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Vegetation development on the glacier moraines in Oobloyah Valley, Ellesmere Island, high arctic Canada

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Abstract: The process of the vegetation development on glacier moraines was surveyed in the lower stream area of Oobloyah Valley (80°50′N, 82°45′W), Ellesmere Island, high arctic Canada. Four glacier moraines, and an outwash plane with different establishment periods in the proglacial field of Arklio Glacier, were surveyed. The oldest moraine was estimated to have been established during the Full Glacial, *ca.* 25000–35000 years ago, and the youngest one during the Little Ice Age, *ca.* 250 years ago. The vegetation properties such as number of species per study plot, cover of vegetation, lichens and bryophytes showed constant increase with the moraine age, suggesting directional vegetation development. Changes in the species composition were such that new species successively appeared during the establishment of the moraines without obvious replacement of the species. It was concluded that the manner of the vegetation development was directional-nonreplacement succession even under extreme high arctic environment, differing from the generally accepted view that under an extreme high arctic environment nondirectional-nonreplacement succession prevails. Vegetation physiognomy approached *Cassiope tetragona*-dominated dwarf shrub heath, which generally prevails in more southern regions than Ellesmere Island. The period required for the vegetation development in the study area was assumed to be quite long, probably at least *ca.* 20000 years.

key words: *Cassiope tetragona*, *Dryas integrifolia*, Ellesmere Island, glacier moraine, vegetation development

Introduction

The High Arctic is characterized by extremely harsh environments with low air temperature and small amount of precipitation. The High Arctic is marginal for establishment of plants. It is naturally assumed that the vegetation development is quite restricted as compared with environmentally more mild regions such as the boreal, temperate and tropical. Svoboda and Henry (1987), reviewing studies on the plant succession in marginal high arctic environments, proposed conceptual changes in three different types of succession in different environments from mesic temperate through near marginal to extreme marginal arctic. The first type is the directional-replacement that appears in a mesic temperate environment, in which the biological driving force of plant establishment is superior to the environmental resistance to plant establishment.

The second one is the directional-nonreplacement that appears in a near-marginal environment, in which the sum of biological driving forces is still stronger than is the sum of opposing, unfavorable factors. The third one is the nondirectional-nonreplacement type that appears under an extreme marginal arctic environment, in which the sum of counteracting forces permanently exceeds the biological driving force for most plant invasions. Despite their conceptual presentation they concluded also that concrete studies in a confined valley having revegetation patterns on ground freed by presently retreating glaciers are still valuable for revealing the successional patterns and processes following deglaciation.

The Oobloyah Valley, Ellesmere Island belongs typically to the High Arctic (Bliss, 1997). During the Last Glacial, the bottom of this valley is postulated to have never been covered completely by an ice sheet (King, 1981a; England, 1986, 1990; Pielou, 1994), although some lateral glaciers certainly developed, making moraines. The area around the valley is also postulated to have been characterized by severe continentality with greater summer cold and aridity during the Last Glacial (England, 1986), corresponding with the northeast fringe of the Wisconsin ice sheet (Ives, 1978). Additionally, this area contains moraines with different development periods by the lateral glaciers. These moraines should provide various vegetation types with different successional stages. Further, owing to an ice-free condition during the Last Glacial, this area is thought to be one of the few postulated floral refugia in central Ellesmere Island at the Last Glacial (Sbovoda and Henry, 1987; Pielou, 1991). Such circumstances of this area at the Last Glacial might provide a unique opportunity to study vegetation development over a fairly long term, probably more than 20000 years, in the extreme High Arctic environment; the present arctic vegetation in the Canadian Arctic began its existence generally only a few thousand years ago (Svoboda and Henry, 1987). Svoboda and Freedman (1994) edited studies on the environment, geology and ecology of Alexandra Fjord, *ca.* 100 km southeast of Oobloyah Bay. Koizumi (2003) presented an empirical hypothesis on the origin and development of the lush vegetated areas of Sverdrup Pass near Alexandra Fjord from the viewpoint of geoecology. However, studies on the vegetation development around the area Oobloyah Valley are still rare, except for Mäusbacher (1981) and King (1981b).

This study aims to clarify the development process of vegetation on glacier moraines with different establishment periods in the lower stream area of Oobloyah Valley near Oobloyah Bay since the Last Glacial. The nomenclature of the plants basically follows Pielou (1994), and the geographical names follow King (1981c).

Study area and study site

The study area is the proglacial field in the southern front of Arklio Glacier of the Krieker mountains, located on the right bank of the Arklio River (Fig. 1). The area is located near the mouth of Oobloyah Valley, *ca.* 6 km east of Oobloyah Bay (80°50′N, 82°45′W), Ellesmere Island, N.W.T., Canada (Fig. 1). Oobloyah Valley is a through valley, running from east to west. It enters Oobloyah Bay at valley's west end. The relief toward the north (Krieger Mountains) is of a high alpine type with valley glaciers, steep slopes, and the relief toward the south is lower mountains (Neil Peninsula) with gentle slopes (Fig. 2). The landforms in the valley are well adapted to the periglacial environment, suggesting a longer development time (Barsch, 1981). The valley is rich in well preserved moraines.

The geological frame of the study area is mainly built up of Younger Paleozoic and Mesozoic sedimentary rocks, dominated by sandstone, siltstone and shale, of the Sverdrup Basin (Völk, 1981).

Although no climatic data are available at Oobloyah Valley, the climate as represented by the weather station at Eureka (80°00′N, 85°56′W), located 130 km south of Oobloyah Valley, is extremely harsh (Atmospheric Environmental Service, 1982 after

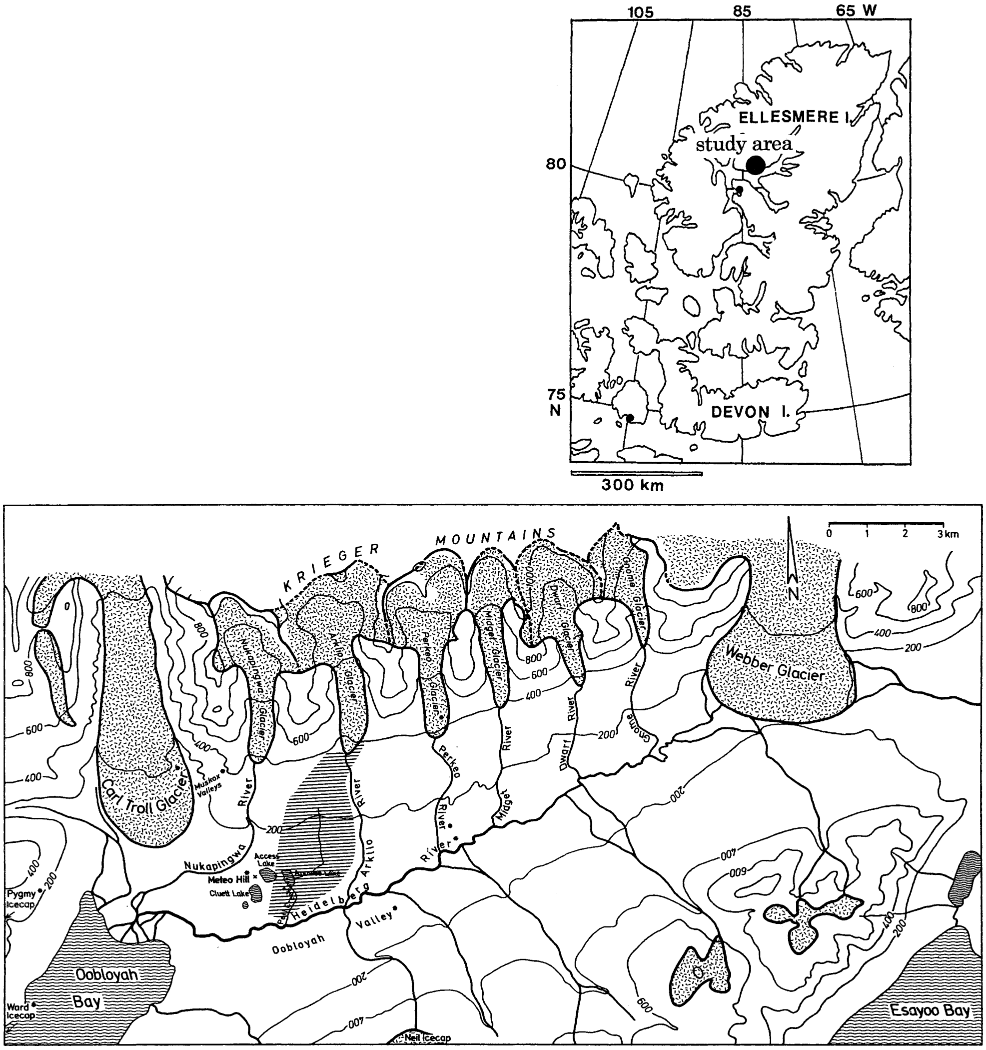

Fig. 1. The geographical location of the study area (upper: modified after Kojima, 1994), and the location of the study area (hatched area), Arklio Glacier and Arklio River in Oobloyah Valley (lower: modified after King, 1981a).

Fig. 2. A view of the study area from the middle part of Krieger Mountains toward the south. The river running from the left lower corner to the center of the picture is the Arklio River. The study area is located on the right bank (the right area of the picture) of the river, having glacial moraines of the Arklio Glacier with different establishment periods. The low mountain covered by the Neil Icecap behind the study area is part of the Neil Peninsula, and has gentle slopes. The main valley in front of the low mountain with the icecap is Oobloyah Valley.

Kojima, 1994). Annual mean temperature is −19.7°C, monthly mean temperature of the warmest month (July) 3.3°C and that of the coldest month (February) −38.0°C. Precipitation is very scarce, with a yearly total of 64 mm.

The Arklio Glacier has developed at least four glacial moraines with different development periods since the Last Glacial (King, 1981a; Fig. 3; Table 1). Figure 3 presents schematically the distribution of the four moraines in the study area, although the precise distribution of individual moraines and outwash planes are still being reviewed. The oldest moraine (I stage, Fig. 4: names of the moraine stages in this paper are tentative, showing only the relative order of their development periods, and are valid for only this paper) lies in the outermost part of the study area. It has a fairly gentle slope, and its morphology is modified by cryogenic processes. This suggests that it is the oldest four moraines, experiencing fairly long term cryogenic processes. Contrarily the youngest moraine (IV stage, Fig. 5) is located just below Arklio Glacier, consisting of fresh, sharp rocks. This moraine apparently originated during the Little Ice Age, *ca.* 250 years ago. The II and III stage moraines (Fig. 6) lie between the I and IV stage moraines. They have sharp ridges and steep slopes, still keeping clear moraine morphology. This suggests that they have experienced relatively shorter term cryogenic processes as compared with the I stage moraine. The development periods of the moraines were tentatively estimated (Table 1) according to geomorphological observations (Sawaguchi and Hasegawa, unpublished) and relative dating by a measuring of weathering rind thickness in angular rock fragments (Hasegawa, 2003), combined with

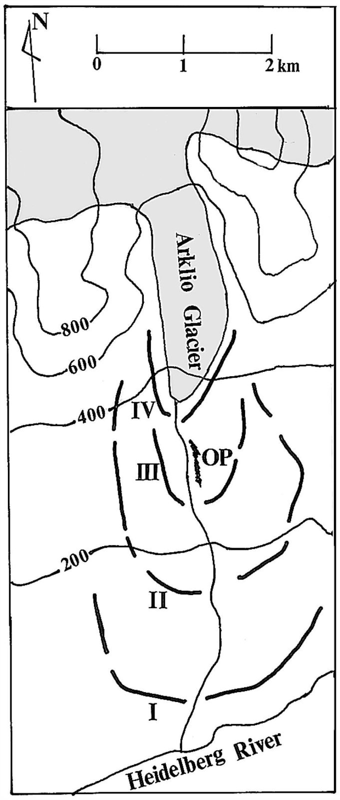

Fig. 3. Schematic representation of the distribution of the four moraines with different development periods (I, II, III, and IV in the figure) and the outwash plane (OP in the figure) surveyed in this study (modified after King, 1981a). The contour interval is 200 m. The figure shows only the approximate stretch of the moraines and the outwash plane; the precise position and the stretch are still being reviewed by Sagaguchi and Hasegawa (personal communication).

Table 1. Development periods of four moraines and an outwash plane. Estimated ages of the moraines and the outwash plane are tentative, but the order of the development periods is certain.

Moraine stage	Development period	Estimated age (years ago)	Number of plots surveyed
I	Full Glacial	25000–35000	7
II	Late Glacial	12000	13
III	Early Holocene	8000	4
Outwash plane between III and IV stage moraines	?	thousands	2
IV	Little Ice Age	250	3

related preceding studies (Barsch, 1981; King, 1981a; England, 1986, 1990). Notably, King (1981a) presents a total of twenty five radiocarbon dates around this area covering the ages from 44000±2500 years to 730±60 years and recent. These radiocarbon dates give a reliable base for the moraine dating. The oldest moraine (I stage) was established between 25000 and 35000 years ago, the youngest (IV stage) 250 years ago. The II stage moraine is assumed to have been established during the latest stage of the Last Glacial

Fig. 4. The I stage moraine (center of the picture). It has almost lost its original moraine morphology, consisting of gentle slopes.

Fig. 5. The IV stage moraine just below Arklio Glacier (the rightmost part of the picture). It consists of fresh, sharp rocks.

(*ca.* 12000 years ago), while the III stage moraine was at an early stage of the Holocene (*ca.* 8000 years ago). Although these estimates are still tentative, the order of establishment of the moraines is apparent. Accordingly the moraines show a total of at least *ca.* 25000 years' ice free period during which a fairly long term of vegetation development occurred.

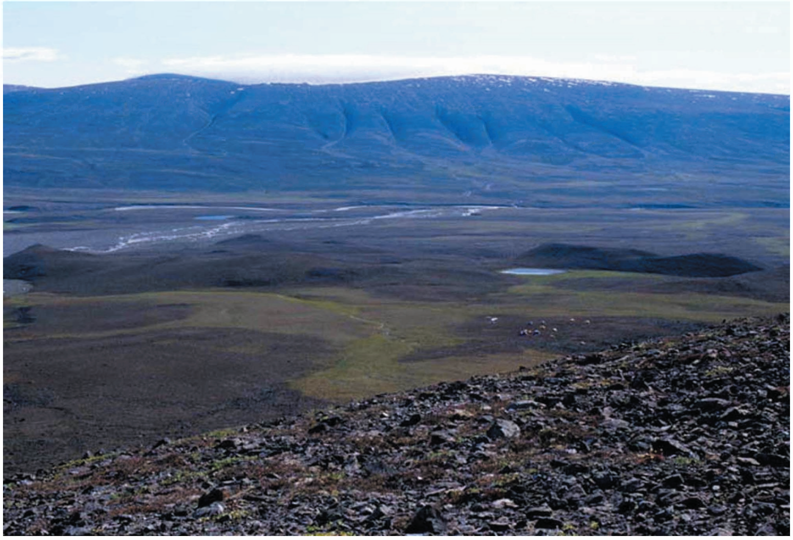

Fig. 6. The II (center of the picture) and the III stage (the leftmost part of the picture) moraines. They have sharp ridges and steep slopes, still keeping clear moraine morphology.

Fig. 7. The surface view of the outwash plane of the Arklio River surveyed in this study. The outwash plane consists of relatively rounded rocks. It is considered to have developed during the period between the IV and III stage moraines, established probably thousands of years ago. The white line in the figure merely shows the line along which twenty 1×1 m quadrats were set successively.

Study sites include these four moraines and an outwash plane of the Arklio River from Arklio Glacier (Fig. 7) that is considered to have been established during the period between the IV and III stage moraines, probably thousands of years ago (Sawaguchi and Hasegawa, personal communication). Thus the youngest study site is the IV stage moraine, *ca.* 250 years, and the oldest one is the I stage moraine, *ca.* 25000–35000 years. These five study sites follow long term developmental processes of vegetation (Table 1).

Methods

Field study was conducted in July, 2002. In each study site, two to thirteen plots were established (Table 1). In each plot twenty 1×1 m quadrats were set successively. In each quadrat, a percent cover of each higher plant and a total cover of lichens and bryophytes are recorded. Vegetation properties in a plot such as mean number of species, mean vegetation cover, lichens and bryophytes were expressed as a total or mean value of the twenty quadrats.

Results

Changes in vegetation properties

The mean number of species per plot basically increased with the age of the study sites (Table 2). This showed the minimum value of 3.7 species on the IV stage moraine, and the maximum value of 10.5 species on the II stage moraine. It slightly reduced its value in the oldest moraine to 9.1 species.

The mean cover of vegetation, lichens and bryophytes increased with the age of the study sites (Table 2). It attained the maximum value of 61% in the I stage moraine.

The total cover of the dwarf shrubs of *Dryas integrifolia* and *Cassiope tetragona*, an indicator of the progress of vegetation development, increased with the age of the study sites. The dwarf shrubs began to appear on the outwash plane with 4% cover, although *Dryas integrifolia* appeared sporadically with cover of less than 1% on the IV stage moraine. This species finally reached 50% cover on the I stage moraine. *Dryas integrifolia* occurred exclusively on the outwash plane and kept its dominance over

Table 2. Changes in vegetation properties per plot associated with the development periods of the moraines and outwash plane.

Property	Moraine stage				
	I	II	III	Outwash plane between III and IV stage moraine	IV
Mean number of species	9.1	10.7	10.5	4.5	3.7
Mean cover of vegetation (%)	61	42	40	10	1<%
Mean cover of lichens (%)	7	4	2	2	0
Mean cover of bryophytes (%)	34	10	4	1	1
Total cover of *Dryas* and *Cassiope* (%)	50	34	42	4	0
Ratio of *Cassiope* cover (%)	71	38	42	0.1	0

Cassiope tetragona until the II stage moraines. However, *Cassiope tetragona* became superior to *Dryas integrifolia* on the I stage moraine.

In summary, these vegetation properties showed constant increase from the IV stage moraine to the I stage moraine, suggesting directional vegetation development.

Changes in species composition

Table 3 presents the changes in the frequency occurrences of plants in twenty quadrats expressed as a mean value of the study plots in each study site. On the IV stage moraine six species appeared, although their occurrences were low. Of them five species occurred also on the I stage moraine, showing basically continuous occurrence through the whole development period at the study sites.

On the outwash plane five species appeared. The frequency occurrence of the species generally increased as compared with that of the IV stage moraine. Here *Dryas*

Table 3. Changes in frequency occurrence of plants in twenty quadrates as expressed by the mean value of study plots associated with development periods of the moraines and the outwash plane.

Species	Moraine stage				
	I	II	III	Outwash plane between III and IV stage moraine	IV
Epilobium latifolium	0	0	0	0	2.2
Dryas integrifolia	19.0	16.5	19.5	15.5	1.7
Salix arctica	13.0	12.9	11.0	13.5	4.0
Saxifraga oppositifolia	2.9	7.0	11.3	6.5	0.3
Papaver lapponicum	1.1	1.8	0.8	0	0.3
Stellaria longipes	0.7	0.8	1.0	0	0.3
Cerastium beeringianum	0	0.3	0.5	0.5	0
Cassiope tetragona	20.0	13.0	16.3	1.5	0
Saxifraga tricuspidata	0	2.0	0.5	0	0
Saxifraga nivalis	0	0.9	0.3	0	0
Huperzia selago	2.3	0.5	0.8	0	0
Carex misandra	0	1.7	3.3	0	0
Luzula arctica	4.1	3.2	0.8	0	0
Saxifraga cernua	0.3	1.1	1.8	0	0
Carex nardina	1.6	7.3	2.8	0	0
Cochlearia officinalis	0.3	0.3	0	0	0
Vaccinium uliginosum	3.6	0.5	0	0	0
Pedicularis arctica	0.1	0.2	0	0	0
Poa arctica	0.3	0.7	0	0	0
Sirene acaulis	0.9	0.5	0	0	0
Saxifraga ceaspitosa	0	0.2	0	0	0
Potentilla hyparctica	0	0.1	0	0	0
Draba bellii	0	0.5	0	0	0
Lesquelleria arctica	0	0.2	0	0	0
Oxyrya digyna	0	0.2	0	0	0
Pedicularis cuspidata	0.3	0	0	0	0
Total number of species	16	24	14	5	6

integrifolia attained a higher frequency occurrence of 15.5, similar figure to that in the earlier development stages of the moraines. *Salix arctica* also showed higher frequency occurrence of 13.5. *Cerastium beeringianum* and *Cassiope tetragona* appeared here first, even though their frequency occurrences were low, 0.5 and 1.5, respectively. They continuously occurred until the I stage moraine.

On the III stage moraine fourteen species appeared. Seven species appeared newly here, *Saxifraga tricuspidata*, *Saxifraga nivalis* and so on. They continuously occurred until the I stage moraine, except for *Saxifraga nivalis.* The frequency occurrence of *Cassiope tetragona* sharply increased here to 16.3.

On the II stage moraine twenty four species appeared, showing the largest number among the five study sites. Ten species appeared newly here, including *Cochlearia officinalis* and *Vaccinium uliginosum.* Of them five species occurred only on the II stage moraine, including *Saxifraga ceaspitosa* and *Potentilla hyparctica.* The appearance of ten new species and the largest number of species on this moraine among the four moraines may correlate with the largest number of the plots surveyed among the five study sites (Table 1).

On the I stage moraine sixteen species appeared. Only one species, *Pedicularis cuspidata*, occurred first here. Fifteen other species had appeared already in moraines with younger development stages. *Cassiope tetragona* was the dominant species with the frequency occurrence of 20, followed by *Dryas integrifolia* with the frequency occurrence of 19. Dwarf shrubs prevailed here. *Vaccinium uliginosum*, one of a typical element of the low arctic tundra (Bliss, 1997), increased in frequency occurrence here.

A whole new species successively jointed with the increment of the ages of the moraines without obvious replacement of the species.

Discussion

The vegetation development on the glacier moraines in this study area shows typical directional-nonreplacement succession as presented conceptually by Svoboda and Henry (1987). In this type of succession, invading species succeed in slow expansion without eliminating or replacing each other. This type of succession occurs usually under near-marginal environments that keep the sum of biological driving forces stronger than the sum of opposing, unfavorable factors (Svoboda and Henry, 1987). However, the study area typically belongs to the High Arctic with extreme, truly marginal environments. Under such harsh environments the succession type is generally expected to be nondirectional-nonreplacement in which a very few species succeed to keep their position while fluctuating in cover and standing crop, and repetitive invasions of other species fail in permanent establishment (Svoboda and Henry, 1987). Thus, the vegetation development in this study area is different from the generally accepted view.

A proposed reason for this difference is that the study area has never been covered completely by an ice sheet (King, 1981a; England, 1986, 1990; Pielou, 1994), and was characterized by severe continentality with greater summer cold and aridity during the Last Glacial (England, 1986). It might be postulated naturally that vegetation in the study area took an exceptionally long time, at least *ca.* 25000 years, to develop owing to an ice-free condition during the Last Glacial, although the environment has been continuously harsh; the present arctic vegetation in the Canadian Arctic began its existence generally only a few thousand years ago (Svoboda and Henry, 1987).

Another supposed reason for directional-nonreplacement succession is that this area is thought to have been one of the few postulated floral refugia in central Ellesmere Island at the Last Glacial (Sbovoda and Henry, 1987; Pielou, 1991). In this case the species could simply invade the newly exposed terrain in the study area from their surviving places near the area. This condition could accelerate the vegetation development.

Dwarf shrubs increase with moraine age. Of them *Dryas integrifolia* prevails first. At the outwash plane this species attains higher occurrence than *Cassiope tetragona*. This high invasion ability of *Dryas integrifolia* probably results from the symbiotic dinitrogen fixation of the *Dryas* species which have *Alnus*-type root nodules (Lawrence *et al*., 1967; Henry and Svoboda, 1986).

Vegetation physiognomy finally approaches that of the *Cassiope*-dominated dwarf shrub heath in the study area. Nams and Freedman (1987) concluded that the *Cassiope*-dominated dwarf shrub heaths reflect the conservative, stress-tolerant growth strategy of *Cassiope tetragona*. Bliss (1997) classified such *Cassiope-dominated* vegetation as dwarf shrub heath tundra in the Low Arctic or dwarf shrub heath tundra in the High Arctic. Both of them occur principally in more southern regions than the study area (Bliss, 1997). In the extremely High Arctic such as Ellesmere Island and Cornwallis Island, vegetation is best represented by polar desert with sporadic occurrences of vascular plants (Kojima, 1991; Bliss, 1997). *Cassiope*-dominated dwarf shrub heaths are relatively uncommon in the extremely High Arctic (Bliss, 1979; Names and Freedman, 1987). The developed vegetation in the study area is in contrast with usual High Arctic vegetation. This might result from such peculiarities of Oobloyah Valley as a long term ice-free condition and, as postulated, refugia during the Last Glacial. However, the directional vegetational change of the vegetation in the study area is supposed to require a quite long period, probably at least *ca.* 20000 years; the vegetation property and species occurrence show a discrepancy between those of the II stage moraine and the I stage moraine, suggesting that even on the II stage moraine the vegetation still remains under development.

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