PERGAMON

Quaternary Science Reviews 20 (2001) 419–436

Last Interglacial (isotope stage 5) glacial and sea-level history of coastal Chukotka Peninsula and St. Lawrence Island, Western Beringia

Julie Brigham-Grette[a,*], David M. Hopkins[b], Victor F. Ivanov[c], Alexander E. Basilyan[d], Sonja L. Benson[e], Patricia A. Heiser[f], Vladimir S. Pushkar[g]

[a]*Department of Geosciences, University of Massachusetts, Amherst, MA 01003-5820 USA*
[b]*Alaska Quaternary Center, University of Alaska, Fairbanks, AK 99775-1200 USA*
[c]*NorthEast Science Center, Russian Academy of Sciences, 16 Portovaya Street, Magadan 685000 Russia*
[d]*Geological Institute of The Russian Academy of Sciences, 7 Pyzhevsky Street, Moscow 109017 Russia*
[e]*P.O. Box 82860 Fairbanks, AK 99709 USA*
[f]*Department of Geological Sciences, Ohio University – Athens, Athens OH 45701 USA*
[g]*Pacific Institute of Geography, Far East Branch, Russian Academy of Sciences Vladivostok 690032 Russia*

Abstract

Study of glacial and marine sequences along the outer coast of Chukotka Peninsula, Bering Strait, is the basis for major revisions of the regional stratigraphy. The Val'katlen Suite at its type section at the mouth of the Enmelen River records the youngest high sea stand of the last interglaciation on Chukotka Peninsula. Marine deposits and glacial diamicton stratigraphically below the type section record, respectfully, the peak of the last interglacial (marine oxygen-isotope substage 5e) and rapid glacierization of the coastal mountains probably during substage 5d or 5b. Correlative deposits recording a similar sequence of intra-stage 5 events, but once thought to be of early and middle Pleistocene age, include the Upper and Lower Pinakul' Suite at Cape Pinakul' and marine deposits near the Nunyamo River on the Gulf of Anadyr, based upon amino-acid analyses, biostratigraphy, and supporting geochronology. These deposits enclose warmer-than-present faunas and floras comparible to last interglacial Pelukian marine deposits found along the coast of Alaska. The last major advance of glacial ice from Chukotka Peninsula across Anadyr Strait and onto St. Lawrence Island was likely initiated during the later part of stage 5 based on our reinterpretaion of the stratigraphy at Cape Pinakul', near the Nunyamo River, and on northwestern St. Lawrence Island. Chukotkan ice probably reached St. Lawrence Island sometime during oxygen-isotope stage 4. Ice extend across Chukotka during the LGM was very imited.

1. Introduction

This paper is the second of two contributions that describe the paleoclimatic history of Beringia during the last interglaciation (see also Brigham-Grette and Hopkins, 1995). The most laterally continuous sequences of marine deposits in the Beringian region (Fig. 1) are those associated with high sea level stands of the last interglacial, oxygen-isotope stage 5 of the marine record. Coastal deposits of substage 5e are represented on Alaskan shores by deposits of the Pelukian transgression (Hopkins, 1967; Brigham-Grette and Hopkins, 1995), and a later high sea level event within stage 5 is recorded by the Flaxman Formation, found on the Beaufort Sea coast of Alaska (Brigham-Grette and Hopkins, 1995). In glaciated areas on Chukotka Peninsula, northeastern Siberia, as well as on nearby St. Lawrence Island, stage 5 deposits are commonly found within glaciotectonically deformed marine and glacigenic sequences. The Val'katlen Suite, exposed in coastal bluffs near the mouth of the Enmelen River (Petrov, 1966) has traditionally been ascribed to substage 5e on the Chukotka Peninsula. In this paper, we propose a revised age within isotope stage 5 for the Val'katlen Suite, and we show that marine sediments of stage 5 age are also present at Cape Pinakul' and at the mouth of the Nunyamo River (Fig. 2).

Here we describe and reinterpret the stratigraphy of stage 5-aged deposits at these three key sites; based on

* Corresponding author. Tel.: 1-413-545-4840; fax: 1-413-545-1200.
E-mail address: brigham-grette@geo.umass.edu (J. Brigham-Grette).

0277-3791/01/$ - see front matter
PII: S0277-3791(00)00107-4

Fig. 1. Location map of Beringia.

our understanding of eustatic sea level fluctuations during stage 5 in northern and western Alaska . From this we draw inferences about past water-mass conditions and time of initiation and extent of glaciation in the Bering Strait region during isotope stage 5. Our discussion is based on joint field studies conducted in 1991, 1992, 1993, on amino-acid geochemistry, paleontology, and other geochronological analyses of material collected during those field studies, and on a past study of regional ELA depression in western Alaska (Kaufman and Hopkins, 1986). Weather data for Chukotka stations were obtained from World Meterorological Stations near the study area (Uelen, 66.2°N, 169.5°E; Lavrentiya, 65.6°N, 171°E; and Providenya, 64.4°N, 173.33°E). It is important to acknowledge that one of the Russian authors (VFI) disagrees with many of the conclusions presented here, But nevertheless has made many contributions to this study and is therefore recognized as a coauthor.

In order to erect a new stratigraphic framework for late Cenozoic glacial and sea level history in central Beringia, we have relied upon the amino-acid geochronology of marine mollusks to determine relative ages and to correlate marine and glaciomarine units between widely spaced exposures. In our regional work, the ratio of D-alloisoleucine to L-isoleucine (hereafter, aIle/Ile) was used in concert with stratigraphic position and biostratigraphy to identify deposits of last interglacial age. As in our earlier paper (Brigham-Grette and Hopkins, 1995), the sampling strategy and laboratory methods follow the recommendations of Miller and Brigham-Grette (1989). For the most part, we have relied upon the

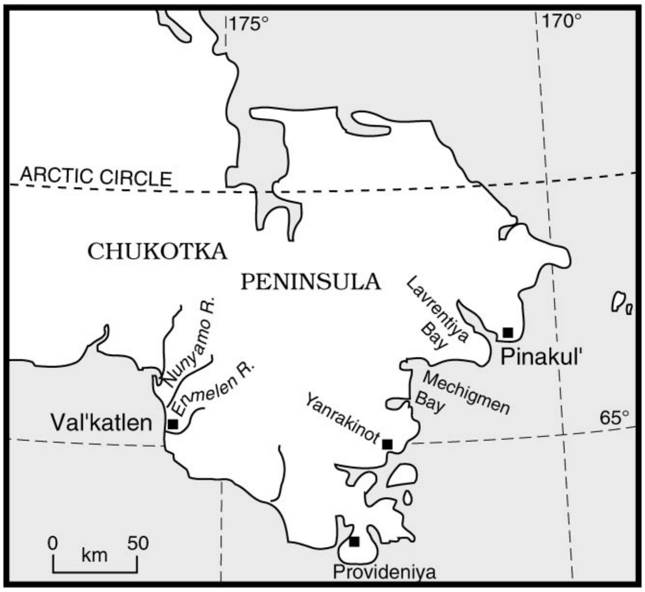

Fig. 2. Regional map of study sites on Chukotka Peninsula, north-eastern Russia.

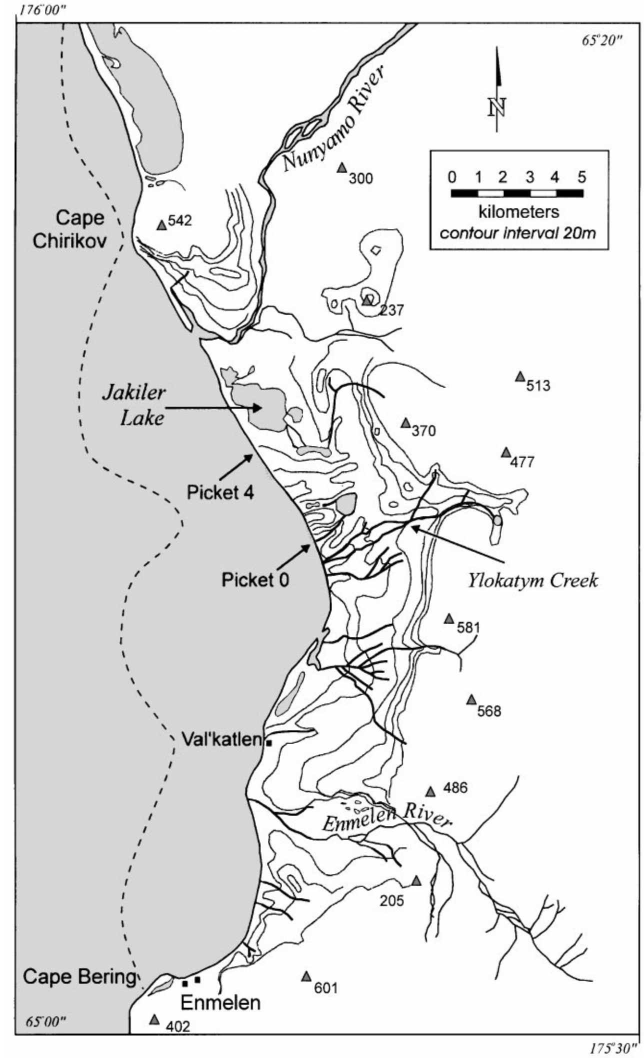

Fig. 3. Coastal plain between Cape Chirikov and Cape Bering, Chukotka Peninsula. Contours are shown in the coastal plain area only. Dashed lines are positions of submerged moraines interpreted from bathymetry and seismic profiling by Ivanov (1986). Enmelen section (Fig. 7) extends northward for ca. 2 km from the mouth of the Enmelen River; Nunyamo Bluff section (Fig. 8) lies north of Ylokatym River and extends from Russian "Picket 0" to "Picket 40" here indicated 0–4.

aIle/Ile ratios on *Mya* and *Hiatella* but have supplemented these data with ratios on *Astarte* and *Macoma* and occasional other taxa at sites where *Mya* and *Hiatella* are rare. Unfortunately, aIle/Ile epimerization rates in mollusk shells at this latitude are too slow to allow us to distinguish between shells from the different substages of stage 5. Although stratigraphic evidence strongly suggests that Chukotkan glaciers expanded to and beyond the present shores of Bering Sea during a substage of stage 5, determination of the precise ages of the glacial and marine units at our study sites will require additional analyses on mollusks from these same sections using the faster racemizing aspartic acid (Goodfriend et al., 1996).

2. Stratigraphic Records From Chukchi Peninsula, Russia

The Pinakul' section is exposed at Cape Pinakul', a coastal bluff that lies between the entrance to Bering Strait to the north and the entrance to Lavrentiya Bay to the northwest. The Val'katlen and Nunyamo sections are coastal bluffs located on a coastal plain a few km wide that extends about 30 km along the shore of the Gulf of Anadyr (Fig. 3).

2.1. Pinakul'

2.1.1. History of investigations

Cape Pinakul', a promontory at the north entrance to Lavrenitya Bay, is probably the most famous Quaternary locality in Chukotka. The Pinakul' exposure consists of coastal bluffs about 5 km long and more than 50 m high (Figs. 4, 5a and b). A rich marine mollusk fauna collected here was described by Slodkevich in 1935. Petrov (1966) named these beds the Pinakul' Suite, distinguishing a normal marine lower sequence and an upper unit composed of glaciomarine sediments. He followed Slodkevich in noting the presence of a boreal fauna containing several extralimital southern mollusks, and he named one new, presumably extinct species, *Astarte invocata.* Ivanov (1986) restudied the Pinakul' locality and in 1991 showed JB-G and DMH the location of an exposure, now covered, in which the Lower Pinakul' Suite was seen to overlie a sequence of diamicton and thick-bedded marine silt with scattered dropstones. This structurally lower sequence, Ivanov correlated with his Yanrakinot

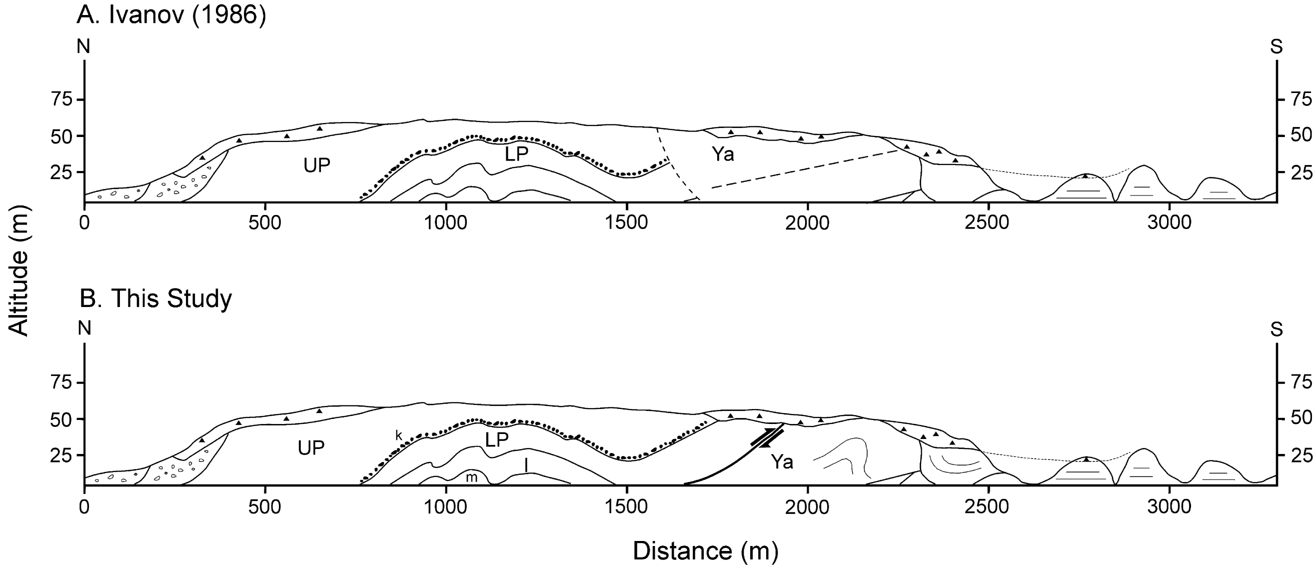

Fig. 4. Schematic cross section of the bluff exposures at Cape Pinakul', north shore of Lavrentiya Bay. (A) is the interpretation of the exposures according to Ivanov (1986) as modified during our field work by VFI and AEB. This interpretation suggests beds of the Yanrakinot suite (Ya) are younger than beds of the Upper Pinakul' (UP) and Lower Pinakul' Suite (LP). (B) is the reinterpretation of the exposure according to this study. We place the so-called Yanrakinot suite stratigraphically below the Upper and Lower Pinakul' Suite as defined. Black diamonds in both sections represent capping glacial till. . Lower case letters are sites where fossil mollusks were collected for amino-acid geochronology as keyed to Table 1.

Suite, named for a type locality 120 km to the south. The Yanrakinot stratotype, however, is reported to be of interglacial character (Ivanov, 1986).

Based on the mollusk fauna and perhaps influenced by the abundant presence of concretions, Petrov (1966) considered the Pinakul' Suite to be "early Pleistocene" — early Brunhes Polarity Chron in the Russian concept. Paleomagnetic samples collected by Ivanov (1986) were determined to be mostly reversed, except for two normally magnetized samples at the base of the Pinakul' Suite, suggesting to him that deposition of the sequence was initiated during the Matuyama Reversed Chron but close in time to either the Olduvai or the Jaramillo normal subchron.

We spent 2 weeks in 1991 studying exposures of the Upper and Lower Pinakul' Suite and the so-called Yanrakinot Suite at Cape Pinakul'. Large-scale folds and faults disrupt parts of the Pinakul' exposure (Figs. 4 and 5b). Petrov (1966) noted these and ascribed them to submarine slumping, while Ivanov (1986) argued on the basis of work by Gasanov (1969) that the large-scale structural deformation is cryogenic (that is, related to permafrost processes). A study by Benson (1993, 1994) shows, however, that both the Upper and the Lower Pinakul' Suites are glacially folded, faulted, and overridden, as is indicated by compressional features cross-cut by thrust faults. This is important, because it suggests that the height of these deposits above sea level is at least partly the result of glaciotectonism.

JBG and DMH argue that the Pinakul' Suite is far younger than proposed by previous workers and that it represents deposition during stage 5. Parts of the Pinakul' exposure that VFI assigns to the Yanrakinot Suite may consist of Upper Pinakul' Suite beds that locally have been overridden by a glaciotectonic thrust sheet involving Lower Pinakul' beds, as suggested in Fig. 4B.

2.1.2. Stratigraphy and paleoecology

The Lower Pinakul' Suite has an exposed thickness of about 37 m and consists of an upward shallowing sequence of marine sediments that grade from thick-bedded silty clay at beach level to thin-bedded, ripple-bedded sand, a few meters below the base of the Upper Pinakul' Suite. The lowest exposed Lower Pinakul' beds are rich in prismatic- and cigar-shaped glendonites, calcite pseudomorphs after ikkaite. Ikkaite, $CaCO_3 \cdot 6H_2O$, is an authigenic precipitate that forms at subzero temperatures from interstitial solutions of organic-rich [marine] sediments undergoing microbial decomposition. Its distribution in the geological record is probably diagnostic of high-latitude environments where "organic-rich sediments accumulate rapidly in cold bottom waters" (Suess et al., 1982). Shells of mollusks, especially *Astarte,* are abundant in these lower beds and commonly occur paired with intact periostracum. The upper part of the unit is laced with *Ophiomorpha* burrows and other trace fossils (Fig. 5c) and contains scattered single valves of various molluscan taxa . The lowest exposed beds evidently accumulated in cold bottom waters, well below wave base, while the uppermost sand appears to be intertidal.

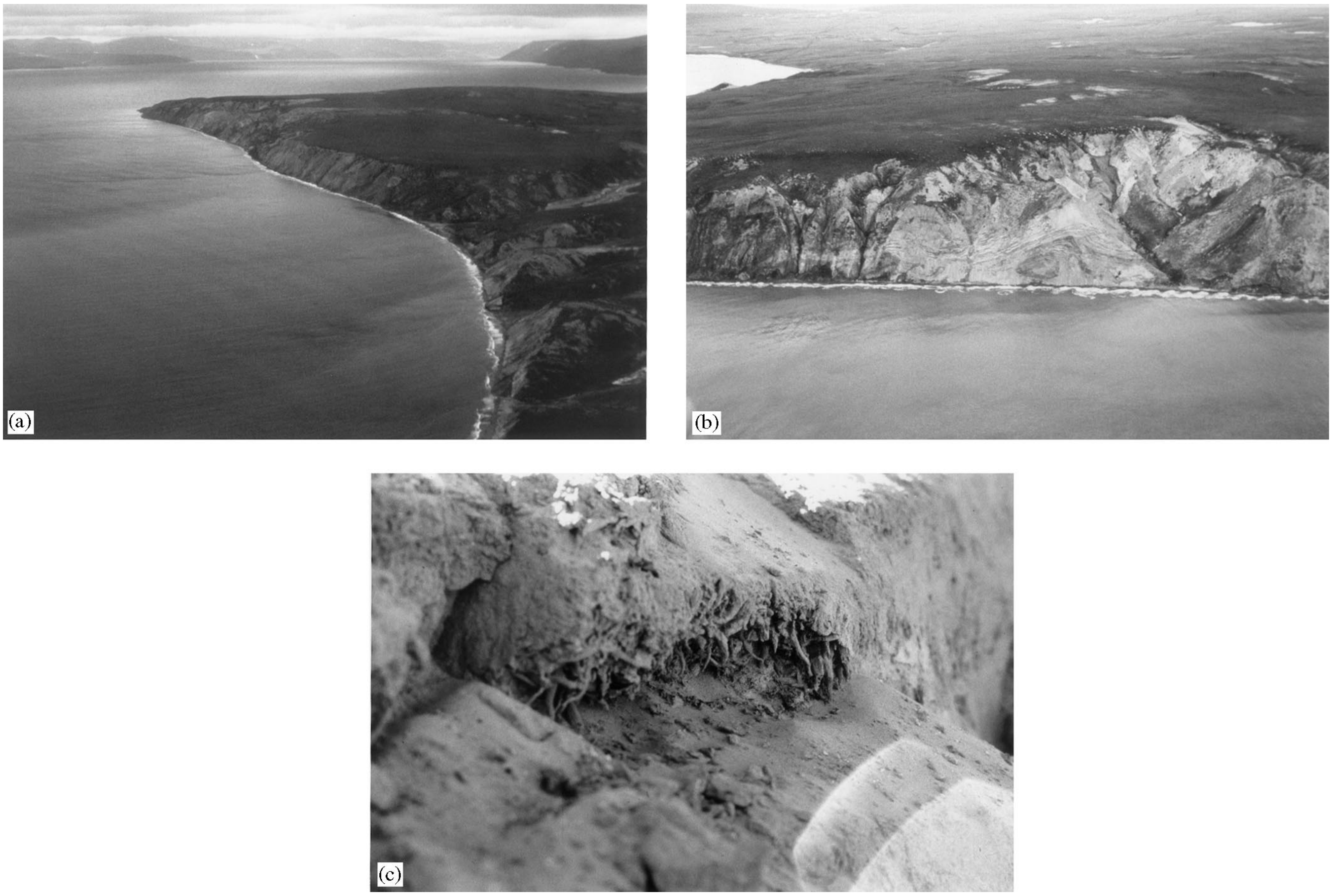

Fig. 5. Views of Pinakul' bluff. (A) Aerial view of the exposures of the Upper and Lower Pinakul' Suite at Cape Pinakul' on the north shore of Lavrentiya Bay, Chukotka Peninsula. The entire section has been glacially tectonized by ice coming down the fjord (Benson, 1993). (B) View of a portion of the exposure. Bluffs are 50–60 m high. Note anticlinal fold. (C) Detail of *Ophiomorpha* (?) burrow casts in the Lower Pinakul Suite indicating rather shallow environments. Burrowed unit about 20 cm thick.

The Upper Pinakul' Suite consists of poorly bedded to massive mud with dispersed shells and rare dropstones. Above the gravel, the upper Pinakul' is at least 15 m thick, but total thickness may be much greater. The basal few meters are very stony and of undoubted glaciomarine origin. Rapid deposition is indicated by pervasive dewatering structures that can be seen in several places along one laterally persistent bed. Mollusks shells are sparse and paleoecologically uninformative, but the foraminiferal assemblage is similar to that found in the Lower Pinakul' (Ivanov, 1986).

The so-called Yanrakinot Suite in the northern part of the bluffs is similar to the Upper Pinakul' Suite — thick-bedded to massive with sparse dropstones and mollusk shells. Exposed well above the base of this unit, however, is a 3 m layer rich in dropstones, some of which indent well-defined bedding planes. This can be traced laterally into a bed of boulders 2 or 3 m across. If the "Yanrakinot Suite" beds actually represent the Upper Pinakul' Suite, then the Upper Pinakul' includes at least two dropstone-rich glaciomarine beds.

Lower Pinakul' molluscan assemblages described by Petrov and foraminifera reported by Khoreav (1974), suggest that Lavrentiy Bay and Bering Strait waters were somewhat warmer than today. For example, *Bucella hannai arctica,* which dominates the foraminifer assemblage, is found today only in modern sediments of the Sea of Okhotsk and the Sea of Japan (Ivanov, 1986). Pollen assemblages suggest terrestrial conditions similar to today (Petrov, 1963; Ivanov, 1986).

2.1.3. Geochronology

Amino-acid aIle/Ile ratios in *Mya* from both the Lower and the Upper Pinakul' Suites are low and average 0.024 ± 0.003 ($n = 4$); these ratios are consistent with ratios of 0.028 ± 0.003 ($n = 13$) on the abundant *Astarte* shells (Table 1). *Hiatella* and *Mya* collected in the 1960s by Petrov yield similar ratios of 0.035 and 0.031, respectively (Brigham, 1985) (these slightly higher ratios were obtained more than 13 yr ago using analytical equipment at the University of Colorado; the slightly higher ratios may reflect instrument differences). The current mean

Table 1
Extent of isoleucene epimerization in mollusks from the last interglaciation, Beringia[a]

Site	Location	Genera	aIle/Ile (Total)	§	No. of shells
	in Figures		Mean	SD	
Nome[b]		*Hiatella*	0.055	0.010	6
		Mya	0.041	0.010	16
St. Lawrence Island[c]		*Hiatella*	0.051	0.014	3
		Mya	0.048	0.018	12
Val'katlen section/Enmelen Bluffs (Fig. 7)					
Upper Val'katlen-type	a	*Mya*	0.022	0.002	6
	b	*Macoma*	0.017	0.001	3
Lower Val'katlen-type	c	*Mya*	0.021	0.003	10
	d	*Macoma*	0.025	0.003	11
Diamicton under type-Val'katlen	e	*Hiatella*	0.021	0.001	3
Marine sand under diamicton south of Enmelen River	Not shown	*Mya*	0.028	0.004	8
Marine unit over diamicton south of Enmelen River	Not shown	*Hiatella*	0.033	0.004	4
Nunyamo River Bluffs (Fig. 8)					
Marine bed/12 m surface north end of Nunyamo bluffs	f	*Mya*	0.021	0.001	7
Arched marine bed/Nunyamo	g	*Hiatella*	0.024	0.005	5
	h	*Mya*	0.022	0.010	6
	i	*Astarte*	0.022	0.009	6
Glaciomarine beds/Nunyamo	j	*Mya*	0.021	0.003	3
Pinakul section (Fig. 4)					
U. and L. Pinakul' Suite	k	*Mya*	0.024	0.003	4
	l	*Astarte*	0.028	0.003	13
	m	*Macoma*	0.046	0.011	2

[a]§ Interlaboratory Standards for ILC-A = 0.151 ± 0.0006; ILC-B = 0.495 ± 0.017;
[b]Nome data from Kaufman (1992).
[c]Data from Brigham-Grette and Hopkins (1995).

Table 2
87Sr/86Sr measured in molluscs from Cape Pinakul' and St. Lawrence Island (Analyses by Lange Farmer, University of Colorado)[a]

Location	Field No.	Genus	87Sr/86Sr	Δ Sr
Lower Pinakul'	ПК32 F6/F7	Astarte	0.709177 ± 6	− 0.8
Lower Pinakul'	ПК32 F6/F7	Astarte	0.709204 ± 3	2.9
Yanrakinot	ПК58/F2	Mya	0.709198 ± 4	1.3
St. Lawrence Is.	SL02A/91	Astarte	0.709155 ± 5	− 2.1
St. Lawrence Is.	SL01/C91	Macoma	0.709154 ± 4	− 2.1

[a]Standard Used: EN-1 USGS = 0.709175 ± 3. External Error = 1×10^{-5} ppm. Δ St = [(87Sr/86Sr) sample-(87Sr/86Sr) standard] × 105.

annual temperature (CMAT) for the town of Lavrentiya, across the bay from Cape Pinakul', is −6.5°C, somewhat colder than at Nome.

Astarte shells ($n = 12$) from the so-called Yanrakinot beds in the north end of the Pinakul' exposure yielded Ile/aIle ratios of 0.080 ± 0.030. Taken at face value, these ratios would suggest deposition of the enclosing sediments during some part of stage 6 or 7. However, the wide range in ratios indicates that shells of more than one age are present (Benson, 1994). Possibly the shells that we analyzed were picked up and redeposited from older beds formerly exposed at the bottom of Lavrentiya Bay.

In an attempt to further constrain the age of the deposits at Cape Pinakul', shell samples from the Lower Pinakul' were submitted for $^{86}Sr/^{87}Sr$ analyses (Table 2). The strontium ratios are indistinguishable from those in modern sea water (L. Farmer, University of Colorado, personal communication, 1992) suggesting that the deposits enclosing the in situ shells are less than a few hundred thousand years old. Note, however, that

Table 3
Radiocarbon ages for last-interglacial deposits, Chukotka Peninsula and St. Lawrence Island

Location	Laboratory number	^{14}C Age (yr B.P.)	Sample material	Total aIle/Ile[a]
St. Lawrence Is.	Beta-69954/CAMS-11185	> 45,900	Shell	0.049
St. Lawrence Is.	Beta-69955/CAMS-11186	> 48,600	Shell	0.025
Lower Pinakul'	AA13008	> 39,100	Shell	0.028
Nunyamo River	AA13009	> 43,200	Shell	0.027
Val'katlen	AA13010	> 39,500	Shell	0.023
Val'katlen	AA13011	> 39,500	Shell	0.028
Nunyamo River	AA13012	38,850 ± 1140	Shell	0.02

[a] AIle/Ile ratio measured in same sample before radiocarbon dating.

strontium ratios for last interglacial shell material from St. Lawrence Island are unexpectedly low, suggesting that the $^{86}Sr/^{87}Sr$ technique may be suspect for emergent marine deposits (see also Kaufman et al., 1993). A glendonite concretion from the Lower Pinakul' yielded a $^{230}Th/^{234}U$ numerical age estimate of 29,720 + 1770/-1740 yr (sample JB6-93, S.E. Lauritzen, University of Bergen, personal commun. to JB-G, 1994), indicating that the most recent diagenesis in these deposits was quite young. An AMS radiocarbon analysis of a mollusk shell produced an infinite age estimate of > 39,000 yr (AA-13008) (Table 3). These geochronological results are consistent with the amino-acid results, which argue for a late rather than an early Pleistocene age for the Pinakul' Suite.

2.1.4. Paleomagnetic studies

Ivanov (1986, p. 53–54) collected 28 paleomagnetic samples distributed through a well-exposed but deformed part of the section (Fig. 5 at about 1000 m). Demagnetization methods and procedures are not given. Reported reversed inclination values range from − 30 to − 60°. Two samples from the base of the section are reported to be magnetically normal.

Disagreements among us concerning the age of the Pinakul' Suite have focused upon the integrity of Ivanov's paleomagnetic samples and the interpretation of the resulting paleomagnetic data. Ivanov trowels out large sediment cubes, 10–20 cm on a side, and takes them back to the lab wrapped in clear plastic. It is unclear whether allowance was made during his collecting at Pinakul' for glaciotectonic deformation, and even more unclear whether such samples could survive the vicissitudes of transportation from this remote site back to the laboratory, intact and without further deformation.

Recently, Pavel Minyuk, paleomagnetist at the Northeast Scientific Research Institute, Magadan, Russia, collected and analyzed 120 new samples from both the Lower and the Upper Pinakul' Suites and found the entire section to be normally magnetized, with inclinations ranging from 20 to 40° (P. Minyuk, personal commun. to JB-G, 1994). Minyuk suggests that the low inclinations are the combined result of their low field intensity and the glacial overriding.

2.1.5. Discussion and interpretation

The geochronology, the stratigraphy, and the warm fauna indicate that the lower Pinakul' records the interglacial high sea level of substage 5e, followed by a regression and shallowing that climaxed with the deposition of the beach gravel at the boundary between the Lower and Upper Pinakul' Suites. This was followed, in turn, by rapid deepening and deposition of the glaciomarine beds at the base of the Upper Pinakul' Suite which record the near approach of a large glacier in the fiord, evidently later in stage 5, while eustatic sea level still lay only a few tens of meters below its present position. After deposition of the glaciomarine diamicton at the base of the Upper Pinakul' Suite, the ice front retreated up-bay, and the stone-poor mud higher in the Upper Pinakul' was deposited.

Finally, the entire Pinakul' sequence was over-ridden, deformed, and arched up by a grounded glacier. A small stream valley at the north end of the main Pinakul' bluff has terraces of glaciofluvial sand and gravel and appears to represent a marginal outwash channel of this glacier. If this interpretation is correct, it would indicate that the final glacial advance at Pinakul' took place at a time when sea level was low, thus probably during stage 4.

The position of the terminus of the ice that overrode Cape Pinakul' is uncertain. Moraine-like forms extending northward from a point near St. Lawrence Island and that lie more than 40 km west of the mouth of Lavrentiya Bay have been identified on seismic reflection profiles (Fig. 6 Nelson and Hopkins, 1972; Hess, 1985; Ivanov, 1986). A more likely terminus, however, may be a submerged moraine identified by Ivanov (1986) about 17 km beyond the bay mouth (Fig. 6).

2.2. Val'katlen section

2.2.1. History of investigations

For more than 35 yr, Russian workers have regarded the Val'katlen Suite, exposed in coastal bluffs north of the

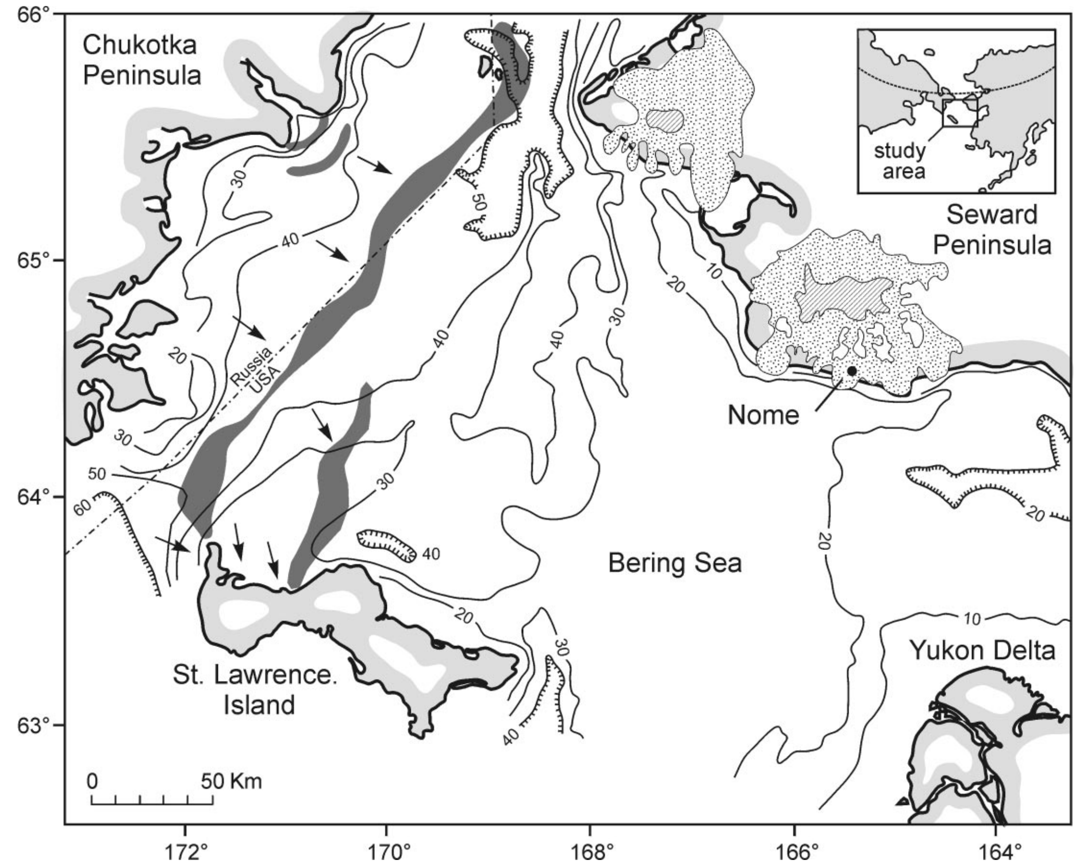

Fig. 6. Map showing submerged moraines (dark gray) in northwestern Bering Sea. Arrows indicate former ice flow directions. Thin contour lines are bathymetry in meters. Stipled areas on the Alaskan coast represent the maximun ice extent during the middle Pleistocene Nome River Glaciation. Diagonal cross hatched area is the maximum extent of glacial ice during the Late Pleistocene.

Enmelen River (Fig. 3), as the stratotype for the last interglaciation on Chukotka Peninsula (Petrov, 1963; Committee for Unified Stratigraphy of Quaternary System of Eastern USSR, 1992; Ivanov, 1986). Petrov (1966, 1967) assigned to the last interglaciation two sets of coastal terraces, one at 20–30 m and the other at 15–20 m asl, both by definition composed of sediments of the Val'katlen Suite. The lower terrace was thought to have formed during either a regressive stillstand or a sea level oscillation. In his 1986 revision of Chukotkan Quaternary stratigraphy, Ivanov continued to postulate two interglacial high sea level episodes, but, like Petrov, offered no suggestions to explain why these terraces would stand as much as 20 m above the 6–7 m altitude of last interglacial shorelines in other parts of the world (Bard et al., 1990; Chen et al., 1991) nor why they would be two to three times higher than Pelukian deposits on stable parts of the Alaskan coast (Hopkins, 1967).

In 1992, we visited the type section of the Val'katlen Suite. Interglacial marine beds here are exposed in bluffs 10–16 m high that extend 2.5 km northward along the coast of the Gulf of Anadyr from the mouth of the Enmelen River (Fig. 7). Sod houses of the abandoned village of Val'katlen stand just north of the exposure. The interglacial beds vary in thickness from about 2 m to more than 13 m and are subdivided by both Petrov (1966, 1967) and Ivanov (1986) into two units, an Upper Val'katlen and a Lower Val'katlen, thought to record two distinct high sea level stands.

2.2.2. *Stratigraphy and paleoecology*

In the southern half of the bluffs (A in Fig. 7), the Upper Val'katlen beds consist of well-sorted sublittoral sand and fine gravel resting on a gravel lag that marks an unconformity above massive, pre-Val'katlen glacial or glaciomarine diamicton. In one exposure, clasts in the diamicton > 5 cm diameter have a weak fabric with an S_1 value of 0.45. Mollusks, especially the bivalves *Mya pseudoarenaria* and *Macoma calcarea* are abundant in the interglacial sand. Some are paired but are not necessarily in growth position. In the central part of the bluffs where the interglacial sand and fine gravel is several meters thick (B in Fig. 7), dewatering structures less than a meter high interrupt the cross-bedding in a few places. Elsewhere, undisturbed burrow casts and trace fossils are

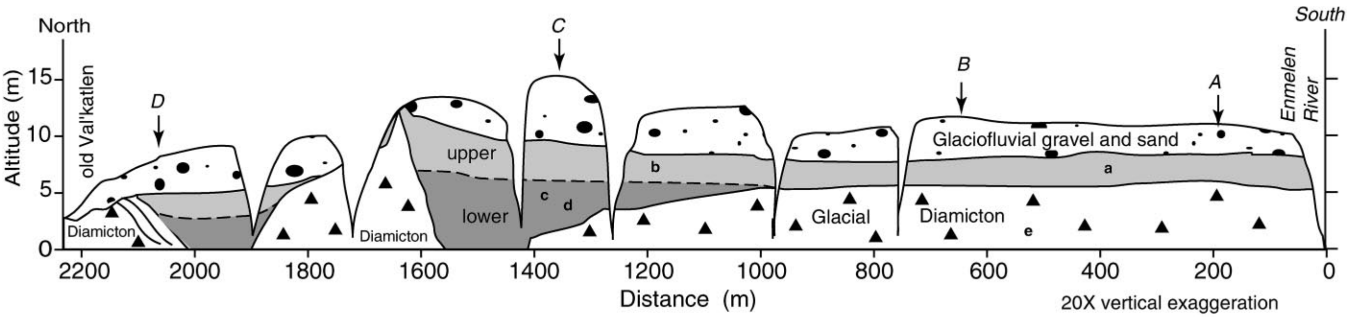

Fig. 7. Sketch of sediment sequence exposed in Enmelen Bluff. The units labeled upper and lower are the type-Val'katlen Suite of the last interglaciation. Upper case letters refer to portions of the exposure discussed in the text. Lower case letters are sites where fossil mollusks were collected for amino-acid geochronology as keyed to Table 1.

clearly evident, etched by the wind. The interglacial beds are overlain by $\leqslant 3$ m of clast-supported cobble gravel probably of glaciofluvial origin. The upper meter of the gravel is heavily infiltrated with silt and bears evidence of frost-jacking.

In the north half of the exposure, an underlying glacial diamicton is faintly bedded and contains shell fragments of *Mya, Hiatella, Macoma,* and *Neptunea* along with crumpled fragments of *Laminaria*, a common marine alga, suggesting that this pre-Val'katlen diamicton incorporates older marine deposits or is itself glaciomarine in origin. The upper surface of the diamicton slopes northward to beach level beneath 10 m of Val'katlen beds and the overlying glaciofluvial gravel (C in Fig. 7). Both the Upper and Lower Val'katlen beds are present in superposition here and for about 300 m lie disconformably on the older fossiliferous diamicton. The Lower Val'katlen consists of interbedded sets, 1–10 cm thick, of yellow to gray-brown medium sand and black to brown sandy silt. In one well-exposed section, the Lower Val'katlen beds coarsen upward, and well-sorted sand becomes dominant in the upper 2 m below the contact with the overlying sandy Upper Val'katlen Suite. The Lower Val'katlen is locally fossiliferous and contains a shell fauna dominated by *Macoma calcarea* and *Mya pseudoarenarea. Laminaria* also occurs as dispersed fragments lying parallel to bedding surfaces.

At the northern end of the exposure (D in Fig. 7), the Val'katlen beds lap onto glacially deformed diamicton, older glaciofluvial gravel, and marine sand. The older, tilted beds strike N 29°E and dip 16–20°SE, an attitude that would be consistent with proglacial deformation in front of an ice mass emanating from the Enmelen River valley. The Val'katlen Suite, itself, is undeformed.

The mollusk and foraminifer faunas from the Upper and Lower Val'katlen Suites are similar; both are dominated by arcto-boreal species still living in nearby waters. The Lower Val'katlen, however, includes three foraminifer species that are restricted today to the warmer waters of the Sea of Okhotsk and the northern Sea of Japan (Ivanov, 1986) (Table 4). Pollen floras in these sediments are similar to modern pollen floras (Ivanov, 1986).

Table 4
Extralimital foraminifera in type-Val'katlen deposits, Chukotka Peninsula (Ivanov, 1986)

Location	Taxa	Northern Limit or Modern Range
Val'katlen, Chukotka	*Nonionella labradorica*	Seas of Okhotsk and Japan
	Cibicides rotundatus	Seas of Okhotsk and Japan
	Elphidiella batialis	Seas of Okhotsk and Japan

2.2.3. Geochronology

AIle/Ile ratios in *Mya* from both the Lower and Upper Val'katlen are indistinguishable, with means of 0.021 ± 0.003 ($n = 10$) and 0.021 ± 002 ($n = 13$), respectively (Table 1). *Macoma* sp., which racemizes faster than *Hiatella* and *Mya*, averages 0.025 ± 0.003 ($n = 11$) in the Lower Val'katlen. AMS radiocarbon ages for Val'katlen shell samples with these low ratios are $> 43,200$ yr BP (AA-13010) and $> 39,500$ yr BP (AA-13011) (Table 3).

The aIle/Ile ratios on mollusks from the type Val'katlen Suite are especially interesting when compared with ratios on fossil shells from underlying diamicton in the Val'katlen bluffs and shells from the sequence exposed in the bluffs south of the Enmelen River. AIle/Ile ratios on *Hiatella* collected from the diamicton underlying the Val'katlen beds 550 m north of the Enmelen River (Fig. 7) average 0.21 ± 0.001 ($n = 3$, loc.e, Table 1) and are indistinguishable from ratios on *Mya* from the overlying Val'katlen Suite.

On the other hand, aIle/Ile ratios in *Mya* shells collected from marine sand at the base of a high bluff a few kilometers south of the Enmelen River (Fig. 3) average 0.028 ± 0.004 ($n = 8$). This marine sand is overlain by > 25 m of glacial diamicton, glaciomarine sediment, and coarse gravel. At the top of the bluff, marine sediments apparently overlying the glacigenic complex contain *Hiatella* shells that yield a mean ratio of 0.033 ± 0.004 ($n = 4$) (note that aIle/Ile ratios for *Mya* are typically 10–20 % lower than ratios on *Hiatella* of the same age). All of these ratios are distinguishable from ratios on *Mya* and *Hiatella* from the Val'katlen stratotype, and they suggest that the marine complex south of the Enmelen River was deposited on the order of $> 100{,}000$ yr earlier than the Val'katlen beds north of the river.

2.2.4. Discussion and interpretation

Based on the stratigraphy and relative ages of the marine and glaciogenic units, JBG and DMH re-interpret the Val'katlen section as having been deposited entirely within oxygen-isotope stages 5 and 4. The similarity in aIle/Ile ratios in shells from the glacial diamicton and the overlying Val'katlen Suite suggests that the diamicton is underlain by additional sediment correlative with stage 5. We suggest that these *unexposed* beds probably represent stage 5e, the peak of the last interglacial. The diamicton evidently incorporated shells from these slightly older deposits during an advance of local mountain glaciers later in stage 5. Retreat of these glaciers and an interstadial rise in eustatic sea level then led to the deposition of the nearshore sediments of the Val'katlen Suite during perhaps stage 5c or 5a. The surficial outwash would have been deposited during a later glacial readvance when sea level was lower, probably during stage 4.

The Val'katlen aIle/Ile ratios are substantially lower than those for Pelukian shells of the same genera from Nome and St. Lawrence Island (Kaufman, 1992; Brigham-Grette and Hopkins, 1995) (Table 2). If we were to assume that the Val'katlen Suite represents isotope stage 5e, then the effective diagenetic temperature (EDT) over the last 125,000 yr would be $-12°C$ at Val'katlen, *considerably* colder then EDTs over the same period at Nome and Gambell, as indeed, they probably are at present. Interpolation from the nearest weather stations suggests that the CMAT at Val'katlen is near $-6°C$, while CMATs at Nome and Gambell are -3.2 and $-4.3°C$, respectively (U.S. National Weather Service, Fairbanks, oral commun. to DMH, 1/15/94). If instead we assume that the Val'katlen Suite dates from, say, stage 5a, the EDT during marine isotope stages 4–1 would be $-9.6°C$, implying a long-term temperature depression of 3°C, which is more consistent with the late Pleistocene EDT depression of 3°C calculated for Nome and St. Lawrence Island over the same period (Kaufman, 1992; Brigham-Grette, unpublished).

Based on the stratigraphy and relative ages of the marine and glaciogenic units, JBG and DMH re-interpret the Val'katlen section as having been deposited entirely within oxygen-isotope stages 5 and 4. The similarity in aIle/Ile ratios in shells from the glacial diamicton and the overlying Val'katlen Suite suggests that the diamicton is underlain by additional sediment correlative with stage 5. We suggest that these *unexposed* beds probably represent stage 5e, the peak of the last interglacial. The diamicton evidently incorporated shells from these slightly older deposits during an advance of local mountain glaciers later in stage 5. Retreat of these glaciers and an interstadial rise in eustatic sea level then led to the deposition of the nearshore sediments of the Val'katlen Suite during stage 5c or 5a. The surficial outwash would have been deposited during a later glacial readvance when sea level was lower, probably during stage 4.

JB-G and DMH recognized no convincing evidence that a double high sea level oscillation is recorded in the exposures of the Val'katlen Suite. Only one terrace is present, The surface consists of glaciofluvial gravel, and no geomorphic shoreline is preserved. The contact between the Upper and Lower Val'katlen is commonly marked by either a sharp upward change to gravelly sand or by a lag gravel several centimeters thick. These are changes that seem likely to record a regression from a single high sea stand.

As VFI would agree, the marine and glaciomarine sequence *south* of the Enmelen River was evidently deposited during an earlier interglacial–glacial cycle, probably during oxygen isotope stages 6 and 7. Although radically different from the traditional Russian interpretation, this scenario satisfactorily explains the sediment sequence and the similarities among amino-acid ratios on shells from the bluffs north of the Enmelen River.

2.3. Nunyamo River Bluff

2.3.1. History of investigations

Near the mouth of the Nunyamoveyem ("*veyem*" in Chukchi means "river"), 10 km north of the Val'katlen section (Fig. 3), a coastal bluff 40–60 m high extends 4 km along the coast, exposing sediments that record a complex series of marine and glacial events (Fig. 8). Winter winds from the northeast regularly build a series of large snow banks that may persist on Nunyamo Bluff through the following summer; consequently Ivanov had not studied this bluff in detail prior to 1992. During our eight-day visit in July, 1992, however, the bluff was almost free of snow banks, and we were able to distinguish two marine sequences intercalated between three sequences of glacial and glaciomarine sediments. These complexes show subtle evidence of glacitectonic deformation at both the eastern and western ends of the bluffs.

Locations of study sections on Nunyamo Bluff were established by a baseline marked on the beach by VFI, placing stakes at intervals of 100 m. The point of origin (marked 4000 m in Fig. 8) was at the mouth of the small creek at the south end of Nunyamo Bluff.

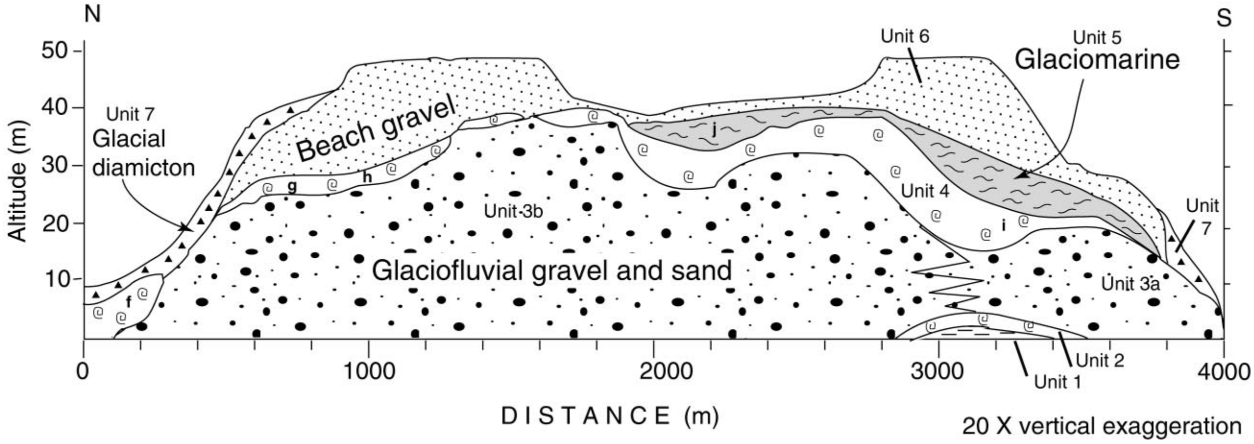

Fig. 8. Cross-section of the Nunyamo Bluff. Unit 1 is black marine clay and unit 2 is upward coarsening littoral sand and fine gravel. Unit 3a is fine sand and gravel which coarsens northward to unit 3b, silty, channelled boulder outwash gravel. Unit 4 is upward coarsening littoral sand and gravel and marine fine sand and silty sand. Unit 5 is glacial marine diamicton. Unit 6 is marine pebble–cobble gravel. Unit 7 is glacial till. Heights and unit thicknesses between 3200 and 4000 m and between 0 and 1000 m are well controlled by hand-leveled measured sections by JBG, VFI, and DMH. Heights and thicknesses elsewhere are based upon observations from top of bluff, upon VFI's uncontrolled sketch of exposure viewed from the beach, and upon a continuous series of panoramic photos taken by DMH from an open boat traveling 300–400 m offshore. Lower case letters alone are sites where fossil mollusks were collected for amino-acid geochronology as keyed to Table 1.

2.3.2. *Stratigraphy and paleoecology*

The oldest beds in the Nunyamo Bluff consist of marine sediments exposed at about 3000 m along the exposure (Fig. 8); elsewhere in the bluff, these marine beds evidently lie below sea level. The sequence consists of a basal 1–2 m of black fossiliferous clay (unit 1) exposed mainly in the beach, grading upward into about 2 m of littoral sand and fine gravel (unit 2). Except for fragments of *Mytilus*, the lower marine unit is devoid of identifiable mollusks, although a few shell fragments were found in one exposure of littoral sand. Exposures of the basal marine sequence in the south end of the bluff evidently result from arching and diapirisim in the marine clay of unit 1, probably in response to loading by encroaching glacial ice that deposited the glacial diamicton of unit 4, described below.

The basal marine beds grade upward into non-marine sand with a few beds of pebble gravel, unit 3a. In places, the sand of unit 3a displays climbing ripples. These beds can be traced northward to the vicinity at about 2800 m, where they grade laterally and abruptly into the thick-bedded, poorly sorted boulder gravel of unit 3b which extends through most of the width of the bluff. The boulder gravel displays filled channels and large, sweeping cross-bedded units (one set is 3 m thick and about 15 m long) as well as rare and local sand interbeds up to a meter thick. Silt and fine sand in the matrix allows the boulder gravel of unit 3b to stand in near-vertical cliffs, and stratigraphic sections can be measured only by scrambling up the occasional steep talus chutes below late-melting snow- banks. Traced northward, the top of unit 3 rises to an altitude of at least 37 m at about 1400 m. At the north end of Nunyamo Bluff, the top of the unit 3 declines abruptly, and the boulder gravel disappears below the beach.

The gravel of unit 3b was evidently deposited by a rapidly aggrading outwash stream flowing over a braided flood plain. The very poor sorting suggests a turbid, overloaded, low-gradient stream. We interpret unit 3 to represent an outwash fan fed by a piedmont glacier that originated in the Nunyamo River basin and terminated against the north end of the Nunyamo Bluff. The abrupt lateral gradation from the boulder gravel of unit 3b to the sand and pebble gravel of unit 3a, presence of climbing ripples in unit 3a, and the gradation from unit 3a downward into the shell-bearing sublittoral marine sediments of unit 2 indicates that unit 3a was deposited within a few meters of the sea level of the time. It is clear that the glacial advance that resulted in deposition of unit 3 took place at a time when relative sea level lay only a few meters below its present level.

Unit 3 is overlain by a complex, sublittoral marine unit 4, which extends throughout most of the width of Nunyamo bluff. Only in the southernmost 800 m of the bluff, the base of the unit includes glacial till overlain by the thin marine littoral sediment which is in turn overlain by the proximal glaciomarine deposits (Unit 5). Unit 4 consists of 0.5–3.0 m of upward-coarsening, thin-bedded, sublittoral silt, sand, pebbly sand, and pebble gravel that rests with sharp contact upon the glacial and glaciomarine sediments of unit 4 throughout most of Nunyamo Bluff. The sediments of unit 4 contain abundant mollusks, including many paired *Astarte* shells with intact periostracum and rare barnacles attached to large stones. Some sand layers are riddled with closely spaced, mostly vertical *Ophiomorpha* burrows a few millimeters in diameter and a few centimeters deep contains *Astarte, Mya* and *Hiatella* and in places cobbles coated with remnant barnicle plates attached.

Unit 4 records a rise in relative sea level which resulted in the submergence of the area of the Nunyamo Bluff and the encroachment upon the south end of the bluff of a large glacier whose source evidently lay in the headwaters of nearby Ylokatym Creek (Fig. 3). The terminus of this glacier was grounded in some places but afloat in others, and it gave rise to glaciomarine diamicton (Unit 5) that is exposed throughout most of the length of Nunyamo Bluff.

Unit 5 consists of thick-bedded glaciomarine diamicton bearing sparse but paired valves of *Mya, Astarte, Macoma,* and *Serripes.* Bedding is defined by sand-rich layers a few cm thick. In most places, the diamicton is strikingly stone poor, but in one place, it contained about 60% rounded stones, some up to a meter across. The diamicton displays little fabric, but many stones have vertical axes. The glaciomarine diamicton of unit 5 ranges in total thickness from less than a meter to more than 20 m, but we lack measured sections that would show how this thickness is accommodated in the section as a whole.

Unit 6 consists of brown pebble-cobble framework gravel with rare sand interbeds. The unit extends through most of the width of Nunyamo Bluff. In places where units 5 and 6 are both thick, the contact is gradational. The gravel of unit 6 is thin in the north and south ends of the bluff , but thickens to 14 m beneath the high points comprising units 6, then thins to less than 2 m in the intervening swale. The gravel coarsens northward and, near the north end of the bluff, contains rare boulders up to a meter across. The gravel is mostly devoid of mollusk fossils; occasional concentrations of shells near the base of unit 6 probably come from thin and poorly exposed layers of unit 5.

Near the north end of Nunyamo Bluff, the brown gravel of unit 6 underlies a plateau 50 m above present sea level, half a kilometer wide, and extending about a kilometer inland. The gravel comprising this plateau is strongly prograded; sweeping south-dipping foreset beds encompass most of the thickness of the unit. In one place, we found a slug of diamicton several decimeters thick intercalated in the inclined gravel beds. At 1000 m along the bluff, we encountered an accumulation of fossil bone that included the rib of a whale (probably a bowhead), the centrum of a whale vertebra, and the articulated forelimb of a brown bear (whale bone identifications by Frank Whitmore, Clayton Ray, and Daryl Downing, US National Museum; bear identification by Majorie Coombs and the late David Klinginer, University of Massachusetts, and Paul Matheus, University of Alaska Fairbanks).

Toward the south end of Nunyamo bluff, the brown gravel of unit 6 underlies a spit-like ridge cresting at 51 m at the coast but sloping inland normal to the bluff face. Here, cross-beds in the gravel are prograded eastward (inland). The spit-like ridge and the delta plateau to the north are separated by a swale that contains a lake and a small stream that drains gently eastward, away from the coast. The south side of the spit-like ridge displays a bench — possibly a marine terrace — several tens of meters wide incised 10 or 15 m below the ridge crest.

Foreset bedding, the presence of whale fossils in the gravel comprising the western plateau, and rare marine shells in the gravel making up the spit-like ridge establishes that the gravel of unit 6 was deposited in standing marine waters. Gravel comprising the western plateau evidently represents the outwash delta of a glacier that emanated from the Nunyamoveyem valley and terminated against the north end of the bluff. The eastern spit-like ridge may, indeed, represent a spit built eastward from a high morainal knob, now eroded away.

The western plateau and the spit-like ridge define relative sea level when the unit 6 was being deposited, and the bench carved a few meters below the crest of the spit-like ridge may define a still-stand that interrupted the emergence of the Nunyamo Bluff after deposition of unit 6. Interestingly, we could see at a distance a pair of beach-like benches at approximately the same altitudes on a colluvial slope extending inland from Cape Chirikov.

Where unit 6 lies at the surface, the upper 2 m of the gravel are whitened by a coating of silt (loess?) on the clasts, and the silty gravel contains many vertically oriented clasts, indicating frost-jacking. At depths of about 2 m, the matrix of the gravel is clogged silt, forming an aquaclude and producing a wet line in the face of the bluff. The silt concentration probably marks the position of the permafrost table away from the face of the bluff.

Unit 7 consists of massive glacial diamicton, evidently till, 3–5 m thick. Till of unit 7 laps onto the north slope of Nunyamo Bluff, where it overlies brown gravel of unit 6. The diamicton contains subangular, rounded, and faceted cobbles and boulders of a variety of lithologies. Active large-scale patterned ground features are conspicuous on the thinly vegetated surface of the diamicton. The contact of the glacial diamicton with the underlying marine mud and sand of unit 4 is poorly exposed due to slumping but proves to be sharp, where carefully excavated. The basal contact over the gravel of unit 6 is also sharp, but the glacial diamicton of unit 7 is easily confused with the silt-impregnated surficial layers of the brown gravel in other parts of the bluff.

2.3.3. Geochronology

AIle/Ile ratios on *Hiatella* and *Mya* shells from unit 4 average 0.024 ± 0.005 ($n = 5$) and 0.022 ± 0.010

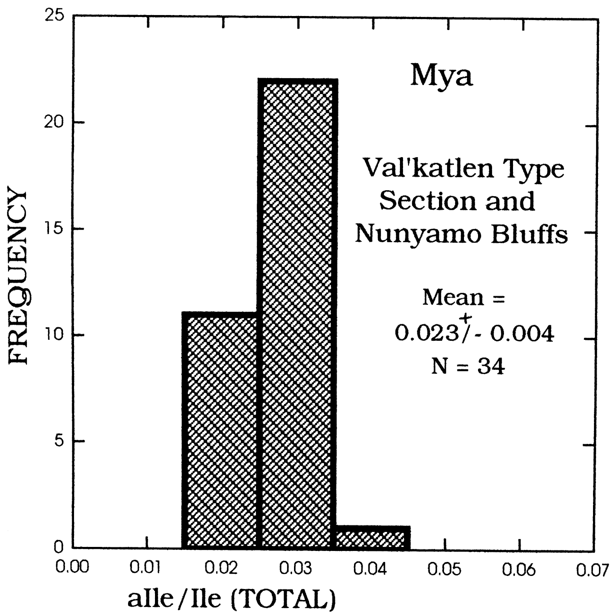

Fig. 9. Histogram of amino-acid aIle/Ile ratios from Val'katlen and Nunyamo Bluff.

($n = 6$), respectively, and are supported by similar ratios in *Astarte* of 0.22 ± 0.009 ($n = 6$) (Table 1). AIle/Ile ratios on *Mya* shells from the glaciomarine unit 5 are 0.021 ± 0.003 ($n = 3$). AIle/Ile ratios on the *Mya* from unit 4, which underlies the lowland at the north end of the bluff, average 0.021 ± 0.001 ($n = 7$). These ratios are indistinguishable from one another, nor can they be distinguished from ratios on the same taxa in the Val'katlen Suite north of the Enmelen River (Fig. 9). These aIle/Ile ratios indicate that neither the non-glacial sediments of units 4 nor the glaciomarine sediments of unit 5 can be no older than some part of isotope stage 5.

A study of sediment samples collected at various levels by Pushkar (unpublished) established that the diatom assemblages are dominated by arctoboreal and northern boreal forms but include rare occurrences of North Pacific subarctic forms, including *Thalassiosira latimarginata.* Samples from unit 4 are similar to those from the Val'katlen Suite at its type locality. Samples from unit 4 differ in that they also yield isolated specimens of *Th. jouseae* (formerly *Th. nidulus* var. *nidulus),* a species hitherto thought to be restricted to deposits more than 300,000 yr old, based on cores recovered from the North Pacific Ocean by the Deep Sea Drilling Program (DSDP) and the Ocean Drilling (ODP) (John Barron, personal communication, 1994).

Despite the presence of a few, possibly reworked tests of the extinct *Thallasiosira jouesae,* a middle Pleistocene age for unit 4 is incompatible with the amino-acid evidence. A calculation using equations that describe the relationship between time, temperature, and aIle/Ile ratios (McCoy, 1987) shows that an aIle/Ile ratio in *Mya* shells of 0.022 would require an EDT below $-19°C$ throughout the period between 300,000 yr ago and the present, not allowing for any short-lived warmings during interglacial stages 5 and 7! JBG and DMH suggest that the rare *Th. jouseae* tests may be redeposited, or alternately, that this diatom may have persisted in the Anadyr Gulf more recently than 300,000 BP.

2.3.4. Discussion and interpretation

It is clear that the sediments exposed in Nunyamo Bluff record two non-glacial episodes and two or possibly three glacial advances, all associated with oscillating but high relative sea levels. The lack of soil profiles and organic layers suggests that there are no large hiatuses recorded in this sequence.

VFI interprets the Nunyamo section as follows: the thick glaciofluvial gravel, unit 3b is assigned to his middle Pleistocene Olayon Glaciation. On the basis of their present altitudes above sea level, he assigns the overlying glaciomarine and normal marine beds, units 4 and 5, to his Mechigmen Suite (the Mechigmen Suite is a middle Pleistocene interglacial sequence whose type locality lies near Mechigmen Bay, some 150 km to the east). The brown gravel of unit 6 is interpreted as glaciofluvial and assigned to a second middle Pleistocene glacial complex, the Kresta Suite of Petrov (1966). VFI ascribes that part of unit 4 that underlies the lowland at the north end of the section, to the Val'katlen Suite on the basis of its low altitude and its diatom and mollusk faunas.

Contrary to VFI, the aIle/Ile ratios on contained mollusks indicate that neither the non-glacial episode recorded by units 4 or the glacial advance and submergence recorded by unit 5 can be older than isotope stage 5. Based on comparisons with the sections exposed at Pinakul' and Val'katlen, JBG and DMH believe that the black marine clay of unit 1 accumulated below wave base when sea level was at its highest during the peak of the last interglaciation, marine isotope stage 5e. Unit 2 records rapidly shallowing waters and unit 3 the arrival at Nunyamo Bluff of a piedmont glacier originating in the Nunyamoveyem basin at a time when relative sea level was only slightly below present sea level. Gradational contacts, lack of an unconformity, and lack of a buried soil at the top of unit 2 indicates that this event took place very shortly after stage 5e. Even allowing for probable subsequent isostatic rebound, the normal marine beds of unit 4 seem likely to represent a non-glacial episode during which sea level must have lain somewhere near its present level. The Simpsonian transgression, represented by the Flaxman Formation of northern Alaska — a transgression thought to have taken place during stage 5c or 5a — comes to mind. No such sea level event is known within isotope stages 4, 3, or 2, so unit 5 probably dates from some part of stage 5. The till and glaciomarine diamicton of unit 5 appear to record at least a slight rise in relative sea level during which the Nunyamoveyem glacier retreated but a piedmont glacier originating in the headwaters of Ylokatym Creek overrode the southern part of Nunyamo Bluff.

The final events recorded in the Nunyamo Bluff include the approach, once again, of a piedmont lobe from the Nunyamoveyem Valley at a time, once again, when sea level could not have been vastly lower than at present, even allowing for isostatic depression and subsequent recovery. The till of unit 7 preserves a record of the extent to which this glacier encroached on the Nunyamo Bluff, and the outwash delta, unit 6, establishes that the glacier, though grounded, was discharging meltwater into the sea. Possibly units 6 and 7 date from stage 4, but it much seems more likely that they were deposited late in stage 5.

3. St. Lawrence Island

Though politically a part of Alaska, St. Lawrence Island is much closer geographically and geologically to the Chukotka Peninsula (Figs. 1 and 6). The proximity of St. Lawrence Island to the Chukotkan coast intimately links the glacial history of the two regions (e.g. Hopkins et al., 1972), but until recently it has not been possible to test the telecorrelations suggested earlier by Hopkins et al. (1965).

Geologic mapping by PAH and aIle/Ile analyses on mollusks from coastal and lagoon bluffs by JBG show that an ice cap originating over the mountains of southwestern Chukotka Peninsula reached and encroached on northwestern St. Lawrence Island at least twice — once subsequent to the Anvilian transgression, 420,000 yr ago, and once in late Pleistocene time (Brigham–Grette and Hopkins, 1995).

Glaciotectonically deformed beds exposed in the coastal bluffs of northwestern St. Lawrence Island are placed in some part of stage 5 on the basis of aIle/Ile ratios and AMS radiocarbon ages. The fossil mollusk faunas are similar to the present-day mollusk fauna found in near-shore waters off the north coast of St. Lawrence Island. No extinct species and no southern extralimital taxa have been found. *Hiatella* and *Mya* from the coastal bluffs have aIle/Ile ratios of 0.051 ± 0.014 ($n = 3$) and 0.048 ± 0.018 ($n = 12$), respectively (Table 1). Two of these shells have yielded AMS radiocarbon ages of $> 45{,}900$ and $> 48{,}600$ yr (Table 3). The aIle/Ile ratios are nearly identical with aIle/Ile ratios on mollusks from the Pelukian type locality at Nome and they are higher than aIle/Ile ratios on shells from the Val'katlen Suite and from the interstadial marine beds at Nunyamo Bluff. The marine beds probably represent isotope stage 5e; the overlying drift, since it represents a grounded glacier, may be as young as stage 4.

4. Discussion

4.1. Age of glaciation at Pinakul', Enmelen, Nunyamo, and western St. Lawrence Island

We assume that all of the glacial sediments exposed at Pinakul', Val'katlen, Nunyamo Bluff, and St. Lawrence Island are older than stage 2 because the large extent of the glaciers and the modest altitudes of the source terrain are inconsistent with the very limited stage 2 glaciation recorded in northwestern Alaska and also because moraines fronting cirques and fjords on the Chukotka Peninsula record a much younger and much more limited glaciation likely to represent stage 2. Ivanov (1986) assigns outwash covering the Val'katlen Suite and till covering unit 5b in Nunyamo Bluff to the Vankarem Glaciation, which he has considered to be an early Wisconsin equivalent.

We recognize that the marine sediments of coastal Chukotka Peninsula have been isostatically loaded and unloaded and that those at Pinakul' and, less intensely, those exposed in the high Nunyamo Bluff have also been glaciotectonically up-arched. Thus, none of them can be assumed to lie at its original depositional position. Glaciomarine deposits preserved above the present sea level must have been laid down when the ice front was near and isostatic loading was at a maximum, but global ("true") sea level, as opposed to local relative sea level, may have been much lower than at present when the glaciomarine sediments were deposited. The normal marine deposits, on the other hand, were deposited at times when glaciers were remote, if present at all. Even if the littoral sediments were deposited fairly early during intervals of crustal rebound, we believe that they must record a sea level no more than a few meters lower than present sea level. Global sea level has evidently never been above -20 m during isotope stages 2, 3, and 4 (Richards et al., 1994), so we assume that the normal marine and littoral deposits exposed at Pinakul', Val'katlen, and Nunyamo Bluff must have been deposited during warm substages of stage 5. It follows that outwash and glaciomarine deposits intercalated in these sequences must have been deposited during cold substages of isotope stage 5.

The final depositional units at Pinakul', Val'katlen, Nunyamo Bluff, and St. Lawrence Island all consist of till of a grounded glacier or of non-marine glacial outwash; at Pinakul', the outwash lies within less than 10 m above the present sea level. The glacial advance recorded by the grounded till and associated outwash may represent stage 4.

4.2. Possible submerged moraines

Several marine geologic studies (Grim and McManus, 1970; Nelson and Hopkins, 1972; Hess, 1985; Ivanov, 1986; his Fig. 1) report a submerged, sinuous moraine shown as extending continuously northward from St. Lawrence Island to a point about 40 km off Cape Pinakul' (Fig. 6). This moraine approaches the north coast of St. Lawrence Island near the westernmost point where a Chukotkan ice cap came ashore. Russian marine geologic studies have also resulted in the recognition of a series of submerged morainal arcs, convex toward fjords and bays that lie only 10–30 km off the southeast and eastern coasts of the Chukotka Peninsula (Ivanov, 1986; his paper, Fig. 1). We speculate that the moraine that extends north from St. Lawrence Island represents the furthest extent of stage 5 glaciers, and that the morainal arcs nearer the coast represent a readvance during stage 4.

4.3. Paleo-oceanographic conditions in Bering Sea during stage 5 and stage 4

The Chukotka Peninsula record is remarkable for its display of evidence for the growth of glaciers large enough to reach the coast during one or more substages of isotope stage 5. At Pinakul', the record seems to indicate that glaciomarine sedimentation ensued with hardly a pause after deposition of sediments recording stage 5e. The non-glacial littoral marine sediments of the Val'katlen Suite type locality are assignable to a mild episode within stage 5, and they are underlain by glaciomarine diamicton also assignable to stage 5. At Nunyamo Bluff, normal marine littoral sediments plausibly correlated with the Val'katlen Suite and assignable to a mild episode within stage 5 are underlain by glaciomarine diamicton and till, then by proximal glacial outwash, and then, at the base of the bluff, by marine clay that probably represents stage 5e. Although our geochronology is presently incapable of resolving just which warm and cold substages of stage 5 are represented by these glacial advances and subsequent sea level recoveries, it is clear that the Chukotka Peninsula recorded very significant glacial episodes within isotope stage 5. How was this possible?

Warm, year-round, ice-free conditions were initiated in the Bering Sea during substage 5e (Brigham-Grette and Hopkins, 1995), and this was evidently conducive to rapid glacierization of the Chukotka Peninsula when summer insolation decreased abruptly and dramatically during a subsequent cold substage within stage 5. The apparently rapid onset of glaciomarine deposition at Pinakul' and the presence of diamicton incorporating interglacial marine sediments at Val'katlen, and the rapid gradation from marine clay to coarse, poorly sorted glacial outwash at Nunyamo Bluff all indicate that glaciers expanded while sea level was still relatively high.

Evidence for intra-stage 5 glaciations have previously been recognized in cores from the North Atlantic Ocean (Ruddiman and McIntyre, 1981) and in exposures on North Atlantic shores (Canadian Arctic and Greenland — Miller and deVernal, 1992; Spitzbergen — H. P. Sejrup, oral communication (talk given at 1st International Conference on Arctic Margins, Anchorage, Alaska, 1992). That this was a circumpolar event is indicated by the Flaxman Member of the northern Alaska Gubik Formation, which records the development of an ice sheet over the Canadian shield followed by a breakup during the Simpsonian transgression, all dated within substages of stage 5 (Carter et al., 1988; Brigham-Grette and Hopkins, 1995). Fossil remains in the Flaxman Member testify to a sea level high enough to allow gray whales to migrate through Bering Strait from the Pacific Ocean to the Beaufort Sea (Carter et al., 1988). New stratigraphic evidence from southwestern Alaska in Bristol Bay region further supports the regional pattern for intra-stage 5 glaciation much more extensive than isotope stage 2 (Kaufman et al., 1996; Kaufman et al., 2001; Manley et al., 2001). The Chukotka Peninsula record is concordant with these records that show that late Pleistocene glaciation was initiated at high latitudes near the end of the last interglacial period and that this intra-stage-5 glaciation took place at a time when eustatic sea level was still high and arctic water masses were still warm, although summer insolation was decreasing.

Sea surface temperatures and proximity to the sea seem to have been more important than amounts of summer insolation in controlling the intensity of glaciation in central Beringia. The patterns of offshore and onshore moraines on St. Lawrence Island, in northwestern Bering Sea, and on Chukotka Peninsula record a series of Late Pleistocene glaciations of gradually diminishing size. We speculate that it was a stage 5 glaciation that reached St. Lawrence Island and a stage 4 glacial event that glaciotectonially deformed the Pinakul' Suite and deposited morainal arcs in the near offshore. Moraines in and near cirques in the mountains south of Lavrentiya Bay and supporting fjord-mouth spits or shallow submarine ridges near the mountainous coast of southeastern Chukotka probably represent marine isotope stage 2.

4.4. Evaluation of the Grosswald-Hughes hypothesis

In a series of recent papers, M.G. Grosswald, T.J. Hughes, and their collaborators have postulated that during the late Pleistocene, "two superlarge ice sheets, composed of a number of terrestrial and marine ice sheets interconnected by floating ice shelves" covered the Arctic Ocean, the arctic continental shelves, and much of the northern Eurasia and North America; a floating ice cap over the deep basin of the Bering Sea is also postulated (Grosswald and Vozovik, 1984; Grosswald, 1988; Hughes and Hughes, 1994). In this model, the Chukchi Sea shelf is mostly under glacial ice and the Chukotka Peninsula is covered by a small ice dome that extends westward to encroach on western St. Lawrence Island. Grosswald (1988, p. 262) places the time of existence of these "super-large ice sheets" in the last (stage 2) glaciation, 17,000–20,000 yr ago, but Hughes (oral communication, 1994) allows the possibility that they may have been somewhat older. Grosswald and Hughes' most recent papers (Grosswald and Hughes, 1995; Grosswald, 1998) call upon the existence of an East Siberian Sea Ice sheet to cover all of Chukokta Peninsula and parts of the Bering Strait region.

Our work does *not* in any way confirm the speculations of Grosswald and Hughes. The glacial and marine record that we have studied is, rather, quite inconsistent with their published ideas. We do find evidence of a stage 2 Wisconsin glaciation on the Chukotka Peninsula, but these late Pleistocene glaciers were confined to cirques except in the highlands of southwestern Chukotka Peninsula where a small, local ice may have been present. Limited ice during the Sartan/late Wisconsin across this region is also demonstrated by extensive mapping by Glushkova (1992) and Ivanov (1986) and new synthetic aperature radar mapping by Heiser and Roush (2001).

There were, on the other hand, a series of intense and widespread glacial advances during isotope stages 5 and stage 4 but not from the East Siberian Sea. Like the much more limited stage 2 glaciers, glaciers during stages 4 and 5 had their sources in the highlands of the Chukchi Peninsula (there were also small glaciers in cirques on western St. Lawrence Island), and they extended down though valleys and fjords. In the area of the Enmelen and Nunyamo Rivers, the glaciers extended no more than 5 or 6 km beyond the present coast, and the same is true off Lavrentiya Bay. From the mountainous massif that comprises southeastern Chukotka, however, glaciers spread well beyond the present shores, covering Anadyr Strait, and encroaching on the west coast and the westernmost 30 km of the north coast of St. Lawrence Island (the eastern limit of glacial drift on the north shore of St. Lawrence Island is clearly delineated by the field mapping of PAH (Heiser, 1997).

The pattern of glaciation that we discern is fairly close to the classical model and departs radically from the model-based postulates of Hughes and Grosswald. We do not see evidence of glaciers encroaching on the Chukchi Peninsula from the East Siberian Sea or the Arctic Ocean shelf, but rather a record of glaciers originating from the Chukchi Peninsula encroaching on the continental shelf of Bering Sea. And the record of large glaciers which expanded onto the Bering shelf dates no younger than stage 4. The stage 2 glaciation on Chukchi Peninsula was very small, as it was, also, on the Seward Peninsula (Kaufman and Hopkins, 1986).

The pattern and history of glaciation and sea level fluctuations on Chukotka Peninsula and St. Lawrence Island is interesting and in many ways surprising. Many unexpected things were found. But *none of them* support the ideas of Grosswald and Hughes.

5. Conclusions

Our reinterpretation of the glacial and interglacial sequences at Cape Pinakul', Val'katlen, and the Nunyamo Bluffs constitutes a radical restructuring of the Pleistocene stratigraphy of the Chukotka Peninsula. Previous interpretations lacked adequate geochronology and suffered from a failure to appreciate the significance of isostatic loading, glaciotectonism, and the complex facies changes commonly associated with dynamic ice margins intermittently in contact with the sea. Our study has established that:

- The Lower Pinakul' Suite is *not* of early Pleistocene age but rather represents the peak of the last interglacial, isotope substage 5e. A strong representation of southern extralimital taxa makes the Lower Pinakul' molluscan and foraminiferal faunas unique among known faunas along the coast of the Chukotka Peninsula, and this may have contributed to Russian investigator's impression that the Lower Pinakul' Suite must be very old.
- The Val'katlen Suite does *not* record two distinct sea level episodes, and it does not represent the peak of the last interglaciation, isotope substage 5e. At its type locality the Val'katlen Suite represents a single inter*stadial* high sea level episode, either substage 5c or substage 5a.
- The sequence exposed at Nunyamo Bluff does *not* include middle or early Pleistocene beds. On the contrary, the Nunyamo Bluff preserves what appears to be the Chukotka Peninsula's fullest and most complete record of stage 5 and stage 4 events.
- Exposures at Pinakul', Val'katlen, and Nunyamo Bluff record a major glacial advance during a cold episode within isotope stage 5. This was not a local event but part of a general, pan-Arctic pattern of initiation of glaciation at a time when seas were warm but summer insolation was low.
- During one of these glacial episodes during stage 5 and stage 4, an ice sheet whose source was in the mountains of southeastern Chukotka Peninsula reached St. Lawrence Island.
- The Vankarem Glaciation of Chukotka Peninsula and the Salmon Lake Glaciation of the Seward Peninsula probably reached their peak intensity during a substage of stage 5, but include a readvance during stage 4 .
- Sea surface temperature and proximity to an open sea were larger factors in governing the intensity of glaciation of central Beringia than were variations in the amount of summer insolation.

- Ice sheet models for northeastern Arctic Russia postulated by Grosswald and Hughes are not supported by geological evidence!

Acknowledgements

This research was supported by grants OPP87-14671 and OPP90-14234 to Brigham-Grette and grants OPP87-20025 and OPP-15469 to Hopkins from the National Science Foundation and the National Park Service Beringian Heritage Program. Field work in Russia was also supported by grants to Anatoly V. Lozhkin and Victor F. Ivanov from the Far Eastern Branch of the Russian Academy of Science. Bruce Boolowon and Robert Tungiyan provided invaluable support with the difficult logistics required to work on St. Lawrence Island in 1991. Finally, we wish to thank the countless kind individuals who provided hospitality in Provideniya on Chukotka and Gambell on St. Lawrence Island.

Samples for amino-acid analysis were prepared by UMass undergraduate students Jahanar Hasan, Jennifer Howe, and Christopher Hamilton, and we are indebted to UMass graduate students Steve Roof and Karen Mulvey for maintaining the amino acid labotory. Steve Roof, Dirk Enters, and Mike Terry also assisted with many of the figures. Thoughtful reviews by Darrell Kaufman (Northern Arizona University) and L. David Carter (U.S. Geological Survey) greatly improved the manuscript.

References

Bard, E., Hamelin, B., Fairbanks, R.G., 1990. U-Th ages obtained by mass spectometry in corals from Barbados: sea-level during the past 130,000 years. Nature 346, 456–458.

Benson, S.L., 1993. Glacially deformed sediments of Lavrentiya Bay, Chukotka Peninsula, Far Eastern Russia, and the North Shore of St. Lawrence Island, Alaska. In: Aber, J.S. (Ed.), Glaciotectonics and Mapping Glacial Deposits. Proceedings of the INQUA Commission on Formation and Properties of Glacial Deposits, University of Regina, Canadian Plains Research Center, pp. 1–8.

Benson, S.L., 1994. Pleistocene stratigraphy and ice extent across central Beringia. University of Massachusetts, M.S. Thesis, Amherst, 159 pp.

Brigham, J.K., 1985. Marine stratigraphy and amino acid geochronology of the Gubik Formation, western Arctic Coastal Plain, Alaska. U.S. Geological Survey Open-File Report 85–381, 218 pp.

Brigham-Grette, J., Hopkins, D.M., 1995. Emergent-marine record of the last interglaciation and paleoclimate along the northwest Alaskan coast. Quaternary Research 43, 159–173.

Carter, L.D., Brouwers, E.M., and Marincovich, Jr. L., (1988). Nearshore marine environments of the Alaskan Beaufort Sea during depostion of the Flaxman Member of the Gubik formation. In: Galloway, J.P., and Hamilton, T.D. (Eds.), Geologic Studies in Alaska by the U.S. Geological Survey during 1987. 27-30. U.S. Geological Survey Circular 1016, pp. 27–30.

Chen, J.H., Curran, H.A., White, B., Wasserberg, G.J., 1991. Precise chronology of the last interglacial period: ^{234}U-^{238}Th data from fossil coral reefs in the Bahamas. Geological Society of America Bulletin. 103, 82–97.

Committee for Unified Stratigraphy of Quaternary System of Eastern USSR, 1992. Mezhvedomstvennogo Stratigraficheskogo Soveshchaniya po Chetvertichnoy Syteme Vostoke SSSR. Decisions (Resheniya) Magadan (In Russian).

Gasanov, S.S., 1969. Stroenie i Istoria formirovaniya Merzlykh porod Vostochnoy Chukotky (Structure and history of the formation of frozen deposits on eastern Chukotka). Nauka, 169 pp. (In Russian).

Goodfriend, G.A., Brigham-Grette, J., Miller, G.H., 1996. Enhanced age resolution of the marine Quaternary record in the Arctic using aspartic acid racemization dating of bivalve shells. Quaternary Research 45, 176–187.

Grim, M.S., McManus, D.A., 1970. A shallow seismic-profiling survey of the northern Bering Sea. Marine Geology 8, 293–320.

Grosswald, M.G., 1988. An Antarctic-style ice sheet in the northern hemisphere: toward a new global glacial theory. Polar Geology and Geography 12, 239–267.

Grosswald, M.G., Vozovik, Yu.N., 1984. A "marine" ice cap in south Beringia (a working hypothesis). Polar Geology and Geography 8, 239–266.

Grosswald, M.G., 1998. Late-Weichselian Ice Sheets in Arctic and Pacific Siberia. Quaternary International 45/46, 3–18.

Grosswald, M.G., Hughes, T.J., 1995. Paleoglaciology's grand unsolved problem. Journal of Glaciology 41, 313–332.

Heiser, P.A., 1997. Extent, timing, and paleogeographic significance of multiple Pleistocene Glaciations in the Bering Straits region. Ph.D. Thesis; Fairbanks, University of Alaska, 133 pp.

Heiser, P.A., Roush, J.J., 2001. Pleistocene glaciations in Chukotka, Russia: moraine mapping using satellite synthetic aperture radar (SAR) imager. Quaternary Science Reviews 20, 393–404..

Hess, R.G., 1985. Quaternary stratigraphy and sedimentation — Northern Bering Sea, Alaska Ph.D. Thesis, Stanford, California, Stanford University, 89 pp.

Hopkins, D.M., 1967. Quaternary marine transgressions in Alaska. In: Hopkins, D.M. (Ed.), The Bering Land Bridge. Stanford University Press, Stanford, pp. 47–90.

Hopkins, D.M., McNeil, Merklin, R.L., Petrov, O.M., 1965. Quaternary correlations across Bering Strait. Science 147, 1107–1114.

Hopkins, D.M., Rowland, R.W., Patton Jr., W.W., 1972. Middle Pleistocene mollusks from St. Lawrence Island and their significance for the paleo-oceanography of the Bering Sea. Quaternary Research 2, 119–134.

Hughes, B.A., Hughes, T.J., 1994. Transgressions: rethinking Beringian glaciation. Paleogeography, Paleoclimatology, Paleoecology 110, 275–294.

Ivanov, V.F., 1986. Quaternary deposits of coastal eastern Chukotka. Vladivostok, Far East Science Center, Academy of Sciences of the USSR, 138pp. (in Russian; partial translation by S.L. Benson , 1992, available from corresponding author).

Kaufman, D.S., 1992. Aminostratigraphy of Pliocene-Pleistocene high-sea-level deposits, Nome coastal plain and adjacent nearshore area, Alaska. Geological Society of America Bulletin 104, 40–52.

Kaufman, D.S., Hopkins, D.M., 1986. Glacial history of Seward peninsula. In: Hamilton, T.D., Reed, K.M., Thorson, R.M. (Eds.), Glaciation in Alaska: the Geologic Record. Alaska Geological Society, Anchorage, pp. 51–78.

Kaufman, D.S., Carter, L.D., Miller, G.H., Farmer, L.G., Budd, D.A., 1993. Strontium composition of Pliocene and Pleistocene molluscs from emerged marine deposits, North American Arctic. Canadian Journal of Earth Science 30, 519–534.

Kaufman, D.S., Forman, S.L., Lea, P.D., Wobus, C.W., 1996. Age of Pre-late-Wisconsin Glacial-Estuarine sedimentation, Bristol Bay, Alaska. Quaternary Research 45, 59–72.

Kaufman, D.S., Manley, W.F., Forman, S.L., Layer, P.W., 2001. Pre-late-Wisconsin glacial history, coastal Ahklun Mountains, southwestern Alaska — new amino acid, thermoluminescence and 40Ar/39Ar results. Quaternary Science Reviews 20, 337–352.

Khoreav, I.M., 1974. Stratigrafifa i foraminifery morskikj chetvertichnykh otlozhenif zapadnogo berega Beringova morfa (Stratigraphy and Foraminifera of the marine Pleistocne deposits of the west shore of Bering Sea). Akademiya Nauk SSSR Geologish es Kogo Instituta Trudy 225, 152 pp. (Translated for the U.S. Geological Survey by Dorthy B. Vitaliano, September, 1974).

Manley, W.F., Kaufman, D.S., Briner, J.P., 2001. Pleistocene glacial history of the Southern Ahklun Mountains, southwestern Alaska: soil development, morphometric and radiocarbon contraints. Quaternary Science Reviews 20, 353–370.

McCoy, W.D., 1987. The precision of amino acid geochronology and paleothermometry. Quaternary Science Reviews 6, 43–54.

Miller, G.H., Brigham-Grette, J., 1989. Amino acid geochronology-resolution and precision in carbonate fossils. Quaternary International 1, 111–128.

Miller, G.H., deVernal, A., 1992. Will greenhouse warming lead to Northern Hemisphere ice sheet growth? Nature 355, 244–246.

Nelson, C.H. and Hopkins, D.M., 1972. Sedimentary processes and distribution of particulate gold in the northern Bering Sea. U.S. Geological Survey Professional Paper 689, 27 pp.

Petrov, O.M., 1963. Stratigraphfiia chetvertichnykh otlozhenii iuzhnoi vostochnoi chastei Chukotskogo poluostroa (The stratigraphy of the Quaternary deposits of the southern and eastern parts of Chukotka Peninsula). Akademy Nauk SSSR, Biul. Komm. po izucheniyu Chetvertichogo Perioda 28, 135–152. (In Russian; English translation available from American Geological Institute).

Petrov, O.M., 1966. Stratigraphy and fauna of marine mollusks in the Quaaternary deposits of the Chukotka Peninsula. Academy of Science of USSR, Trudy Geological Institute 155, Nauka, Moscow, 288pp. (In Russian).

Petrov, O.M., 1967. Paleogeography of Chukotka during late Neogene and Quaternary time. In: Hopkins, D.M. (Ed.), The Bering Land Bridge. Stanford University Press, Stanford, California, pp. 144–171.

Richards, D.A., Smart, P.L., Edwards, R.L., 1994.. Maximum sea levels for the last glacial period from U-series ages of submerged speleothems. Nature 367, 357–360.

Ruddiman, W.F., McIntrye, A., 1981. Oceanic mechanism for amplication of the 23,000 ice-volume cycle. Science 214, 612–627.

Suess, E., Balzer, W., Hesse, K.-F., Müller, P.J., Ungerer, C.A., Wefer, G., 1982. Calcium carbonate hexahydrate from organic-rich sediments of the Antarctic Shelf: precursors of glendonite. Science 216, 1128–1131.