ARCTIC
VOL. 44, NO. 3 (SEPTEMBER 1991) P. 206-216

Clastic Sedimentology of the Beaufort Formation, Prince Patrick Island, Canadian Arctic Islands: Late Tertiary Sandy Braided River Deposits with Woody Detritus Beds

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(Received 11 July 1990; accepted in revised form 13 November 1990)

ABSTRACT. The Beaufort Formation (probably of Pliocene age) exposed on Prince Patrick Island in the western Canadian Arctic Islands is an unlithified and poorly exposed unit consisting of the following assemblage of facies: A) clast-supported gravel (channel floor lags, longitudinal bars); B) cross-bedded sand (transverse bars, channel floor dunes); C) rippled sand; D) horizontally laminated fines — mixed sand, silt and woody detritus; E) clay-rich mud (overbank suspension deposits); and F) woody plant detritus, beds of flat-lying logs, sticks, twigs, wood chips, bark, leaves, needles, seeds, and moss (overbank suspension and traction deposits). Minor facies include pebble bands, plane laminated sand, and a thin bouldery basal gravel horizon.

The sediments are interpreted to be sandy braided river deposits that are notable for their regionally abundant beds of coarse woody detritus, a feature uncommon in most ancient braided fluvial deposits. Facies A to C represent bar and channel deposits, with Facies B the most abundant. Facies C to F are relatively minor and are interpreted as low-stage overbank deposits such as abandoned channel fills. Rapid, small-scale lateral facies changes are the norm. Well-defined fining-upward sequences 1.2-2.5 m thick are uncommon. The relative rarity, thinness, and lateral impersistence of overbank facies compared to bar-channel facies suggests that significant amounts of meandering river deposits are not present. The common allochthonous woody fossils were sourced from boreal forests nearby. A thin horizon in one stratigraphic section contains tidal bundles with slack water mud drapes.

The Beaufort sediments exposed on Prince Patrick Island appear to be the most proximal portion of a northwest- (offshore-) thickening clastic sheet. The eroded upper surface of the Beaufort Formation, of regional extent on the western arctic coastal plain, is covered with a highly polymict gravel lag that is far coarser and compositionally more diverse than gravel within the Beaufort Formation. Beaufort clasts and younger gravels (former glacial deposits?) appear to have been mixed together to form this residual lag, which at one site has been reworked into (glacio-?)fluvial gravel and sand filling a paleovalley.

Key words: Beaufort Formation, Prince Patrick Island, sandy braided river deposits, allochthonous plant fossils, supra-Beaufort polymict lag

RÉSUMÉ. La formation de Beaufort (datant probablement du pliocène) exposée dans l'île Prince Patrick dans l'archipel arctique canadien occidental est une unité non lithifiée et peu exposée composée d'un assemblage des faciès suivants: A) du gravier reposant sur des dépôts clastiques (dépôts résiduels au fond des chenaux, barres longitudinales); B) des lits sableux entrecroisés (barres transversales, dunes de fond de chenal); C) des rides de sable; D) des laminites horizontales de fractions fines — sable mélangé, limon, détritus ligneux; E) de la boue riche en argile (dépôts d'inondation de suspension); F) des détritus de plantes ligneuses, couches de troncs, de bâtons, de rameaux, de copeaux de bois, d'écorce, de feuilles, d'aiguilles, de graines et de mousses reposant à plat (dépôts d'inondation de suspension et de traction). Des faciès moins importants comprennent des bandes de galets, des lamines de sable planes et un horizon de gravier à fond de blocs rocheux.

On interprète les sédiments comme étant des dépôts de rivière anastomosée, caractérisés dans cette région par des couches abondantes de détritus ligneux grossiers, trait peu commun dans les anciens dépôts fluviatiles anastomosés. Les faciès A à C représentent les dépôts de barres et de chenaux, le faciès B étant le plus abondant. Les faciès C à F sont relativement peu importants et on les interprète comme étant des dépôts primaires d'inondation tels que du remblai de chenaux abandonnés. Les changements rapides et à petite échelle de faciès latéraux sont courants. Les séquences bien définies de granoclassement vertical de 1,2 à 2,5 m sont peu communes. La rareté, faible épaisseur et irrégularité latérale du faciès d'inondation par rapport au faciès des barres-chenaux laisse à penser qu'il n'existe pas de grosses quantités de dépôts de rivière à méandres. On a retracé l'origine des fossiles ligneux communs allochtones comme étant la forêt boréale proche. Dans une coupe stratigraphique, un mince horizon contient des faisceaux de marée avec des pellicules de boue d'eau stagnante.

Les sédiments de la formation de Beaufort exposés dans l'île Prince Patrick semblent être la partie la plus proche d'une nappe clastique qui va en s'épaississant vers le nord-ouest (c.-à-d. vers le large). La surface supérieure érodée de la formation de Beaufort, qui s'étend sur la plaine côtière arctique occidentale, est couverte d'un résidu de gravier extrêmement polymictique qui est beaucoup plus grossier et de composition beaucoup plus variée que le gravier à l'intérieur de la formation elle-même. Les roches clastiques et les graviers plus récents (qui sont peut-être d'anciens dépôts glaciaires) de la formation de Beaufort semblent avoir été mélangés pour donner ce dépôt résiduel qui, sur un site, a été retransformé en gravier (glacio-?)fluviatile et en sable comblant une paléovallée.

Mots clés: formation de Beaufort, île Prince Patrick, dépôts sableux de rivière anastomosée, fossiles végétaux allochtones, résidu polymictique déposé au-dessus de la formation de Beaufort

Traduit pour le journal par Nésida Loyer.

INTRODUCTION

This paper is the result of a two-week reconnaissance of the Beaufort Formation, a poorly exposed unit of unlithified sand, gravel, mud, and wood on Prince Patrick Island in the western Canadian Arctic Islands (Fig. 1). The Beaufort Formation is thought to be of late Miocene (Hills, 1970; Matthews, 1989) or Pliocene age (Matthews *et al.*, 1990). It forms the northwest coastal plain of the Arctic Islands, from Banks Island to Meighen Island (Arctic Continental Terrace Wedge of Trettin, 1989).

The purpose of the field work was to describe the clastic sedimentology of the formation, interpret its depositional paleoenvironment(s), and collect mud and woody organic samples for paleontologic study. Prince Patrick Island contains the type area of the Beaufort Formation, first named and described by Tozer (1956; Tozer and Thorsteinsson, 1964). Subsequent work was done by Fyles (1965) and Hills (1970), but detailed sedimentological studies were not performed.

Although brief descriptions of the formation's facies and fossils on Banks Island (Vincent *et al.*, 1983; Matthews, 1987, 1989) and Meighen Island have been published, little is known about the Beaufort Formation. Bustin (1982) referred to some non-marine Miocene sediments on Axel Heiberg Island as "Beaufort Formation," but exposures located outside of the Arctic Coastal Plain (Banks Island to Meighen Island) and

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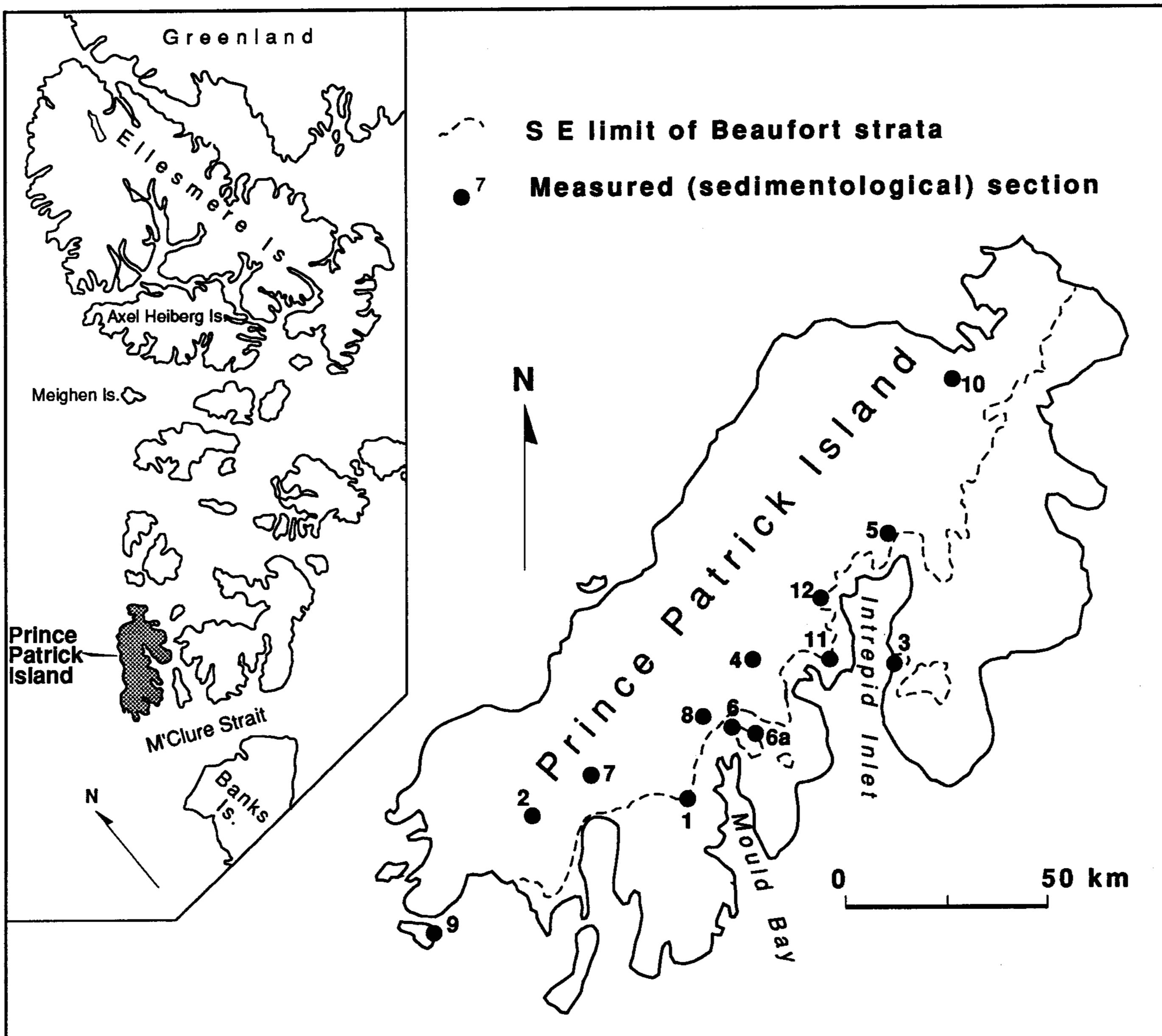

FIG. 1. Location map.

its northwestward submarine extension are not considered to be true Beaufort Formation by most arctic workers (Fyles, 1990). Also, the Axel Heiberg Island exposures are now thought to be of Eocene age, according to Ricketts and McIntyre (1986) and Ricketts (1988).

It is hoped that this study can serve as a small contribution to knowledge of the late Tertiary history of the Arctic Islands. The descriptions and interpretations herein apply to Prince Patrick Island only. Parts of this paper have been presented by Devaney and Fyles (1988). Regional stratigraphic aspects are discussed by Fyles (1990). A recently published preliminary report by Matthews *et al.* (1990) contains information on the plant and insect fossils from samples collected during this study.

Topography and Exposure

Prince Patrick Island is a region of low hills, dissected plateaux (including bedrock sea cliffs), and a nearly flat coastal plain to the northwest. The exposed Beaufort Formation (Fig. 1) is thought to represent the proximal portion of a northwest-thickening homoclinal wedge or sheet (Tozer and Thorsteinsson, 1964; Trettin and Balkwill, 1979; Meneley *et al.*, 1975; Fyles, 1990). The top of this wedge is being reworked by modern rivers in both the bedrock highlands and along the coastal plain. Cross-sections of the approximately flat-lying Beaufort Formation are not exposed on most of the coastal plain (Fig. 1). To the southeast the formation mantles Devonian and Mesozoic bedrock (Harrison *et al.*, 1988) and is exposed in gullied hillsides and stream cutbanks (Fig. 2). The discontinuous east margin of the Beaufort Formation in Figure 1 is the product of topography (bedrock in valleys, Beaufort Formation on hilltops) and southeastward thinning to an erosional edge. Exposures showing the Beaufort Formation lying on bedrock are up to about 50 m thick. Subsurface data indicate that the formation thickens westward to at least 500 m (Fyles, 1990).

FIG. 2. Light-coloured Beaufort Formation overlying dark Cretaceous shale. A dark, 1 m thick (partially slumped), laterally tapering woody lens is visible (arrow). Section 1.

Good stratigraphic sections of the Beaufort Formation are rare and are only 13-34 m thick, which includes many covered intervals (up to 50% of the *well-exposed* surfaces). There are probably fewer than 20 reasonably good cross-sectional exposures on Prince Patrick Island. The stratigraphic height above the base of the formation is unknown for most of the sections. Close examination of the sections required much laborious excavation with a shovel. Because of the steep sandy slopes and permafrost at about 30 cm depth, the exposure surfaces are highly prone to slumping, particularly during shovelling. The poor quality and quantity of the Beaufort exposures have severely limited the sophistication of this study's paleoenvironmental interpretations.

FACIES DESCRIPTIONS

The following facies descriptions are based on the detailed measurement of 12 stratigraphic sections (Figs. 1, 2, 3; see also Fyles, 1990: Fig. 3), observations of small-scale lateral facies changes in the sections and other exposures, and many brief observations made during ground traverses and helicopter flights. The character of the Beaufort Formation is nearly uniform throughout its Prince Patrick Island surface exposures; no regionally significant lateral (along strike) or proximal-to-distal changes were recognized, except for a minor horizon in one stratigraphic section described under "Anomalous Facies."

The Beaufort Formation is treated as a facies assemblage composed of six main facies, Facies A to F, and several minor facies. Most of the facies are conceptually gradational (i.e., form a spectrum) to the next facies in sequence in the assemblage: A grades into B, B to C, C to D, D to F, and B, C, or D grade into plane laminated sand. The beds normally have sharp bases and tops.

Basal gravel horizons, beds of plane laminated sand, and atypical types of woody layers are all relatively rare and thus were not given the same status as the classified Facies A to F.

Facies A: Clast-Supported Gravel

These gravel beds are 5-30 cm thick, often taper laterally, and may be erosively based. Clast-supported frameworks rich in small (up to 3 cm) pebbles are characteristic. Cobbles form a very minor part of the gravel content, and small boulders are extremely rare. The largest clasts tend to be platy. Mud intraclasts may be present, including armoured mud balls (up to 25 cm).

The gravel may be internally massive, horizontally stratified (either crudely or well defined, the latter being gradational to plane laminated pebbly sand), or cross-bedded (with increased sand content, gradational to cross-bedded pebbly sand). Texture varies from clast-supported to matrix-supported, the matrix being coarse to fine sand.

Pebble bands may be considered as components of either Facies A or B. The thin bands are typically one clast thick and laterally discontinuous, the clasts being scattered between cross-sets or along a bedding plane, scour floor, or thin horizon. Bands one to several clasts thick and having good lateral continuity (i.e., a clast-supported framework) are the thinnest examples of Facies A. In rare cases, wood logs form laterally discontinuous bands (see description under "Other Woody Layers" below).

The clasts are equidimensional to platy and round to subround. Source lithologies were dominantly sandstone (including quartzite), chert, and shale.

Basal Gravel

At Section 3 (Fig. 1) the gravelly basal horizon of the Beaufort Formation is well exposed. The lowermost 1.6 m is rich in massive to crudely bedded, bouldery polymict gravel with a very poorly sorted, clast-supported framework (Fig. 4). The basal contact is knife sharp, is channelled in places, and over tens of metres laterally exhibits metres of vertical relief; therefore, it is at least locally an angular unconformity.

The gravel is interbedded with plane laminated and cross-bedded coarse to medium sand, minor rippled sand, mud, and very thin woody beds. Most of the clasts were derived from underlying Jurassic fossiliferous sandstones and ironstones; Jurassic fossils are present as clasts. Boulders are up to 66 cm long. A minor amount of wood forms clasts in the gravel framework.

One other exposure of the basal gravel horizon, near Section 6A in Figure 1, also displays cobble-bearing, clast-supported polymict gravel with a knife-sharp bed sole.

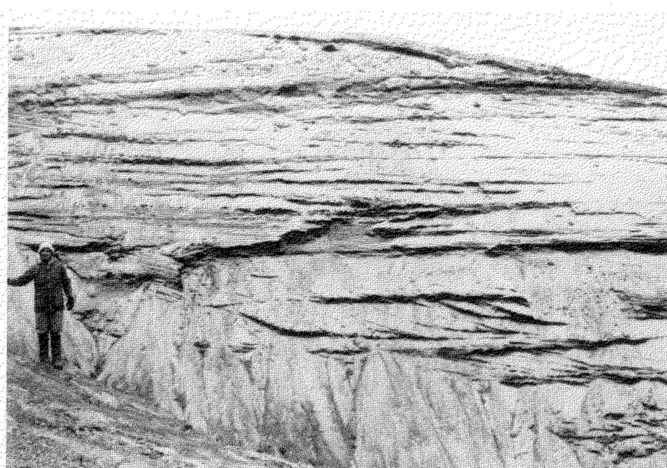

FIG. 3. Stacked planar-tabular cross-sets with foresets tangential to bedding planes; woody detritus outlines some foresets-toesets. A Platte-type profile, and probably the best exposure of the Beaufort Formation on Prince Patrick Island. Section 12.

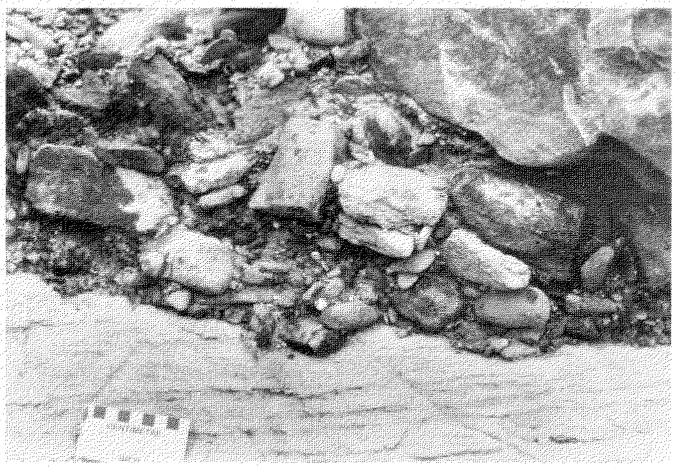

FIG. 4. Base of the Beaufort Formation: Clast-supported gravel in knife-sharp contact with white Jurassic sandstone. Section 3.

Facies B: Cross-Bedded Sand

The vast majority of the exposed Beaufort Formation strata consist of cross-bedded sand (Figs. 3, 5). Most of the cross-sets are 10-50 cm thick, the largest being 2.3 m thick. Good exposures that are several metres wide show planar-tabular cross-sets (Fig. 3), trough cross-sets and small channels, and wedge-shaped cross-sets. (Poor exposures often made it difficult to distinguish between trough and planar cross-beds.) Good examples of reactivation surfaces are rare. Some planar-tabular sets are stacked vertically (in cosets); two thinning-upward sequences were seen (cross-set thicknesses in centimetres: 100, 50, 30, 20 and 110, 60, 25, 15).

The cross-beds are of coarse to fine sand with foresets/toesets that may contain or be outlined by pebbles (up to 10 cm in size), mud intraclasts, or wood fragments (sticks up to 30 cm long). Minor amounts of rippled and plane laminated sand are interbedded within these cross-bedded units.

Cross-bed paleocurrents are generally to the northwest, west, and southwest, the paleoflow having been directed to the approximate direction of thickening (to the northwest?) of the formation. The paleocurrent directions are estimates; compass measurements were not made, and because of the poor quality slump-prone exposures the cross-bed foresets were rarely seen in three dimensions. (Compass azimuth directions would not be very reliable because the study area is close to the North Magnetic Pole. Orientation via visual sightings of the topography was not always possible owing to the flat, relatively featureless landscape and the position of some of the sections in narrow gullies.)

The sand is quartz-rich. Most grains are rounded, particularly the coarser ones.

Facies C: Rippled Sand

Beds are 5-40 cm thick, with individual ripples (by definition) up to 5 cm thick. Trough, planar-tabular, and wedge-shaped forms are present (Fig. 6). Grain size is medium to fine, commonly fine grained, and well sorted. Tiny plant fragments ("coffee grounds") frequently outline the ripple foresets/toesets.

Plane Laminated Sand

Rare beds of coarse to fine planar, horizontal to very low-angle parallel laminated sand are up to 1 m thick. Small ripples may be intimately mixed with the flat strata. In wide enough exposures the flat to low-angled laminae can sometimes be seen to be the toesets (tangential lower foresets) of cross-sets. Pebbles or mud intraclasts may be present.

Facies D: Horizontally Layered Sandy Fines

These beds of fine to very fine sand, silt, and wood fragments are rarely more than 15 cm thick. They are either internally massive or laminated to thinly bedded (Fig. 7), with some minor ripples. Woody detritus (up to 50%) is often present as either discrete laminae/thin beds or scattered fragments. With decreasing sand content, this facies is gradational to Facies F.

Facies E: Mud (Clay and Silt)

Black, brown, green, or grey mud beds 1-10 cm thick are generally massive and relatively pure (sand free, almost no visible woody detritus).

FIG. 5. Upper: Sand- and wood-filled scour (arrow) incised into cross-bedded sand. Scour fill is concave-up and 9 m wide. Woody detritus (dark) fills the upper part of this scour, probably a small abandoned channel fill (modern slumped sand covers part of the scour fill). Lower: Geologist is on top of 1-2 m thick, laterally impersistent, layered woody unit. Section 6A.

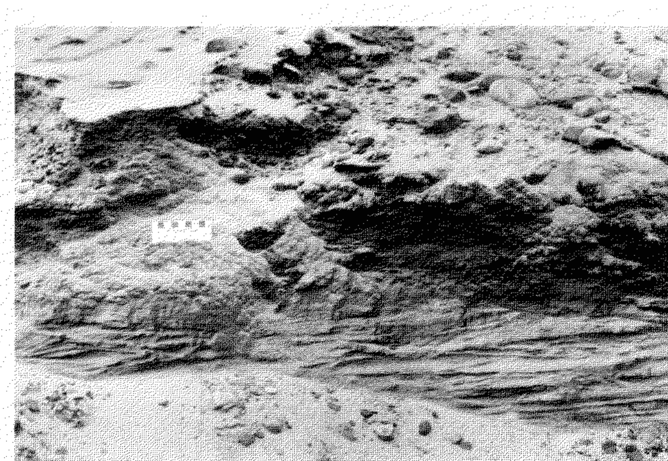

FIG. 6. Bottom: Plane laminae overlain by ripples (paleocurrent to left). Middle right: Dark woody and sandy laminae (Facies D) at top of a fining-upward sequence. Top: Slumped-over exposure of fine gravel; cross-sectional views (shovelled out) at middle and far left. Section 8.

FIG. 7. Well-segregated 1-2 cm thick beds of laminated silty fine sand and fine woody detritus (Facies D). Section 7. (In this photo some of the layers appear thicker than they really are; some thin, resistant woody layers protrude and hang downward, exposing bed plane views.)

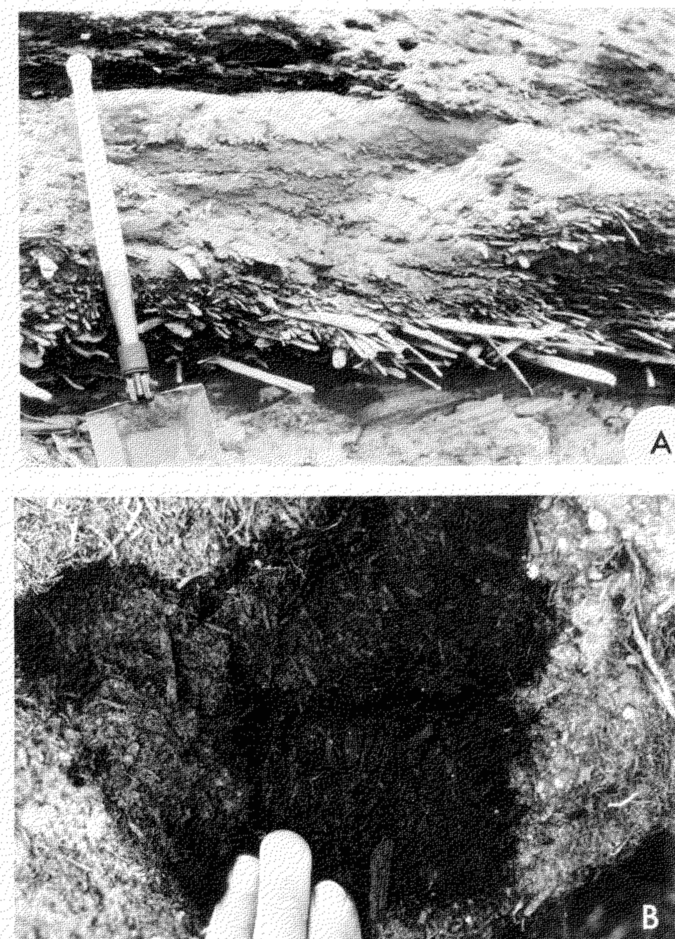

FIG. 8. A) Lower woody bed: Sharp-based bed of flat-lying sticks up to 30 cm long, crudely layered via wood fragment size (Facies F). Upper left (top of shovel handle): Fine plant detritus (1 cm twigs) interlaminated with muddy sand. Section 1. B) Bed plane view of relatively small (fine) woody detritus; dark fresh surface, light weathered surface. Section 2.

Facies F: Detrital Woody Layers

As noted by Tozer (1956:26), "The most striking characteristic of the formation is that it contains much fossil wood in a completely unlithified and uncarbonized condition." Facies F units, are defined as those layers within the Beaufort Formation having greater than 50% woody fragments by volume, as opposed to Facies D units, which have less than 50% fragments, thinner woody layers, and better developed stratification. Most Facies F units are relatively "pure," containing little fine sand as either matrix or interbeds.

Woody units up to 2 m thick are resistant to weathering and form dark, slightly protruding beds on light-coloured hillsides (Figs. 2, 5, 8). Beds or units (groups of beds) can often be observed to thin or wedge out laterally and to have concave-up bases (some obviously erosive), and they may coarsen in the direction of thickening.

The maximum wood fragment size within individual beds/units varies from: 1) logs and large sticks (greater than 20 cm long); to 2) small sticks, twigs, and pieces of wood (broken or rounded, including flat chips) and bark; to 3) tiny wood detritus (wood chips, bark, needles, seeds, moss, and fragments of twigs, up to 1 cm long; Fig. 8B).

Very rare fragment types include small leaves and pine/spruce cones (only three cones found). The woody layers are internally unstratified to crudely bedded (via variation in fragment size). There is a weak trend towards the thicker beds being coarser. Units of the finest fragment size (subcentimetre) are laminated and mat-like; some fine beds rich in moss have a peat-like appearance.

The woody fragments are almost always flat lying. Ends of sticks vary from angular to erosionally rounded. Wood may be compressed or uncompressed. Most of the wood is fresh, pliable, and uncharred; the wood grain is easily visible, and the fragments appear very similar to deadwood in a modern boreal forest.

Woody foresets are considered part of Facies B, even though the foreset internal textures and other characteristics may be identical to typical flat-bedded Facies F units. Facies F is never pebbly, whereas Facies B woody foresets and toesets may be pebbly.

Other Woody Layers

Logs can form laterally discontinuous bands within or at the base of dominantly cross-bedded sand horizons. Individual logs are up to 4.25 m long and 0.5 m in diameter. One example of a cross-bedded wood bed was seen.

Fossils

From preliminary analyses of woody detritus samples (mostly from Facies F and D), J.V. Matthews, Jr. (Geological Survey of Canada) has identified seeds of the following plant families: pine, birch, willow, pondweed, sedge, crowfoot, buckwheat, water milfoil, gentian, saxifrage, rose, arum, buckthorn, vervain, bayberry, water lily, caper, loosestrife, heath, dogwood, water plantain, honeysuckle, and mint (nearly 100 vascular plant species; Matthews *et al.*, 1990). Amber, insects, leaves, buds, conifer needles, and actinorhizal nodules have also been identified by Matthews. More than 50 species of mosses have been identified by L. Ovenden (Matthews *et al.*, 1990). Some of the above flora have been identified from the Beaufort Formation on nearby Banks and Meighen islands (Matthews, 1987, 1989; Matthews *et al.*, 1990).

From preliminary analyses of pollen from mud samples (Facies E), D.J. McIntyre (Geological Survey of Canada) has identified flora of the following families: pine, birch, myricaceae, grasses, walnut, heath, rushes, and honeysuckle. The mud also contains abundant reworked Late Cretaceous pollen, spores, and dinoflagellates (D.J. McIntyre, written comm. 1988).

FACIES ASSEMBLAGE OBSERVATIONS

Abundance of Facies

Most of the Beaufort Formation is composed of cross-bedded sand (Facies B), with common woody layers (Facies F, D) and relatively thin and uncommon beds of gravel (Facies A) and mud (Facies E). An estimate of the relative abundance of the facies is, in order of decreasing abundance: B, F, C, A, D, E. A representative vertical profile of part of Section 1 has been included in papers by Matthews *et al.* (1990:Fig. 4) and Fyles (1990:Fig. 3).

No bioturbation (including rhizoliths), paleosols, or *in situ* plant material were recognized.

Fining-Upward Sequences

Well-defined fining-upward sequences 1.2-2.5 m thick are uncommon in the Beaufort Formation (Figs. 6, 9) and form a minor part of 4 of the 12 sections measured (Fig. 1). The sequences consist of thick intervals of coarse to fine cross-bedded sand, capped by relatively thin horizons of finer rippled sand and woody detritus that may be interlaminated with sand (e.g., sequences of Facies BCF, BCD; Fig. 6). Less commonly, muds cap the sequence (sequence BCE; Fig. 9), and gravel beds, pebble bands, mud intraclasts, or bands of logs form a coarse sequence base (sequences ABCD, ABCBE; Figs. 6, 9). Alternations of cross-bedded sand horizons that are metres thick and woody layers tens of centimetres thick suggest poorly developed sequences (sequences BD, BF), or small-scale sequences that are components of similar but thicker fining-upward sequences (i.e., nested sequences), or random alternations.

Lateral Facies Changes

Based on observations of the formation's best exposures, rapid lateral facies changes at a scale of 5-50 m are the norm. Individual beds (and cross-sets) commonly thin significantly or wedge out over only several metres.

Anomalous Facies

The lower part of Section 9 (Fig. 1) contains an unusual horizon up to 4.7 m thick notable for its horizontally laminated and cross-bedded medium to fine sand, distinctive muddy layers, and tiny (up to 1 cm) woody fragments, in contrast with the dominantly cross-bedded, pebbly coarse to fine sand, and associated larger wood detritus present in both the rest of Section 9 (21 m thick) and elsewhere in the Beaufort Formation.

Within this unusual horizon is a 1.1 m thick cross-bedded unit. Cross-sets about 10 cm thick contain numerous dark, muddy sand foresets 1-15 mm thick and often spaced 1-3 cm apart (Fig. 10). These muddy foreset laminae thin and diminish up the foreset slopes. Paleocurrents are approximately to the *east*, opposite in direction to the rest of the Beaufort Formation.

The remainder of the 4.7 m horizon contains a 34 cm thick sandy cross-bed with east-directed cross-sets and horizontally, thinly bedded sand and mud (muds 2-20 mm thick). At 0.5-1.5 m above this horizon, horizontal muddy sand layers 1-20 mm thick and spaced 10-15 cm apart vertically are present in cross-bedded sand with muddy intraclasts.

Basal Beaufort Surface

A small number of altitude measurements of the basal contact of the Beaufort Formation indicate that this surface dips to the northwest (Fyles, 1990). As noted above, this is also the general direction in which the formation thickens and towards which the paleocurrents are approximately oriented.

INTERPRETATION

Facies A, B, C, D, E, and F correspond to the following facies codes of Miall (1977, 1978): Gm (plus some Gp), Sp and St, Sr, Fl, Fm, and C respectively; plane laminated sand is coded as Facies Sh.

The volumetrically dominant cross-bedded sand (Facies B) in the Beaufort Formation records the bar and channel facies of a sandy braided river paleoenvironment (Fig. 11),

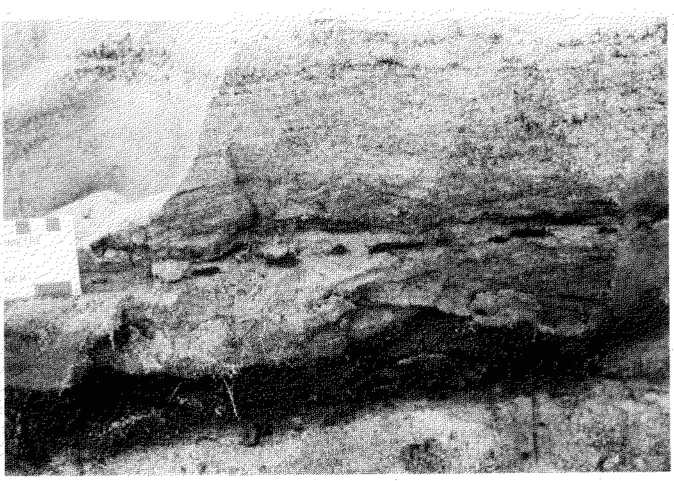

FIG. 9. Lower: Dark brown sandy mud bed, at top of fining-upward sequence. The fine, stringy roots are modern contamination. Middle: Rippled sand (not readily visible) overlain by muddy intraclasts identical in composition to the mud bed below. Top: Coarse cross-bedded sand. Section 2.

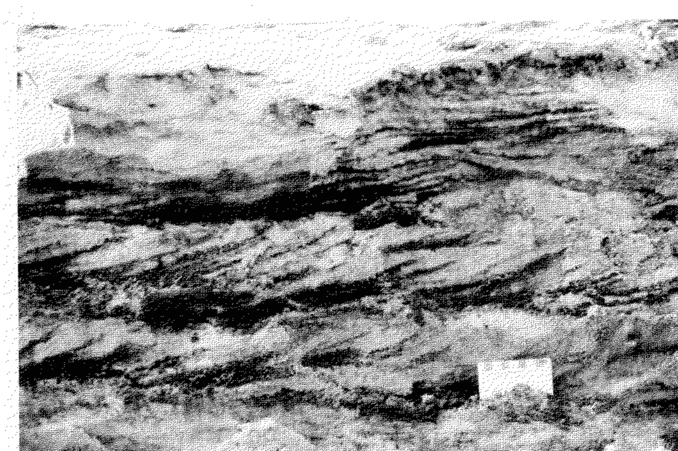

FIG. 10. Sandy cross-sets with dark muddy foresets, regularly spaced in places. Dominant paleocurrent to left, eastward. These are interpreted to be tidal bundles, with slack water mud drapes on lower foresets.

FIG. 11. A modern analogue to the Beaufort Formation: Aerial oblique view of a sandy braided river on Prince Patrick Island, N.W.T. Flow to lower left, at low stage (late summer 1987). The large compound bars (lower and upper middle) are composed of many smaller sandwaves (light, lobate features) and abandoned bar top channels (small, dark areas elongate in the local flow direction). Note the local variations in flow direction of more than 90°.

with associated ripples, plane beds, and scours. Planar cross-beds represent transverse bars (Smith, 1970, 1971; synonymous with sandwaves, linguoid bars: Boothroyd and Nummedal, 1978), microdeltas, and the cross-channel bars of Cant (1978, 1982). Trough cross-beds formed as solitary dunes or sinuous-crested sandwaves, which migrated along channel floors and bar flanks. Allen (1983) has shown how complex such bars can be when small bedforms and bars accrete into larger compound units.

Traction deposits of massive to crudely bedded, clast-supported gravel formed thin longitudinal bars and gravelly channel deposits within the sand-dominant channel systems. Where currents deposited sand and fine gravel synchronously, a sandy matrix-supported gravel resulted. Planar cross-bedded gravel (or gravelly sand) was produced by gravelly transverse bars or the slipface margins of longitudinal bars (Hein and Walker, 1977). The pebble bands are lags — either erosional lags produced by migrating bedforms (e.g., in scour troughs: Bluck, 1979:Fig. 4B) and winnowing away of finer sediments (e.g., armoured channel floors) or lags formed through loss of flow competence. Waterlogged wood logs settled from suspension and likely rolled along the channel floors as traction deposits. The basal surface of the Beaufort Formation was at least partially eroded and filled in by gravelly braided streams.

As river levels (or flood stages) dropped, sandbars became exposed and were dissected by bar-top channels ("chute," or "higher-order" channels of Williams and Rust, 1969), and microdeltas were built outwards at the mouths of these channels (Collinson, 1970; Boothroyd and Nummedal, 1978), laterally extending the bars. Flow diversion around the emergent bars caused braiding of the channel (Fig. 11) and eroded bar margins; erosion surfaces became reactivation surfaces if foresets mantled eroded foresets.

At low enough local energy conditions, sand forming the uppermost surface of dunes, transverse bars, longitudinal bars, and channel floors was reworked into current ripples (Facies C). Much of this rippled sand was produced by low-stage local reworking, a sub-population of fine, well-sorted sand winnowed from a parent population of generally coarser and more poorly sorted sand. Ripples formed in both bar-channel and overbank settings.

Mud settled from suspension and accumulated as overbank deposits (Facies E) located either outside and marginal to a main river tract (e.g., floodplain lakes, ponds, swamps) or in abandoned bar-top channels (Fig. 11). There is no record of thick, laterally extensive mud deposits. Since the rivers had sandy, easily erodible banks, lateral erosion was rapid and frequent, removing most of the muddy overbank beds (Cant, 1978). Muds were uncommonly preserved as thin beds, some being partially eroded or channelled, but are much more abundant as locally derived intraclasts than as beds. Some of these mud chips likely originated as desiccation polygons in abandoned channels and floodplain ponds. Bank caving is the simplest way of producing the large, blocky intraclasts, some of which were later rolled and picked up pebbles to form armoured mud balls. Shale clasts are a common component of the gravel, so presumably abundant mud was supplied to the rivers and much of it bypassed the system.

The paleontological data, consisting of allochthonous fossils, indicates boreal forest and floodplain conditions and a paleoclimate with a mean July temperature of about 13°C (Edlund, 1987; Matthews *et al.*, 1990). Feeder streams carried woody detritus to the main river channels, with undercutting of banks toppling trees into the streams and channels. Abrasion by sand and gravel and the tearing apart of temporary stick and log jams (e.g., Desloges and Church, 1987) wore the trees and wood fragments into smaller pieces — bark was peeled off, twigs were broken. Being of low density (easily floated) and deposited mostly in overbank sites probably topographically higher than the deep channel facies, the woody detritus was highly prone to reworking (e.g., Rust *et al.*, 1987).

Woody detritus floated along the rivers, became waterlogged, and settled from suspension. Some woody fragments then rolled; both the suspension and traction deposits formed thinly layered beds in overbank settings (Facies F, D). Where sand, silt, and woody fragments were deposited together as alternating thin beds or as sand-rich horizons, Facies D formed. During flood splay events, unconfined subaerial overbank flows could have rapidly thinned to nothing and deposited wood fragments.

Units with small-scale concave-up bases and lateral tapering (e.g., Fig. 5) represent abandoned channel fills (e.g., bar-top chutes), some of which are scour based. Abandoned channels and scour hollows form a spectrum from small stream channels of low competence, to backwaters (sloughs) and stagnant ponds, to periodically dry areas. As with the muddy overbank deposits, no thick (no more than 2 m), laterally extensive (no more than 100 m) woody overbank deposits were preserved.

The well-defined fining-upward sequences record lateral facies shifts from deep, higher-energy channel facies (A, B), to lower energy facies (B, C, D), to the lowest-energy overbank facies (C, D, E, F). The thickness of the sequences, 1.2-2.5 m, is only an estimate of the actual channel depth, since channel floor aggradation may have occurred during deposition. The thickest cross-bed, at 2.3 m, gives the minimum depth of the deepest known preserved channel within the Beaufort Formation. Thinning-upward sequences of planar-tabular cross-sets likely reflect the aggradation of sand bars up toward stationary or falling water levels.

Poorly developed sequences suggest the common preservation of thick (metres) bar-channel and thin (tens of centimetres) woody overbank facies. Random alternations of facies include stacked multistoried units. Some of the best Beaufort exposures display sections similar to the Platte type of Miall (1977, 1978) and the South Saskatchewan type profiles of Cant (1978) and Miall (1978).

Rapid lateral facies changes record small bedforms truncating each other, small erosively based channels, or partial preservation of formerly thicker and larger channel facies.

The sandy braided river interpretation is subject to some limitations; not every fluvial sequence in the Beaufort Formation can be reliably interpreted as braided in origin. Meandering sequences with their muddy overbank tops truncated by erosion can appear quite similar to braided fluvial sequences (Miall, 1980). The sandy braided interpretation is a generalization that applies to the Beaufort Formation as a whole on Prince Patrick Island, but only to most and not all of the individual sequences or horizons. Some natural variation to meandering is to be expected in a dominantly braided system, and at least some of the more equivocal sandy cross-bed-dominated sequences could have been deposited by meandering channels. The best evidence for braided fluvial conditions comes from the overbank facies (Facies D, E, F); their relative rarity, lateral impersistence, and relative thinness compared to the sandy bar-channel facies (Facies B, minor A and C) suggest that braided rather than meandering rivers deposited most of the Beaufort Formation on Prince Patrick Island. (One example of inclined [point bar?] strata was seen in Section 4 [Fig. 1], but the exposure is probably a younger fluvial deposit of sediments reworked from the Beaufort Formation, plus some autochthonous peat. According to Matthews *et al.* [1990], this site's organics have yielded a relatively impoverished flora, likely indicative of a cooler and possibly younger paleoclimate.)

The paleoenvironmental interpretation is also limited by the poor quality of the exposures. In many cases the slumping of sand over slope-parallel permafrost surfaces did not allow adequate excavation and examination of cross-beds, so the ratio of trough to planar cross-stratification is not reliably known and quantitative paleocurrent data is lacking. Most of the exposures displayed little lateral continuity, so features such as large channels were never observed. (Compared to many outcropping Phanerozoic sandstone formations, the Beaufort Formation is very poorly exposed.)

The source area of the rivers was probably to the southeast, since the formation's thickening and paleocurrents are approximately to the northwest. Suitable source lithologies for the gravel clasts are exposed today to the southeast, such as orange Devonian sandstone on Prince Patrick Island and black chert (Ibbet Bay Formation) on northwest Melville Island.

The Beaufort rivers reworked earlier Tertiary and possibly Cretaceous sandy sediments, the evidence for the latter being abundant palynomorphs. Sandstone bedrock units in both the Franklinian and Sverdrup basins are very quartz rich, so it is not surprising that the Beaufort Formation, probably derived from these sandstones, is also highly quartzose.

Tidal Facies

The 4.7 m thick horizon of anomalous facies in Section 9 is interpreted to be a fine-grained sandy and woody subpopulation of sediments winnowed by marine or estuarine processes from a parent population of typically coarser Beaufort Formation. The regularly spaced muddy foresets with paleocurrents to the east (Fig. 10), approximately opposite in direction to the fluvial cross-beds in the Beaufort Formation, record tidal flood phase-oriented cyclic alternations of sandy foreset deposition and slack water mud draping, similar to the tidal bundles of Terwindt (1981), Kreisa and Moiola (1986), and Smith (1988). Some tidal reversals left muddy drapes in the form of horizontal laminae and thin beds.

DISCUSSION

The Beaufort Formation facies assemblage descriptions and interpretations are typical of sandy braided river deposits except that it is unusual to find abundant woody (detritus) overbank facies preserved in such deposits, modern or ancient. Had the Beaufort Formation been lithified, we would see thin, laterally impersistent coal beds hosted in dominantly cross-bedded sandstone — the common presence of coal is very unusual in braided fluvial sandstones. The Beaufort Formation is in some ways similar to the South Bar Formation (Pennsylvanian) of Rust *et al.* (1987).

Unfortunately, sedimentological knowledge of the thin detrital woody overbank facies does not give us an unequivocal picture of the paleogeomorphology and paleobotany of Prince Patrick Island. This study has raised the following questions regarding the spatial relationships between braided rivers and the forested Arctic during the deposition of the Beaufort Formation in the late Tertiary: How local was the source of the plant fossils? Did a forested source area (watershed) supply a poorly vegetated braidplain, or did most of the plants grow next to active river channels on vegetated alluvial terraces and abandoned portions of a braidplain? In the former case rivers could have been sourced from a sandy boreal forest, draining down across the tree line and depositing the Beaufort Formation in a less vegetated (forest-tundra?) setting. If the latter case is more applicable, the apparent absence of root traces, paleosols, and *in situ* plant material signifies that the braided streams were highly efficient at reworking the laterally adjacent vegetated braidplain.

Moss-rich layers superficially resemble *in situ* peat, but all the samples examined contain species representing several different biotopes (Matthews *et al.*, 1990) and thus are most likely allochthonous. However, like the vascular plant and insect fossils, the moss assemblages are consistent with what one would expect in river plain sediments, and their presence as thick mats suggests nearby sources. Matthews *et al.* (1990:123) noted that "many of the plants . . . are typical of floodplain (areas) or poorly drained sites nearby."

Matthews (1989; Matthews *et al.*, 1990) and others currently consider the age of the Beaufort Formation to be early Pliocene, rather than late Miocene, based on evidence from Meighen Island. In assigning a Pliocene age to the Beaufort Formation of Prince Patrick Island (Matthews *et al.*, 1990), it has been assumed that there was not a paleontologically significant time gap between floral growth and woody detritus deposition and burial. Also, extrapolating the age of the Beaufort Formation on Meighen Island to the Beaufort Formation on Prince Patrick Island may not be entirely correct; the Beaufort Formation of Prince Patrick Island may be either early Pliocene in age or it may *range* from Miocene to Pliocene in age.

Paleoclimatic Speculations and the Age of the Beaufort Formation

One interesting speculation is that a climatic change caused or influenced the deposition of the Beaufort Formation. An increase in aridity and/or a change to a cooler climate would result in less vegetation and more runoff and gullying. Any source-proximal sandy precursor to the Beaufort Formation could have been eroded away, destroying paleosols and root traces, followed by redeposition of the clastic sediments and woody detritus on a (poorly?) vegetated braidplain, thus forming the Beaufort Formation.

In order to explore this climatic idea one must look beyond arctic Canada. Evidence from circum-Pacific volcanic deposits (Kennett *et al.*, 1977) and benthic foraminifera (Savin, 1977) were integrated by Axelrod (1981) to produce a picture of Tertiary cooling trends genetically linked to increased volcanism (Axelrod, 1981:Fig. 2). For example, the early late Miocene "Andean" volcanic episode of Kennett *et al.* (1977), 8-11 Ma ago, appears to have been synchronous with cooler paleotemperatures indicated by both marine foraminifera (Savin, 1977; Axelrod, 1981) and "Homerian" age (8-13 Ma) nonmarine floras (Wolfe, 1978, 1981). Since the Beaufort Formation on Prince Patrick Island has been thought to be of probable Homerian age (Hills, 1970; Matthews, 1989), perhaps increased circum-Pacific volcanism and resultant climatic cooling (and also probably increased aridity) could have caused a southward retreat of the tree line in the then-forested Canadian Arctic. This in turn could have resulted in the scenario outlined above: less vegetation, more erosion and runoff and sediment transport, and deposition of the Beaufort Formation by sandy braided rivers.

Note also that an areal increase in fluvial transport and deposition would be expected during a major drop in sea levels, and the apparently widespread sea level lowstands approximately 11 Ma ago (Blackwelder, 1981; Haq *et al.*, 1987) might have resulted in the late Miocene deposition of the Beaufort Formation.

Such fluctuations in climate and relative sea level during the Miocene or Pliocene could have been very important, but until the age of the Beaufort Formation on Prince Patrick Island is better known, the above scenarios will remain speculative.

SUPRA-BEAUFORT SURFACE AND YOUNGER DEPOSITS

Accurate description and analysis of the Beaufort Formation relies on the exclusion of younger non-Beaufort sediments from the picture. Since confusion of the Beaufort Formation with physically similar younger sediments *is* a potential problem, a brief account of the overlying deposits, emphasizing a gravelly lag surface, is necessary. Vincent (1983:13) dealt with this same problem of the supra-Beaufort surface at localities farther south, on Banks Island.

Supra-Beaufort Lag Surface

Forming the contemporary Arctic Coastal Plain and parts of the highlands, the Beaufort Formation's exposed and eroded upper surface is distinguished by its orange-brown colour, a veneer of gravelly lag deposits (including 1-3 m boulders), and well-developed ice wedge polygon cracks, and it commonly displays a modern dendritic fluvial drainage pattern (Tozer and Thorsteinsson, 1964). The orange colour at least partly results from the accumulation of abundant orange-pink Devonian sandstone clasts, identical to those within the Beaufort Formation. Logs and smaller wood fragments are found scattered on hilltops, slopes, and flat areas.

This supra-Beaufort lag surface contains numerous distinctive clast lithologies not present within reliable exposures (i.e., stratigraphic sections not affected by slumping) of the Beaufort Formation. The lag's granite, granitic gneiss, diabase, basalt, arkosic conglomerate, sandstone, bioclastic limestone, and other clast lithologies are either extremely rare (granite) or are not found within the Beaufort Formation. Rarely, the lag cobbles and boulders display glacial striations.

The obvious contrast between the Beaufort Formation clasts (sandstone, quartzite, chert, shale) and the far coarser and much more polymict supra-Beaufort lag clasts strongly suggests that the coarse fractions of the Beaufort Formation and at least one other younger deposit have been mixed together to form the gravelly and woody supra-Beaufort lag. This lag was probably partly sourced from a local (how local?) glacial deposit (Tozer, 1956; Tozer and Thorsteinsson, 1964). Despite recent field work by J. Fyles and D. Hodgson (Geological Survey of Canada), good, unequivocal examples of glacial till have not been found on Prince Patrick Island.

Post-Beaufort Valley Fill

At Section 6 in Figure 1, bedded highly polymict gravel, cross-bedded sand, and mud were found *below* the level of the local base of the Beaufort Formation. In this section (Table 1) only the upper 8 m are well exposed. Within a few kilometres, bedded silt (glaciolacustrine?) more than 10 m thick is exposed above the Beaufort Formation.

The relative positions of the lithofacies in Table 1 and above suggest the following scenario: 1) erosion of a glacial meltwater valley incised into the Beaufort Formation; 2) deposition of coarse and highly polymict glaciofluvial gravel (2.2-15.5 m level in Table 1), possibly via streams reworking glacial till; followed by 3) glaciofluvial sand (above 15.75 m level in Table 1); all spatially and likely temporally associated with lacustrine (or marine?) silt.

Modern Rivers and the Supra-Beaufort Surface

Modern river channels draining the Beaufort surface, both in the highlands and on the low coastal plain, are of variable sinuosity: braided, meandering, or transitional between the two. On the Arctic Coastal Plain (northwest half of Prince Patrick Island) the uppermost horizon of the Beaufort For-

TABLE 1. Stratigraphic Section 6, above the Beaufort Formation, northeast of head of Mould Bay (see Fig. 1)

15.75–27.0 m	cross-bedded sand, minor ripples (similar to Facies B of the Beaufort Formation)
15.5–15.75 m	diamict; pebbles to boulders in a black mud matrix
2.2–15.5 m	highly polymict gravel — same composition as the supra-Beaufort lag; one coarse sand interbed observed
0.0– 2.2 m	bedded coarse silt and clayey mud

mation, or younger deposits of reworked Beaufort sand, are being reworked by modern rivers. When examining the small stratigraphic sections in the recent cutbank exposures on the coastal plain, it is difficult or impossible to distinguish primary (true) Beaufort Formation strata from fluvially reworked sand containing wood fragments and sandstone, chert, and shale pebbles; the presence of granite and gneiss clasts in some of the cutbank sections suggests reworked material. Mud beds were sampled for palynomorphs, but such microfossils could also be locally reworked.

Tilted Beaufort Strata

Sub-parallel surface lineaments along the Arctic Coastal Plain are the surface expression of post-Beaufort faulting (Tozer and Thorsteinsson, 1964; Harrison *et al.*, 1988). Close to one such lineament, Beaufort strata in one wide (*ca.* 100 m) cutbank exposure were observed to have an apparent dip of about 20°. No evidence of sediment gravity flows was found, so the Beaufort strata are assumed to have been locally tilted. An alternative explanation, based on field observations by J.G. Fyles, is that a segregated ice body (modern permafrost) within the porous Beaufort strata may have caused the tilting.

ACKNOWLEDGEMENTS

Discussions and assistance in the field were provided by John Fyles, Doug Hodgson, and Jay Timmerman. John Matthews, Jr., kindly supplied Figure 1. Thanks also to the friendly staff at the Mould Bay weather station and to Ashton Embry and the Geological Survey of Canada for sending me back to the Arctic. Fyles, Hodgson, A.D. Miall, an anonymous reviewer, and the late Brian Rust critically read this manuscript and offered helpful comments.

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