# “Back-arc” marine ice sheet in the Sea of Okhotsk

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[1] Geomorphologic, marine geological, and paleoclimatic evidence, along with modeling results, indicate that, during the Late Pleistocene, the Sea of Okhotsk was glaciated by a “back-arc” marine ice-sheet, which was a continuous spillover of glaciation from the highlands of Northeast Siberia, buttressed by a submarine ridge of the Kurile Island Arc. That marine ice sheet also impounded and deflected the Lower Amur and Uda Rivers which resulted in reorganization of their drainage systems. The Okhotsk marine ice sheet was grounded on seafloor and reached to the outer (southern) edge of the submarine Academy Sill. From that limit, the ice sheet extended farther south, across the deep Kurile Basin, as a floating ice shelf. The Okhotsk Sea and Beringian Ice Sheets were the only “back-arc” Quaternary glaciers; they were two major sources of icebergs, meltwater, and ice-rafted debris supplied to the North Pacific Ocean during the Ice Ages. *INDEX TERMS:* 0700 Cryosphere (4540); 0726 Cryosphere: Ice sheets; 0732 Cryosphere: Icebergs; *KEYWORDS:* marine ice sheet, Sea of Okhotsk, Last Glacial Maximum, Kuril Islands, last deglaciation, climate change, Ice sheet buttressing, Iceberg armadas.

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## Introduction

[2] The problem of past glaciations on the Northwest Pacific Rim remains controversial. As of today, despite our arguments, recently presented in a nutshell Letter to the Editor of Quarternary Research [*Grosswald and Hughes,* 2004], it is broadly believed that these glaciations were of minor extent, having been merely restricted to the high mountains of Northeast Siberia and Alaska. This view has been advocated by a majority of Russian geographers, from Voeikov of late XIX century to our contemporaries Velichko and Glushkova; who believed, and keep believing, that the climate of Pleistocene Siberia was too dry to support any great ice caps on lowlands [e.g., *Biryukov et al.,* 1988; *Velichko,* 2002]. This view was shared by *McIntyre* [1981], by many researchers of the region’s Quaternary [*Brigham-Grette et al.,* 2003; *Elias et al.,* 1996; *Glushkova,* 2001], and by designers of a multitude of international research programs.

[3] Challenging them, we presented our general case for ice-sheet glaciation of the Northwest Pacific Rim and Beringia [*Grosswald,* 1998a; *Grosswald and Hughes,* 1995, 2002; *Grosswald and Vozovik,* 1984; *Hughes,* 1998; *Hughes and Hughes,* 1994; *Hughes et al.,* 1991]. In this paper, the discussion will be focused on a major constituent part of the region – the Sea of Okhotsk. We addressed the problem of an Okhotsk Ice Sheet previously in the IPPCCE Newsletter edited by Shoji Horie [*Grosswald and Hughes,* 1998], with a very restricted circulation. We now update our earlier arguments and seek greater exposure for them.


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## Background

[4] **Paleoclimate.** The Northwest Pacific Rim is remarkable for its low present-day snowline. On the northern Kurile Islands and southern Kamchatka Peninsula that snowline is at an altitude of 600–800 m a.s.l. [*Braitseva et al.,* 1968; *Vlasov,* 1958], on the Iskaten’ and Pekul’ney Ranges of Chukchi Peninsula at elevations of 650–750 m a.s.l., in a more maritime area of the peninsula, near the Provideniya Harbour at 450–550 m a.s.l. [*Sedov,* 1997] and on a mountain of the northern Okhotsk-Sea coast, near Magadan, at about 1000 m a.s.l. [*Sedov,* 2000]. The equilibrium line rises to 2300 m only on the present-day glaciers of Suntar-

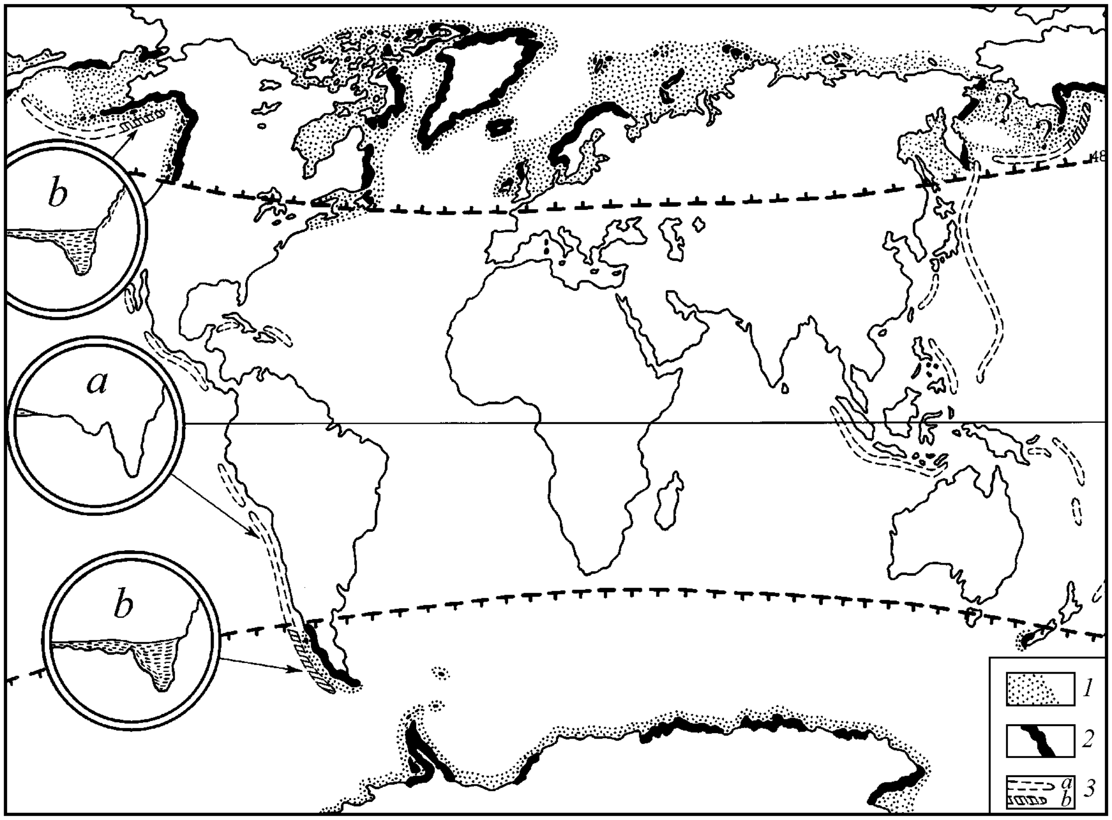

**Figure 1.** Distribution of glaciated continental shelves (1), fjord-type coasts (2), and debris-filled deep-sea trenches (3) in the world [after *Flint,* 1971; *Grosswald and Glazovsky,* 1984; *Kaplin,* 1962, with some authors' changes] Here *a* – deep-sea trenches containing no sedimentary infills, *b* – deep-sea trenches filled with glacial and marine-glacial sediments. Note that, regardless of tectonic or seismic environments, all of them occur north of 48°N in the Northern Hemisphere, and south of 42°S in the Southern Hemisphere. Here, both the Okhotsk-Sea and Beringian continental shelves are shown as glaciated based on geographic and climatic probability.

Khayata Range [*Koreisha* 1991]. These observations all strongly suggest that the Ice-Age snowline on the northern Kurile Islands, eastern Kamchatka and Chukchi Peninsula dropped to sea level (which is consistent with the fjord-type geomorphology of the east Chukchi, Koryak and Kamchatka coasts), and was only a few hundred meters above that level in more continental mountains of Pacific Siberia.

[5] With such low present-day snowlines, all the climate-based computer simulations indicate that climate perturbations of the Ice Ages had inevitably led to inception and growth of continental-sized ice sheets on the Northwest Pacific Rim, and that the past ice sheets had covered not only mountains and coastal plains of the region, but also its continental shelves.

[6] The modeling experiments by *Verbitsky and Oglesby* [1992] were first to demonstrate that the last glaciation of Northeast Siberia had been about as extensive as the Scandinavian and North American ice sheets and, in addition, that it incepted easier and earlier than those ice sheets. Later, the computer models of *Budd et al.* [1998] more specifically implied that, first, a continuous ice sheet had developed over the highlands of Northeast Siberia and, second, the ice sheet expanded to the southeast and invaded the Sea of Okhotsk. The same extent was obtained in the paleo-ice sheet simulations by *Greve et al.* [1999] and *Bintanja et al.* [2002]. Also, according to a modeling of the former glaciation of the Northwest Pacific Rim, produced by *Fastook* [1997, unpublished], a broad Okhotsk-Sea ice stream not only existed, but it moved at the rate of 2 km $yr^{-1}$, despite its lower (floating) part being buttressed by the Kurile Island Arc.

[7] If we place the Sea of Okhotsk and adjacent Beringia into a broader context of the Northern Hemisphere's marine paleoglacial systems with their indispensable geological attributes, such as glaciated continental shelves, fjord-type coasts, and debris-filled deep-sea trenches, we see that they fall into the huge zone north of 48°N, to which all marine paleoglacial systems belong in the Northern Hemisphere. Thus from purely geographic and paleoclimatic considerations, it is highly probable that both the regions were glaciated by former marine ice sheets (Figure 1).

[8] **Results of deep-sea drilling.** In 1992, the inferences based on paleoclimatic modeling and geographic considerations became strongly supported by the results of

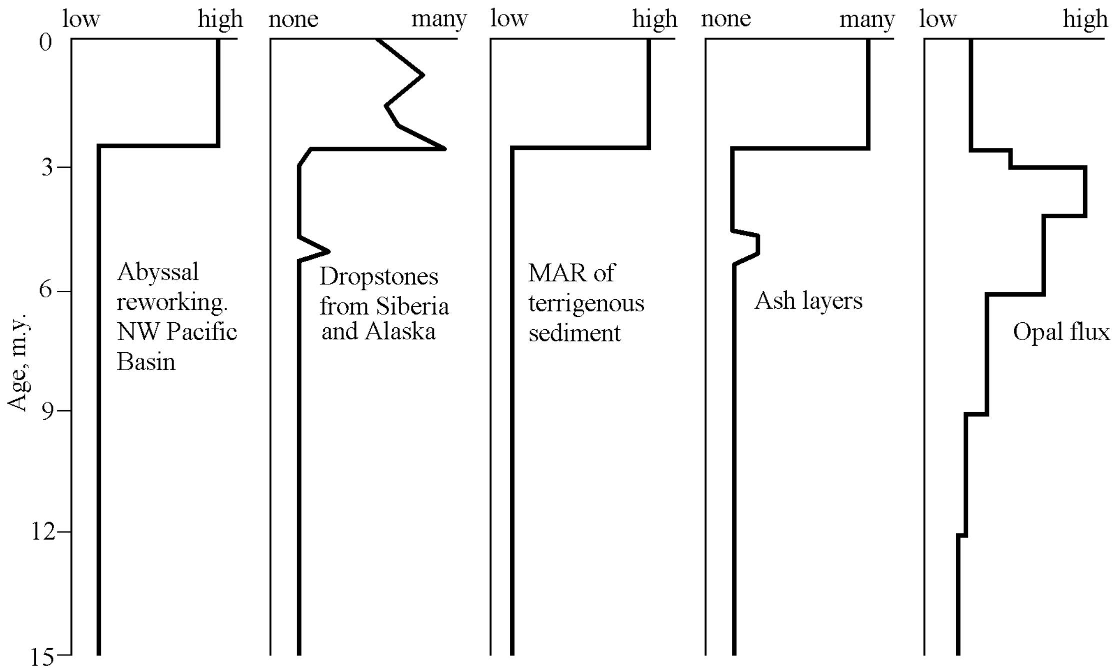


**Figure 2.** Major changes in the late Cenozoic sedimentary record of the North Pacific Ocean, as established by deep-sea drilling near the Detroit Seamount [*Roberts,* 1993].

deep-sea drilling in the northwest Pacific Ocean [*Roberts,* 1993]. The drilling was conducted during the ODP Leg 145 of the R/V *JOIDES Resolution*; its drilling sites were located 700–800 km east of the southern Kamchatka Peninsula tip, near Detroit Seamount in water depth exceeding 3 km. Based on their preliminary analyses, the on-board scientific party arrived at the solid conclusion that, 2.6 million years ago, the sedimentary environment of the North Pacific Ocean had experienced dramatic change: deep-sea circulation had abruptly become vigorous; rates of sedimentation increased many-fold, and the composition, density, and magnetic characteristics of the bottom sediments also suddenly changed (Figure 2). Abyssal redistribution and reworking of the sediments had intensified, the amount and concentration of fine-grain terrigeneous debris (relative to the in situ siliceous oozes) had increased as well. Notably, at that time, 2.6 million yr ago, the influx of all kinds of continental materials enormously accelerated, and dropstones of Siberian provenance, up to 5 cm across, became abundant in sites seaward from the Sea of Okhotsk. Ash layers also became quite abundant in the bottom sequences, attesting to enormous increase in volcanic activity unmatched by any found earlier in the Miocene through Pliocene record.

[9] Members of the on-board party had little doubt that all these changes clearly indicated that a large-scale glaciation had incepted in the North Pacific Ocean at 2.6 million yr ago – at the same time as in the North Atlantic Ocean.

[10] This was further developed by detailed studies of *Kotilainen and Shackleton* [1995], which demonstrated that the rate of the ice rafting, reflected in densities of deep-sea cores, had experienced periodic variations. A curve depicting these variations for the last 95,000 years exhibited some 20 cycles of ups and downs in ice rafting, thus implying about 20 cycles of climate coolings and warmings. These researchers stated that the cycles were similar to and likely synchronous with the Dansgaard-Oeschger climate events revealed by the Greenland ice cores.

[11] Actually, extensive glaciation of the Northern Pacific Rim was suggested much earlier, over 30 years ago, when abundant ice-rafted erratics were discovered in deep-sea sediments of the North Pacific Ocean [*Conolly and Ewing* 1970], and 15 years later the onset of the ice-rafting was dated to about 2.5 million years ago [*Rea and Shrader,* 1985]. In this context, it is noteworthy that a multitude of dropstones were located in the Upper Pliocene through Upper Pleistocene deep-sea cores (to the very tops of them!) recovered by drilling east of Honshu Island, Japan [*Okada,* 1980]. Importantly, one of the drilling sites was situated east of the Japanese Trench, which implied that the dropstones could have only come from icebergs transported by the Oyshio Current from far north, and not from nearby Honshu Island (Figure 3).

[12] The consistent LGM oceanographic changes in NW Pacific Ocean were, in fact, an outright "thermal revolution". In particular, extending of a cold, iceberg-infested Oyshio Current to the shores of southern Japan [*Oba et al.,* 1991], and tremendous cooling of the Sea of Japan due to isolation, infilling by the Amur-River water and freezing [*Grosswald,* 1998b], inevitably resulted in cooling, much deeper than it is generally thought, and glaciation of the

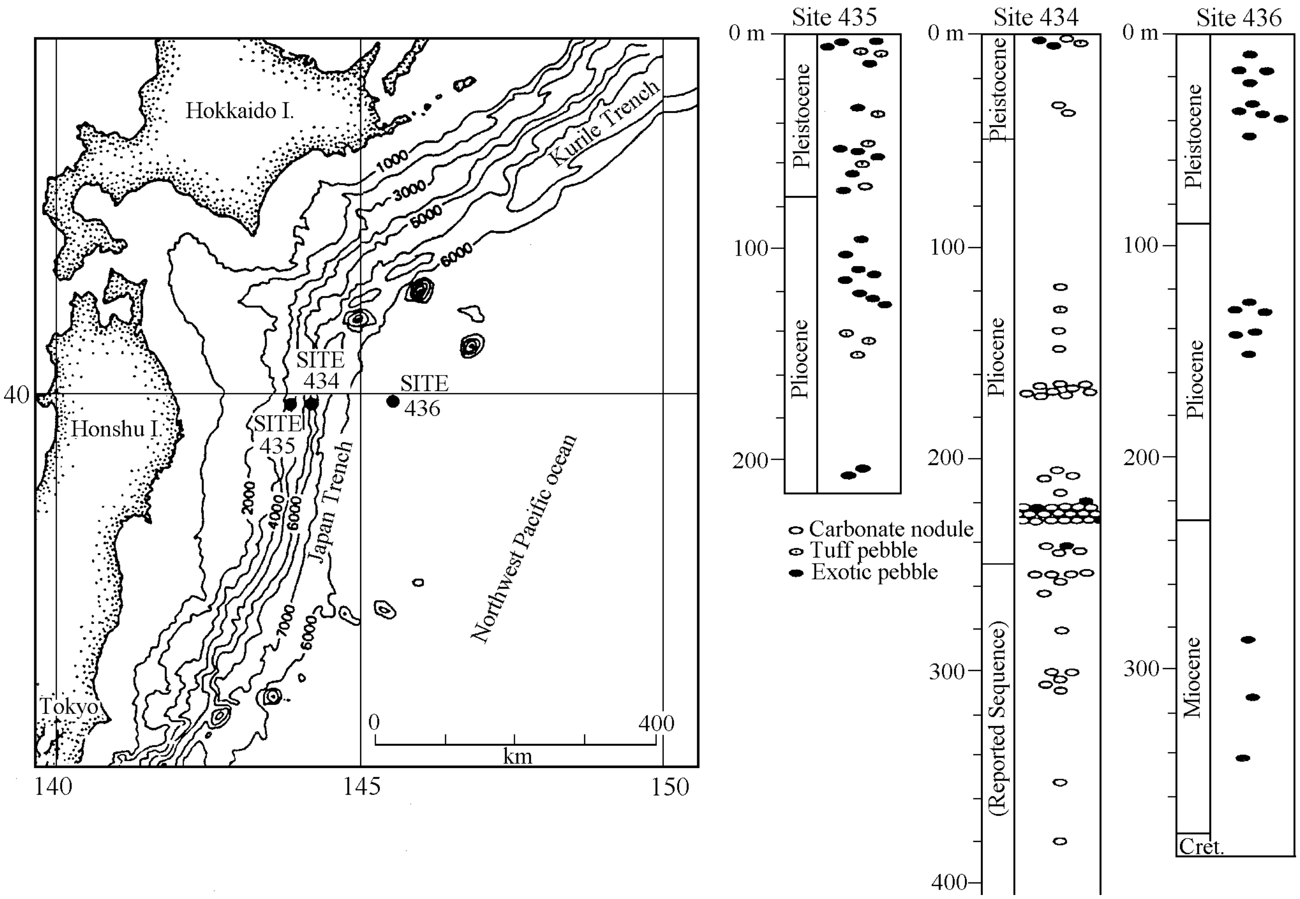


**Figure 3.** Exotic pebbles and chips of carbonate nodules in cores from Sites 434, 435 and 436 DSDP Leg 56 [*Okada,* 1980]. Bathymetry on the location map is in meters. Note that, in core sections, the exotic pebbles occur up to the very end of the Pleistocene.

Islands of Japan much greater than presently reconstructed [*Grosswald,* 2002].

[13] Still, a big problem remains: from where did all these erratics come, and what were the path tracks of North Pacific icebergs that transported the erratics?

[14] **Search for the source of North Pacific icebergs.** The issue of this source is not resolved; yet the number of options cannot be great. *Keigwin* [1995a], who was the first to pose this problem, conceived only two probable alternatives; first, that the icebergs came from the Alaskan and Siberian coasts after calving from tidewater glaciers, and second, that they had been released by a nearby full-sized marine ice sheet of unknown size and location.

[15] From our perspective, only the second option is realistic. The ODP Leg 145 drilling site and Honshu Island, on the one hand, and the coastal zones of Alaska and Siberia, on the other, are thousands of miles apart, and such a long-distance rafting of erratics appears hardly possible. By contrast, a marine ice sheet, or ice sheets, on the Northwest Pacific Rim would explain not only the distribution of erratics, but also the entire complex of paleoceanographic changes established by the deep-sea drilling. In particular, it would account for the abrupt acceleration of abyssal circulation in the North Pacific, and for the sudden growth in influx of all kinds of continental materials (including the erratics). Being located in marginal seas of the ocean, the ice sheet or ice sheets would be much closer to the depositional sites than the coasts of Alaska and Siberia and also would be a much more productive source of icebergs and meltwater than any mountain glaciers. They would even account for the enormous increase in volcanic activity, as, according to computations by *Nakada and Yokose* [1992], there are direct links between glacial and volcanic phenomena. Specifically, these geophysicists have found that ice sheets placed upon the Northwest Pacific Rim would have been a sufficiently heavy load to push the hydrostatic pressure in deep magma centers over critical thresholds and trigger massive volcanic eruptions.

[16] Where were those hypothetical ice sheets located? Members of the *Roberts* [1993] speculated that the Sea of Okhotsk had been the most probable source of the icebergs. Our analyses of the Okhotsk Sea and its environ's geomorphology, of the pattern and causes for Amur River reorganizations, coupled with new climate-based modeling experiments, strongly suggest that this assumption was correct.

## The Sea of Okhotsk

[17] What is known of that sea? The Sea of Okhotsk is a large embayment of the North Pacific, it deeply penetrates the continental mass of Eurasia between Kamchatka Peninsula and Sakhalin Island and is separated from the rest of the ocean by the Kurile Island Arc. The areal extent of the sea is 1,590,000 km$^2$, and the average depth is 860 m. It opens to the southeast, and is semi-surrounded by a highland amphitheater formed by mountain ranges of the Dzhugdzhur, Suntar-Khayata, Chersky, Kolymsky, and Kamchatka's Sredinny Ranges, which include many active volcanoes. Dozens of glacial U-shaped valleys descend into the sea down the amphitheater, as well as from the Koryak Mountains. In some places, like in Gulfs of Penzhina and Gizhiga, the glacial valleys converge to form large fjord-type inlets.

[18] **Climate and water masses.** The present-day Okhotsk-Sea region is characterized by the coldest air temperatures, and heaviest sea-ice conditions within the entire North Pacific Ocean. Yet, its climate is temperate, with monsoon-type atmosphere circulation bringing in warm air masses from the southeast in summers and cold Siberian air from the northwest in winters. Summer temperatures are $+11°$ to $+18°$C while winter temperatures quite often drop to $-25°$C. The annual atmospheric precipitation grades from 230 mm in the north to 1250 mm in the south. In the bordering mountains, a considerable proportion of the precipitation comes as snowfall.

[19] Oceanographically, the Okhotsk Sea is a major source of the present-day "Intermediate Water" flow into the North Pacific. The Okhotsk-Sea surface water also interacts with the open Pacific Ocean and contributes to the formation of the cold Oyashio Current. On merging with the southward flowing East Kamchatka Current, Okhotsk surface water forms a core of the Oyashio. During glaciations, the Sea of Okhotsk was source area of the Ice-Age Pacific deep water, controlling the extent of the deep water ventilation and nutrient distribution [*Duplessy et al.,* 1988; *Keigwin,* 1995b].

[20] **Sea floor. The evidence.** The Sea of Okhotsk, in particular its bottom topography and geologic structure, is rather well studied. The floor of the Sea of Okhotsk is tectonically young and active. It was affected by the India-Eurasia collision tectonics, which is believed to have produced normal faults, half-grabens, shearing, folding, and thrusting during the Eocene through Pliocene. These structures often followed the course of the older Mesozoic structural lines of the Mongol-Okhotsk-Chukchi active margin [*Worall et al.,* 1996]. With all this in mind, it seems obvious, at least to us, that the sea floor has a glacial geomorphology superimposed on this relatively passive tectonic background, the geomorphology of the kind typical for glaciated continental shelves in general [*Holtedahl,* 1970; *Shepard,* 1973]. In addition, a reconstruction by a LGM-sedimentation model, as well as present-day geomorphic processes operating on that floor, appear typical for glaciated shelves, with their steep-sloped channels and sills [*Wong et al.,* 2000].

[21] As early as in 1949–1955, expeditions of the Institute of Oceanology, an oceanographic branch of the USSR Academy of Sciences, charted a system of submarine troughs, basins and ridges, as well as the "back-arc" deep-sea Kurile Basin. The depth of the Shelikhov Deep was fathomed to 445 m, of the TINRO Deep – to 991 m and of the Deryugin Deep – to 1795 m. Further, it was found that all the deeps are interconnected by submarine troughs which, in turn, are subdivided by transverse ridges and turned into alternations of basins and sills. The minimum depths in the troughs were located on inter-basin divides, and were found to be 369 m in Shelikhov Bay, 539 m in Lebed' Trough, 1354 m in Makarov Trough, and 1315 m in Pioter-Schmidt Trough. The deepest part of the sea was found in its southern sector, the Kurile back-arc Basin, which is characteristically 3000 m to 3200 m deep, with a maximum depth of 3372 m [*Udintsev,* 1957].

[22] Several broad submarine sills, or "uplands", also became known. The two largest sills, the Academy and the Institute of Oceanology Sills, with their tops being deeper than 900 m, tower above the adjacent troughs and basins by 400 m to 800 m. The straits crossing the Kurile Island Arc were also explored and found to be characterized by the same U-shaped profiles, as the intra-sea troughs. The major Bussol and Kruzenstern Straits were 2318 m and 1929 m deep, while four other straits were deeper than 500 m [*Udintsev,* 1957; *Udintsev et al.,* 1981].

[23] A number of smaller-scale seafloor forms were also uncovered during the expeditions. Among them were submarine canyons incised into the slopes of the "uplands", flat platforms on upland tops, erosional terraces on their slopes, and giant grooves and ridges of the TINRO Deep. Some other troughs aligned parallel to their long axes were also charted, as well as swarms of hills and ridges scattered over the bottom of the Deryugin Deep. On the submarine slopes of Sakhalin Island and Kamchatka Peninsula, within the depth range of 200 m to 1000 m, staircases of ridge-and-channel pairs were also recorded. The pairs had a relief of 5 m to 6 m, and were aligned subhorizontally facing each other across the Sea of Okhotsk [*Udintsev,* 1957; *Udintsev et al.,* 1981]. The longitudinal ridges of the TINRO Deep were found to be made up of silts and fine sands, and characterized by gradational bedding and frequent occurrence of scattered pebbles [*Volnev,* 1983]. These ridges were up to 200 km long and 1.5 km to 0.6–0.8 km wide, their relief changes from 100 m in the north to 25–30 m and less in the south, and they diverge southward into systems of subparallel ridges.

[24] It was also found that bare rock outcrops, patches of nonsorted gravel, and glacial erratics were widespread on the Sea of Okhotsk floor and on the bottoms of the Kurile straits [*Bezrukov,* 1960]. The erratic boulders were typically faceted and striated, and their number and size appeared totally independent of the distance from shores; as to their abundance, it was so great that, as a rule, the overwhelming ubiquity of erratics totally obscured the results of dragging for local bedrock fragments (B. V. Baranov, pers. comm.). As for the deep Kurile Basin, it is infilled by a sequence of terrigenous sediments of a thickness measured in kilometers [*Zonenshain et al.,* 1990].

[25] There are some indications of past glaciation. So far it has been reported only in two places: from the north-

eastern coast of the sea, and from an offshore area of southwestern Kamchatka Peninsula. The first area included the Gulfs of Penzhina and Gizhiga where *Bondarenko* [1931] and *Udintsev* [1957] described extensive fields of glacial and glaciofluvial deposits. Both the researchers visualized big valley glaciers that formerly debouched from near-shore mountains into the sea and filled in Shelikhov Bay. In the second area, on the shallow shelf of Kamchatka, a 3 to 8 m-thick sheet of unsorted solid boulder clays, interpreted as lodgement till, was encountered in the process of drilling; this till sheet occurred beneath a 15-m thick sequence of late-glacial and postglacial sediments [*Kuz'mina and Eremeeva,* 1990].

[26] However, the glaciation responsible for these landforms and deposits was considered local and insignificant, and its role in the geological history of the sea was thought to have been negligible. Glacial erosion and accumulation was never taken into account when explaining the seafloor geomorphology [e.g., *Antipov et al.,* 1997; *Savostin et al.,* 1983]. The range of environmental change in the Okhotsk-Sea region over the last glacial-interglacial cycle has been discussed only in terms of sea-ice expansions and shrinkages [*Gorbarenko et al.,* 2003; *Shiga and Koizumi,* 2000; *Wong et al.,* 2003].

[27] **Sea floor. Interpretation of the data.** Until recently, the origin of all described submarine landforms of both larger and smaller scale was either explained by operation of diverse nonglacial processes or considered enigmatic. In particular, the seafloor troughs, basins, and sills were taken for products of tectonic faulting and folding [*Udintsev et al.,* 1981]; the longitudinal ridges of TINRO Deep were results of downslope turbidity currents and near-bottom sediment transport [*Volnev,* 1983]; the submarine terraces and subhorizontal ridge-and-channel pairs were ascribed to near-shore impact of waves during the stages of lower sea levels; and the submarine canyons were attributed to normal river erosion operating on dry land before the land became the seafloor [*Udintsev,* 1957]. As for the bottom erratics, their spreading was (and still is) commonly accounted for by rafting activity of sea ice and icebergs [*Bezrukov,* 1960].

[28] Today, the situation has changed and Quaternary glaciations of the Sea of Okhotsk appear probable. What is more, glaciations are strongly suggested by the concerted data coming from paleoclimatic, geomorphologic, and marine geological studies [*Grosswald,* 1998b; *Grosswald and Hughes,* 1998]. Actually, the best documentation of glacial invasion of the Sea of Okhotsk comes from the geomorphology of its bottom, first of all from the system of deep U-shaped valleys and dividing sills that dominate the Okhotsk sea floor topography, and also from the smaller seafloor landforms. Previously, as we pointed out above, there had been a tendency to account for all the landforms by operation of only nonglacial processes, ascribing a specific mechanism for each kind of landforms.

[29] We repeat, however, that the entire submarine geomorphology of the Sea of Okhotsk is typically glacial, having resulted from the impact of a grounded ice sheet and subglacial meltwater activity. The marine Okhotsk Ice Sheet was grounded in the larger northern province of the sea, lying north of 47–49°N. From geological and geophysical standpoints this regions is a genuine continental shelf (B. V. Baranov, L. P. Zonenshain, personal communication). A Kurile ice shelf, an extension of the grounded ice sheet, was floating in the second (smaller) province, the Kurile Basin, confined between the above continental shelf and the Kurile Island Arc. Tectonically, that basin is a typical "back-arc" part of the deep ocean; during the Quaternary Ice Age, it was turned into a basin of intense glaciomarine deposition.

[30] Major glaciological agents of that process were the Okhotsk-Sea ice streams that unloaded debris as they exited their troughs and became afloat. In particular, large ice streams exited from Pioter-Schmidt and Makarov Troughs, as well as from Golyginsk Channel, entering Kurile Basin northwest of Paramushir Island. The ice stream in Golyginsk Channel appears to have drained the ice masses of the Central Depression of Kamchatka Peninsula. The depression of Golyginsk Channel is similar to the Bering Trough on the Alaskan continental shelf, which may have been also occupied by an Ice Age ice stream [*Grosswald and Vozovik,* 1984].

[31] The Okhotsk-Sea assemblage of basins and sills, including Deryugin and TINRO Deeps, Lebed', Makarov and Pioter-Shmidt Troughs, and Institute of Oceanology and Academy "Uplands", conform to the geomorphology that is typical of a continental shelf deeply eroded by an ice sheet (Figures 4 and 5). That assemblage is a regular combination of deep U-shaped troughs, both longitudinal and transverse, and huge bedrock sills, that is similar both in scale and pattern to what was revealed by surveys of the world's glaciated continental shelves [*Holtedahl,* 1970; *Shepard,* 1973], notably in Antarctica [*Anderson,* 1999].

[32] The deepest troughs of the assemblage have depths of 1.5 km to 2 km as do their analogues from elsewhere, for instance from the Weddell Sea floor in Antarctica, and are as closely tied to the sources of ice inflow as are the submarine troughs of Antarctica [*Vaughan et al.,* 1994]. The mean depth of glacial scour of the Okhotsk-Sea floor implied by its geomorphology amounts to many hundred meters, which is commensurate with the depth of glacial erosion of other glaciated continental shelves, e.g., of the Barents-Sea shelf, where the depth of scour was found to be in the range of 500 m to 1500 m [*Solheim et al.,* 1996], and beneath the expanded marine ice sheet in West Antarctica [*Anderson,* 1999].

[33] We have also found the Okhotsk ice-sheet hypothesis provides the best clues to the origin of the smaller-scale forms of the sea floor in question. Specifically:

[34] (a) V-shaped submarine canyons incised into sill-slopes are similar to the forms typically occurring on all glaciated continental shelves. They are commonly accounted for by erosional activity of high-pressure subglacial meltwater [*Shepard,* 1973];

[35] (b) the terrace-like ledges of the sill-slopes, which are believed to have formed through wave erosion, could be as readily produced by glacial scour. The "terraced" slopes of this kind were found to be common features of glaciated terrains in Antarctica [*Evteev,* 1964];

[36] (c) the longitudinal sea-floor ridges and grooves of the TINRO and other submarine troughs, currently thought


**Figure 4.** Physiographic image of the Sea of Okhotsk floor and major sources of Pleistocene ice inflow. Compiled from several sources, including the Okhotsk-Sea chart, presented in Figure 5: (1) principal directions of ice inflow from coastal mountains, (2) system of elongated ridges, linear scarps and furrows in West Kamchatka (suggestive of lateral moraines), (3) "submarine ridges of unknown origin", from "The Geomorphological Map of the USSR", on the scale of 1:2 500 000 (Moscow, GUGK, 1987), and (4) sites of offshore drilling recovering a Pleistonene lodgement-till bed overlain by marine sediments [*Kuz'mina and Eremeeva,* 1990]. Lettering: DZH – Dzhugdzhur Range; K – ice inflow from Koryak Highland; Sh – Trough of Shelikhov Bay; T – TINRO Deep; D – Deryugin Deep; L – Lebed' Trough; M – Makarov Trough; PS – Pioter-Shmidt Trough; OS – Institute of Oceanology Sill; AS – Academy Sill; KB – Kuril Basin; P – Paramushir Island; B – Bussol Strait.

to be produced by turbidity flows or to be of "unknown" origin, can be simply taken for the products of ice and meltwater activity at the base of large paleo-ice streams. This glacial interpretation comes from the mechanisms operating at the base of ice sheets and from studies of formerly glaciated troughs in Antarctica [*Anderson,* 1999] and, in Arctic Siberia, in Saint Anna Trough of the Kara Sea, at depths between 300 m and 550 m, where side-scan sonar

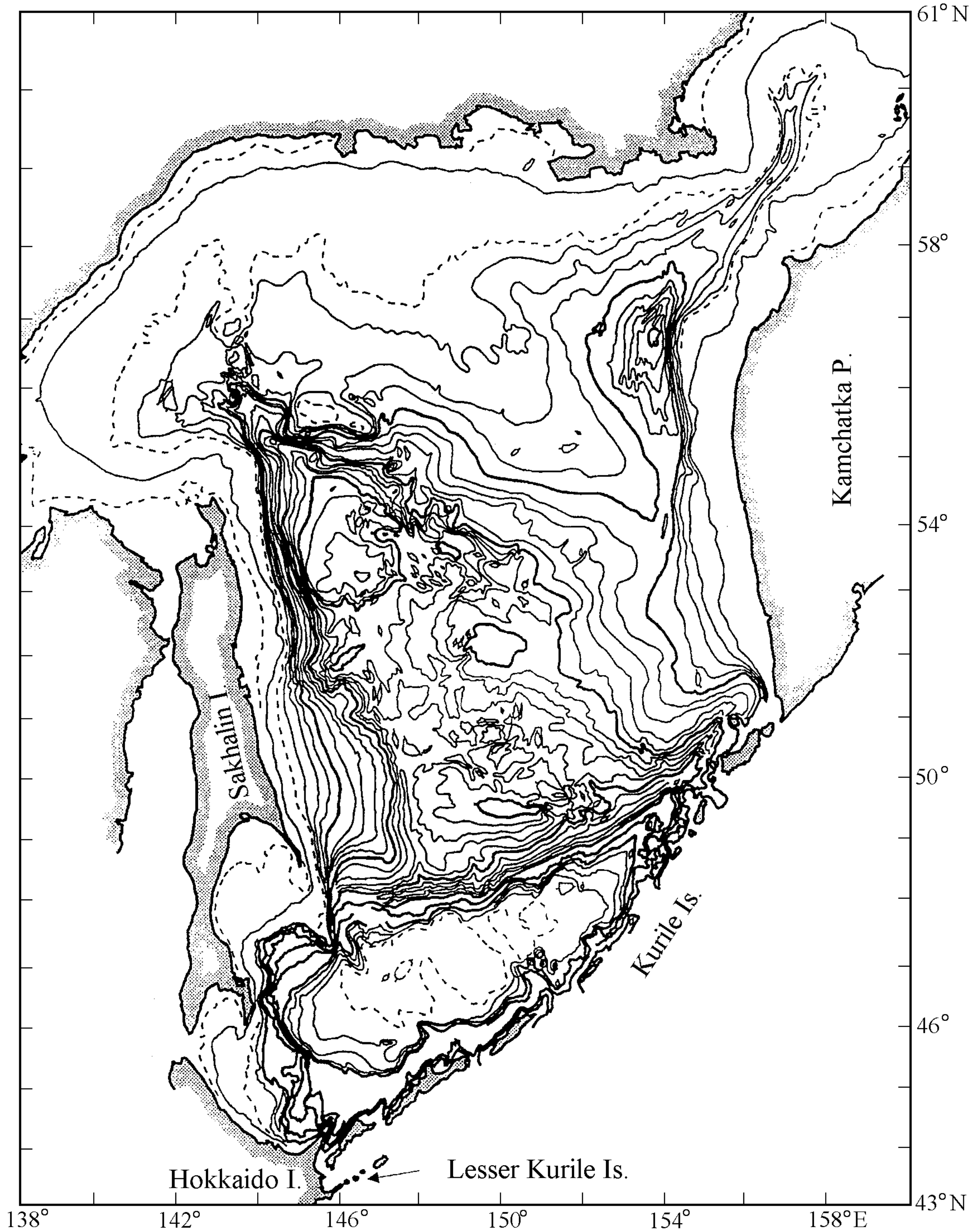


**Figure 5.** Bathymetric chart of the Sea of Okhotsk. Compiled by A. S. Svarichevsky [in *Baranov et al.,* 1997].

records have revealed a system of longitudinal furrows and ridges made up of basal diamictons, or lodgement till [*Polyak et al.,* 1997]. The Saint Anna furrows are up to 20 m deep and 200 m wide, and the ridges are up to 30 m high and 5 km wide, thus similar in shape and size to the TINRO-Deep forms. In that Siberian trough, numerous smaller ridges and hummocks with prevailing heights of 5 m to 10 m were also located, which are similar to the respective features of the Deryugin-Deep;

[37] (d) finally, the staircases of ridge-and-channel pairs occurring on submarine slopes of Sakhalin Island and Kamchatka Peninsula, now believed to have formed in coastal

environments when sea-level was 200 m to 1000 m below present, can be naturally explained in terms of glacial and meltwater erosion and accumulation operating beneath the moving ice-sheet margins. These features may have formed along the grounding line of an ice shelf, where bottom crevasses would open and be filled with glacially eroded material, somewhat like the ribbed moraines that form where a frozen subglacial bed becomes thawed [*Hättestrand,* 1997], but on a larger scale for larger crevasses.

[38] (e) sea-floor terraces could also form during deglaciation as rising sea level forced the ice-shelf grounding line to retreat.

[39] All in all, based on the premise of the Okhotsk marine ice sheet, we have gained new insights into the genesis of all the sea's submarine forms, both of large and small scale. In this new light, they can be explained by operation of only one process – the glacial one, instead of resorting to a multitude of unrelated diverse mechanisms.

## Adjacent Highlands and Coasts

[40] The highlands and mountain ranges adjacent to the Sea of Okhotsk are commonly believed to have been glaciated by cirque and valley glaciers; a few bigger paleoglacier complexes are envisioned only in Verkhoyansk, Koryak and Kamchatka mountains [*Velichko,* 2002]. However, interpretation of space images of Northeast Siberia along with numerical modeling based on the 1000 m to 1200 m snowline depression led us to conclude that all the mountains, piedmonts and intramontane basins were virtually completely ice-covered in that region [*Grosswald,* 1998a; *Grosswald and Hughes,* 2002]. According to our model, a continuous chain of large glacier complexes extended from the Pamirs to Chukchi Peninsula and merged with the marine ice sheets of the Eurasian Arctic margins. Specifically, the northeastern link of that chain, the Cherski-Kolyman glacier complex of Cordilleran type, together with a local ice cap on Kamchatka Peninsula, semi-surrounded the Sea of Okhotsk and discharged their ice into the sea.

[41] Judging by the Okhotsk-Sea coastal geomorphology, the strongest ice inflow was focused in two sectors, first – on the concave southeastern side of Suntar Khayata Range, and second – in the sea's northeastern embayment where broad valleys of Penzhina and Belaya-Talovka-Kuyul occur. The first sector was fed by ice of the Suntar Khayata and Cherski Ranges centers, the second – by ice of the Kolyman and Koryak mountain complexes. A paleo-ice stream flowing along the huge submarine Shelikhov-TINRO trough is evidenced by the fjord-like Gulfs of Gizhiga and Penzhina, glacially-cut "corners" on their sides and on both sides of Shelikhov Bay (see, e.g., Cape Utkholoksky of western Kamchatka, and Cape Piyagina, east of Magadan), as well as by a linear system of elongated ridges, scarps and erosional furrows that extend along the western coastal plain of Kamchatka Peninsula. This system has not been recognized or studied previously, yet judging by its appearance on maps and air-photographs, and by its relation to the Okhotsk-Sea geomorphology, the system is an assemblage of lateral moraines, eskers, and meltwater drainage channels.

[42] This reconstruction of a glacial setting in the near-Okhotsk coastal zone is consistent with the at-or-near-sea-level paleo-snowline of the region. It is also consistent with the aforementioned modeling experiments. Our own modeling results [*Grosswald and Hughes,* 1998], yielded the shape, elevation, and thickness of the Okhotsk spillover ice sheet, based on these specific geomorphic and climatic constraints. An additional constraint, most favorable to inception, growth and stabilization of that ice sheet, was the fact that the Kurile Ice Sheet was buttressed by the Kurile Island Arc, i.e., by an extensive submarine ridge (see below).

## Drainage Reorganizations

[43] Evidence for Late Pleistocene reorganizations of a continental drainage network linked to the Sea of Okhotsk is also relevant to this discussion. The Amur, Amgun, Togur, and Uda River basins exhibit traces of vast paleo-lakes and repetitive river-flow diversions, while the morphology of adjacent mountain ranges and uplands is made conspicuous by a number of canyon-like breaches. In particular, there is geomorphic evidence for past deflections of the Middle Amur River to the south and southwest, toward the Japan and Yellow Seas via the Ussury- and Sungary-River valleys. Also, several abandoned valleys attest to a few episodes when the Lower Amur River, on reaching certain positions, was deflected southeastward to Tartar Strait. It is also clear that lower reaches of the Uda River were impounded and their discharge was rerouted to the Lower Amur by a lake-and-channel system extending parallel to the sea's shoreline, while the upper reaches of the same Uda River were, and still are, deflected to the south, across the mountain ridges of Tukuringra and Dzhagdy [*Nikolskaya,* 1969].

[44] These reorganizations of network of drainage, like many other phenomena of this kind, were believed to have been controlled by neotectonics; i.e., ascribed to the effects of recent crustal displacements. There was a tendency to associate formation of paleolakes and river diversions with river damming by rising fault-blocks, and breaching of mountain ranges with tectonic faulting and antecedent river incisions [*Lebedev,* 1995].

[45] However, this interpretation appears inconsistent with the geography of network reorganizations as displayed in Figure 6. If the changes were tectonically controlled, they would be inevitably random, whereas Figure 6 shows a continuous, internally coherent spatial record of drainage reorganization. This record fits well into a hydrologic setting that would emerge if the rivers had been dammed by an ice sheet in the embayment of the Sea of Okhotsk [*Grosswald,* 1998a].

[46] Having moved from the present shoreline for 300–350 km landward, the western margin of the Okhotsk ice sheet would ensure formation of the ice-dammed lakes and overflow channels, and would force all the river deflections and re-routings into Tartar Strait, the Sea of Japan and the Yellow Sea. All these discharge reorganizations were due to advances and retreats of the ice sheet's margin. The lake

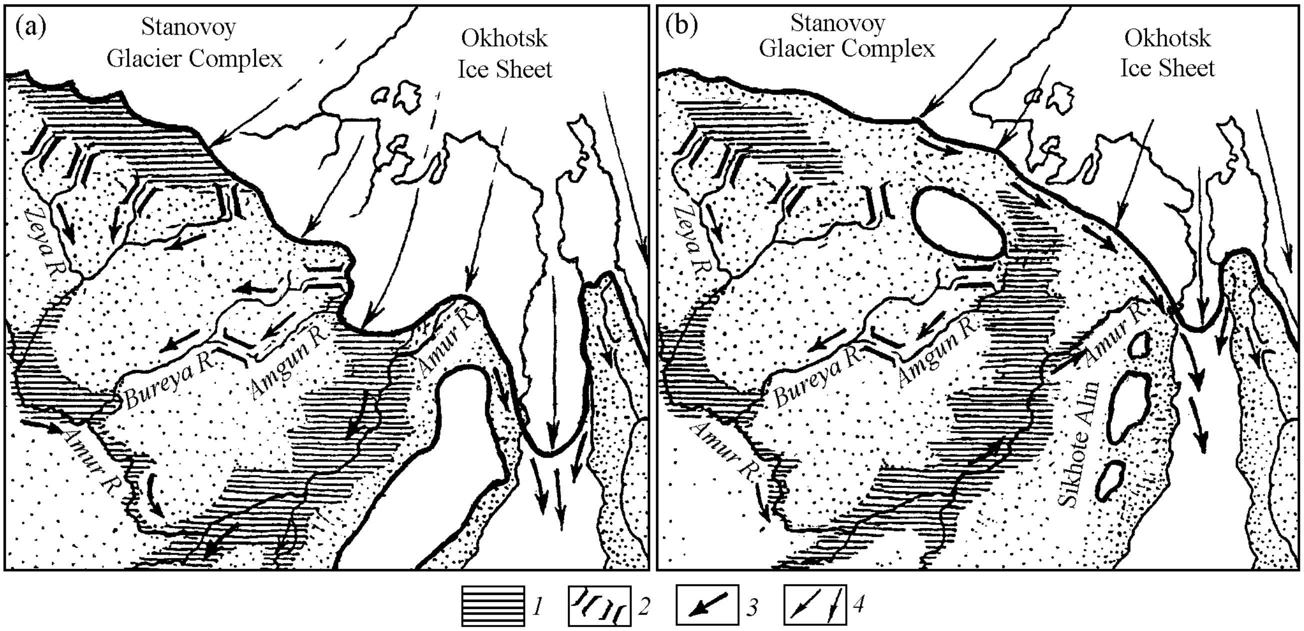


**Figure 6.** Late Quaternary reorganizations of the drainage network, the Amur River's and Uda River's catchments. Evidence for ice-damming and river-flow diversions effected by the last Okhotsk-Sea Ice Sheet [*Grosswald,* 1998b]: (1) Late Quaternary paleo-lakes, (2) spillways and overflow channels, (3) directions of past proglacial drainage, (4) glacierized areas.

and river geography would experience step-by-step changes during retreat of the ice margin. One of the steps, shown in Figure 6a, would favor a complete turnover of several rivers, such as the Amgun', Ussuri and Sungari. Another step, depicted in Figure 6, forced the marginal meltwater runoff, when a few waterways would provide shortcuts from the Lower Uda River to the Lower Amur River, from where the water would turn southeastward, crossing the northern Sikhote Alin' Range into Tartar Strait. As for the meltwater lake of the Upper Uda River, its outlets crossed the adjacent Tukuringra and Dzhagdy Ranges by a series of overflow channels and joined the Zeya River flow during both the steps. Thus, as we already emphasized, the concept of an Okhotsk ice sheet and its damming effects can naturally account for the drainage reorganizations displayed in Figure 6.

## The Marine "Back-Arc" Ice Sheet, Its Specificity

[47] Reconstructing the Okhotsk Ice Sheet presents challenges not encountered in previous reconstructions of Pleistocene ice sheets using the geometrical force balance [e.g., *Grosswald and Hughes,* 1995, 2002; *Hughes,* 1995, 1998; *Hughes and Hughes,* 1994]. As we envision it, based on evidence provided here, the Okhotsk Ice Sheet is a marine ice sheet in which flow begins along a highland arc that rings the Sea of Okhotsk on the east and north, transgresses onto the Asian mainland to the west, and ends along the Kuril Island Arc to the south. Did the ice sheet form as glaciers from these highlands advanced onto the shallow continental shelf in the Sea of Okhotsk during lowering sea level at the beginning of Quaternary glaciation cycles? Or did sea ice thicken and ground in the Sea of Okhotsk and cause snowlines to lower to sea level in surrounding mountains, thereby allowing the mountain glaciers to advance and merge with the grounded sea ice to produce the marine ice sheet that ended as a floating ice shelf? How far did the mountain glaciation extend to the north of the highland arc? Did the precipitation shadow cast by the Okhotsk Ice Sheet confine these highland glaciers to the northern mountain slopes, or did they merge with a marine ice sheet in the East Siberian Sea that transgressed onto the Siberian coastal plain? Was there a connection to the east with a largely marine Beringian Ice Sheet that originated in the Chukchi Sea, poured through Bering Strait into the Bering Sea, and ended as an ice shelf calving along the Aleutian Island Arc? If any of these connections existed, when did they exist? If none of these ice sheets existed, what are we to make of the evidence presented here?

[48] In the geometrical force balance [*Hughes,* 1992, 1998], the surface slope along an ice-sheet flowband of width $w_I$ is given by the expression:

$$
\begin{aligned}
\frac{\Delta h^*}{\Delta x} = &\left[\frac{(1-\rho_I/\rho_W)}{(1+r)^{1/2}}\left(\frac{P_W}{P_I}\right)^2\right] \\
&\times \frac{\left[a+\delta h_I/\delta t\right]\left[h_G+(1+r)^{1/2}(h^*-h_G)-h_R\right]}{(a+\delta h_I/\delta t)x+(h^*-h_G)u_G} \\
&- \left[\frac{(1-\rho_I/\rho_W)}{(1+r)^{1/2}}\left(\frac{P_W}{P_I}\right)^2\right] \\
&\times \frac{\left[h_G+(1+r)^{1/2}(h^*-h_G)-h_R\right]^{n+2}}{(a+\delta h_I/\delta t)x+(h^*-h_G)u_G} \\
&\times \left[\frac{\rho_I g}{4A}\left(1-\frac{\rho_I}{\rho_W}\right)\left(\frac{P_W}{P_I}\right)^2\right]^n \\
&+ \frac{\left[h_G+(1+r)^{1/2}(h^*-h_G)-h_R\right]}{2(1+r)^{1/2}}\left(1-\frac{\rho_I}{\rho_W}\right) \\
&\times \frac{\Delta(P_W/P_I)^2}{\Delta x} + \frac{2\tau_S(P_W/P_I)}{(1+r)^{1/2}\rho_I g w_I} \\
&+ \frac{\tau_0}{(1+r)^{1/2}\rho_I g[h_G+(1+r)^{1/2}(h^*-h_G)-h_R]} \; .
\end{aligned} \tag{1}
$$

Surface slope $\Delta h^*/\Delta x$ is the incremental increase in ice elevation $\Delta h^*$ in incremental horizontal distance $\Delta x$ measured upslope along an ice flowline from $x = 0$ at the ice margin. Densities are $\rho_I$ for ice, $\rho_W$ for water, and $\rho_R$ for Earth's mantle. Isostatic sinking beneath the ice load lowers ice elevation $h$ on an undepressed bed of height or depth $h_R$ relative to sea level. Lowered ice elevation $h^*$ lies on a depressed bed lowered from $h_R$ to $h_R^*$, with $r$ defined as $r = (h_R - h_R^*)/(h^* - h_R)$ such that $h_R = h_G$ remains constant at an ice-shelf grounding line. For grounded ice, $r = r_0[1-\exp(-t/t_0)]$ during time $t$ of ice-sheet advance and $r = r_a \exp(-t/t_0)$ during time $t$ of ice sheet retreat, where $t_0$ is the relaxation time of Earth's mantle to the ice load, $r = r_0 = \rho_I/(\rho_R - \rho_I)$ for isostatic equilibrium at $t = \infty$, and $r = r_a$ for $t = 0$ at the glacial maximum. Assuming present-day isostatic equilibrium, present-day bed topographies can be used for $h_R$ along flowlines of a former ice sheet. Transitions from sheet flow to stream flow to shelf flow downslope along ice flowlines are controlled by basal buoyancy factor $P_W/P_I$, where $P_W = \rho_W g h_W$ is the basal water pressure that supports water of height $h_W$ above the bed, $P_I = \rho_I g h_I$ is the ice overburden pressure for ice of thickness $h_I$, $g$ is gravity acceleration, $P_W/P_I \approx 0$ for sheet flow in which $h_W = 0$ for a frozen bed and $h_W \ll h_I$ for a thawed bed, $P_W/P_I = 1$ for shelf flow because $h_I = (\rho_W/\rho_I)h_W$ for floating ice, and $P_W/P_I$ increases from nearly zero to nearly unity downslope along ice streams, which are fast currents of ice that drain most of a marine ice sheet. Accumulation rate $a$ along an ice flowline is taken as constant, and ice thickness changes at a rate $\delta h_I/\delta t$ that is positive for a thickening ice sheet and negative for a thinning ice sheet. Ice thickness is $h_I^* = h^* - h_G$ across an ice-shelf grounding line, where $h_I^* = h_I$ and ice velocity $u_G$ is negative for $x$ positive upslope. Stresses in equation (1) are $\tau_S$ for side shear in stream flow and shelf flow, $\tau_0$ for basal shear in sheet flow and stream flow, and $\sigma_T$ for longitudinal tension and its gradient $\Delta\sigma_T/\Delta x$, expressed in terms of $P_W/P_I$ and $\Delta(P_W/P_I)/\Delta x$, and linked to the mass balance through longitudinal extending strain rate $\dot{\varepsilon}_T$, ice hardness parameter $A$, and ice viscoplastic parameter $n$ in the flow law $\dot{\varepsilon}_T(\sigma_T/A)^n$ for creep in ice. The quantity $\tau_S(P_W/P_I)$ allows a reduction in resistance from side shear as basal shear increases due to decreasing $P_W/P_I$.

[49] In the geometrical force balance, $\tau_0$ is determined by the ice surface slope $\Delta h^*/\Delta x$ and by the ice thickness $h_I^* - h_W^*(\rho_W/\rho_I)$ that is supported by the bed, not by basal water pressure:

$$
\begin{aligned}
\tau_0 &= \rho_I g\left[h_I^* - h_W^*(\rho_W/\rho_I)\right]\Delta h^*/\Delta x \\
&= \rho_I g h_I^*(1 - P_W/P_I)\Delta h^*/\Delta x
\end{aligned} \tag{2}
$$

and $\sigma_T$ is determined by the ice thickness $h_W^*(\rho_W/\rho_I)$ that is supported by basal water pressure, not by the bed, where $\sigma_T$ appears in longitudinal tensile force $F_T$ given by:

$$
\begin{aligned}
F_T &= \sigma_T w_I h_I^* \\
&= \left[\frac{1}{2}\rho_I g h_W^*(\rho_w/\rho_I)\right]\left[w_I h_W^*(\rho_W/\rho_I)\right] \\
&\quad - \left[\frac{1}{2}\rho_W g h_W\right]\left[w_I h_W^*\right] \\
&= \left[\frac{1}{2}\rho_I g h_I^*(1-\rho_I/\rho_W)(P_W/P_I)^2\right] w_I h_I^*
\end{aligned} \tag{3}
$$

so that:

$$
\sigma_T = \frac{1}{2}\rho_I g h_I^*(1-\rho_I/\rho_W)(P_W/P_I)^2 \; . \tag{4}
$$

Therefore, $\tau_0$ decreases as $\sigma_T$ increases, and vice versa. The controlling variable is $P_W/P_I$.

[50] The decrease of $P_W/P_I$ upslope from an ice-shelf grounding line is a consequence of progressive loss of hydraulic continuity as the ice overburden becomes increasingly supported by the bed, not by basal water pressure. In ice streams, this loss is accompanied by side shear and basal shear which contribute to a back-force $F_B$ that becomes progressively larger with distance $x$ upslope from the calving front of an ice shelf. For floating ice, the back force is also due to average water pressure $\overline{P}_W = \frac{1}{2}P_W = \frac{1}{2}\rho_W g h_W$ exerted on cross-sectional area $w_I h_W$ for a flowband of width $w_I$ at $x = 0$. The back stress $\sigma_B$ for both grounded and floating ice at any distance $x$ is given by the negative term in equation (3):

$$
\begin{aligned}
F_B &= \sigma_B w_I h_I^* = \frac{1}{2}\rho_I g h_I^*(\rho_I/\rho_W)(P_W/P_I)^2 w_I h_I^* \\
&= \left(\frac{1}{2}\rho_W g w_I h_W^2\right)_0 + \int_0^L \left[\partial\left(\frac{1}{2}\rho_W g w_I h_W^2\right)/\partial x\right] dx \\
&\quad + 2\overline{\tau}_S\left(\overline{P}_W/\overline{P}_I\right)\overline{h}_I^* x + \overline{\tau}_0 \overline{w}_I x \; .
\end{aligned} \tag{5}
$$

For right-hand terms in equation (5), the first term is the back force exerted by water at the calving front of an ice shelf where $x = 0$, the second term is the increase of the water back force due to ice-shelf thickening over floating length $L$ from the calving front to the grounding line of the ice shelf, the third term is the average side shear force along $x$ due to

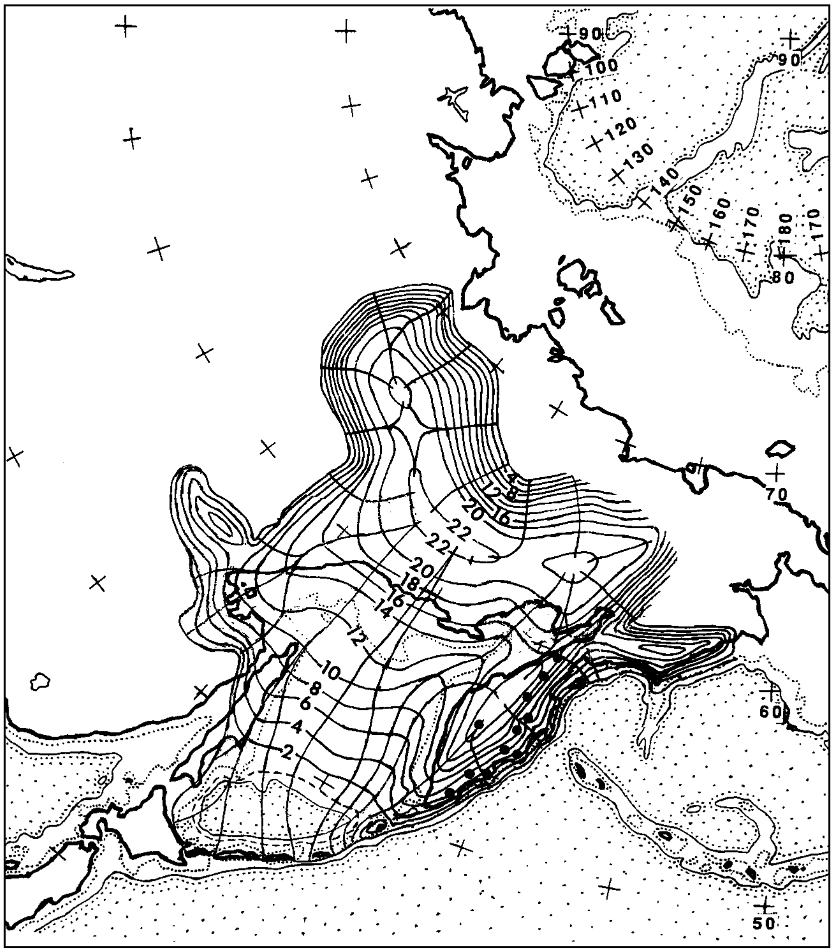


**Figure 7.** A reconstruction of the Okhotsk Ice Sheet using the geometrical force balance [*Hughes,* 1992, 1998]. Ice elevations were constructed along the ice flowlines shown, and are connected at 200 m contour intervals. Broken lines are ice-shelf grounding lines. Bold lines are present-day shorelines. Dotted lines are the 200 m bathymetric contour. Thin lines are the 2000 m bathymetric contour. Solid dots are prominent active Kamchatka volcanoes. Dotted areas are abyssal ocean floors.

average side shear stress $\overline{\tau}_S$ acting on average ice thickness $\overline{h}_I$ for $\overline{P}_W/\overline{P}_I$ veraged over $x$, and the fourth term is the average basal shear force along $x$ due to average basal shear stress $\overline{\tau}_0$ acting on average flowband width $\overline{w}_I$.

[51] In applying equations (1) through (5) to flowlines of the Okhotsk Ice Sheet, ice-shelf buttressing is virtually complete because floating ice over Kuril Basin would have been grounded along Kuril Island Arc. Therefore floating ice would have had a nearly constant thickness, so the second term in equation (5) can be ignored. An average side shear stress of $\overline{\tau}_S = 250$ kPa can be applied, taking measurements along West Antarctic ice streams [*Raymond et al.,* 2001]. An average basal shear stress can be determined from equation (2) for average values of $h_I^*, P_W/P_I$, and $\Delta h^*/\Delta x$, using an iterative procedure for successive steps of $\Delta x = 20$ km along ice flowlines. In the first iteration, $P_W/P_I = 1$ for floating ice and $P_W/P_I = (1 - x/L_s)^c$ for grounded ice, with $L_s$ being the length of the grounded flowline and $c$ ranging from 2 to 5 such that all flowlines have comparable heights at the interior ice divide. For the first $\Delta x$ step, $\tau_0 = 100$ kPa is taken for ice margins grounded on land or in water, assuming the ice shelf is grounded at the calving front along the Kuril Island Arc. A frozen bed is assumed for ice flowlines north of the interior ice divide, so $P_W/P_I = 0$ and $\tau_0 = 100$ kPa are taken along these flowlines. In the flow law of ice, $n = 3$ and $A = 231 \pm 10$ kPa a$^1$/3 were used, assuming an average ice temperature of $-20°$C. In adition, $r = r_0, a = 0.2$ m a$^{-1}$ and $\delta h_I/\delta t = 0$ were assumed, with $\rho_R = 3200$ kg m$^{-3}$, $\rho_I = 917$ kg m$^{-3}$, $\rho_W = 1020$ kg m$^{-3}$, and $g = 980$ m s$^{-2}$. Present-day topography and bathymetry were used for $h_R$, with $h_G = 1000$ m and $u_G$ determined from mass-balance conservation.

[52] Figure 7 presents our reconstructed Okhotsk Ice Sheet, with ice elevations calculated by numerically integrating equation (1) along the flowlines shown. Four ice domes appear along the ice divide; over the Verkhoyansk Range, the Cherski Range, The Kolyma Range, and on Kamchatka Peninsula. A continuation of the glaciation along the Anadyr

Range of Chukchi Peninsula is in dispute [*Brigham-Grette et al.,* 2003; *Grosswald and Hughes,* 2004], so is not shown. Also not shown are possible mergers of the Okhotsk Ice Sheet with a postulated Beringian Ice Sheet that originated as a marine ice sheet on the broad Arctic continental shelf of northeast Siberia [*Grosswald and Hughes,* 1995, 2002; *Grosswald,* 1998a; *Hughes,* 1998]. Two major marine ice streams drain most of the Okhotsk Ice Sheet, one in Deryugin Deep and one in TINRO Deep, see Figure 4, and the downdrawn converging ice flowlines in Figure 7. Marine ice transgressing onto the Asian mainland causes reroutings in the Amur River system, see Figure 6. Calving that intermittently freed the ice shelf from pinning points on the Kuril Islands may have caused iceberg outbursts and cooling that *Kotilainen and Shackleton* [1995] reported.

## Conclusions

[53] Evidence from geomorphologic, marine geologic and paleoclimatic studies leads us to conclude that the Sea of Okhotsk has been glaciated by a marine "back-arc" spillover sector of a highland ice sheet on the North Pacific Rim. This conclusion is supported, at least partly, by a sedimentation model, based on research on Sakhalin Shelf and in Deryugin Deep [*Wong et al.,* 2000]. The grounded ice sheet became a floating ice shelf that spread over the Kurile Basin and was buttressed by the submarine Kurile Island Arc. The last Okhotsk ice sheet was of Late Pleistocene age. It could have existed during both Early and Late Weichselian (Wisconsin) time, and, in accord with the arguments of *Braitseva et al.* [1968], and of *Ono and Naruse* [1997], the earlier of the two stages could be a little more extensive than the later stage.

[54] The Sea of Okhotsk is a close neighbor of Beringia, and its new glacial image lends additional credence to our concept of Beringian glaciation [*Grosswald,* 1998b; *Grosswald and Hughes,* 1995, 2002; *Hughes,* 1995; *Hughes and Hughes,* 1994; *Hughes et al.,* 1991]. Also, it is consistent with the North Pacific paleogeography implied by the ODP Leg 145 drilling results and, more specifically, with the Late Pleistocene oceanographic changes in the Sea of Japan, in the offshore zone of eastern Honshu Island, and on the Islands of Japan themselves [*Grosswald,* 2002; *Oba et al.,* 1991; *Okada,* 1980]. Among other things, the concept of the glacial Sea of Okhotsk accounts for the fact that dropstones became most abundant during the Ice-Age in the North Pacific, in particular, in sites seaward from the Sea of Okhotsk. We conclude that an ice sheet in the Sea of Okhotsk, along with the Beringian ice sheet, was a major source of icebergs, meltwater, and ice-rafted debris supplied to the North Pacific Ocean during the Ice Ages. Icebergs would have calved from the Kurile and Bering ice shelves after they rode over the Kurile and Aleutian Island Arcs and squeezed through their straits.

[55] We make one final observation. Asians crossed a stormy ocean passage to Australia 60,000 years ago, but did not cross the Beringian land bridge into North America in significant numbers until after 12,000 years ago, even though the west wind was at their back and the land bridge was presumably wide and teeming with game. Perhaps that presumption is wrong. Perhaps ice sheets on the North Pacific Rim blocked the land bridge, as we repeatedly suggested.

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