Ma (MIS 19; an interglacial). Unit 8 is underlain by normally magnetized sediments of the Jaramillo subchron. At RC, this unit is a thin remnant of outwash sediments that are preserved intermittently along an erosional and discontinuous contact with units 9 and 7 (Figs. 7, 11).

In the Mackenzie Delta cores, the latest Matuyama is represented by fluvial silty-sands. In the Smoking Hills, the uppermost of three reversed tills may be the equivalent to unit 8 in the Tintina Trench.

The B–M boundary (MIS 19) is present in most stratigraphic records in northwestern Canada. It occurs within a thick loess sequence at both the EFR and WFR sites and at the Midnight Dome site, while at the RC site and Fort Selkirk, the boundary is marked by an unconformity. In the Mackenzie Mountains, it is marked by a paleosol, while in the Old Crow Basin (12 mile Bluff, Old Crow Flats) and the Smoking Hills, it is marked by organic beds, and on Banks Island by marine sediments (Figs. 1, 11).

Early Brunhes (outwash and loess, MIS 18 and (or) MIS 16?)

The normally magnetized outwash of unit 9 unconformably overlies the reversed outwash of unit 8 at the RC site and is correlative with the normal loess deposits (unit 9) at the EFR and WFR sites. The loess of units 8 and 9 at EFR and WFR sites do not reveal a clear sedimentary break. Polarity changes that are not accompanied by obvious stratigraphic boundaries are commonly reported for loess (Pewe 1992). Stratigraphically, unit 9 appears to be bracketed by two interglacials. The lower interglacial is established on the basis of a pollen assemblage found at the contact between units 8 and 9 (which also marks the B–M boundary), while the upper interglacial conditions are marked by a luvisol (of Wounded Moose type) at the top of unit 9 at the RC site. The upper part of the unit 9 loess probably accumulated during the MIS 18 and (or) 16 (cold stages). The 1.2 m thick luvisol that developed on the outwash at RC is a typical Wounded Moose-type paleosol described in Tarnocai and Schweger (1991) and may have developed intermittently over a considerable span of time (>100 ka).

Upper Brunhes till and paleosol (MIS 6–8)

The normally magnetized surface till at the EFR and WFR sites (unit 10, Reid till, MIS 6–8) forms a generally thin veneer (3 m) and is of local provenance. The weakly developed luvisol (of normal polarity) developed on this till is thinner than that seen at the Reid-type locality (Diversion Creek paleosol, Smith et al. 1986). It is also thinner than the underlying paleosols at these sites. During the Reid and sub-

sequent McConnell glaciation, neither local nor Cordilleran ice reached the RC area. The MIS 6–8 glaciation was as extensive as the first local glaciation (G-6) in the area, and these glaciers extended from the Fifteenmile River valley to the Yukon River, damming it and forming a large glacial lake (informally named glacial Lake Dawson, Fig. 4). Glaciers did not reach the Tintina Trench area from MIS 22 to MIS 10 (units 7, 8, and 9). During this time, outwash from a Cordilleran source was deposited at RC and loess was laid down at EFR and WFR, beyond the limits of the local glacier (Figs. 4, 6).

Equivalents to the MIS 6–8 glaciation are likely present in the Mackenzie Mountains (where up to three normally magnetized tills occur beneath Laurentide till), on Banks Island (where two normal tills occur beneath the late Wisconsinan surface till), and also in the Smoking Hills (where two normal tills occur beneath Laurentide glacial sediments; Fig. 11).

Regional correlation summary

A comparison of the terrestrial paleoclimate record of the Tintina Trench and other sites in northwestern Canada and Alaska with the marine isotopic record (Fig. 12) suggests that warm and cold periods varied considerably both in terms of duration and intensity, as did ice extent. The record suggests that there may have been at least four periods of little or no glacial deposition or pedogenesis during the late Cenozoic: (1) an earliest period from 3.5–2.8 (~700 ka duration), (2) an early period from 2.2–2.0 Ma (~200 ka), (3) a middle period from 1.55–1.10 Ma (~450 ka), and (4) a later period from 0.85–0.50 Ma (~350 ka). These periods were apparently characterized by tectonic stability, regional denudation, and pediment formation (McNeil et al. 2001). Multiple pediment surfaces are reported in the Richardson Mountains (Duk-Rodkin and Hughes 1992) as well as in the British Mountains (L. Lane, oral communication, 1995) and may correspond to such periods.

The multiple paleosols reported for the Tintina Trench and Mackenzie Mountains (Duk-Rodkin et al. 1996) are unique in Canada. They provide a first approximation of paleoclimatic conditions during interglacials, and their magnetostratigraphic record provides an estimate of age. Profile thickness and soil type in the Mackenzie Mountains indicate a progressive regional cooling and drying of climate from early Matuyama to Brunhes, perhaps reflecting conditions of greater continentality with time. Drier conditions likely reflect the loss of moisture as the western flow of Pacific air passed over a continental divide, which was still undergoing uplift (Duk-Rodkin et al. 2004). The Tintina Trench paleosols do not reflect the deterioration of climate seen in the Mackenzie Mountains, and their record is more complex (Fig. 5, 11). In the trench, local topography and variable ice extent, as well as variable water table conditions, influenced soil formation to a greater degree. Soils in the trench sites are considerably closer to a north Pacific moisture supply, exhibit a greater degree of leaching, and are mostly luvisolic in nature.

Conclusions

While the West Tintina Trench Allogroup contains one of

the most extensive records of preglacial, glacial, and interglacial sediments in northwestern Canada, perhaps its most notable attribute is the high number of glaciations that occurred within the latest Pliocene and Early Pleistocene. Seven of the eight glaciations documented in the WTTA 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 eight glaciations and six interglaciations defined for the WTTA, the trench contains an overlying till and loess sequence, which is assigned to the late Brunhes.

Where suitable sediments were found, characteristic magnetizations were obtained. On the basis of the magnetic polarity data, units were assigned to the Geomagnetic Polarity Time Scale and, where possible, to the $\delta^{18}\text{O}$ isotopic record (Figs. 5, 11). In this manner, a systematic comparison was made with records in Banks Island, the Mackenzie Mountains, Klondike Plateau, south-central Yukon, Alaska, and central and northern British Columbia. The Tintina Trench holds the most complete glacial–interglacial record in northwestern North America. The preservation of these sediments is likely owing to the relatively narrow graben structure of the trench and to the repeated channeling of ice into this tectonic depression. The bulk of the glacial sediments in the Tintina Trench were deposited by glaciers from the Ogilvie Mountains (Figs. 1, 4, 6, 8), while some of the tills and outwash were deposited by ice from the much larger Cordilleran ice center to the east.

The early appearance of ice in the late Pliocene is probably related to the close proximity of the Tintina Trench region to a large moisture supply (the north Pacific and Arctic oceans), as well as to the onset of global cooling around 3.0 Ma. The extent and timing of glaciations for the region (Figs. 5, 6, 11, 12) are strongly influenced by regional tectonics and a nearby moisture supply. During cold conditions (glacial periods), the region experienced the buildup 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 and in turn influenced loess deposition. During warmer conditions (interglacial periods), fluvial, alluvial, and colluvial processes predominated, and weathering of landscape surfaces produced a variety of soils that today are preserved as paleosols (buried soils). The paleosol record in the Tintina Trench is extensive and suggests a complex relationship between local soil forming factors and microclimate. The paleosols in the trench are similar to their modern counterparts. Most are luvisols, indicating relatively moist and warm interglacial conditions commonly found in the intermontane basins of west-central Yukon.

Both glacial and interglacial regimes in west-central Yukon responded to uplift associated with mountain building, changes in moisture supply, shifting jet stream positions, and changes in wind patterns. The sedimentary record in the trench serves as a proxy of the amplitude and frequency of these changes, while paleomagnetism, tephra, paleosols, and pollen provide a chronology of these events. The West Tintina Trench Allogroup serves as a type section for the region and can be used for stratigraphic correlation of less complete sequences found throughout the western Yukon.

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