Terrain, Vegetation and Landscape Evolution of the R4D Research Site, Brooks Range Foothills, Alaska
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Maps of the vegetation and terrain of a 22 km^2 area centered on the Department of Energy (DOE) R4D (Response, Resistance, Resilience to and Recovery from Disturbance in Arctic Ecosystems) study site in the Southern Foothills Physiographic Province of Alaska were made using integrated geobotanical mapping procedures and a geographic-information system. Typical landforms and surface forms include hillslope water tracks, Sagavanirktok-age till deposits, nonsorted stone stripes, and colluvial-basin deposits. Thirty-two plant communities are described; the dominant vegetation (51% of the mapped area) is moist tussock-sedge, dwarf-shrub tundra dominated by *Eriophorum vaginatum* or *Carex bigelowii*. Much of the spatial variation in the mapped geobotanical characters reflects different-aged glaciated surfaces. Shannon-Wiener indices indicate that the more mature landscapes, represented by retransported hillslope deposits and basin colluvium, are less heterogeneous than newer landscapes such as surficial till deposits and floodplains. A typical toposequence on a mid-Pleistocene-age surface is discussed with respect to evolution of the landscape. Thick *Sphagnum* moss layers occur on lower hillslopes, and the patterns of moss-layer development, heat flux, active layer thickness, and ground-ice are seen as keys to developing thermokarst-susceptibility maps.

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Introduction

A thorough knowledge of the foothills vegetation and its environmental controls is necessary for making sound land-management decisions in the Southern Foothills Physiographic Province of northern Alaska (Wahrhaftig 1965). The trans-Alaska pipeline passes through about 150 km of the foothills (Brown and Berg 1980), and future oilfields and transportation corridors will undoubtedly impact other foothill areas. This study is the first detailed geobotanical study in this region. It presents a classification, description, and map of the terrain and vegetation in a 22 km^2 area defined by the boundaries of a 1:6000-scale geobotanical map centered on the DOE R4D research area (Fig. 1). This information is used to develop a hypothesis of landscape evolution with a view toward making terrain sensitivity maps of the Foothills region.

Regional description

The R4D site is representative of the Southern Foothills Physiographic Province, a broad expanse of glaciated valleys and hills "...characterized by irregular buttes,

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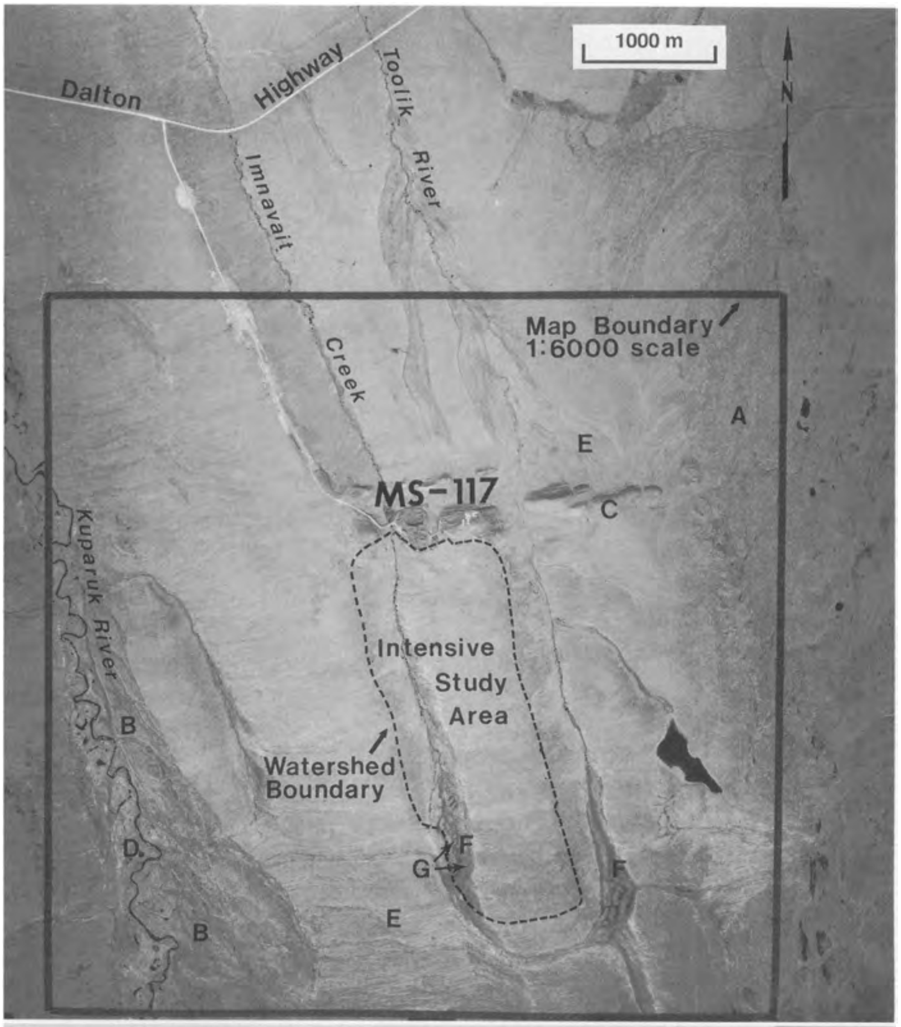

Fig. 1. R4D study area. (A) a recently glaciated (Itkillik-age) surface, (B) glaciofluvial outwash plain of similar age, (C) bedrock outcrop, (D) floodplain deposit. Most of the other upland surfaces are mantled with Sagavanirktok-age glacial till and retransported hillslope deposits (see text for details). Also note well developed hillslope water tracks (E), colluvial basin deposits (F), and lowland water tracks (G). (CIR photo 1–4, 8–2–85).

Fig. 2. R4D Imnavait Creek watershed. View is toward the south into the Philip Smith Mountains of the central part of the Brooks Range. The mined area is Material Site 117. The crest of the low ridge to the right of the stream is the western boundary of the watershed.

knobs and mesas, east trending ridges, and intervening rolling tundra plains". (AEIDC 1975). The R4D watershed is at the headwaters of the informally named Imnavait Creek, which is situated in a shallow basin at the foot of the central Brooks Range (Fig. 2). The 2.2 km^2 watershed is 10 km north of Atigun Gorge, 3 km south of the Dalton Highway, and located between the meandering Kuparuk River to the west and the beaded headwaters of the Toolik River to the east. In this study, the watershed is part of a larger 22 km^2 area (Fig. 1).

The hills in the vicinity of the R4D site are generally gently rolling, rising less than 100 m from the valley bottoms to the ridge crests, and elongated in a NNW direction. Two lines of steeper rounded sandstone and shale outcrops are oriented perpendicular to Imnavait Creek. The maximum elevation within the watershed is about 945 m, and the lowest elevation along Imnavait Creek is about 875 m. The maximum elevation within the 1:6000 map area (Fig. 1) is 980 m near a small lake on the eastern side of the area, and the lowest elevation is about 790 m where the Kuparuk River leaves the area.

The designated northern boundary of the watershed is a weir located in Imnavait Creek just south of the road at Material Site No. 117 (MS-117). The east and west divides of the watershed are two parallel NNW to SSE trending ridges. The southern divide is indistinct and occurs in the flat expanse of a colluvial basin and runs eastward up a gentle west-facing hill to the eastern divide of the watershed.

The local hills are covered by glacial till of the Sagavanirktok River Glaciation (Middle Pleistocene) (Detterman et al. 1958, Hamilton 1986). Most hill crests have till at the surface, providing rocky mineral substrate for plant communities, whereas hill slopes and valley bottoms are generally smoothly eroded and covered by colluvium and shallow peat deposits. This contrasts markedly with terrain of a nearby lobe of Itkillik (Late Pleistocene) till in the Sagavanirktok River valley, where the deposits are generally stony and little eroded.

Methods

Classification and mapping

Field work was done during 1–10 August 1984 and 17 August – 4 September 1985. During these times, 73 permanent vegetation plots were sampled, and geobotanical surveys were conducted along transects within the 1:6000-scale map area (Walker et al. 1987a). Plant species identifications were verified by D. Murray (vascular plants) and B. Murray (mosses and lichens) at the University of Alaska Herbarium, and we follow their nomenclature. Vegetation types were defined by using the Braun-Blanquet table analysis approach described by Mueller-Dombois and Ellenberg (1974) and Westhoff and van der Maarel (1978). Details of the sampling procedures and copies of the sorted table can be obtained from D. A. Walker (Walker et al. 1987a).

The vegetation, surface forms, landforms, and percentage water cover were mapped at 1:6000 scale using an integrated mapping approach developed at Prudhoe Bay, AK (Walker et al. 1980, 1986). Field surveys for the map were conducted in the summer of 1985 following a preliminary classification of the vegetation data. Transects were established, and photographs and descriptions made of vegetation and surface forms at predetermined points along the transects. This information was the basis for photointerpretation, which was done on color-infrared (CIR) photographs (11 October 1984, original scale 1:36,000 enlarged to a scale of 1:6000).

The surface forms (mostly periglacial features that are superimposed over primary landforms, e.g. ice-wedge polygons, stone stripes, and frost scars) were mapped according to the legends developed by Everett (1980, Walker 1985) at Prudhoe Bay with additions to include new units encountered in the foothills. The terrain-unit classification is that of Kreig and Reger (1982), who mapped the route of the trans-Alaska pipeline. These authors originally termed these units *landforms*, but have since used the term *terrain unit* to apply to elements of the landscape with definite composition. Their use of the term *landform* differed from the traditional use which implies shape only (Kreig, pers. comm.).

Floristically-defined plant communities derived from table analysis (and field observation in a few cases where no detailed plot information was obtained) were grouped into mapping units based on site moisture and vegetation physiognomy.

In several instances, it was possible to photo-interpret units on the basis of dominant species. This was particularly true for the dry dwarf-shrub, fruticose-lichen vegetation types, where, for example, it was possible to consistently delineate *Dryas*-, *Arctous*-, *Vaccinium*-, and *Cassiope*-dominated communities.

Map analysis

The mapped data were digitized and entered into a geographic information system (GIS) (Evans et al. 1989), and computer-drawn maps of terrain units, surface forms, and primary vegetation were prepared using the ARC/INFO GIS software (Env. Systems Res. Inst., Redlands, CA). The statistical analyses were conducted using a grid-cell data base, and the correlation methods are described in Evans et al. (1989).

The Shannon-Wiener index of diversity (Shannon and Weaver 1949) was calculated to determine the relative vegetation diversity of five terrain-type groups (bedrock outcrops, till deposits, retransported hillslope deposits, basin colluvium, and floodplain deposits). The formula for the index is:

$$H_i = -\Sigma p_i (\log P_i)$$

Tab. 1. Summary of R4D plant community types.

Physiognomic Units	Plant Communities	Other Common Plants	Typical Microsite	Permanent Plots (Walker et al. 1987a)
D1. Dry dwarf-shrub, fruticose-lichen tundra	a. *Dryas octopetala-Selaginella sibirica*	Vascular plants: *Salix phlebophylla, Minuartia obtusiloba, Antennaria alpina* var. *media, Saxifraga nivalis, Smelowskia calycina, Kobresia myosuroides, Oxytropis nigrescens, Saxifraga bronchialis, S. tricuspidata, Douglasia ochotensis, Bupleurum triradiatum Phlox sibirica, Potentilla uniflora, Poa glauca, Carex obtusata* Mosses: *Polytrichum piliferum* Lichens: *Cetraria* spp., *Thamnolia* spp., *Cornicularia divergens, Stereocaulon tomentosum, Alectoria* spp., *Sphaerophorus globosus, Asahinea chrysantha*	Windblown south-facing slopes on sandstone and shale outcrops	SW33, 52, 53, 54, 58A
	b. *Dryas octopetala-Vaccinium vitis-idaea*	Vascular plants: *Arctous alpina, Salix phlebophylla* Mosses: *Polytrichum piliferum* Lichens: *Cetraria* spp., *Thamnolia* spp., *Stereocaulon tomentosum, Alectoria* spp., *Cornicularia divergens, Sphaerophorus globosus*	Windblown glacial till and outwash deposits	SW42
	c. *Arctous alpina-Hierochloë alpina*	Vascular plants: *Vaccinium vitis-idaea, Salix phlebophylla* Mosses: *Dicranum elongatum, Polytrichum strictum* Lichens: *Cetraria* spp., *Alectoria ochroleuca, Cornicularia divergens, Sphaerophorus globosus, Thamnolia* spp., *Dactylina arctica, Cladonia amaurocraea, C. gracilis*	Glacial till with shallow snow cover	SW09, 28, 38
	d. *Vaccinium uliginosum-Arctous alpina*	Vascular plants: *Vaccinium vitis-idaea, Dryas octopetala, Hierochloë alpina, Bistorta plumosa, Artemisia arctica, Pedicularis capitata* Mosses: *Rhytidium rugosum, Polytrichum strictum* Lichens: *Cetraria* spp., *Stereocaulon tomentosum, Cladonia* spp., *Peltigera malacea, Thamnolia* spp.	Shallow south-facing snowbeds	SW51, 60

Tab. 1. Cont.

Physiognomic Units	Plant Communities	Other Common Plants	Typical Microsite	Permanent Plots (Walker et al. 1987a)
	e. *Cassiope tetragona-Calamagrostis inexpansa*	Vascular plants: *Vaccinium vitis-idaea, Salix phlebophylla, Ledum palustre* spp. *decumbens, Carex bigelowii, Betula nana, Diapensia lapponica, Pedicularis lanata, Bistorta plumosa, Petasites frigidus* Mosses: *Rhacomitrium lanuginosum, Hylocomium splendens, Aulacomnium turgidum* Lichens: *Cetraria* spp., *Cladonia* spp., *Dactylina arctica, Thamnolia* spp., *Peltigera aphthosa*	Nonsorted stone stripes with shallow snowbeds	SW29A, 30A, 32A, 39, 43, 44A
	f. *Cassiope tetragona-Dryas integrifolia*	Vascular plants: *Vaccinium uliginosum, Salix reticulata, Carex bigelowii, Pedicularis capitata, Bistorta vivipara, B. plumosa, Parrya nudicaulis, Equisetum scirpoides* Mosses: *Hylocomium splendens, Dicranum angustum, D. acutifolium, Tomenthypnum nitens, Ptilidium ciliare* Lichens: *Cetraria* spp., *Cladonia* spp., *Dactylina arctica, D. ramulosa, Stereocaulon tomentosum, Thamnolia* spp., *Alectoria ochroleuca*	Minerotrophic snowbeds	SW26, 59
	g. *Betula nana-Hierochloë alpina*	Vascular plants: *Vaccinium uliginosum, Cassiope tetragona, Bistorta plumosa, Carex microchaeta, Arctous alpina, Artemisia arctica, Vaccinium vitis-idaea* Mosses: *Polytrichum strictum, Hylocomium splendens* Lichens: *Cladonia* spp., *Stereocaulon tomentosum, Cetraria richardsonii, Thamnolia subuliformis Dactylina arctica*	Till outcrops and dry areas with moderate snow cover	None

Tab. 1. Cont.

Physiognomic Units	Plant Communities	Other Common Plants	Typical Microsite	Permanent Plots (Walker et al. 1987a)
M1. Moist dwarf-shrub, moss, fruticose-lichen tundra, or Moist dwarf-shrub, fruticose-lichen tundra	a. *Cassiope tetragona-Carex microchaeta*	Vascular plants: *Vaccinium vitis-idaea, Pyrola grandiflora, Ledum palustre* spp. *decumbens, Salix rotundifolia, S. phlebophylla, Pedicularis lanata, P. capitata, Luzula arctica, Senecio atropurpureus, Vaccinium uliginosum, Diapensia lapponica, Bistorta plumosa, Saxifraga nelsoniana* Mosses: *Hylocomium splendens, Aulacomnium turgidum, Rhytidium rugosum, Dicranum acutifolium, D. elongatum, Rhacomitrium lanuginosum* Lichens: *Cetraria* spp., *Cladonia* spp., *Dactylina arctica, D. ramulosa, Stereocaulon tomentosum, Nephroma arctica, Peltigera aphthosa, Thamnolia* spp.	Moderately deep snowbeds, particularly on north-facing slopes	SW40, 55, 56, 57
	b. *Salix rotundifolia-Saxifraga nivalis*	Vascular plants: *Poa paucispicula, Aconitum delphinifolium, Arnica lessingii, Luzula confusa, Artemisia arctica, Polemonium acutiflorum, Saxifraga nelsoniana, Arctagrostis latifolia, Poa arctica* Mosses: *Drepanocladus uncinatus, Polytrichastrum alpinum* Lichens: *Stereocaulon tomentosum, Cladonia chlorophaea, Solorina crocea*	Deepest snowbeds	SW72, 73
M2. Moist tussock-sedge, dwarf-shrub tundra, (*Eriophorum vaginatum* dominated), or Moist nontussock-sedge, dwarf-shrub tundra, (*Carex bigelowii* dominated)	a. *Eriophorum vaginatum-Sphagnum* spp.	Vascular plants: *Vaccinium vitis-idea, Carex bigelowii, Betula nana, Salix planifolia* spp. *pulchra, Ledum palustre* ssp. *decumbens, Bistorta plumosa, Rubus chamaemorus, Petasites frigidus, Empetrum hermaphroditum, Vaccinium uliginosum, Cassiope tetragona, Salix reticulata, Pyrola grandiflora, Saxifraga nelsoniana* Mosses: *Hylocomium splendens, Aulacomnium turgidum, A. palustre, Dicranum angustum, Polytrichum strictum, Tomenthypnum nitens, Ptilidium ciliare* Lichens: *Cetraria* spp., *Cladonia* spp., *Dactylina arctica, Peltigera* spp.	Stable, mesic sites with flat or gentle slopes	SW03, 04A, 50, 61, 62

Tab. 1. Cont.

Physiognomic Units	Plant Communities	Other Common Plants	Typical Microsite	Permanent Plots (Walker et al. 1987a)
	b. *Carex bigelowii-Sphagnum* spp.	Same as above except dominanted by *Carex bigelowii*, with *Eriophorum vaginatum* much less abundant	Mesic sites on steeper slopes with some solifluction	SW01, 06, 08, 12, 27, 31
	c. *Carex bigelowii-Dryas integrifolia*	Vascular plants: *Eriophorum triste, Salix arctica, S. planifolia* ssp. *pulchra, S. reticulata, Bistorta vivipara* Mosses: *Tommenthypnum nitens, Aulacomnium turgidum, Dicranum elongatum* Lichens: *Thamnolia* spp., *Dactylina arctica, Cetraria* spp.	Minerotrophic mesic sites, often with cryoturbation	None
M3. Moist dwarf-shrub, moss tundra or Moist dwarf-shrub, moss, lichen tundra	a. *Betula nana-Rubus chamaemorus*	Vascular plants: *Vaccinium vitis-idaea, Carex bigelowii, Ledum palustre* ssp. *decumbens, Salix planifolia* ssp. *pulchra, Bistorta plumosa, Petasites frigidus, Eriophorum vaginatum, Pedicularis lapponica* Mosses: *Sphagnum* spp., *Aulacomnium turgidum, A. palustre, Hylocomium splendens, Dicranum angustum, D. elongatum, Drepanocladus uncinatus* Lichens: *Thamnolia* spp., *Cetraria* spp., *Cladonia* spp., *Dactylina arctica*	Palsas, high-centered polygons, margins of water tracks, hillslopes	SW15, 17
	b. *Betula nana-Cladonia rangiferina*	Vascular plants: *Vaccinium vitis-idaea, Ledum palustre* ssp. *decumbens, Eriophorum vaginatum, Pedicularis lapponica* Mosses: *Sphagnum* spp., *Aulacomnium turgidum, Hylocomium splendens, Dicranum elongatum, D. angustum*	Palsas	SW24, 67
M4. Moist low-shrub tundra	a. *Betula nana-Rubus chamaemorus*	Same as M3a. above, except dominated by *Betula nana* low shrubs	Hillslopes, water track margins	SW05, 10, 13, 46, 48
	b. *Salix planifolia* ssp. *pulchra-Eriophorum vaginatum*	Same as M2a. above, except dominated by *Salix planifolia* ssp. *pulchra* low shrubs	Lower hillslopes	SW07, 35A
	c. *Salix planifolia* ssp. *pulchra*	Closed canopy shrubland with varied understories	Riparian margins	None
	d. *Salix planifolia* ssp. *pulchra-Calamagrostis canadensis*	Vascular plants: *Salix chamissonis, Polemonium acutiflorum, Artemisia arctica* Mosses: *Hylocomium splendens*	Riparian areas along Kuparuk River	SW68

Tab. 1. Cont.

Physiognomic Units	Plant Communities	Other Common Plants	Typical Microsite	Permanent Plots (Walker et al. 1987a)
W1. Wet sedge tundra	a. *Carex rotundata-Sphagnum lindbergii*	Vascular plants: *Carex rariflora, Eriophorum scheuchzeri, Salix fuscescens, Eriophorum angustifolium, Pedicularis albolabiata* Mosses: *Sphagnum imbricatum*	Wet meadows, poor fens on colluvial basin deposits	SW21A, 22A, 25B
	b. *Carex-aquatilis-Eriophorum angustifolium*	Mosses: *Drepanocladus revolvens, Sphagnum* spp.	Wet meadows	None
	c. *Eriophorum angustifolium*		Water tracks	None
W2. Wet sedge, dwarf-shrub, moss tundra or Wet sedge, dwarf-shrub tundra	a. *Salix fuscescens-Sphagnum lenense*	Vascular plants: *Carex rariflora, Eriophorum scheuchzeri, Betula nana, Pedicularis lapponica, Andromeda polifolia, Carex rotundata* Mosses: *Aulacomnium turgidum, Sphagnum rubellum, S. aongstroemii*	Hummocks, strangs, and raised microsites in colluvial basins	SW19, 20, 22B, 25A
	b. *Carex aquatilis-Salix fuscescens*	Vascular plants: *Carex rariflora, Salix planifolia* ssp. *pulchra, Betula nana, Rubus chamaemorus, Andromeda polifolia, Pedicularis lapponica* Mosses: *Polytrichastrum alpinum, Sphagnum* spp., *Aulacomnium turgidum, A. palustre, Dicranum angustum, Calliergon stramineum*	Margins of colluvial basis	SW14
	c. *Carex aquatilis-Salix chamissonis*	Vascular plants: *Valeriana capitata, Eriophorum angustifolium, Aconitum delphinifolium, Anemone parviflora* Mosses: *Aulacomnium palustre, Sphagnum* ssp., *Bryum* sp.	Stream margins with deep winther snow	SW18, 47
W3. Wet low-shrub, sedge tundra	*Salix planifolia* ssp. *pulchra-Eriophorum angustifolium*	Valcular plants: *Betula nana, Rubus chamaemorus, Carex bigelowii, Petasites frigidus, Saxifraga nelsoniana, Polemonium acutiflorum, Valeriana capitata, Bistorta plumosa* Mosses: *Drepanocladus uncinatus, Hylocomium splendens, Sphagnum* spp., *Aulacomnium palustre, A. turgidum, Tomenthypnum nitens*	Water tracks, wet hillslopes	SW02, 11, 34, 36A
A1. Aquatic marsh	a. *Carex aquatilis-Eriophorum angustifolium*	Vascular plants: *Eriophorum scheuchzeri, Carex rotundata* Mosses: *Sphagnum* spp.	Stream channels	SW16, 23
	b. *Carex rotundata-Eriophorum scheuchzeri*		Wet meadows	None

Tab. 1. Cont.

Physiognomic Units	Plant Communities	Other Common Plants	Typical Microsite	Permanent Plots (Walker et al. 1987a)
	c. *Carex chordorrhiza*		Wet meadows, lake margins	None
	d. *Sparganium hyperboreum-Hippuris vulgaris*	Mosses: *Sphagnum lindbergii, S. squarrosum, Calliergon sarmentosum*	Beaded ponds, oxbow lakes	SW35, 65, 66
	e. *Arctophila fulva*		Lake margins	None
D2. Dry lichen rockland	*Rhizocarpon geographicum-Cetraria nigricans*	Mosses: *Rhacomitrium lanuginosum, Chandonanthus setiformis, Dicranum acutifolium* Lichens: *Cetraria* spp., *Cladonia* spp., *Cornicularia divergens, Alectoria* spp., *Umbilicaria* spp., *Xanthoparmelia centrifuga, Sphaerophorus globosus, Thamnolia* spp., *Parmelia omphalodes, Lecidea flavocaerulescens*	Blockfields, glacial erratics	SW63, 64
D3. Dry grassland	*Festuca rubra-Poa glauca*	Vascular plants: *Trisetum spicatum, Poa alpina, P. lanata, Epilobium angustifolium, E. latifolium, Crepis nana, Stellaria* spp., *Minuartia rubella, Equisetum arvense, Arctagrostis latifolia*	Revegetated areas	None
D4. Dry rush, forb, lichen barren	*Juncus biglumis-Luzula arctica*	Vascular plants: *Cassiope tetragona, Bistorta vivipara, Vaccinium vitis-idaea, Salix phlebophylla* Mosses: *Rhacomitrium lanuginosum* Liches: *Thamnolia* spp., *Cetraria* spp., *Cladonia* spp.	Frost scars	SW69, 70, 71

where H_i is the index and p_i is the fraction of the total number of individuals belonging to the ith class. In this study, high index values indicate terrain with many vegetation types and relatively high cover of each type, whereas low values indicate relatively homogeneous terrain.

Results

The floristically-defined vegetation community types are grouped into physiognomically-defined units (Tab. 1) and into map units (Tab. 2-left-hand column). The vegetation types on the map (Fig. 5) are arranged along a moisture gradient from dry to aquatic sites, and with barren and partially vegetated types listed at the bottom of the legend.

Figs 3 to 5 are the terrain-unit, surface-form, and vegetation maps prepared from the GIS data base. These black and white versions are for journal publication, but color maps were also prepared and are available from the North Slope Borough GIS, Anchorage, AK. The legends of the maps contain area summaries for each geobotanical type within the entire map and within the R4D watershed. Fig. 5 is a map of the primary (i.e. dominant) vegetation. Maps were also prepared for the secondary and tertiary vegetation types (i.e. vegetation types occurring with secondary or tertiary importance in mosaics of vegetation).

For sake of simplification, many of the more minor terrain units in Fig. 3 were grouped with closely associated terrain units to form terrain-unit groups. For example, floodplain deposits include meander floodplains, nonmeander floodplains, alluvial fans, and glaciofluvial outwash deposits. Tab. 2 is a summary of the areas of the dominant vegetation within the major terrain unit groups. The left column of the table shows how the community types of Tab. 1 are grouped within the vegetation map units. The second column contains the purely numeric vegetation codes that are in the GIS data base.

Floodplain deposits are by far the most diverse (H_i = 0.857) and retransported hillslope deposits are the least diverse (H_i = 0.471) (Tab. 2). Bedrock outcrops, till deposits, and basin culluvium have intermediate diversity (H_i = 0.624, 0.599, and 0.583, respectively).

Descriptions of the major terrain and vegetation units

Although the Arctic Foothills are largely dominated by tussock-tundra vegetation, there are local areas of high vegetation diversity due to bedrock outrops, and riparian systems, and regional variation due to influences such as loess, glacial history, elevation and snow gradients. Hillslope deposits dominate the local RAD watershed landscape, but the features that give the R4D site its distinctive character are the sandstone outcrops, the site's position along the contact between Sagavanirktok- and Itkillik-age glacial tills, and the floodplain of the Kuparuk River. The vegetation descriptions that follow are organized according to the five terrain unit groups (Tab. 2), the results of which are appropriate for extrapolation to other foothill landscapes.

Bedrock outcrops

Geology and surface forms

Several bedrock knolls of the Fortress Mountain formation (Chapman et al. 1964, Brosgé et al. 1979) occur within the mapped area (Figs 1 and 3). These cover only 1% of the map but add considerably to the overall topographic and floristic diversity. Thirty-two out of a total of 151 species recorded at the site (D. Murray, unpubl. data) have been found only on the sandstone outcrops. The highest knoll is at the benchmark 'Gal' (Fig. 3), which is 68 m above the base of the knoll. Most of the hills are oriented along an east-west axis with steep north- and south-facing slopes. MS-117 is an open-pit rock mine on one of these knolls (Fig. 2); material from this mine was crushed for gravel to construct a portion of the Dalton Highway. The Fortress Mountain Formation is Lower Cretaceous in age and "...composed dominantly of thick units of dirty graywacke-type gray to green sandstone and pebble-cobble conglomerate; thick units of clay shale and siltstone are interbedded with the sandstone and conglomerate" (Chapman et al. 1964).

The surfaces of these outcrops range from smooth gravelly slopes on the windward south-facing slopes to talus slopes on the steep north-facing slopes. The south slopes are largely snow-free in the winter, and the north slopes accumulate deep snow drifts. The summit ridges and flatter areas of the outcrops have frost scars [Everett 1980 = nonsorted circles and mud hummocks of Mackay (1980) and Mackay and Mackay (1976) and nonsorted circles of Washburn (1973)]. Glacial erratics on the outcrops indicate that the bedrock outcrops were covered by Sagavanirktok-age glaciers.

Vegetation

Vegetation on these knolls is complex due to the large variety of microsites; only the more common and distinctive vegetation types are described here. The vegetation on these features is to a large extent controlled by the amount of winter snow cover and exposure to winds.

Exposed south-facing slopes are floristically the most interesting sites within the study area. These areas are largely snow free during the winter due to southerly catabatic yiwinds blowing out of the Brooks Range valleys. Dry *Dryas octopetala, Selaginella sibirica* dwarf-shrub, fruticose-lichen tundra (Tab. 1, Community Type D1a has many herbs that are locally uncommon, such as *Minuartia obtusiloba, Smelowskia calycina, Kobresia myosuroides, Oxytropis nigrescens, Douglasia ochotensis, Anemone drummondii, Bupleurum triradiatum, Phlox sibirica,* and *Carex obtusata. The threatened plant Erigeron muirii* (Murray 1980) occurs on the exposed portions of some of the outcrops. Vegetation cover varies considerably depending on exposure to winds; the most exposed sites are totally barren except for patches of *Dryas octopetala, Polytrichum piliferum,* and scattered lichens.

South-facing snowbeds at the foot of the knolls have a complex variety of vegetation types. One of the more common types is dry *Vaccinium uliginosum, Arctous alpina* dwarf-shrub, fruticose-lichen tundra (Community Type D1d) which occurs in relatively warm, well-drained sites with early melting snow. Dry *Cassiope tetragona, Dryas integrifolia* dwarf-shrub, fruticose-lichen tundra (Community Type D1f) is a snowbed community of relatively minerotrophic sites, such as shallow basins at the foot of knolls, where nutrients are concentrated from upslope. Numerous locally rare basophiles such as *Salix reticulata, Astragalus umbellatus, Rhododendron lapponicum, Salix arctica, Saussurea angustifolia, Tofieldia pusilla,* and *Equisetum variegatum* occur in these sites. Other shallow south-facing snowbed sites are dominated by *Empetrum hermaphroditum* or *Arctous alpina.*

North-facing slopes have deep late-lying snow drifts (late June to early July). Well drained slopes with moderate snow cover have moist *Cassiope tetragona, Carex microchaeta* dwarf-shrub, fruticose-lichen tundra (Community Type M1a). These sites have a deep moss (*Hylocomium splendens*) carpet that often occurs on talus with very little soil development (Ranker soil of Tedrow 1977). *Salix planifolia* ssp. *pulchra* or *Betula nana* can be locally important in these sites.

A variety of other more poorly defined vegetation types occurs in shallow snow beds, but more samples are needed to fully document the variation along the

Tab. 2. Area of dominant vegetation and surface forms within the major terrain units groups.

Community Types (See Tab. 1)	GIS Code(s)	Vegetation Map Unit	Bedrock Outcrops (240)				Till Deposits (650)			
			Entire Map		Watershed		Entire Map		Watershed	
			Ha	%	Ha	%	Ha	%	Ha	%
D1a,b	671, 672	Dry dwarf-shrub, fruticose-lichen tundra (*Dryas octopetala*)	8.06	36.44	0.87	59.59	4.96	2.91	0	0
D1c	613	Dry dwarf-shrub, fruticose-lichen tundra (*Arctous alpina*)	2.80	12.66	0.27	18.49	95.33	56.04	7.52	63.09
D1d	612	Dry dwarf-shrub, fruticose-lichen tundra (*Vaccinium uliginosum*)	3.00	13.56	0	0	0	0	0	0
D1e,f,g	453, 611, 681	Dry dwarf-shrub, fruticose-lichen tundra (*Cassiope tetragona*)	0.53	2.40	0.32	21.92	24.49	14.40	1.55	13.00
M1a,b	451, 452	Moist dwarf-shrub, moss, fruticose-lichen tundra (*Cassiope tetragona*) or Moist dwarf-shrub, fruticose-lichen tundra (*Salix rotundifolia*)	7.26	32.82	0	0	0	0	0	0
M2a,b,c	411, 412, 421	Moist tussock-sedge, dwarf-shrub tundra (*Eriophorum vaginatum*) or Moist nontussock-sedge, dwarf-shrub tundra (*Carex bigelowii*)	0	0	0	0	13.53	7.96	2.6	21.81
M3a,b	461	Moist dwarf-shrub, moss tundra (*Betula nana*)	0	0	0	0	0	0	0	0
M4a	471	Moist low-shrub tundra (*Betula nana*)	0.47	2.12	0	0	18.09	10.63	0	0
M4b,c,d	431, 441, 472, 482, 482	Moist low-shrub tundra (*Salix planifolia* ssp. *pulchra*)	0	0	0	0	5.96	3.50	0	0
W1a,b,c	211, 212, 213	Wet sedge tundra (*Carex* spp. or *Eriophorum* spp.)	0	0	0	0	1.18	0.69	0	0
W2a,b,c	241, 242, 243	Wet sedge, dwarf-shrub, moss tundra or Wet sedge, dwarf-shrub tundra (*Carex* spp., *Salix fuscescens*)	0	0	0	0	2.30	1.35	0	0
W3	251	Wet low-shrub, sedge tundra (*Salix planifolia* ssp. *pulchra*)	0	0	0	0	0	0	0	0
A1a,b,c	031, 032, 033	Aquatic sedge marsh (*Carex aquatilis, Eriophorum angustifolium*)	0	0	0	0	0	0	0	0
A1d	041	Aquatic forb marsh (*Sparganium hyperboreum*)	0	0	0	0	0	0	0	0
A1e	021	Aquatic grass marsh (*Arctophila fulva*)	0	0	0	0	0	0	0	0
A2	010	Unvegetated water	0	0	0	0	0	0	0	0
D2	821	Dry lichen rockland (*Umbilicaria* spp.)	0	0	0	4.11	2.42	0.25	2.10	
D3	831	Dry grassland (revegetated) (*Festuca rubra*)	0	0	0	0	0	0	0	0
U	991	Unvegetated	0	0	0	0	0.17	0.10	0	0
		Total	22.12	100.00	1.46	100.00	170.12	100.00	11.92	100.00
		Shannon-Wiener Index		0.624				0.599		

snow gradient. Dry vegetation (primarily *Dryas*-dominated) types cover 64.9% of the sandstone knolls, and most of the remainder (32.8%) is moist *Cassiope* snowbeds (Tab. 2).

Till deposits

Geology and surface forms

Much of the watershed is covered by clay-rich glacial till. Areas along the Kuparuk River and along the eastern side of the map are Itkillik till (late Pleistocene), whereas the deposits on most hill crests are from the Sagavanirktok River Glaciation (middle Pleistocene), which at other sites in the region is composed primarily of Kanayut Conglomerate sandstones and limestones (Hamilton 1986). On the ridge crests and at scattered sites on the hill slopes, till is exposed at the surface. About 4% of the watershed and 9% of the total map have exposed till deposits. Flat exposed till deposits generally are rocky with gently undulating surface relief that includes blockfields (Washburn 1980) and sorted frost scars (Everett 1980).

Vegetation

As on the sandstone knolls, the vegetation of till deposits is largely controlled by the amount of winter snow cover and the degree of rockiness of the surface. The tops of small till knolls generally are blown free of snow in winter and are vegetated by dry *Dryas octopetala, Vaccinium vitis-idaea* dwarf-shrub, fruticose-lichen tun-

Area and Percent of Terrain Unit Groups															
Retransported Hillslope Deposits (330, 500)				Bassin Colluvium (340, 890)				Floodplain Deposits (400, 420, 440, 450, 711)				All Units Combined			
Entire Map		Watershed		Entire Map		Watershed		Entire Map		Watershed		Entire Map		Watershed	
Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
0	0	0	0	0	0	0	0	4.54	2.04	0	0	18.7	0.87	1.1	0.39
7.74	0.54	0.13	0.07	0	0	0	0	27.57	12.36	0	0	146.6	6.80	7.4	3.34
0.05	0	0	0	0	0	0	0	0	0	0	0	3.2	0.15	0	0
187.00	13.12	44.03	25.22	0	0	0	0	3.13	1.40	0	0	229.7	10.65	35.3	15.44
0	0	0	0	0	0	0	0	0	0	0	0	7.7	0.36	0	0
1012.90	71.06	123.66	70.82	12.42	9.51	5.21	19.20	68.62	30.77	0	0	117.23	54.36	139.3	62.62
41.40	2.90	0	0	32.92	25.20	5.88	21.67	2.67	1.20	0	0	81.8	3.80	6.4	2.90
48.17	3.38	0.37	0.21	0.07	0.05	0	0	31.67	14.20	0	0	106.1	4.92	0.3	0.13
37.50	2.63	3.21	1.83	0	0	0	0	43.51	19.51	0	0	94.0	4.36	2.7	1.23
9.22	0.65	0.04	0.02	43.96	33.66	6.99	25.76	14.75	6.61	0	0	74.7	3.47	11.0	4.93
31.43	2.20	0	0	40.42	30.95	9.01	33.21	13.89	6.23	0.34	55.74	94.9	4.40	10.4	4.70
49.94	3.50	3.16	1.81	0.36	0.28	0	0	9.37	4.20	0	0	64.7	3.00	2.9	1.28
0	0	0	0	0.26	0.20	0	0	0.08	0.04	0	0	2.0	0.09	0	0
0	0	0	0	0.20	.015	0.04	0.15	1.73	0.78	0.27	44.26	1.4	0.06	0.2	0.08
0	0	0	0	0	0	0	0	0	0	0	0.5	0.02	0	0	0
0	0	0	0	0	0	0	0	0	0	0	15.0	0.70	0	0	0
0	0	0	0	0	0	0	0	0.33	0.15	0	0	5.2	0.24	0.1	0.03
0	0	0	0	0	0	0	0	0	0	0	0	12.6	0.58	0.9	0.42
0	0	0	0	0	0	0	0	1.16	0.52	0	0	25.4	1.18	5.3	2.39
1425.35	100.00	174.60	99.98	130.54	100.00	27.13	99.99	223.02	100.01	0.61	100.00	126.6	100.0	222.4	100.0
	0.471				0.583				0.857				0.754		

dra (Community Type D1b), which is similar to *Dryas* vegetation on sandstone knolls (described above) but without the rich assemblage of forbs.

Dry *Arctous alpina, Hierochloë alpina* dwarf-shrub, fruticose-lichen tundra (Vegetation Type D1c, Fig. 6) is one of the more common types on dry till deposits. The vegetation in most areas mapped as this type is actually quite complex, and local small areas, not discernible at 1:6000 scale, may be dominated by any of several plant taxa including *Arctous alpina, Salix phlebophylla, Calamagrostis inexpansa, Betula nana,* or *Vaccinium vitis-idaea.* The dominance of one of these species over the others at any particular site appears to be a function of subtle differences in the local snow and moisture regimes and depth of soil.

Snow accumulation areas on till deposits have a wide variety of vegetation types including those described above for sandstone outcrops (especially Community Type M1a). Dry *Cassiope tetragona, Calamagrostis inexpansa* dwarf-shrub, fruticose-lichen tundra (Vegetation Type D1e, described below with "nonsorted stone stripes") is common in depressions on clay-rich till and on nonsorted stone stripes on the shoulders of ridges where there are shallow snowbeds. Dry stony areas often have communities dominated by *Betula nana* (Community Type D1g). Blockfields, sorted stone polygons, and isolated glacial erratics are dominated by dry *Rhizocarpon geographicum, Cetraria nigricans* lichen barren. Like the sandstone outcrops, till deposits are covered primarily by dry vegetation types (73%), but with a preponderance of the *Arctous*-dominated types (Tab. 2).

Fig. 3. Terrain units of the R4D site.

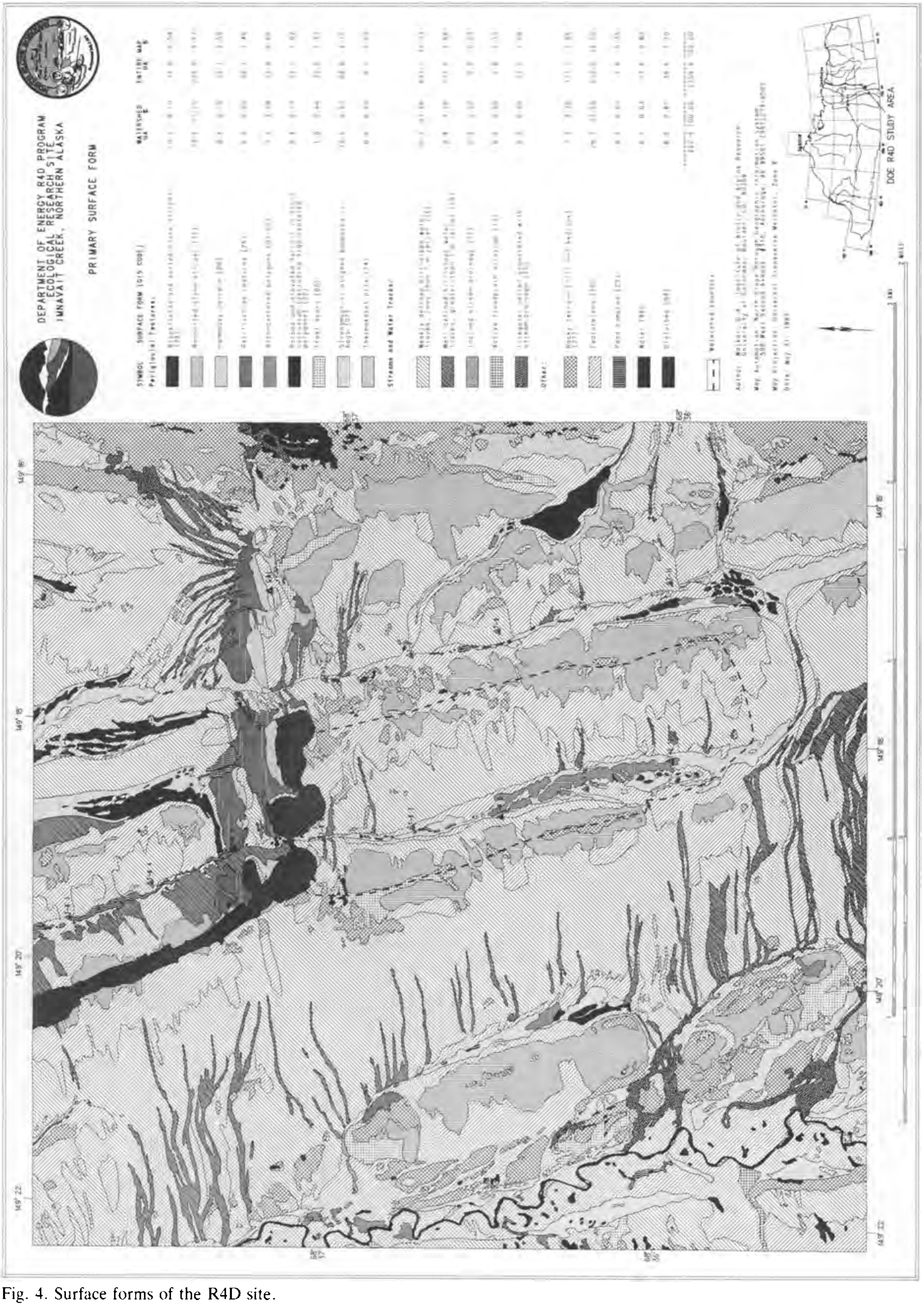

Fig. 4. Surface forms of the R4D site.

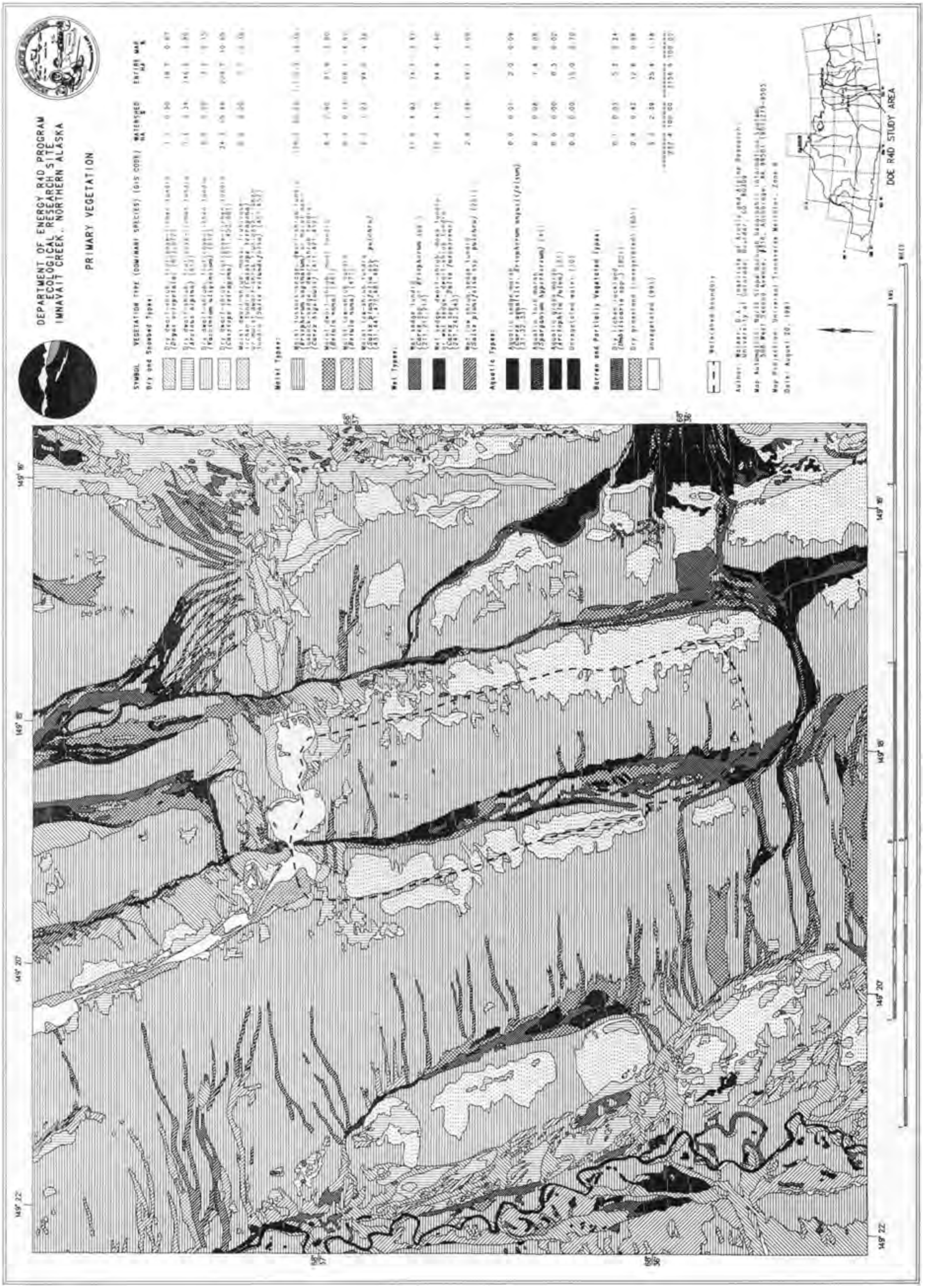

Fig. 5. Vegetation of the R4D site.

Fig. 6. Till deposit with dry *Arctous alpina, Hierochloë alpina* dwarf-shrub, fruticose-lichen tundra. Other visible species include *Cladonia* spp., *Dicranum elongatum, Vaccinium vitis-idaea,* and *Sphaerophorus globosus.*

Retransported hillslope deposits

Geology and surface forms

Kreig and Reger (1982) have mapped most hill slopes in the region as "retransported deposits", which are "relatively fine-grained organic-rich materials moved downslope by slopewash, solifluction and piping. This unit is frozen and commonly contains massive ice". Till on most hill slopes of the R4D watershed is covered by clay loam that has been redistributed downslope and vegetated with tussock tundra. Glacial erratics protrude up to a meter above the accumulated colluvium and peat. About 76% of the watershed and 70% of the total mapped area are mapped as retransported deposits. Surface forms associated with retransported deposits include water tracks, frost scars, and nonsorted stone stripes. The lower portions of stone-stripe complexes often grade into and may be the foundation for water-track complexes.

Nonsorted stone stripes

The shoulders of most hills have well-vegetated nonsorted-stone-stripe complexes (Fig. 7), described by Washburn (1956) as "...patterned ground with striped pattern and a nonsorted appearance due to parallel lines of vegetation-covered ground and intervening strips of relatively bare ground oriented down the steepest available slope". Stripes at the R4D site consist of a dry to moist well-vegetated stony element 1.5 to 2 m wide and a comparably-wide moist to wet peaty element. The dry elements usually have frost scars and well-developed hummocks. The interstripe element, in spite of its wetness, is often elevated above the level of the dry element because of the accumulation of organic matter.

Vegetation on the dry portion of the stone-stripe complex is primarily dry *Cassiope tetragona, Calamagrostis inexpansa* dwarf-shrub, fruticose-lichen tundra (Tab. 1, Community Type D1e, Fig. 8). The inter-stripe areas generally have a variant of the moist *Carex bigelowii, Sphagnum* spp. nontussock-sedge, dwarf-shrub tundra, see 'hillslope water tracks' below). This variant contains *Cassiope tetragona* and a few basophilous taxa, such as *Dryas integrifolia, Tomenthypnum nitens* and *Salix reticulata.*

Hillslope water tracks

Most hill slopes have water tracks, which Everett describes as "...shallow channels that conduct snow melt-water and subsurface water during the thaw season... giving the topography a ribbed appearance". (Walker et al. 1982). These 'hillslope water tracks' are distinct from the lowland 'water-tracks' described in mires of Minnesota, Labrador and northern Europe (Heinselman 1970, Glaser et al. 1981, Glaser 1983), where the term 'water track' applies to minerotrophic drainage tracks in lowlands through generally flat peatlands. Lowland water tracks occur in the R4D study area in colluvial basin deposits (see Fig. 7, and below).

The hillslope water tracks are subparallel channels spaced tens of meters apart. Most water tracks within the R4D watershed are shallow with no clear drainage channel. There are a few well-developed water tracks within the watershed, but better examples occur north of the 'Gal' benchmark (Fig. 3) and on the lower part of

Fig. 7. Hillslopes and basin colluvium. (A) Nonsorted stone stripes radiating from hillcrest; wet elements of stripe complex are labeled "W" and are lighter due to cover of sedges and dwarf shrubs; and those labeled "X" and are darker due to more bare soil; (B) circular frost scars on hill crest; (C) well developed hillslope water tracks; (D) weakly developed hillslope water tracks; (E) glacial erratics; (F) boundary of colluvial basin deposit; (G) high-centered polygons; (H) palsas; (I) strangmoor; (J) thermokarst pits; (K) caribou trails; (L) off-road vehicle trails; (M) lowland water tracks (color aerial photo, 9–6–86, Flt 2–1).

the long west-facing hill slope of the watershed just west of the R4D watershed (Fig. 1).

Vegetation in the well-developed tracks is often wet *Salix planifolia* ssp. *pulchra, Eriophorum angustifolium* low-shrub tundra, but can vary considerably depending on the volume of water carried by the track. The best-developed tracks have several vegetation types within them. The wettest part of these tracks is often a narrow unvegetated zone or an almost pure community of *Eriophorum angustifolium* that intergrades with the *Salix*

Fig. 8. Nonsorted stone-stripe complex. Plot in background is on drier element of the complex, and plot in foreground is on relatively wet element. The dry element has *Cassiope tetragona, Calamagrostis inexpansa* dwarf-shrub, fruticose-lichen tundra. The wet element is dominated by *Carex bigelowii.* Note the well-developed moss hummocks on both elements of the complex.

planifolia ssp. *pulchra* community (Tab. 1, Community Type W3) along the margins of the channel. This same community also occurs on the wet east-facing hillslopes of the watershed, where there are water seeps but few clearly defined water tracks. These areas often have weakly defined solifluction features, with little difference between the vegetation on the tops of the solifluction hummocks and the interhummock areas due to the overall wetness. In these situations, this community often grades into moist *Carex bigelowii, Sphagnum* spp. nontussock-sedge, dwarf-shrub tundra (Community Type M2b) (see below).

The somewhat elevated margins of water tracks often have moist *Betula nana, Rubus chamaemorus* dwarf-shrub, moss tundra (Community Type M3a). This same community also occurs along weakly developed water tracks where water flows only briefly in interhummock areas during storm events or for a short period during the spring melt. It also occurs and is best expressed on hummocks, palsas and high-centered polygons in collu-

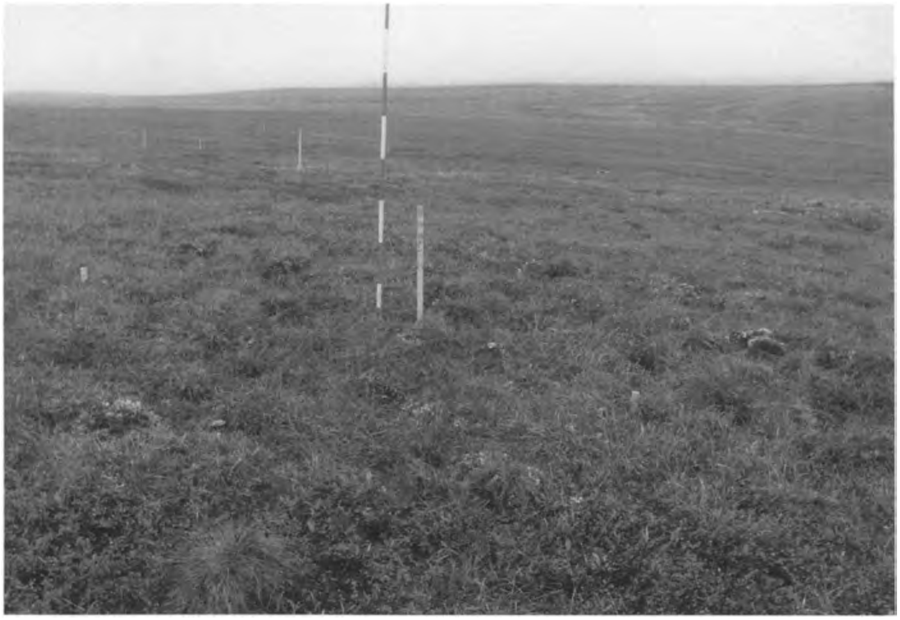

Fig. 9. Interfluve with moist *Eriophorum vaginatum, Sphagnum* spp. tussock-sedge, dwarf-shrub tundra. Other visible taxa include *Carex bigelowii, Salix planifolia* spp. *pulchra,* and *Betula nana.*

vial basins (see below). In some sites, the birch is taller than 20 cm, and the community is classed as moist low-shrub tundra (Community Type M4a).

Interfluves between hillslope water tracks are generally vegetated with moist *Eriophorum vaginatum, Sphagnum* spp. tussock-sedge, dwarf-shrub tundra (Community Type M2a, Fig. 9) or a variant dominated by *Carex bigelowii* (Community Type M2b). These communities are not very variable with regard to species composition, but they are variable with regard to species dominance. *Eriophorum vaginatum* is usually dominant on the more stable hillslope shoulders and on the upper backslopes. Shrubs (primarily *Betula nana* and *Rubus chamaemorus*) tend to become dominant on the footslopes in association with deep *Sphagnum* mats, and *Carex bigelowii*-dominated communities tend to occur in areas with weakly developed solifluction features.

Frost scars occur on most slopes, particularly on the ridge crests and shoulders and wherever there is mineral material near the surface. These features can be totally barren or with communities similar to Community Type D1e (see above discussion of nonsorted stone stripes). *Luzula arctica, Juncus biglumis,* and *Rhacomitrium lanuginosum* are characteristic species on frost scars (Community Type D4).

About 71% of the retransported hillslope deposits on the total map and 71% of the hillslopes within the watershed have *Eriophorum* tussock tundra or one of its close variants. *Cassiope*-dominated dwarf-shrub, fruticose-lichen tundra covers 13% of hillslope deposits on the entire map and 25% of similar deposits in the watershed. Moist low-shrub communities associated with water tracks cover only about 2% of the retransported slope deposits in the watershed and 3% on slopes within the entire map.

Basin colluvium

Genesis and surface forms

Imnavait Creek originates in a gently sloping basin which collects water from weakly defined water tracks in the headwaters of the basin (Figs 1 and 7). Similar basins are common throughout the Foothills Physiographic Province. Kreig and Reger (1982) mapped the deposits of these features as "organic basin fillings" and have since called them "basin colluvium" (Kreig 1985 pers. comm.). They are "generally fine-grained, organic-rich deposits with variable amounts of granular material present in basins occurring between smoothly rounded slopes on the Arctic Slope. They are usually associated with frozen upland silt... The origin of this landform is not definitely known. However, the material appears to have moved into small basins from surrounding slopes by solifluction, creep and/or slopewash. Other processes that could have a role in the genesis of this deposit are thaw basin formation and drainage, organic deposit development, and perhaps eolian deposition. Basin colluvium is differentiated from thaw lake materials by smooth gradation with surrounding slopes and the highly variable and thin character of accumulated deposits" (Kreig 1985 pers. comm.).

These basins have complex microtopography consisting of raised features, such as strangs (raised hummocks aligned in sinuous strings perpendicular to the line of drainage), palsas (ice-cored mounds), high-centered ice-wedge polygons and wet areas with lowland water-track patterns [sense of Glaser (1983)], flarks (ponded depressions between raised strangs in strangmoor complexes), wet meadows, and thermokarst pits. Basin colluvium covers about 16% of the watershed and 6% of the total map.

Vegetation

The vegetation in colluvial basins is typically complex. A common characteristic of most peatlands is the occurrence of raised microsites that are isolated from mineral input from water flowing through the basin (Sjörs 1948, 1963, Drury 1956, Damman 1977, Heinselman 1963, 1970, Glaser et al. 1981, Glaser 1983, Foster and Glaser 1986). The details of water chemistry in the R4D colluvial basin deposits have not been examined, but the *Sphagnum*-rich bog vegetation (including numerous ericaceous shrubs and *Betula nana,*) on the raised surfaces indicate relatively ombrotrophic conditions, and the occurrence of poor-fen species (e.g. *Carex rotundata, C. rariflora, Eriophorum scheuchzeri, Sphagnum lindbergii*) in the water tracks and lower microsites indicate relatively minerotrophic conditions.

Low hummocks generally have wet *Salix fuscescens, Sphagnum lenense* dwarf-shrub, sedge, moss tundra (Community Type W2a). Well drained palsas and hummocks have moist *Betula nana, Rubus chamaemorus* dwarf-shrub, moss tundra (Community Type M3a, Fig. 10, described above with water track vegetation). The best drained palsas and hummocks have the variant moist *Betula nana, Cladonia rangiferina* dwarf-shrub, fruticose lichen tundra (Community Type M3b). This type is similar to Type M3a except it is drier and has abundant fruticose lichens, dominated by *Cladonia* spp.

Wet sites in the colluvial basins have a variety of wet sedge tundra types that are dominated by any of a variety of sedges including *Carex rotundata, C. rariflora, C. chordorrhiza, C. aquatilis, Eriophorum scheuchzeri,* or *E. angustifolium.* Not all of these types were sampled. The most common type in the R4D watershed is wet *Carex rotundata, Sphagnum lindbergii* sedge tundra (Community Type W1a). The margins of many basins have *Sphagnum* meadows similar to wet *Salix fuscescens, Sphagnum lenense* dwarf-shrub, sedge, moss tundra (Community Type W2a described above) or a variant with *Carex aquatilis.* This type has an open cover of ericaceous shrubs, *Betula nana, Rubus chamaemorus,* and other bog species, and has a light color on aerial photographs (note light margins around colluvial basins in Figs 1 and 7). It grades into the tussock tundra on the lower slopes of the surrounding hills.

Fig. 10. Wet meadow in colluvial basin with small ice-cored mounds (palsas). Vegetation on the palsas is moist *Betula nana, Rubus chamaemorus* dwarf-shrub, moss tundra. Vegetation in the wet meadow is a complex of hummocks and inter hummocks. Hummocks have wet *Salix fuscescens, Sphagnum lenense* dwarf shrub, sedge, moss tundra and the interhummock areas are dominated by wet *Carex rotundata, Sphagnum lindbergii* sedge tundra.

The most common vegetation types in colluvial basins are wet sedge tundra (34%), wet sedge, dwarf-shrub, moss tundra (31%) and moist dwarf-shrub, moss tundra (25%) (see Tab. 2).

Floodplain deposits

Floodplain deposits cover 11% of the total map, but are relatively uncommon within the watershed (0.3%). The large floodplain of the meandering Kuparuk River contrasts markedly with the small beaded Imnavait Creek. The colluvial basin gradually funnels into the narrow floodplain of Imnavait Creek. The stream "beads" are small ponds formed wherever the stream has eroded massive ground-ice deposits. The margins of the stream are predominantly peaty although there are short sections with stony creek banks.

Vegetation

Most of the small beaded ponds of Imnavait and Toolik Creeks have aquatic communities with almost pure stands of *Sparganium hyperboreum* (Community Type Ald). *Hippuris vulgaris,* and aquatic mosses (*Sphagnum lindbergii, Calliergon sarmentosum*) also occur in most ponds. The edges of these ponds may have other species including *Comarum palustris,* and *Carex aquatilis.* The streams linking the ponds are usually dominated by *Carex aquatilis* and *Eriophorum angustifolium* (Community Type A1a).

Stream margins are highly variable. The margins of small beaded streams have a distinctive sedge community dominated by *Carex aquatilis* with *Salix chamissonis* and numerous species of forbs (Community Type W2c). Many streamside communities are similar to wet *Salix planifolia* ssp. *pulchra, Eriophorum angustifolium* low-shrub, sedge tundra. *Carex aquatilis* and *E. angustifolium* are common along stream margins and isolated stands of almost pure *Arctagrostis latifolia* also occur. The banks of the Kuparuk River have well developed low-willow communities (Community Type M4b).

Landscape evolution

Influence of Terrain Age

The patterns of vegetation are controlled to a large extent by surface topography of the different-aged glacial units (see Figs 1 and 5). The terrain along the Kuparuk River and along the eastern edge of the map are part of younger glacial till and outwash surfaces than that of the rest of the map. The Shannon-Wiener indices (Tab. 2) indicate that the more mature terrains, represented by the retransported hillslope deposits and basin colluvium, are less heterogeneous than the till or floodplain deposits.

The younger Itkillik-age till surfaces are generally coarse-grained with irregular relief and relatively high cover of dry vegetation types. The older surfaces tend to have Sagavanirktok-age till exposed on the ridge crests, but are dominated by tussock-tundra and colluvial-basin deposits on the lower slopes. Idealized catenas based on vegetation and soils data from the long west-facing slopes of the R4D site illustrate this sequence (Fig. 11). These trends are consistent with patterns described by Hamilton (1986) on end moraines of Sagavanirktok age. Hamilton used the surface morphology, weathering features, clast lithology, and vegetation cover on six different glacial deposits to help distinguish between these different aged surfaces.

Jorgenson (1984a, b), has built on Hamilton's (1978) observations to develop a concept of landscape evolution for three of these deposits [Sagavanirktok River (>125 000 ybp), Itkillik I (50–125 000 ybp), and Itkillik II (about 12 000 ybp)]. He concluded that as glaciated landscapes mature, tussock tundra and bogs become increasingly dominant, and a variety of factors, including colluviation, paludification, ice-aggradation, and eolian deposition, lead to the generally subdued hillslopes of the older surfaces. He also presents an hypothesis of organic terrain development based on thermophysical changes to the surface. The central concept is that as highly insulative peat builds up on the older surfaces, heat flux is reduced and active layers are decreased, leading to ice aggradation and terrain that is susceptible to thermokarst. Palsas and high-centered polygons in colluvial basins are examples of areas where ground-ice volumes are high, and these peat plateaus are highly susceptible to collapse if disturbed.

Although the details of Jorgenson's concept of foothills landscape evolution need to be expanded to include the other glaciated surfaces of the Foothills, the basic concept has significance in relation to the terrain in the Imnavait Creek watershed and the development of an approach to predict terrain sensitivity to disturbance. The lower hillslopes at the site should have greater quantities of ground ice because of the deeper accumulations of *Sphagnum* peat. *Sphagnum*, because of its highly insulative character and rapid growth rates, is a major factor contributing to large amounts of ground ice (see Sepällä 1986, Zoltai and Tarnocai 1971, Hinkel et al. 1987 regarding the effects of insulative organic layers on massive ground ice). Paludification of the foothills landscape is an important process that needs a fuller examination with regard to terrain sensitivity.

Hill crests and shoulders along typical west-facing hillslopes on Sagavanirktok-age till (Fig. 11) have rocky mineral soils with relatively high heat flux, thick active layers (>80 cm), and low amounts of interstitial ground ice near the top of the permafrost table. This contrasts markedly with the lower slopes, where *Sphagnum* forms thick carpets on the fine-grained retransported deposits. The moss insulates the soil, creating a shallow active layer (20–30 cm thick) and ice-rich soil B horizons. At this point in our investigations, it is uncertain how deep the ice-rich zones extend because our observations have been limited to chipping frozen soils in the bottom of soil pits. Deeper cores are needed to determine the total ice content of the soils. A possible explanation for the ice-rich zones could be the process of "upfreezing" described by Mackay (1981). This process involves the accumulation of ice at the interface between the active layer and the permafrost by ice-lensing during the summer thaw period.

It would be interesting to contrast the ground-ice contents of acidic, *Sphagnum*-rich foothill tundras with that of alkaline foothill tundras where there is calcareous loess. These areas lack *Sphagnum* and may show very different moss productivity and ground-ice patterns. Both of these tundra types cover large areas of the foothills and have distinct spectral signatures on aerial photographs and Landsat imagery (Walker and Acevedo 1987).

Role of ground water and snow

Another important consideration for *Sphagnum* growth and massive ground ice is the amount of water available. The degree of water-track development is a clue to local subsurface water regimes. For example, at the R4D site, the west-facing slopes have relatively few well-developed water tracks particularly below snow accumulation zones, except on the lower parts of the longer slopes. In contrast, north-facing slopes have well-defined tracks. [Compare the tracks on the west-facing slopes of the R4D watershed with those on the north side of the sandstone knoll in the upper left corner of the mapped area (Figs 1 and 4)]. This is at least partially related to snow distribution patterns (see Evans et al. 1989). The west-facing slopes have relatively shallow winter snow that melts rapidly during the first few days of the snow melt season (Liston 1986, Hinzman and Kane 1987, Evans et al. 1989), whereas the steeper north-facing slopes have deep snowbanks that provide water well into the summer dry season to the lower slopes where water tracks are common. The tracks, once established, also tend to trap snow and provide an additional source of moisture. The longer west-facing slopes have well-developed tracks because they have larger source areas to collect summer precipitation for water-track formation. The details of subsurface water movement are being explored by other investigators in the R4D project.

Terrain sensitivity maps

In the Southern Foothills, it is clear that terrain sensitivity to disturbance can be related to landscape evolution and that it should eventually be possible to accurately predict thermokarst susceptibility based on the age of the landscape, surface morphology, existing vegetation, and hillslope geometry. These are common elements of geographic information system (GIS) data bases (Evans et al. 1989) and would make derivation of terrain sensitivity maps feasible. Detailed ground-ice studies in the R4D area and on slopes of other ages would help develop models for predicting ground ice. Core data from long transects through a variety of till deposits [e.g. the vertical support member (VSM) logs from the trans-

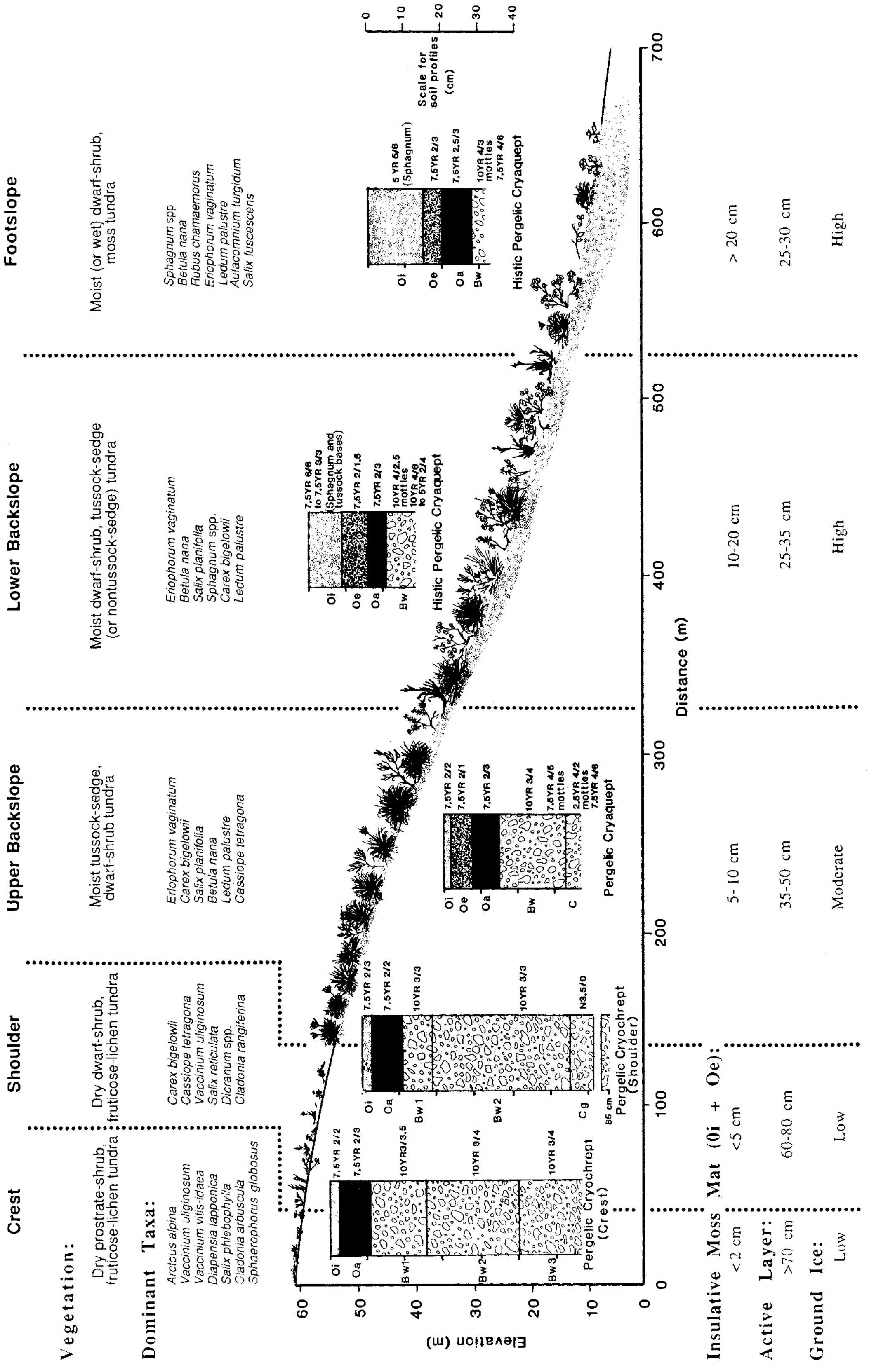

Fig. 11. Idealized R4D toposequence for west-facing slope.

Alaska pipeline] would be invaluable for testing the reliability of such models.

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