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Arctic Continental-Shelf Sediment Dynamics

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Abstract

Sediments covering Arctic continental shelves are uniquely impacted by ice processes. Delivery of sediments is generally limited to the summer, when rivers are ice free, permafrost bluffs are thawing, and sea ice is undergoing its seasonal retreat. Once delivered to the coastal zone, sediments follow complex pathways to their final depocenters—for example, fluvial sediments may experience enhanced seaward advection in the spring due to routing under nearshore sea ice; during the open-water season, boundary-layer transport may be altered by strong stratification in the ocean due to ice melt; during the fall storm season, sediments may be entrained into sea ice through the production of anchor ice and frazil; and in the winter, large ice keels more than 20 m tall plow the seafloor (sometimes to seabed depths of 1–2 m), creating a type of physical mixing that dwarfs the decimeter-scale mixing from bioturbation observed in lower-latitude shelf systems. This review summarizes the work done on subtidal sediment dynamics over the last 50 years in Arctic shelf systems backed by soft-sediment coastlines and suggests directions for future sediment studies in a changing Arctic. Reduced sea ice, increased wave energy, and increased sediment supply from bluffs (and possibly rivers) will likely alter marine sediment dynamics in the Arctic now and into the future.

1. INTRODUCTION

Modern Arctic continental shelves (**Figure 1*a***) are sedimentary environments that are uniquely impacted by ice. These cold-region shelves were flooded and shaped during sea-level transgression over the past ∼7,000 years and presently receive sediment from eroding coastlines and Arctic rivers. Today, Arctic margins lie at one of the major frontiers of changing global climate, where seasonal ice cover is diminishing and wave energy is growing.

The relatively thin Holocene sediment cover on Arctic shelves is sculpted by ice scour (see Sections 2.2 and 5.2). Sediment yields from rivers and coastal erosion tend to be lower than those in many lower-latitude systems, yet Arctic continental shelves make up 20% of global shelf area (even though the Arctic Ocean constitutes just ∼1% of the global oceans by area and volume). Thus, sedimentary processes on Arctic shelves may be disproportionately important in terms of global margin dynamics.

This review focuses on modern Arctic subtidal sedimentary processes and deposits from the nearshore zone to continental slope. Most of the examples presented are drawn from the Canadian Beaufort Shelf (seaward of the Mackenzie River Delta), the Alaskan Beaufort Shelf, the Chukchi Shelf, and the expansive Siberian Shelf. These regions were the targets of much research in the 1970s and 1980s, when regional oil development was accelerating. For example, the construction of artificial islands for drilling rigs and laying of seafloor pipelines necessitated studies of coastal

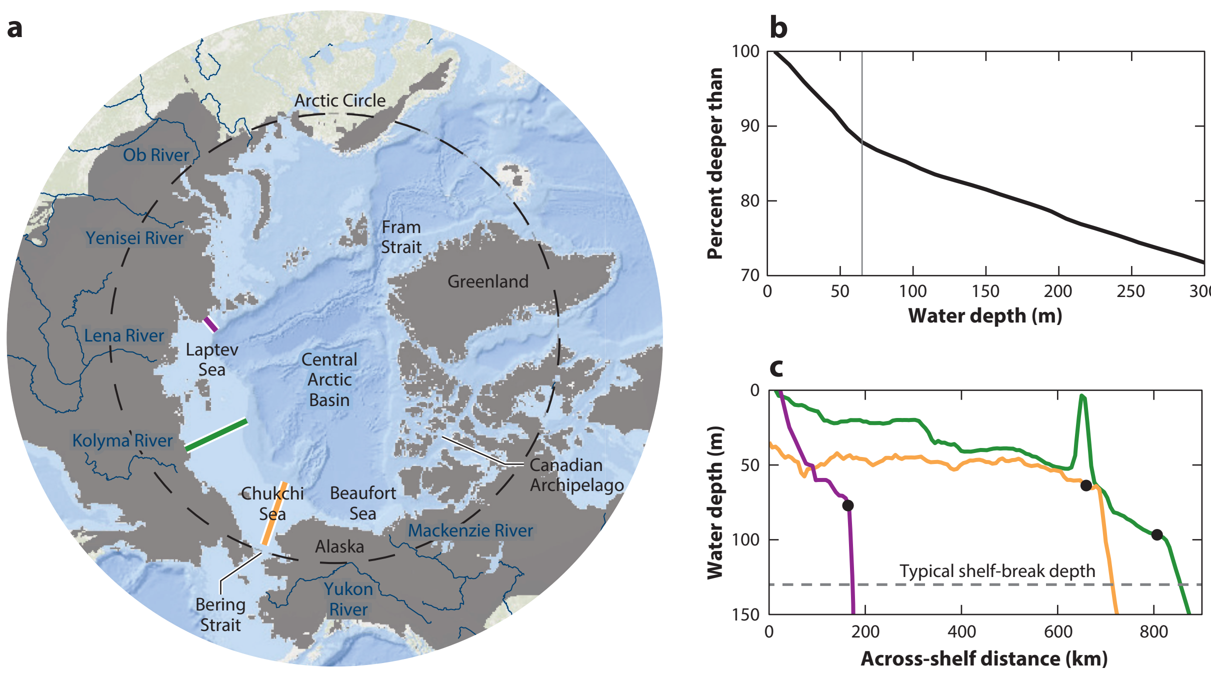

Figure 1

Arctic Basin map and shelf physiography. (*a*) Map of the Arctic Basin, including marginal seas. Colored lines on the Siberian and Chukchi margins show the locations of elevation transects in panel *c*; gray regions denote continuous to discontinuous permafrost soils. Base map adapted from ESRI ArcMap Online. (*b*) Hypsometric curve from International Bathymetric Chart of the Arctic Ocean (IBCAO) data (at latitudes >66.5°N). Note the inflection point at ∼65-m water depth. (*c*) Elevation profiles of the three transects shown in panel *a*. Black dots denote shelf-break depths.

erosion, sediment transport, and scour of seabed sediments by ice (e.g., Barnes & Reiss 1983, Barnes et al. 1984).

During the 1990s, key studies focused on the Canadian Beaufort Shelf, which receives sediment from the large Mackenzie River (e.g., Hill et al. 1991, Forbes & Taylor 1994). In the early 2000s and 2010s, more process-based and modeling studies were published, including a suite of papers under the umbrella of the Arctic Coastal Dynamics project (Rachold et al. 2005). Recently, much work has focused on coastal erosion and river dynamics (e.g., Irrgang et al. 2022, Zhang et al. 2022), with many links to carbon transport from terrestrial sources to marine sinks in high-latitude systems (e.g., Macdonald et al. 1998, Holmes et al. 2012). Two recent syntheses have addressed the dynamics of Arctic deltas (Forbes 2019, Overeem et al. 2022), which serve as sinks for some sediments and organics. Angelopoulos et al. (2020) reviewed the dynamics of subsea permafrost. In deeper water, paleoceanographic reconstructions using sediment cores and geophysical surveys have been advancing (e.g., Darby et al. 2006, Polyak et al. 2009, Coakley et al. 2016).

On Arctic continental shelves, modern studies have sought to improve knowledge of seafloor geology and sediment-transport dynamics using summer and sometimes overwinter mooring deployments, geophysical techniques, and remote sensing technology, though much work remains to be done in these spheres, especially given (*a*) reductions in sea ice, which are leading to more energetic wave climates (and thus more sediment-transport energy) but also making many shallow areas more accessible to vessel-based surveys; (*b*) increases in sediment supplies from bluff erosion and forecasted increases from rivers; and (*c*) more navigation traffic and human use of these regions. This review explores suspended-sediment and seabed dynamics in detail in order to provide a clear picture of modern processes and features and motivate new research in a changing Arctic (see Section 8). The discussion sections are focused on soft-sediment coasts and transport dynamics across shelves of shallow to intermediate depths (generally <200 m), with the goal of explaining the sediment sources, transport processes, depositional features, and reworking mechanisms that make subtidal Arctic environments unique.

2. OVERVIEW OF REGIONAL GEOGRAPHY AND OCEANOGRAPHY

The Arctic region includes the central Arctic Basin, the Canadian Archipelago, fjords of Greenland and northern Scandinavia, and broad continental shelves backed by soft-sediment coasts throughout the surrounding regions (**Figure 1**). Large-scale gyres and coastal currents are key circulation features, but wind-driven dynamics and stratification imposed by sea ice also impact water motions. Arctic continental shelves are relatively important globally; they constitute 20% of global shelf area (even though the Arctic Ocean makes up just 1% of the global ocean by area and volume) (Costello et al. 2010). They also constitute 30% of the total Arctic Ocean area (Macdonald et al. 1998).

2.1. Arctic Coastal Plains and Coastal Bluffs

During the Last Glacial Maximum [20,000 years before present (BP)] and lowstand in sea level, the Bering Land Bridge connected Alaska and Siberia, and modern continental shelves were exposed as broad, subaerial coastal plains (Dinter 1982, Hill et al. 1985, Hequette et al. 1995). The Laurentide Ice Sheet covered much of northern Canada, but much of northern Alaska and Siberia was arid mammoth steppe and grassland (Mann et al. 2013, Hoffecker et al. 2020). Permafrost soils (ground frozen for $\geq$2 years) developed in these environments and now cover much of the Arctic. A hallmark of permafrost regions is polygonal or patterned ground separated by ice wedges, which are a form of massive ground ice that develops when the ground cracks in polygonal patterns each winter, and snow and moisture enter the cracks and refreeze to form ice wedges (for more

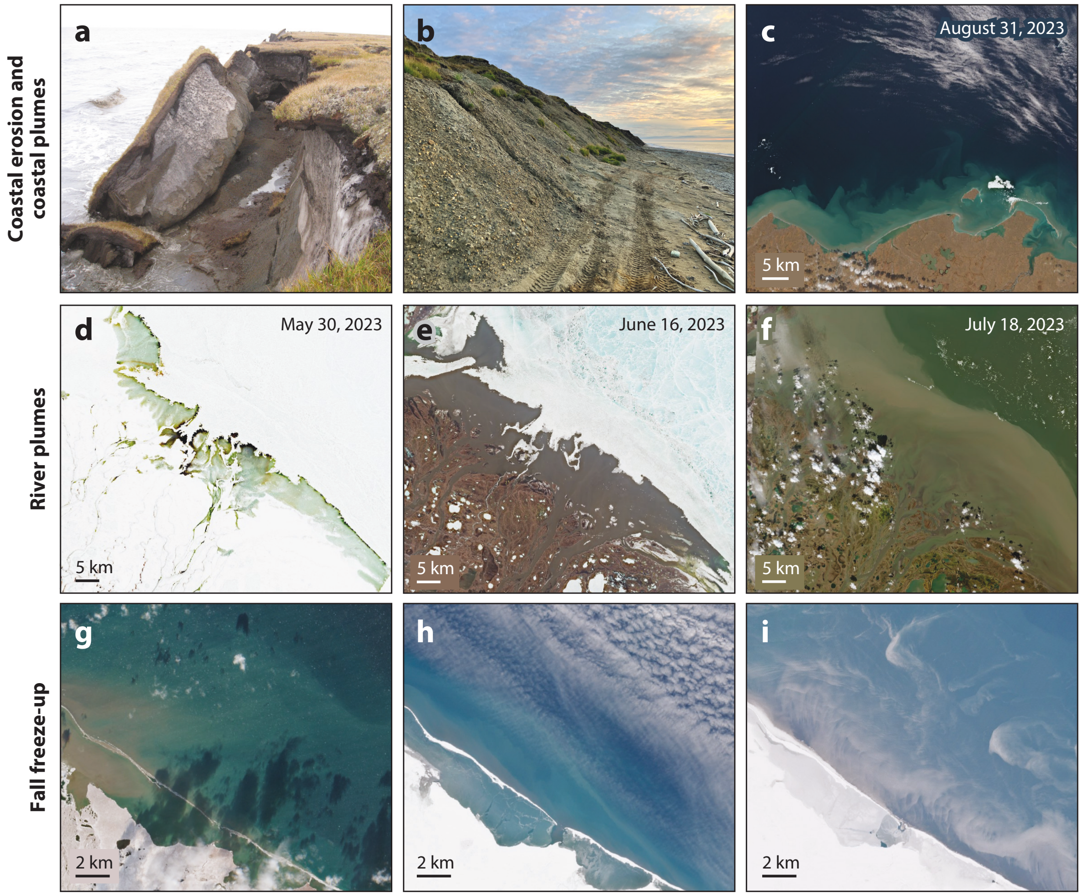

Figure 2

Coastal suspended-sediment sources and patterns. (*a*) Polygonal ground failure in northern Alaska. (*b*) Bluff erosion near Kaktovik, Alaska. (*c*) Coastal resuspension plumes in western Siberia. (*d–f*) River breakup and plume dispersal of the Indigirka River, Siberia. (*g–i*) Freeze-up east of Kaktovik, Alaska. Photo in panel *a* by Ben Jones; photo in panel *b* by Emily Eidam; Sentinel satellite images in panels *c–i* adapted from the Copernicus Open Access Hub (CC BY-SA 3.0 IGO). This figure is licensed under a Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) license.

detail, see French 2017; see also Duchkov 2006, Jorgenson et al. 2008). Permafrost soils are also characterized by thermokarst (thaw) lakes that form in depressions left by degrading permafrost.

Since the Last Glacial Maximum, sea-level transgression has flooded large areas of Arctic coastal plains and converted them back into continental shelves. Modern coastal plains now terminate at the shoreline in low bluffs that are typically 2–4 m (and up to 20 m) high and experience rapid erosion (**Figure 2*a*,*b***). Bluff soils contain up to 40–70% ice by volume in the form of ice wedges or massive ground ice (Reimnitz et al. 1985, Vasiliev et al. 2005, Lantuit et al. 2012) (**Figure 2*a***). The ice content in these coastal bluffs makes them particularly susceptible to rapid coastal erosion (Section 3.1).

2.2. Arctic Continental Shelves: Holocene History and Sediment Cover

During the Holocene (~11,000 BP to present), rates of sea-level rise have varied around the Arctic depending on location. The resulting continental shelves are shallow, with shelf-break depths at

<100 m in many places (**Figure 1**). Thin Holocene sediments (with maximum thicknesses on the order of a few tens of meters) have accumulated over older formations.

The Siberian Shelf (the Barents, Kara, and Laptev Seas) is the widest shelf globally at >1,200 km in some locations (Herman 1974). The Laptev Sea, which is 300–500 km wide and has a shelf-break depth of ~50–85 m (Holmes & Creager 1974) (**Figure 1*c***), offers an interesting example of the history of sea-level rise. This sector of the Siberian margin began flooding around 15,300 BP, and the 50-m isobath flooded by 11,100 BP. Subsequent rates of sea-level rise varied from 5.4 to 13.3 mm y^{-1} until ~5,000 BP (Bauch et al. 2001). Most of the Holocene sediment cover likely accumulated before 6,000 BP (Bauch et al. 1999). Kleiber et al. (2001) measured Holocene sediment thickness ranging from ~0.5 to 18 m. They also noted that Holocene sediments were absent near the slope break and attributed this to erosion by historical shelf-break currents.

Farther east, in the Chukchi Sea, sea level rose by ~50 m between 12,000 BP and the present (Keigwin et al. 2006), and Holocene deposits range from a few meters thick to >10 m thick where infilled paleochannels are present (relics of Beringia) (McManus et al. 1969, Phillips & Reiss 1984, Kolesnik et al. 2023). On the Alaskan Beaufort Shelf, Holocene sediments have been accumulating since the post–Last Glacial Maximum lowstand at 17,000 BP, when sea level was ~100 m lower. These deposits are now ~40 m thick on the outer shelf (Dinter 1982, 1985) but are only a few meters thick on the inner shelf and sometimes give way to outcrops of Pleistocene clays (Reimnitz et al. 1972; see also Dunton et al. 1982).

In Canada, the Canadian Beaufort Shelf extends ~100–150 km seaward of the Mackenzie River Delta to a shelf-break depth of ~100 m. Transgression began in this region at ~12,000 BP, and rates of sea-level rise have ranged from 2 to 14 mm y^{-1} since that time (with the slowest rates of 2 mm y^{-1} occurring today) (Hequette et al. 1995). North of the Mackenzie River Delta, several Holocene sediment wedges and lobes with maximum thicknesses of >30 m on the inner shelf taper northward toward the outer shelf. Outside of these (on both the middle and outer shelf), sediments are on the order of 5 m thick (Hill et al. 1991). Farther north, shelves ~100–150 km wide fringe the Canadian Archipelago. However, unlike other Arctic shelves, these tend to be quite deep (200–650 m). Sediment transport by processes such as waves thus may be limited, due to both the depths and the more persistent ice cover than in other parts of the Arctic (e.g., Li et al. 2021).

2.3. Arctic Oceanography and Sea-Ice Dynamics

The Arctic Ocean connects to the Pacific Ocean at the Bering Strait and to the Atlantic Ocean at the Fram Strait (with some additional exchange through the Barents Sea and connections through Baffin Bay) (Rudels & Carmack 2022). Many Arctic continental shelves are microtidal, and wind-driven dynamics are important for circulation (e.g., Hill et al. 1991). Several major currents, including the Alaskan Coastal Current and Siberian Coastal Current, flow in an anticyclonic direction. In the Canada Basin (north of the Beaufort Shelf), the Beaufort Gyre flows in a cyclonic direction (Rudels & Carmack 2022).

In coastal areas, sea ice breaks up from late May through early July. In the fall, cooling air temperatures and storms promote heat loss from the ocean, which allows sea ice to form. Landfast ice grows from the shoreline seaward and can be ~1 m thick (Barry et al. 1979). Near shore, some landfast ice is also bottomfast, meaning it contacts the seabed sediments (Barry et al. 1979). A distinctive morphologic feature referred to as a bench occurs at 2-m water depth along many Arctic coastlines; its formation is likely related to the presence of seasonal landfast ice (Reimnitz & Bruder 1972, Barnes & Reimnitz 1973, Cooper 2023).

Farther seaward, pack ice grows from the central ocean toward the margins and can be ~1–3 m thick. Where pack ice and landfast ice meet, pressure ridges form (Kovacs & Mellor 1974). These ridges create large ice keels in the water column that are 20–40 m deep and are moved by slow

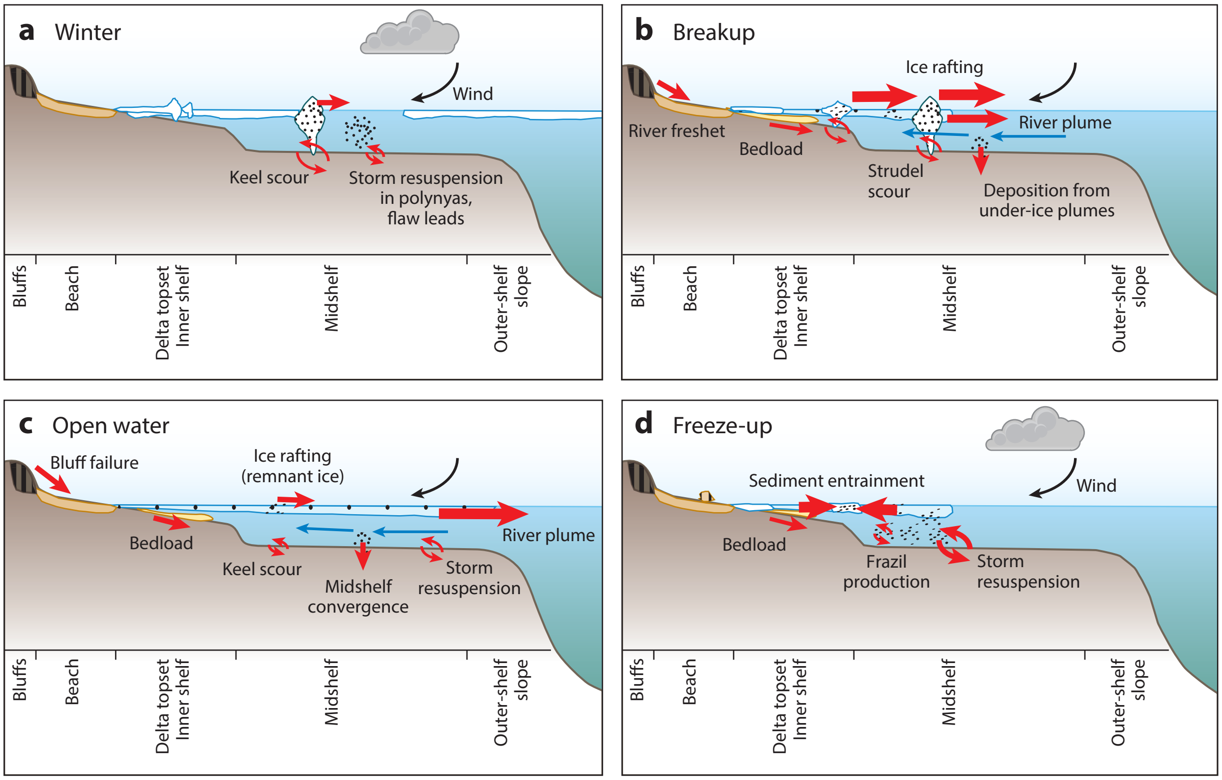

Figure 3

Schematic of physical processes occurring on Arctic continental shelves during four seasons. (*a*) Winter (ice-covered season). (*b*) Breakup season (when river discharge is high, if a river is present). River plumes may flow over or under the ice. (*c*) Open-water season. (*d*) Freeze-up season.

circulation and winds (Reimnitz et al. 1978). Wind events during the winter can cause pack ice to deform, allowing flaw leads (areas of open water) to develop between the pack ice and landfast ice (Holland 2013, Rudels & Carmack 2022). Polynyas are areas of open water that can also form in sea ice as a product either of wind or of latent heat release (related to sea-ice formation) (Holland 2013). General processes are schematized in **Figure 3** and discussed in later sections.

3. MODERN SEDIMENT SOURCES

In the Arctic Ocean, the primary sources of sediment are different from those in lower latitudes. Globally, rivers dominate the supply of sediment to the oceans (~72–89%), followed by glaciers (~6–11%) (see Regard et al. 2022). Coastal erosion supplies less than 10%. In the Arctic, however, coastal erosion contributes the majority of sediment in many regions (e.g., 70% in the Laptev Sea), except for places dominated by discharge from large rivers such as the Mackenzie (Rachold et al. 2000).

3.1. Coastal Bluff Erosion

Arctic soft-sediment coasts are eroding at ~0.5 m y^{-1} (on average), with localized rates of up to ~20 m y^{-1} (e.g., Lantuit et al. 2012, 2013; Overduin et al. 2014; Gibbs & Richmond 2017).

Accelerated erosion of permafrost coastal bluffs has been observed in many regions since the 1950s (e.g., Jones et al. 2009) as a product of thermal effects (warm air and water temperatures) and mechanical erosion (from waves), the latter of which is most important during late summer and fall storms (e.g., Lantuit et al. 2012).

Quantifying volumes of sediment released from bluffs is approached through estimates of bluff height, coastal retreat rate, ice content, and/or sediment size distribution (e.g., Barnhart et al. 2014, Gibbs et al. 2019). Bluff height and retreat rate can be quantified from remotely sensed or drone data with increasing accuracy (e.g., Gibbs & Richmond 2017, Obu et al. 2017), but ice contents and sediment sizes remain labor intensive to sample in situ. Along the Canadian Beaufort coast, Hequette & Barnes (1990) found that these subaerial properties did not correlate well with shoreline retreat rate and proposed that submarine erosion of the shoreface profile (by sea ice and/or waves) is also a critical factor driving shoreline retreat.

Relatively warm ocean waters thaw ice wedges, and wave attack undercuts the polygonal ground, leading to abrupt collapses of large soil blocks on the order of 10 m wide (e.g., Thomas et al. 2020) (**Figure 2*a***). These blocks quickly disintegrate in the surf zone, releasing their relic marine, fluvial, and glacifluvial gravels, sands, and muds to the inner shelf (Jorgenson & Brown 2005). Some bluffs exhibit a seasonal cycle of erosion: Soils thaw in the summer and slump to form a protective apron on the beach, and fall storm waves remove this apron before freeze-up (Gibbs et al. 2019).

3.2. Rivers

Rivers contribute $\sim 227 \times 10^6$ t y^{-1} of suspended sediment to the Arctic Ocean, constituting ∼1% of global fluvial sediment flux (Gordeev 2006). This sediment yield is low given that Arctic rivers supply ∼11% of global river discharge (McClelland et al. 2012). Arid climates, low-relief permafrost landscapes, and seasonal water discharge are some of the factors accounting for the low yields (Milliman & Farnsworth 2013). Arctic river discharges are increasing (with varying regional trends; Feng et al. 2021), but there is debate in the literature about whether sediment loads are also changing. Syvitski (2002) modeled increasing Arctic sediment loads. Doxaran et al. (2015) calculated an increase in the Mackenzie River sediment load based on satellite records from 2003 to 2013. In contrast, Holmes et al. (2002) reported no change in sediment load based on decades of aggregated historical data from 19 Arctic rivers.

Arctic rivers are strongly seasonal, with minimal to no flow during winter except for the largest rivers (e.g., the Mackenzie and Yukon). During spring freshets, river ice breaks up sooner than sea ice, and river plumes often flow under or over the ice (**Figure 3*b***). This phasing of river discharge prior to sea-ice breakout is important because a majority of fluvial sediment delivery often occurs during the spring freshet (see Section 4.1).

3.3. Distant Sources

A small amount of sediment is delivered to the Arctic Ocean from other sources, including aeolian transport and transport through straits. For example, silts and clays (many originating from the Yukon River) are transported northward through the Bering Strait in the Alaska Coastal Current. Some sediments settle north of the strait to form a delta-like feature, while others continue northward toward the Arctic Basin (McManus et al. 1969). Aeolian transport to the Arctic has been considered particularly in the context of winter deposition on pack ice (and release to the ocean in the spring and summer) but remains a relatively small sediment source (e.g., Pfirman et al. 1989).

4. SUSPENDED-SEDIMENT TRANSPORT

Although a substantial amount of Arctic fluvial sediment is deposited within deltaic environments (e.g., an estimated 50% of Mackenzie River sediments are retained in the delta; Macdonald et al. 1998), the remaining sediments are broadly dispersed by river plumes (Section 4.1), by waves and currents during the open-water and freeze-up seasons (and occasionally winter) (Section 4.2), and by sea ice (Section 6; **Figure 3**). Sediment transport thus varies temporally in response to river discharge (which wanes following the spring freshet and occasionally peaks late in the season) and the wave climate (which grows from summer to fall because sea ice recedes and fetch increases). Transport patterns also vary spatially based on water depth, proximity to a major river, shelf morphology, available grain size, and other factors.

4.1. Sediment Transport in River (and Other) Plumes

Spring freshets in rivers often start before sea ice breaks out. Ice blocks the seaward flow of river plumes, causing them to flow either over or under the ice (**Figure 3*b***). Overflow plumes can travel distances on the order of 10 km from shore (Reimnitz & Bruder 1972), while under-ice plumes can be larger in area than open-water plumes formed under similar flow conditions (e.g., Ingram & Larouche 1987, Alkire & Trefry 2006, Kasper & Weingartner 2015) (**Figure 2*d–f***). Under-ice plumes may also coalesce (Okkonen & Laney 2021), causing mixing of both plume water and sediments, which has implications for the shelf sedimentary record.

Many rivers generate peak sediment discharges for the year during the spring freshet. For example, the Colville, Kuparuk, and Sagavanirktok Rivers in Alaska have reportedly discharged 60–80% of their annual sediment loads in 3–13 days (Arnborg et al. 1967, Rember & Trefry 2004). The presence of ice in the nearshore during the freshet season thus promotes substantial sediment bypass of the nearshore zone (Reimnitz & Bruder 1972), which has implications for the long-timescale morphodynamic evolution of Arctic deltas (Lim et al. 2019, Cooper 2023). The mean annual number of open-water days in the Arctic is increasing, however (e.g., Crawford et al. 2021), and thus the springtime dispersal of fluvial sediments may no longer coincide with the ice-covered season (e.g., Cooper 2023).

The Mackenzie River, one of the largest sources of freshwater and sediment to the Arctic Ocean, creates a freshwater (or mostly fresh) pool on the continental shelf during winter that, if it were considered a true lake, would rank among the 20 largest lakes globally (Carmack & Macdonald 2002). This pool forms because river water becomes trapped behind the stamukhi, a zone of sea-ice pressure ridges (Section 5.2) that create a seasonal ice dam on the continental shelf. In the spring, river water breaches this dam, sending a plume up to 160 km seaward to the shelf break (O'Brien et al. 2006). The summer Mackenzie plume is deflected by winds and creates an $\sim$500 × 100 km estuary on the shelf (Carmack & Macdonald 2002). Plume sediments are delivered to the shelf both east and west of the river depending on wind conditions and can even be advected as far as the Canada Basin before settling (see O'Brien et al. 2006).

In the Kara Sea, Osadchiev et al. (2019) found that the plumes of the large Ob and Yenisei Rivers generate broad sediment dispersal and interact with one another according to multiyear trends in river discharge and wind dynamics. Typically, both plumes spread northward (seaward), but northerly winds coupled with high discharge in the Ob River can cause the Ob plume to spread eastward and confine the Yenisei plume to nearshore waters. Because the two rivers drain watersheds of different lithologies, a 10-year period of strong Ob River influence was identified in the Yenisei Gulf based on seabed sediment mineralogy (Osadchiev et al. 2019).

Some remote sensing calibrations have been performed for suspended particulates on Arctic margins. For example, Doxaran et al. (2012) developed regional relationships for suspended sediments and particulate organic carbon in the Mackenzie River plume and described strong cross-shelf gradients in both properties. Tang et al. (2013) developed a regional algorithm for the Beaufort Sea suspended-sediment concentrations using Medium Resolution Imaging Spectrometer data.

Some sediment plumes are not directly related to rivers. Resuspension plumes have been observed in lagoons (Naidu et al. 1984) and in shallow nearshore areas distal to rivers (e.g., Eidam et al. 2023) (see **Figure 2*c***). Perhaps the most unusual type of plume observed in the Arctic is a whale plume. In the Chukchi Sea, researchers have observed turbid plumes at the sea surface near gray whales, and concluded based on box core sediments that the plumes were generated by whales feeding on benthic amphipods and isopods (Phillips et al. 1988).

4.2. Sediment Transport on the Continental Shelf

On the inner shelf, sediment-transport processes include suspended-sediment transport (Section 4.1) as well as vigorous bedload transport driven by waves and storm events. Reimnitz & Kempema (1983) noted that 6-m-deep strudel-scour pits (Section 5.2) on the Colville Delta front were filled by bedload (gravels, sands, and organics) after just 2–3 years. Because strudel scours form under sea ice near rivers, the infilling bedload sediments represent a uniquely ice-related deposit that may be useful in identifying cold-region deltas in the stratigraphic record (Reimnitz & Kempema 1983). Near Prudhoe Bay, an artificial gravel island was constructed on top of nearshore muddy sands, and Barnes & Reiss (1983) reported that it lost one-third of its volume through storm-driven erosion in just one year. They also noted that because of the high rates of transport on the inner shelf, the seabed should in general be self-healing in response to construction activities that cause bed disturbance, with the exception of causeway construction (Barnes & Minkler 1982), which could block sediment traveling along-shelf. Seaward of these coarser-grained inner-shelf regions, substantial sediment transport has also been inferred from the infilling of muddy keel scours (Section 5.2) at water depths of up to 13 m (Barnes & Reimnitz 1979). In fact, keel scours can be completely reworked in just one season or even one storm event (Barnes & Reimnitz 1979, Reimnitz & Kempema 1983, Eidam et al. 2024).

Several case studies have described summertime across-shelf transport pathways for fine-grained sediments (**Figure 3*c***). Wegner et al. (2005) deployed two moorings offshore of the Lena River in the Laptev Sea and observed that sediments were deposited on the middle shelf during the spring freshet. Throughout the subsequent open-water season, sediment transport in the muddy plume was dominantly northward (seaward), but on the middle shelf, wind events created southward (landward) near-bed currents that led to maximum deposition rates at 20–30-m water depth.

On the narrower Alaskan Beaufort Shelf, Eidam et al. (2023) noted summer sediment convergence at ~15-m depth using ship-based observations and six small moorings. Seaward of this depth (where an Ekman spiral can develop), winds established southward/landward transport in the bottom boundary layer. Inshore of this depth, sediment fluxes were generally northward throughout the water column. This convergence resembles transport patterns observed on the Laptev Shelf (see above), but the fate of these sediments during the remainder of the year remains poorly constrained (Eidam et al. 2023).

Sediment transport on the Mackenzie Beaufort Shelf is heavily influenced by the Mackenzie River plume. Based on observations and modeling, Mulligan et al. (2010) found that easterly winds promote upwelling during the open-water season, which leads to seaward advection of the surface plume and landward flow near the bed (see also Bornhold 1975). Shallow inshore waters remain stratified. These patterns could presumably promote landward transport of sediments from the middle shelf, similar to processes occurring on the Laptev and Alaskan Beaufort Shelves. Under downwelling conditions associated with northwesterly storms, however, sediments are transported to the outer shelf and beyond (Hequette et al. 2001, Osborne & Forest 2016). Waters inshore of 10 m are typically stratified except during storm events, and sediment concentrations exhibit strong gradients at water depths of 5–10 m (e.g., decreasing from 100 mg L^{-1} to <20 mg L^{-1}; see Hill et al. 1991). The shelf has been classified as having high, low, and intermediate current energy on the inner (0–20 m), middle (20–60 m), and outer (>0–60 m) portions, respectively (Hill et al. 1991). The outer shelf is influenced by the shelf-break jet. On the middle and outer shelf, waves are thought to mobilize sediment for only 1% of the year (Hill et al. 1991). Based on a synthesis of multiple data sources, Osborne & Forest (2016) found that ∼48% of sediments delivered to the shelf are trapped in the delta, ∼39% are trapped on the shelf, and ∼13% are exported to the slope and canyons (the latter by ice rafting, the surface plume, and turbidity currents).

5. SEABED SEDIMENTS OF ARCTIC SHELVES AND SLOPES: GENERAL DISTRIBUTIONS, GEOLOGIC PROPERTIES, AND SIGNATURES OF ICE DISTURBANCE

Sediments on Arctic continental shelves and slopes demonstrate some of the same properties as lower-latitude sediments—for example, sands are commonly found on the inner shelf and muds are found more distally, and both waves and currents facilitate transport. However, Arctic sediments are uniquely impacted by ice—for example, sediment sizes can include anomalously coarse, ice-rafted grains; sea-ice keels commonly rework sediments (creating unique seabed morphology, confounding efforts to apply radiochemical dating methods, and impacting the geotechnical properties); and sediments delivered to slopes may be disturbed or reshaped by ongoing post–Last Glacial Maximum margin adjustment and degradation of permafrost. This section presents an overview of relevant literature on these topics.

5.1. Seabed Sediment Properties

As is typical of global continental shelves, sediments on Arctic shelves tend to be dominated by silts and clays, though sands are found in some nearshore and shelf-edge subenvironments (e.g., Hill et al. 1991). Where coarse sediments do occur in nearshore areas, they are often mixed with muds (Reimnitz et al. 1977, Barnes et al. 1980, Eidam 2023, Heath et al. 2024). Coarse-grained and even fine-grained deposits on the inner shelf are sometimes interrupted by outcroppings of Pleistocene clay (as in the case of the Gubik Formation; e.g., Dinter 1985). Unlike lower-latitude shelves, Arctic shelf sediments commonly contain ice-rafted sediments and debris, a hallmark of environments where sea ice is common. Near Prudhoe Bay, Alaska, an anomalous boulder patch has been identified, which may represent an extreme case of ice-rafted debris. These boulders are interpreted to be erratics based on the nonlocal lithology and likely originated from the northern Canadian Shield or northern Greenland as a result of land-ice or sea-ice delivery (Dunton et al. 1982).

Naidu & Mowatt (1983) mapped clay mineral properties around coastal Alaska. They found 10–30% expandable clays (<2 μm) in the grain-size distributions from the inner and middle Beaufort Shelf and middle Chukchi Sea and <10% in adjacent areas. The highest concentrations were found offshore of the Colville Delta, but lower concentrations were found offshore of smaller rivers to the east as well as on the broad shelf north of the Mackenzie River. Clay concentrations near the Colville Delta were patchy and interpreted as relic deposits, however, and the authors concluded that the clay assemblages could not readily be linked to specific sediment sources, as a consequence of the high level of mixing by ice, seasonal ice cover, and other peculiarities of the regional environment.

Seabed sediments can be frozen seasonally in shallow regions (especially where porewater salinities are lowered by groundwater flow), which has implications for seabed strength. However,

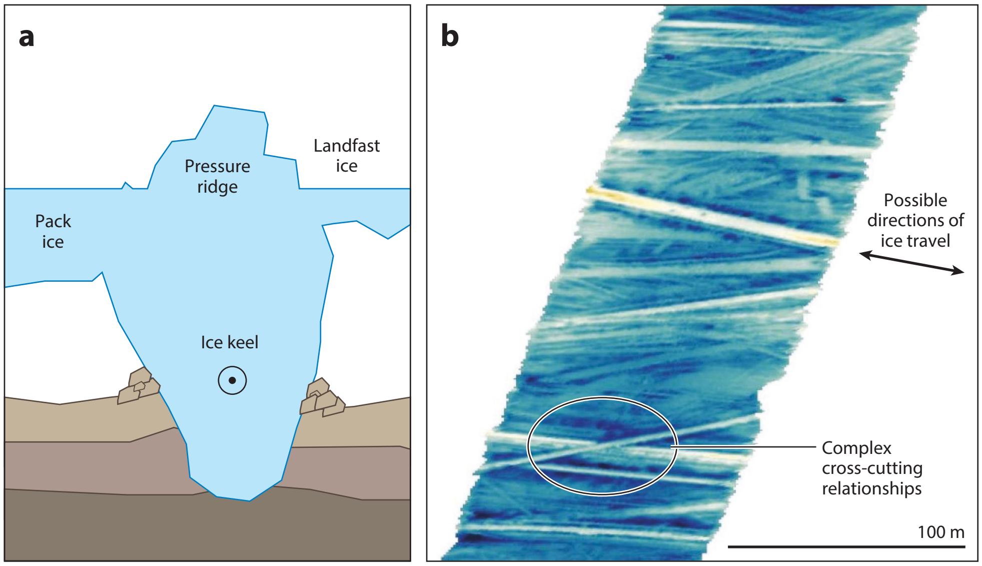

Figure 4

Keel-scour formation. (*a*) Schematic of keel-scour gouging of seafloor. Note that the water depth is not shown to scale; the water depth is ∼8–45 m, but the keel gouge is only ∼1 m deep. (*b*) Multibeam bathymetry of keel scours on the Alaskan Beaufort Shelf (E.F. Eidam, D. Duncan, N. Brilli, N. Stark & J. Nienhuis, unpublished data). The scour relief is up to 1 m; this panel is intended to emphasize the shapes of scours rather than the absolute depth. Ice motions are oriented along-track relative to the gouges. Complex cross-cutting relationships exemplify a complex history of repeated scouring events.

while subsea permafrost may have been widespread shortly after transgression, modern outcrops of subsea permafrost are patchy (e.g., Osterkamp 2001, Angelopoulos et al. 2020).

5.2. Ice Scours

Ice keels (defined in Section 2.3) move during the winter under the influence of winds and currents and gouge tracks in the seafloor (**Figures 3*a*** and **4**). These tracks, or keel scours, can be a few meters to a few tens of meters wide and tens of centimeters to a few meters deep (Rearic 1982, Barnes et al. 1984, Kokin et al. 2023). In the Beaufort Sea, keel scours generally form at 15–45-m water depth (Barnes et al. 1984), a zone called the stamukhi zone. On the Alaskan Beaufort Shelf, a secondary stamukhi zone may form at ∼8–12-m depth (Barnes et al. 1984).

Keel scours are ubiquitous across Arctic shelves (e.g., Myers 1996, Kokin et al. 2023). Scours found in deeper water may reflect exceptionally deep keels (see Ogorodov 2003) or may be relics from times when the sea level was lower. Keel scours form intricate and chaotic patterns of cross-cutting and changes in ice direction (**Figure 4*b***). The degree to which keel scouring impacts sediment transport has been debated (e.g., Rearic et al. 1990), but in general, keel scours are thought to disturb sediment locally rather than transporting it long distances (e.g., Hill et al. 1991). Disturbance can affect the upper meter or more of the seabed, however, and may expose older sediments from different depositional environments (Barnes et al. 1980). Keels represent a major hazard for subsea pipelines, which are typically buried only a few meters below the surface (e.g., Barnes et al. 1984). For example, in spring 2023, an ice keel severed a fiber optic cable north of Oliktok Point in Alaska, disrupting internet service across northwestern Alaska for about two months (Lionas 2023).

While keel scours are the dominant agent of seabed reworking in the Arctic, other forms of scour do occur. Strudel scours are pits and runnels in the seafloor that form where river water overflows the ice in the spring and then escapes to the bed through cracks in the ice formed by tides or wind-driven water-level changes (Reimnitz & Bruder 1972, Reimnitz & Barnes 1974, Reimnitz et al. 1974, Walker 1974). The river water is effectively forced down to the bed as a jet-like flow and in some cases then flows in a confined space under the ice to deeper water. This type of scouring, which has been observed within ∼25 km of river mouths (e.g., the Colville), presents a substantial hazard to buried subsea pipelines (Reimnitz 2002, Barrette 2011). Strudel-scour pits ∼20 m wide and up to ∼4–6 m deep were mapped with a density of 25 per kilometer of ship track near the Colville Delta, while scours up to ∼15 m wide and ∼5 m deep with a density of 2.5 km^{-2} have been observed offshore of the Sagavanirktok River (Reimnitz & Barnes 1974).

5.3. Seabed Sediment Accumulation (and Challenges of Dating Methods)

Century-scale rates of seabed sediment accumulation in the Arctic vary by as much as two orders of magnitude depending on the setting and locally active processes of sediment redistribution. Radioisotopes (e.g., ^{7}Be, ^{210}Pb, ^{137}Cs, or parent–daughter isotopic ratio ^{14}C) serve as one of the primary tools used to date seabed sediments in diverse global marine environments over seasonal to millennial timescales (Li et al. 2021). These data are also used to estimate deposition or accumulation rates and identify key sediment depocenters.

In the Arctic, use of these tracers is complicated. Atmospheric fallout of ^{7}Be, ^{210}Pb, and ^{137}Cs is known to be lower at the poles than at midlatitudes (Baskaran 2011, Foucher et al. 2021, Zhang et al. 2021), resulting in lower seabed inventories. Furthermore, sea ice intercepts atmospheric fallout and then releases the isotopes upon ice breakup, resulting in spatial redistribution of isotopes based on ice drift and reduced inventory of short-lived species such as ^{7}Be (Cooper et al. 2005). Once radioisotopes adsorb to particles and become buried in the seafloor, decay profiles are susceptible to disturbance by bioturbation (where present), winnowing by currents, and keel and strudel scouring (Hillaire-Marcel et al. 2022). Note that keel scour accomplishes mechanical mixing to depths that are an order of magnitude greater than those typically accomplished by bioturbation (i.e., 1-m scale versus 10-cm scale). In nearshore environments, floating landfast ice constricts the cross-sectional area for tidal-current flow, causing flow speed and related erosion to increase (Reimnitz 2002, Cooper 2023). If sea ice thickens enough to become bottomfast, the underlying seabed sediments are then protected from further current-driven disturbance (Reimnitz 2002), but freezing-on processes may disturb sediments. Baskaran & Naidu (1995) also noted based on Chukchi Sea cores that seabed isotope activities may be low simply because of lateral advection of sediments out of the area.

Analyses of the particle-reactive species ^{210}Pb and ^{137}Cs have proven somewhat useful for evaluating century-scale sediment accumulation in some Arctic environments. Sheltered back-barrier lagoons (generally <4 m deep) preserve sediment records with deposition rates of 0.02–1.64 cm y^{-1}, where the higher rates occur proximal to river deltas (Naidu et al. 1984, Hanna et al. 2014). In slope and archipelago environments with water depths of ∼200–600 m, accumulation rates are generally lower (0.05–0.20 cm y^{-1}) and less variable than those in shallower water (Kuzyk et al. 2013). Accumulation rates are similarly low in deep-water canyons and straits (∼600 to >2,000 m, 0.06–0.24 cm y^{-1}). Analysis of sedimentation in shelf environments <100 m deep is often complicated by low and near-constant ^{210}Pb activity with depth (Kuzyk et al. 2013, Heath et al. 2024). In some circumstances, analysis of multiple species can help overcome isotope-specific limitations and validate calculated accretion rates (Naidu et al. 1984, Kuzyk et al. 2013, Hanna et al. 2014).

5.4. Geotechnical Properties

Geotechnical seabed properties characterize sediment response to stresses and loads and are important for planning seabed-based engineering and predicting sediment dynamics. In Arctic environments, geotechnical properties can be affected by soil ice content, freeze–thaw cycling, loading and unloading by sea ice, and other processes impacting the seafloor (Lee et al. 1985, Sættem et al. 1996, Allard et al. 1998, Arenson & Springman 2005, Qi et al. 2006). Geotechnical measurements can be determined in situ (typically through different types of penetrometers) or by laboratory testing of seabed cores and grab samples (typically combined with geophysical surveying) (Stark et al. 2022). These approaches can be cost and time intensive, however, and often require vessel infrastructure, which is scarce in the Arctic. Geotechnical data are also relatively sparse in the Arctic, especially apart from the large engineering and exploration projects that drive funding for such investigations but also result in large amounts of data that remain private or unpublished.

Early geotechnical work in the Beaufort Sea nearshore zone by Kurfurst & Dallimore (1989) highlighted complex sediment mixtures that included clay, silt, and sand with deep permafrost and a thick thawed soil layer at the seabed surface with traces of frost heave, thaw settlement, and ice push and scour scars. Martens et al. (2009) conducted three cone penetration tests at ~14-m water depth in the Canadian Beaufort Sea for an offshore drilling platform project. The sediments were medium- to high-plasticity silty clays with a soft surface (i.e., an undrained shear strength of <20 kPa in the upper meter of the seabed) but with a significant increase of undrained shear strength in the upper 2–3 m of sediment. Becker et al. (2006) characterized Beaufort Shelf sediments and found clays to silts with clay contents ranging from 0% to 70%. Based on detailed laboratory and in situ measurements, sediments had an undrained shear strength of <20 kPa in the uppermost meter of the seabed, with a steep increase in strength to sediment depths of approximately 5 m. Soil conditions also varied greatly across the Beaufort Shelf, and seabed clays featured significant differences in geotechnical behavior relative to their terrestrial counterparts. While these studies demonstrate the value and feasibility of marine sediment coring and cone penetration test studies for geotechnical characterization, they are labor and cost intensive and do not adequately preserve seabed surface conditions.

Free-fall penetrometers and specialized coring equipment have gained attention in the last decade for detailed geotechnical seabed characterization, including in Arctic environments (Dayal 1980, Albatal & Stark 2017, Stark et al. 2017, Bilici & Stark 2019, Brilli 2022, Stark et al. 2022). While free-fall penetrometers test only the uppermost meter(s) of the seabed surface, and penetration depth is directly related to the sediment properties (with less penetration depth in stiffer sediments and more penetration depth in softer sediments), they enable rapid geotechnical characterization of the seabed surface. This is advantageous in areas that are difficult to access, shallow water (e.g., Arctic continental shelves), and locations where heavy vessel infrastructure is limited (e.g., the Arctic in general). Stark et al. (2017) successfully utilized a portable free-fall penetrometer near Herschel Island in the Canadian Beaufort Sea. They found increasingly variable seabed conditions (in terms of morphology and grain sizes) with water depth. Thick layers of soft and poorly consolidated fine-grained surface deposits were found in the nearshore zone adjacent to retrogressive thaw slumps. Hard-surface areas were associated with erosive environments. Similarly, Brilli (2022) found significant variations of geotechnical seabed sediment properties—including erodibility—in Harrison Bay near the Colville Delta, Alaska. This is relevant for emerging models of Arctic seabed sediments (Section 7).

5.5. Continental Slope Sediments

Arctic continental slopes generally do not receive substantial modern sediments due to low fluvial sediment yields and the wide nature of Arctic shelves. Local depocenters have been observed on Arctic slopes, where sedimentation rates can reach 1.4 m ky^{-1}; contributing factors include current focusing associated with submarine canyons (Darby et al. 2009) and topographic depressions offshore of large river sources (the Mackenzie Trough) (Saint-Ange et al. 2014). Currents such as the Beaufort Jet can also promote modern sediment bypass or even erosion on the slope.

Generally, Arctic slope sediments deposited during the Holocene are heavily influenced by processes active during past sea-level lowstands. Glaciation intensity is particularly important. Lowstand ice streams produced shelf-edge topographic lows, incised slope gullies, and inhibited the formation of permafrost (Batchelor et al. 2014). Continental slope sediments seaward of glacial troughs are predominantly till and proglacial deposits. Arctic slope sediments in areas with less intense glaciation are still partially glacial in nature but can also include deltaic and marine characteristics (Cameron 2019).

Holocene Arctic continental slope stability is controlled by the same factors as in temperate margins, with the additional interaction of high-latitude factors such as ice-bonded sediments and glacial history. Regions of the slope that were heavily sedimented during lowstands, including paleodeltas and trough mouth fans, are preconditioned for failure (Cameron 2019). The triggering factors for failure are not well understood but include infrequent seismicity and dissociation of gas hydrates within and below permafrost (Saint-Ange et al. 2014). Morphologic evidence of slide scars indicates that large failures have occurred over the last 1,000 years.

Permafrost occurring at the shelf edge influences seabed stability in several ways. Relic permafrost that formed during sea-level lowstands on arid margins can take thousands of years to thermally equilibrate to marine transgression, leading to modern, geologically rapid (>1 m y^{-1} vertical change) thermokarst collapses (Paull et al. 2022). Additionally, relic permafrost-sourced groundwater can discharge at the shelf edge, producing marine pingos (ice-cored mounds) where bottom water temperatures are sufficiently cold. To date, pingos have been observed only along the Canadian Beaufort margin but are predicted to also occur on analogous margins, such as the East Siberian margin.

6. SEDIMENT ENTRAINMENT AND RAFTING BY SEA ICE

Sediment entrainment and rafting by sea ice represents an important sediment-transport process not seen at lower latitudes and may contribute to net shelf erosion (or at least sediment bypass) in the Arctic. Sediment can be entrained into surface ice through diverse mechanisms, including aeolian transport, bluff collapse onto ice, and water-column processes (e.g., Reimnitz et al. 1972), but incorporation through frazil ice is one of the most important mechanisms. Once entrained, sediment generally travels with the ice until the spring thaw season, when it may be released far from the source (and often in deeper water than where it originated) together with associated organic matter and/or pollutants (e.g., Kempema & Reimnitz 1989, Reimnitz et al. 1992).

6.1. Sediment Entrainment into Sea Ice by Frazil and Anchor-Ice Formation

The term frazil refers to small ice crystals that form in seawater that has been supercooled and is subjected to turbulence—conditions that occur during fall storms in the Arctic (Martin 1981). Frazil crystals flocculate into 3–30-mm aggregates in a manner similar to fine-grained sediment (Martin 1981, Kempema et al. 1993). Slushy frazil layers up to 2 m thick have been observed to accumulate at the water surface (Martin 1981) (see examples of sea ice forming during turbid water conditions in **Figure 2*g*–*i***). These layers then consolidate into surface ice.

Fine-grained silts and clays that are resuspended by storm energy during frazil production can become entrained in the frazil ice crystals and thereby become incorporated into the newly forming sea ice. Sands are thought to be excluded because they settle too quickly (Ackermann et al. 1994). Kempema & Reimnitz (1989) found some sands entrained in sea ice from the inner Beaufort Shelf, but the dominant sizes were clays and silts.

The concentration of sediment entrained in sea ice tends to reflect the concentration observed in the water column during the freeze-up process. For example, ice–sediment concentrations of ~1,500–1,600 mg L^{-1} have been measured in slush ice and consolidated landfast ice in northern Alaska (Barnes et al. 1982, Kempema & Reimnitz 1989), which is comparable to the ~1,300 mg L^{-1} of suspended sediment observed in the water column near Prudhoe Bay during a fall storm.

The formation of frazil requires open water, turbulence, and supercooled waters, and thus frazil formation—and associated sediment entrainment—typically occurs during the fall storm season on the shelf or in flaw leads or polynyas during the winter (Kempema & Reimnitz 1989, Eicken et al. 2005, Wegner et al. 2017) (**Figure 3*a*,*d***). However, in the case of flaw leads and polynyas, these must occur in water depths that are sufficiently shallow to allow wave-driven resuspension of sediment in order for sediment–ice entrainment to occur. For example, landfast ice breakout events, which occur when offshore winds force the detachment of landfast ice from shore, create good conditions for frazil and sediment entrainment. When flaw leads develop at the edge of landfast ice far from shore, the water may be too deep to allow substantial sediment resuspension, and thus little sediment–ice entrainment occurs (Eicken et al. 2005). Sediment entrainment into sea ice is most prevalent at water depths of <20 m (Lindemann et al. 1999, Eicken et al. 2005) but may be possible at depths of up to 50 m (Reimnitz et al. 1993, Smedsrud 2003).

While sediment entrainment through frazil production is complex and generates variable sediment loading in sea ice (e.g., Kempema & Reimnitz 1989), progress has been made in modeling this process. Sherwood (2000) developed a one-dimensional model that incorporates marine hydrodynamics and sediment dynamics, as represented in the Community Model for Coastal Sediment Transport (Warner et al. 2008), together with a prescribed rate of frazil formation. Smedsrud (2002) also devised a frazil–sediment entrainment model that mimics differential frazil growth and frazil–sediment aggregation under turbulent conditions.

Anchor ice is a different type of ice that makes a smaller contribution to sea-ice sediment budgets. Anchor ice nucleates around hard substrates such as anchors, trash, gravels, and coarser sands (Arden & Wigle 1972, Reimnitz 1987). It can form as discrete ice crystals or large, aggregated pillows of ice with a solid core. Like frazil, it forms during high-energy conditions when water is supercooled (and can form from frazil; e.g., Kempema et al. 1993). Because fall storms tend to cool and mix the water column to ~15–20-m depth, anchor ice may also form to such depths but is more commonly observed at depths of ~2–5 m (Reimnitz 1987). Large pillow structures can be rooted 5–10 cm into the sediment (Reimnitz 1987). After a storm ceases and the ocean water or substrate water warms slightly, smaller anchor ice breaks free and floats to the surface to form a layer of soft ice on the underside of the sea-ice cover (note that larger chunks may be too heavy to float) (Reimnitz 1987). As a result, patchy masses of sediment as well as gravel clasts and even bits of kelp become entrained in ice. Because anchor ice sometimes forms on ice-bonded seabed sediments, its occurrence may be linked to the presence of coastal groundwater, which freshens the seabed and enhances seabed ice bonding (Reimnitz 1987).

Frazil and anchor ice entrain different sizes of sediment. Frazil tends to accumulate fine-grained sediments that are easily resuspended by waves and currents, leading to dominantly silt- and clay-size particles in surface ice (60–75% silt and 30–90% clay have been observed in the Laptev and Kara Seas) (Nürnberg et al. 1994, Dethleff 2005, Dethleff & Kuhlmann 2009). These fine-grained sediments make geologically important contributions to paleo records on Arctic continental slopes and basins (Darby et al. 2009). In contrast, anchor ice aggregates on heavier, coarser sediments and thus tends to contribute sands and even gravels to the surface ice (e.g., Darby et al. 2011). When considering the sea-ice sediment budget, mass contributions from anchor ice are much lower than those from frazil ice (e.g., Kempema & Reimnitz 1989, Darby et al. 2009).

The incorporation of sediment into sea ice through both frazil and anchor ice can lead to varying distributions of sediment in sea-ice cores, which Eicken et al. (2005) described in a five-part classification scheme. Deformation of ice during the winter as well as entrainment in polynya versus nonpolynya environments can further complicate the vertical patterns of sediment distribution in the sea ice (Eicken et al. 2005).

6.2. Importance of Ice Rafting for Shelf Sediment Budgets and Stratigraphic Records

The importance of ice rafting in Arctic sediment-transport budgets has been debated. Late in the melt season, ice-entrained sediments become concentrated in decaying sea ice, and satellite images often show large areas of very muddy ice across Arctic margins. This suggests substantial sediment transport and dispersal. Based on 183 ice measurements, drifting buoy tracks, and synthetic aperture radar images, Eicken et al. (2005) estimated that $5–8 \times 10^6$ tons of sediment were exported from the Chukchi and western Alaskan Beaufort Shelves in winter 2001–2002, equivalent to ~10% of the annual Colville River discharge (5.9×10^{10} kg, or 65×10^6 tons; Arnborg et al. 1967). In the Laptev Sea, Wegner et al. (2017) estimated that 8.4×10^5–1.3×10^5 metric tons of sediment had been entrained into the ice during a previous four-day midwinter polynya event, based on one ice core and synthetic aperture radar data. This sediment load is three orders of magnitude less than either the annual river (24×10^6 metric tons) or coastal erosion (58.4×10^6 metric tons) sediment fluxes to the Laptev Sea (Ivanov & Piskun 1999, Rachold et al. 2000) but still represents a substantial amount of sediment. Eicken et al. (2000) estimated that 18.5×10^6 metric tons of sediment were entrained in sea ice in winter 1994–1995 in the Laptev Sea, based on remotely sensed data and ice cores. This mass is closer to the annual sediment export from the Lena River (Ivanov & Piskun 1999) and is approximately equal to the annual sediment deposition in two down-drift deep-water depocenters (see Eicken et al. 2000).

A pan-Arctic study of ferrous sediments entrained in ice sought to determine sediment source areas. Throughout the Canadian, US, and Siberian Arctic, the dominant sources were Banks Island (in the northwest part of the Canadian Archipelago) and the Laptev Sea (Darby et al. 2009). Similar results have been obtained through analysis of clay mineralogy (Darby et al. 2011). Interestingly, for sea ice in the Alaska sector of the study area, less than 1% of sediments were traced to the Alaskan Beaufort Shelf (Darby et al. 2009). These results suggest distal transport of sediments from some sites (Canada and Siberia) and perhaps substantial local retention of ice-borne sediments in Alaska. It is thus unclear to what extent sea-ice rafting removes sediment from the Alaskan Beaufort Shelf. Eicken et al. (2000) further confirmed that a small number of sites (e.g., sites on the Siberian Shelf) account for a disproportionate amount of ice-entrained sediments in the Arctic. Extending the ice-entrainment process studies that have been conducted on the wide Siberian shelves to the narrower Alaskan and Canadian shelves remains an interesting topic for research.

Quantification of the total sea-ice sediment load in pan-Arctic environments also remains a topic for investigation. Sediment entrained in ice is patchy and does not always occur at the ice surface (e.g., Eicken et al. 2005). When sediment occurs at depths of ~20–30 cm within the sea ice, it impacts light transmission through the ice but not surface albedo (reflectance), making detection by remote sensing difficult (Light et al. 1998). When ice decays in the spring, however, sediments become concentrated near the ice surface and may be more visible in imagery. Huck et al. (2007) addressed issues of atmospheric corrections and varying albedo for different ice classes in order to improve remotely sensed estimates of sediment loads. Waga et al. (2022) used machine learning to predict sediment loads based solely on remotely sensed data, using an assumption of different sea-ice surface types and 15 classes of sediment loads.

In spite of reductions in Arctic sea-ice extent over the past few decades, the rate of sediment transport in sea ice is likely increasing. Eicken et al. (2005) noted that increasing storminess (see Serreze et al. 2000), increasing fetch (and thus wave energy), and decreasing abundance of multiyear ice may all contribute to enhanced entrainment of sediments in sea ice. (The decrease in multiyear ice means that more first-year ice is present in continental-shelf areas and is more likely to break out during winter due to greater mobility.)

7. EMERGING MODELS OF ARCTIC SEDIMENT DYNAMICS

Models of Arctic continental-shelf sedimentation are still in their infancy, though interest in their application is growing. Sediment models can help to predict future changes in shelf morphology (Malito et al. 2022) as well as interactions of sediments with ice (Sherwood 2000), oil (French-McCay et al. 2017), infrastructure (Nederhoff et al. 2023), and coasts (Erikson et al. 2020) and to upscale field measurements for pan-Arctic studies (Gordeev 2006). Sediment models of the Arctic continental shelf can largely be divided by scale: Small-scale models are typically morphodynamic and focus on interactions between the shelf and the coast, whereas larger-scale models are typically morphostatic, meaning that they compute sediment fluxes but do not update bathymetry.

Using a small-scale (regional) approach, Erikson et al. (2020) modeled the Arey Lagoon (Alaska) using a combination of XBeach and Delft3D, both of which are coupled hydro- and morphodynamic models. Erikson et al. (2020) simulated the impact of storms on barrier islands under various climate change scenarios. Coupling of the nearshore with the shelf remains uncertain, particularly in terms of the available sediment on the shelf for landward storm transport. This uncertainty motivated Malito et al. (2022) to use a broader modeling domain, which indicated that future coastal change depends in large part on the response of the shelf morphology to changing wave height and coastal erosion.

Other types of small-scale models focus on continental shelves near deltas, using Delft3D (Cooper 2023) as well as DeltaRCM (Lauzon et al. 2019, Piliouras et al. 2021, Chan et al. 2023), a reduced-complexity morphodynamic model. These studies incorporate the effects of sea ice, which are more relevant around deltas because of the high fluxes at the time of sea-ice breakup. Results suggest that the thickness of bottomfast ice and the delay in ice breakup control near-delta shelf morphology. Field-specific model application and validation remain challenging because of hazards posed by ice.

In addition to regional morphodynamic models, other models of continental-shelf sediments focus on larger-scale (basin) dynamics. Some larger models are physics based and aim to elucidate sediment-transport processes, such as the Coupled Ocean–Atmosphere–Wave–Sediment Transport (COAWST) model (Warner et al. 2010). Undzis & Moriarty (2024) employed COAWST to build a summer model (no sea ice) focused on wave- and current-driven sediment suspension on the inner shelf. Harms et al. (2000) used a three-dimensional coupled ice–ocean model to study sediment in sea ice and found that sediment is incorporated and transported in sea ice particularly during the fall freezing season. Other large-scale models aim to construct sediment budgets of the continental shelf. Osborne & Forest (2016) used a box model and found that 80% of the deltaic sediment transport into the Canadian Beaufort Sea is deposited on the shelf, and the remaining 20% is exported beyond the shelf edge (see also Li et al. 2020). In contrast, Gebhardt et al. (2005), who used a box model of the estuary-fed Kara Sea, found that coastal erosion is the dominant sediment source and that shelf-edge export exceeds fluvial sediment supply.

Although box models can help identify sinks and sources, they remain difficult to use for understanding processes or for projecting future conditions. In general, large gaps remain between the small-scale models, large-scale process models, and large-scale sediment-budget models. The sparsity of data on seabed sediments and seabed erodibility (Brilli 2022, Zimmermann et al. 2022) remains a challenge that prevents further integration of these models. Other remaining model knowledge gaps include the coupling of sediment and ice dynamics. For much of the continental shelf, the ice-covered period is likely mostly dormant, which simplifies modeling. But in the near-shelf environment, ice-keel scouring and ice breakup are very important morphologically but remain understudied. The recent proliferation in Arctic coastal morphologic research needs and models (e.g., Korte et al. 2020, Frederick et al. 2021, Irrgang et al. 2022, Nielsen et al. 2022) will hopefully also incentivize further development of continental-shelf models.

8. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

Arctic continental shelves are a depositional environment uniquely impacted by ice. These systems may evolve toward more temperate conditions, but this process will take time. While an ice-free Arctic may not occur within the lifetimes of the next few generations of residents and researchers, we have a special opportunity at present to observe a system that is transitioning through several types of tipping points. The length of the open-water season is increasing, waves are becoming more energetic, storm climates are changing, sediment loads may be changing, and navigation traffic is increasing. Based on these changes, the following are a few of the many aspects of Arctic sedimentary systems that are in need of further research:

- Sediment export from the shelf: Wave energy is increasing, but many summer transport patterns favor retention on the shelf due to wind-driven circulation. If off-shelf export is accomplished primarily during the fall freeze-up season (by storms) or winter (in flaw leads and polynyas), will export increase or decrease as the timing of the storm season changes and sea-ice cover and duration decrease?
- Development activities: Shipping is increasing, and studies (observations and models) of contaminant transport exist largely in the private consulting sphere; work remains to be done in the public research domain to explore these types of transport through the lens of particle-associated contaminant and nutrient transport.
- Geotechnical engineering: Data are lacking (especially in the public sphere) on seafloor stability and strength, which have applications to port construction, dredging, and pipelines.
- Sea-ice sediment rafting: The importance of this process for overall sediment budgets remains poorly constrained. Advances have been made through remote sensing, but much in situ validation is still needed to constrain this Arctic sediment-budget term.
- Coastal erosion and coastal landform evolution: While this review has not focused on these specifically, many outstanding questions remain concerning feedbacks between coastal erosion, coastal landform evolution (including barrier island emergence), and shoreline–shelf sediment interactions.
- Nutrient transfer: While this review has also not addressed the details of particle-associated carbon (and other nutrient) transfer from coastlines to continental shelves, this remains an open area for further study.

All of these lines of inquiry are further challenged by sparse bathymetric and other mapping data. Arctic continental shelves thus offer a challenging but fascinating environment for process-based studies of sedimentation and related environmental factors.

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