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Origin of sediment pellets from the Arctic seafloor: sea ice or icebergs?

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Abstract—Sediment cores from the Norwegian and Greenland Seas and the Nansen Basin were studied to determine the origin of sediment pellets, centimetre-sized aggregations of clay to sand-sized sediment occurring in the cores. By comparing the grain size, grain shape and composition of the pellet sediments to sediments collected directly from the surfaces of sea ice in the Nansen Basin and from icebergs in the Barents Sea, the pelleted sediment was found to be more similar to that in the icebergs than that on the sea ice. The pellets may be formed on, in or under a glacier or during transport on/in an iceberg. When icebergs overturn or melt, the pellets fall out and are consolidated enough to survive a drop of up to 4 km to the ocean bottom and to retain their integrity even after burial on the seafloor.

INTRODUCTION

IN 1987, during the ARK IV/3 cruise of the German icebreaking research vessel *Polarstern*, aggregates of sediment with diameters of less than 1 to about 5 cm were discovered in several gravity and box cores from the Arctic seafloor. Such aggregates also were observed in sediments cored during the *Meteor* II/2 cruise into the Norwegian Sea (1986) and the ARK VI/2 cruise of *Polarstern* into the Greenland Sea (1989). The Norwegian Sea aggregates were called mud-dropstones by HENRICH *et al.* (1989), while those in the Nansen Basin were called mudclasts (POLARSTERN SHIPBOARD SCIENTIFIC PARTY, 1988; SPIELHAGEN *et al.*, 1988). Similar aggregates found on sea ice and in central Arctic sediment cores by CLARK *et al.* (1980) and GOLDSTEIN (1983) were named sediment pellets. We prefer this term to mud-dropstones or mudclasts because they are aggregates and can contain sediment coarser than mud. By using the modifier "sediment", these structures can be clearly distinguished from the more familiar "fecal pellets".

Origin of sediment pellets

The origin and method of deposition of sediment pellets is not clear. Millimetre-sized mud pellets were observed in deep-sea sediment cores from the central Arctic Ocean by

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Clark *et al.* (1980), Minicucci and Clark (1983) and Goldstein (1983). Clark *et al.* and Minicucci and Clark attributed a glacial origin to their pellets, while Goldstein believed that silty pellets have a sea ice origin and sandy pellets come from either sea ice or icebergs. Clay pellets, also millimetre-sized, also were found in the Antarctic (Halvor Jahre, personal communication, 1990; see also Stetson and Upson, 1937). Mackiewicz *et al.* (1984) mention frozen pellets of sediment in iceberg-rafted sediments in Alaska. Ovenshine (1970), in a study of both modern sediments in Alaska and Precambrian rocks in Canada, found 2–3 mm-sized pellets in both areas. He stated that the pellets were originally accumulations of sediment between ice crystals. Ovenshine also observed pellets between shear planes in the glacier. Since the Canadian rocks are of known glacial origin, he postulated that the pellets could be a valuable indicator for iceberg-deposited sediments. Numerous other reports of sediment pellets in sediments and rocks that have been interpreted through other criteria to be glacial exist (see Goldschmidt, in preparation). The centimetre-sized sediment pellets found in the Norwegian Sea that are a part of this study were interpreted to be deposited by icebergs due to their association with dropstones and other sediments (Henrich *et al.*, 1989; Yoon *et al.*, 1991).

Millimetre-sized sediment aggregates frequently have been observed on sea ice (e.g. Polarstern Shipboard Scientific Party, 1988; Pfirman *et al.*, 1989a,b; Barnes *et al.*, 1990) and are known to be deposited from melting sea ice (Berner and Wefer, 1990). Sediments in these aggregates are typically fine-grained; more than 90% of the sediment is $<63\ \mu m$ (Pfirman *et al.*, 1989a,b, 1990; Berner and Wefer, 1990; Wollenburg, in preparation). Centimetre-sized sediment aggregates are not reported as frequently from the sea ice surface, although Pfirman *et al.* (1989a,b, 1990) and Wollenburg (in preparation) observed large aggregates on multi-year sea ice in the Transpolar Drift Stream during the 1987 *Polarstern* cruise to the Nansen Basin.

If deposited by ice rafting, occurrence of sediment pellets in seafloor sediments indicates regions where sediment-laden sea ice or icebergs melted. The distribution of these pellets thus may be an important paleoenvironmental indicator. Another possibility, however, is that sediment pellets are not deposited by either sea ice or icebergs, but are fecal pellets or result from slumping or bottom currents on the seafloor. The large size of the sediment pellets makes them unlikely to be of fecal origin, but if they are, they should be rounded and contain biogenic remains (Goldstein, 1983). On the other hand, if seafloor processes form the pellets by redepositing previously compacted sediments, evidence for slumping or bottom currents should exist in the sediments surrounding these pellets.

Sediment incorporation in ice

The entrainment of sediment into glaciers and sea ice has been qualitatively investigated for about a century. While sediment is incorporated into Arctic sea ice primarily along the shelves on the ocean basin margins, sediment occurring in icebergs is derived from inland locations as well as on the shelves; incorporation on shelves occurred particularly when glaciers were more extensive in glacial periods. In order for sediment-laden ice to be transported to the central Arctic and Norwegian/Greenland Seas, where the sediment pellets have been observed, both sea ice and icebergs must survive transport away from the margin to the basin interior. Currently, there is no definitive way to determine whether sediments sampled in seafloor sediment cores are deposited from sea ice vs icebergs. However, by examining possible sediment incorporation processes, general character-

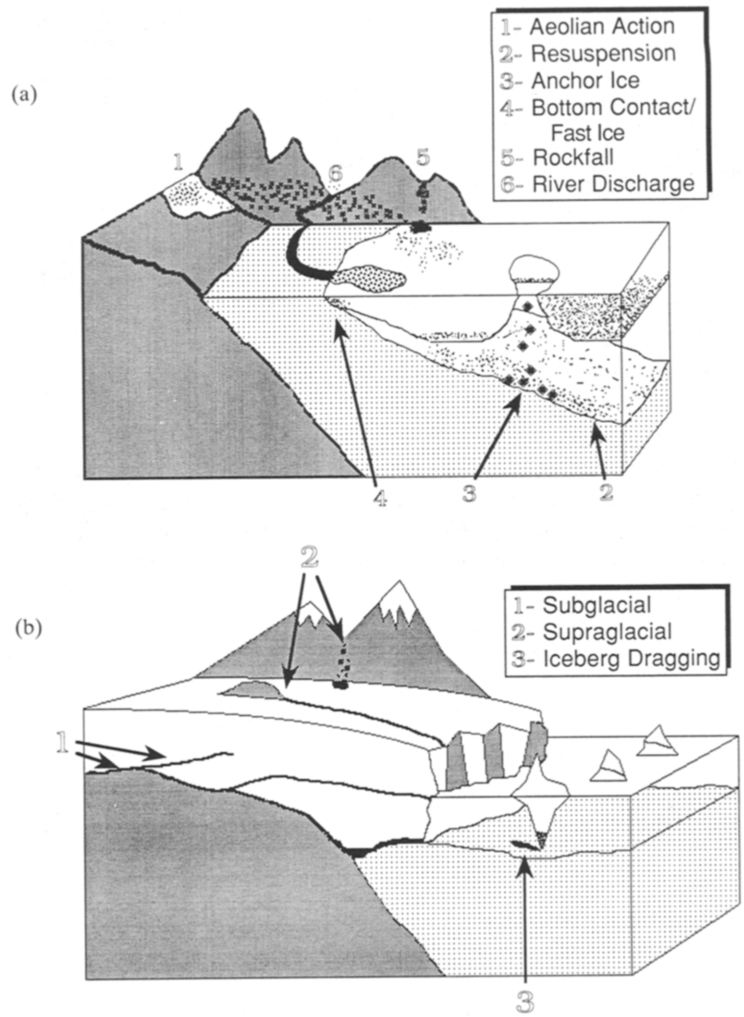

Fig. 1. Schematic, scaleless illustration of the processes involved in the incorporation of sediment into (a) sea ice and (b) glaciers/icebergs. See text for details. Dense dots = rock; uniform dots = sediments; irregular dots = sediments being incorporated into ice; white = ice, snowbor water. Glacier face in (b) shows pattern for relief. Notice "turbid ice", resulting from frazil ice formation toward the right side of (a). ((a) after WOLLENBURG, 1992.)

istics can be established to aid in assessing the likelihood of sediments being deposited from sea ice or icebergs. The following, including Fig. 1, is adapted from discussions in REIMNITZ and BRUDER (1972), BARNES and REIMNITZ (1972, 1974), OSTERKAMP and GOSINK (1984), DREWRY (1986), KEMPEMA *et al.* (1986), LARSSEN *et al.* (1987), REIMNITZ and KEMPEMA (1987), REIMNITZ *et al.* (1987), DOWDESWELL and DOWDESWELL (1989), PFIRMAN *et al.* (1989a,b, 1990), BARNES *et al.* (1990) and GILBERT (1990).

Sediment can be incorporated into sea ice in the nearshore zone by a variety of processes (see Fig. 1a).

(1) Aeolian action can deposit sediment onto the ice surface. Strong winds can blow

sand and coarser sediment onto the ice (STEFANSSON, 1921); sands have been known to be blown over several kilometres (SUNDBORG, 1955, 1956; KUHLMAN, 1960; GOLDSCHMIDT *et al.*, submitted). Fine sediments are transported larger distances. Wind also may be important in redistributing sediment on the surface of the Arctic ice pack (see review by PFIRMAN *et al.*, 1989b)

(2) Storm waves and strong tidal currents generating turbulence during ice formation can resuspend sediment from the shallow marine bottom, allowing it to be incorporated into newly-formed frazil or slush ice (BARNES *et al.*, 1982; OSTERKAMP and GOSINK, 1984; REIMNITZ *et al.*, 1987). Resuspension also can occur after the ice cover has formed (GILBERT, 1990). These processes would lead to the entrainment of some coarse, but predominantly fine, sediments. Storms also can lead to the formation of anchor ice (BARNES *et al.*, 1982; OSTERKAMP and GOSINK, 1984; KEMPEMA *et al.*, 1986, 1989; REIMNITZ and KEMPEMA, 1987; REIMNITZ *et al.*, 1987). Anchor ice forms on the shallow marine bottom from super-cooled water; when the anchor ice is sufficiently buoyant, it rises to the sea surface, taking along any attached sediment. This process, which occurs in limited regions today, is able to incorporate very coarse material.

(3) In very shallow water (<0.3 m; MART SAARSO, personal communication, 1989) sea ice can incorporate sea floor sediment by coming into contact with or freezing to the bottom. More sediment can be entrained in areas with a large tidal range when ice forms in the intertidal zone during ebb tide ("frozen crust") and then floats upward with its incorporated sediment during flood tide (KNIGHT and DALRYMPLE, 1976). This process, along with the associated removal of beach sediments by ice, may be the primary means by which coarse sediment is entrained into sea ice (WOLLENBURG, in preparation).

(4) Rockfalls, which occur primarily in the spring when interstitial ice on cliffs melts, can be deposited on adjacent shorefast ice before breakup. Sediment of every size could be deposited in this manner. However, the abundant sediment in a rockfall may accelerate sea ice melting because of the albedo difference between the ice and the sediment. (If the thickness of the fallen sediment is greater than about 2 cm, the sediment blanket serves to *retard* ice melting [HIGUCHI and NAGOSHI, 1977]). Furthermore, most rockfalls due to melting of interstitial ice occur as sea ice is also melting, not freezing, suggesting that sediment incorporated by this process will not normally be transported away from the coast for significant distances. Although rockfalls also can occur throughout the year when a seismic tremor dislodges sediment onto the ice (BRUCE MOLNIA, personal communication, 1990), this could only occur in seismically active coastal areas.

(5) Rivers can carry sediment either onto or under the ice surface in spring (KINDLE, 1924; BARNES and REIMNITZ, 1972; REIMNITZ and BRUDER, 1972; WALKER, 1973). SYVITSKI and MURRAY (1981) observed 10–35 μm clay pellets in a river entering a fjord in British Columbia; these are much smaller than the centimetre-sized pellets discussed in the present paper. River ice also can incorporate sediments if it freezes to the river bed; sediments entrained in this manner may be well sorted. But, as with rockfalls, the large amount of sediment and the time of year that sediment incorporation occurs preclude significant sediment transport by ice to the central Arctic basins. Also, river ice generally would not survive the trip to the river mouth and then far out into the ocean during spring breakup.

(6) Finally, the keel of an ice floe can drag along the bottom, picking up both fine- and coarse-grained sea floor sediments. This is not thought to be a quantitatively important sediment incorporation process (see REARIC *et al.*, 1990).

Thus, sediment-laden sea ice that has a high probability of being transported off the shelves and into the interior of the Arctic Ocean is likely to carry predominantly fine-grained sediment with a composition reflecting exposed coastal land or sea floor sediment on the shallow shelf (Table 1). This conclusion is consistent with observations of fine-grained sea ice surface sediments in the Nansen Basin (PFIRMAN *et al.*, 1989a,b, 1990; WOLLENBURG, in preparation). Because most of the sediment on the Siberian and Alaskan continental shelves has been transported by fluvial action to the sea, the sediment is likely to be fairly well-rounded from its journey downriver (see HOPKINS and HERMAN, 1981).

If the centrimetre-sized sediment pellets observed in the sea floor sediment cores are rafted by sea ice, they could form when sediment-laden sea ice is subjected to surface melting, which concentrates sediment on the surface. Meltwater drainage may then coalesce the sediment into regions with higher concentrations. These "dirty" regions on the ice surface have a lower albedo than the surrounding ice. They absorb solar radiation and transfer heat to the immediately surrounding ice, melting this ice and forming a "cryoconite" hole, a well in the ice (Fig. 2). With continued melting, more sediment is collected from the adjacent ice. As the sediment undergoes periodic freeze-thaw cycles, the sediment may be aggregated into pellets. Biogenic material often found growing on the surface of the ice may aid in sticking particles together (GRAN, 1904; NANSEN, 1906; PFIRMAN *et al.*, 1989a,b, 1990; WOLLENBURG, in preparation), as can periodic desiccation (GILBERT, 1990). When the ice floe tilts or melts, the sediment aggregates, possibly still frozen, fall to the bottom of the sea, and may be observed in the geologic record as sediment pellets. Because unaggregated sediment may also be deposited at the same time, the sediment pellets may be expected to have a composition similar to each other and to that of the matrix.

Sediment pellets dropped by sea ice under the scenario outlined above would represent deposition from a multi-year sediment-laden floe that has undergone conditions conducive to forming aggregates, most likely including extensive melting. Under present conditions, the sediment within the pellet would likely be predominantly rounded and fine-grained due to its downriver journey, with a mineralogy reflecting the composition of the shelf where the floe originally entrained its sediment load.

In contrast, sediment with sizes and shapes more varied than than found in modern sea ice can be entrained into glacial ice (Fig. 1b).

Table 1. *Factors which may be used to distinguish Arctic sediments derived from modern sea ice from those derived from modern icebergs*

Parameter	Sea ice	Iceberg/Glacier
Grain shape	Usually rounded	Angular (supraglacial) Rounded (subglacial)
Grain size	Usually fine	Fine to coarse
Mineralogy	Alaskan & Siberian shelves	Areas of calving tidewater glaciers
Biogenic matter:		
Pollen	Present	Supraglacial only
Spores	Present	Supraglacial only
Marine species	Planktonic and shallow benthic	Planktonic (for iceberg)
Freshwater species	Present	Present

(1) As a glacier moves over its bed, it incorporates sediment of every size subglacially (CHAMBERLAIN, 1894). Grains also can be entrained and released during subglacial freeze-thaw action (HODEL *et al.*, 1988). The mineralogy of the entrained sediment reflects the composition of the bedrock or basal till. Some of the entrained sediments may be transported into the glacier along shear planes forming englacial deposits. Because of the constant grinding by the ice and other sediment and flow of basal meltwater, the subglacial grains may become strongly rounded (BOULTON, 1978; DOWDESWELL *et al.*, 1985; DOWDESWELL and DOWDESWELL, 1989). While some grains may shatter, they can still exhibit rounding on the faces where breakage did not occur (HODEL *et al.*, 1988).

(2) Supraglacial sediment falls down onto the surface of glaciers from nunataks (isolated outcrops of bedrock within the glacier) and glacial valley slopes. The mineralogy of the entrained sediment reflects that of the bedrock outcrop. This sediment is predominantly angular; since it is incorporated into the glacier to only shallow depths, the sediment will remain angular until it is deposited either at the glacier snout or further out to sea by iceberg rafting (BOULTON, 1978; DOWDESWELL *et al.*, 1985; DOWDESWELL and DOWDESWELL, 1989). In addition, winds can transport sediment from exposed land to the surfaces of glaciers and icebergs.

(3) Sea floor sediment also can be entrained into an iceberg if the drifting berg's keel drags along the shallow marine bottom (MOIGN, 1976; OSTERKAMP and GOSINK, 1984). As with sea ice, this process of incorporation does not appear to be of major importance for sediments carried to deep ocean basins (see REARIC *et al.*, 1990).

Sediment pellets could form as sediment is concentrated on the surface of the berg by melting, formation of cryoconite holes, and freeze-thaw processes as described above for sea ice. They also may form in shear planes as observed by OVERSHINE (1970). Icebergs calved from even nearby valley glaciers may contain markedly different sediment if they are from an area where bedrock geology is variable, although glaciers advancing over the continental shelf may incorporate more uniform shelf sediments. As a result, iceberg-rafted sediment may have more variable size and mineralogical characteristics (Table 1; see also BOULTON, 1978). Because drifting icebergs take longer to melt and are more influenced by wind than sea ice, sediment may be expected to be deposited from icebergs over a wider geographic range.

Past vs present glacial–marine environments

The processes responsible for incorporating sediment in sea ice and icebergs discussed above may have been different during glacial times. For example, most tidewater glaciers emptying into the Arctic seas presently derive from valley–fjord systems while ice sheets were more common during glacial maxima. Supraglacial sediments are more common on valley glaciers than on continental ice sheets. Therefore supraglacial sediments may be more common on icebergs today than they would have been during the past. Also, the relative importance of sea ice vs iceberg rafting for sediment transport has changed through time (DARBY *et al.*, 1990; HENRICH *et al.*, 1989; HENRICH, 1990). Tidewater glaciers now cover only a small percentage of the Arctic coastline and icebergs are rare in the Nansen Basin, while sediment-laden sea ice is common. Therefore, coarse iceberg-rafted debris is infrequent in seafloor surface sediments (NANSEN, 1906).

Unfortunately, Arctic paleoenvironments are not well known, so only general conclusions can be reached about the processes important in sea ice and iceberg rafting in the

Fig. 2. Cryoconites on the surface of sea ice in the Nansen Basin in 1987. Photograph by I. Wollenburg.

Fig. 5. (a) Photograph of pellets from GKG 15/050-2, 23 cm lying *in situ* after overlying sediment was removed. Largest pellet is about 5 cm in diameter.

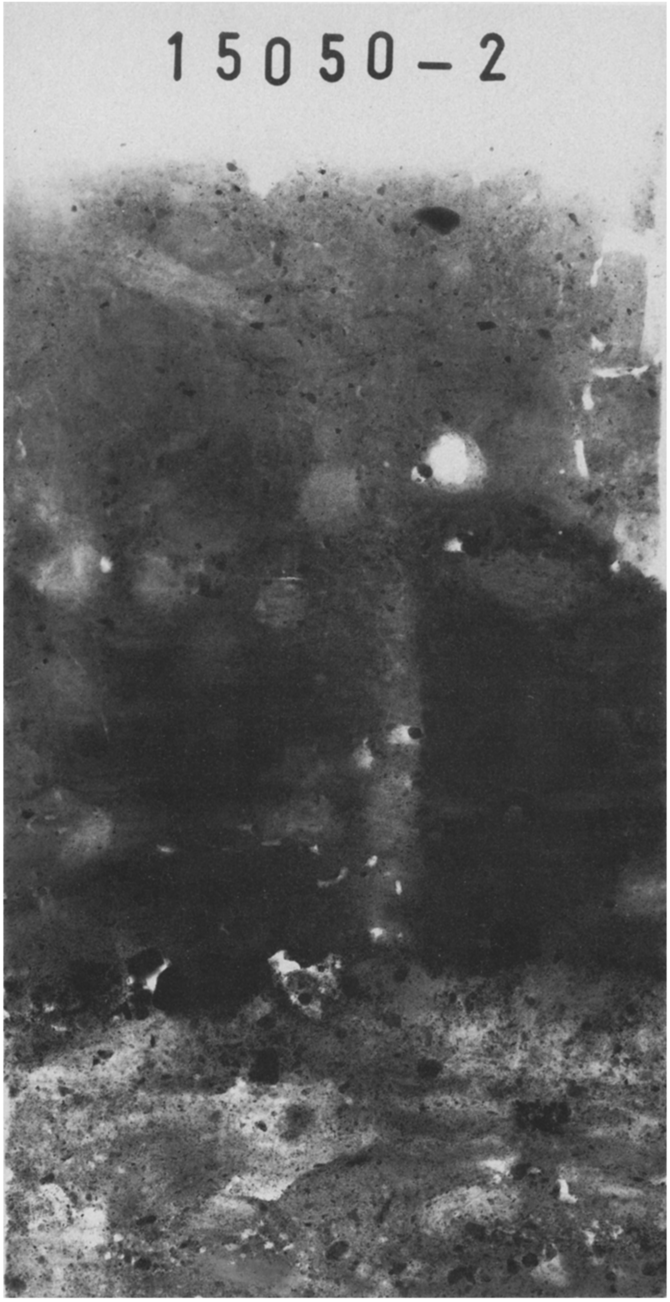

Fig. 5. (b) Radiograph of GKG 15/050-2 core, 0–27 cm core depth. Normal sediment pellets were found at 11 cm from the top, unusual pellets at 23 cm. No sediment finer than sand is visible in the area of the unusual pellets. In this and Figs 6 and 7, dark grey features are sediment pellets, black features are iceberg dropstones, and white features are holes; length of radiographs is 27.5 cm.

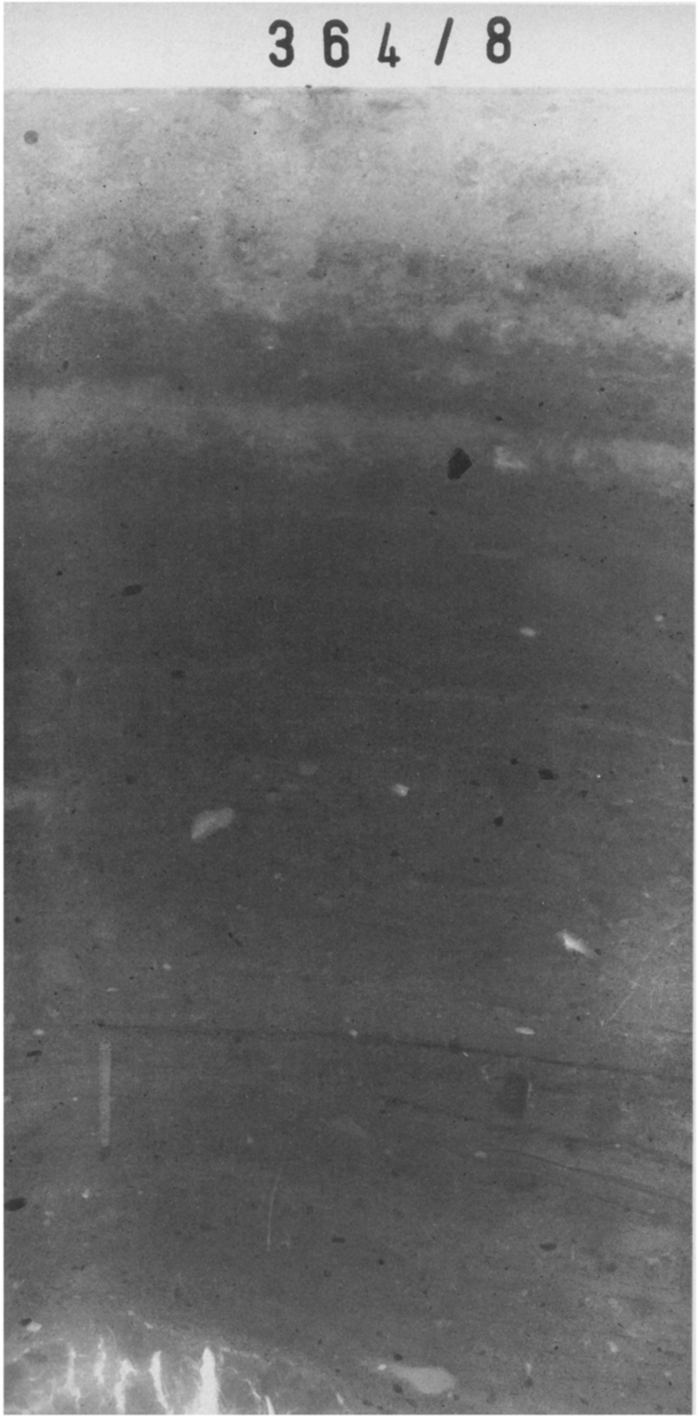

Fig. 6. Radiograph of core 11/364, 193–220 cm core depth, showing association of sediment pellets with bottom currents.

Fig. 7. Radiograph of core 15/063, 0–27 cm core depth, showing association of sediment pellets with iceberg dropstones.

past. Estimates of glacial coverage range from ice shelves covering the entire Arctic Ocean basin (HUGHES *et al.*, 1977; GROSSWALD, 1988), to 20 m thick sea ice which did not melt in summer (Biryukov *et al.*, 1988), to seasonally open pack ice in the basin interior (LAMB, 1977).

During glacial and deglacial periods sources of icebergs would have increased in the Arctic region because tidewater glaciers were much more extensive. Ice sheets extended out over many of the marginal shelves. Icebergs calved from these glaciers would have transported shelf sediments as predominately sub- and englacial deposits out to the deep ocean basins (HENRICH *et al.*, 1989; HENRICH, 1990).

Lowered sea level during glacial maxima would have dramatically influenced sediment incorporation by sea ice. Sea levels during past glaciations were as much as 120 m lower than they are today (HOLMES and CREAGER, 1974; FAIRBANKS, 1989). Because the shelf break along the Siberian margin is at only about 200 m, much of the broad shallow shelves were exposed either subareally or to glaciation, with sea ice formation most likely taking place largely over deep water. Under these circumstances, resuspension of seafloor sediment and incorporation in the ice cover would not have been a dominant process. Sediment entrainment in sea ice during glacial maxima may have been predominantly through aeolian transport from the exposed shelves (PFIRMAN et al., 1989a). However, if the ice cover over the basins was as thick as that proposed by HUGHES *et al.* (1977), BIRYUKOV *et al.* (1988), or GROSSWALD (1988), then sediment incorporation and transport by the ice cover would have been minimal, except along the basin margins. During deglaciation and flooding of the shelves, entrainment of fluvial and sea-floor sediments in sea ice most likely became more important.

Because sediment incorporation processes may have differed through time, a variety of factors should be examined when trying to determine if there is a greater likelihood that ice rafted material is derived from icebergs or from sea ice (Table 1). There are very few factors that are found only in sea ice and never in icebergs or *vice versa*. But if a sediment pellet contains grains that, for example, are rounded, predominantly fine-grained, and exhibit mineralogy very similar to that of other pellets and the adjacent matrix, then it is more likely that it was deposited from sea ice than from an iceberg.

METHODS

Sediment pellet samples were obtained from cores taken during the 1986 *Meteor* II/2 cruise into the Norwegian Sea, the 1987 *Polarstern* ARK IV/3 cruise into the central eastern Nansen Basin (north of Svalbard) and the 1989 *Polarstern* ARK VI/2 cruise to the Greenland Sea (Fig. 3). Thirty-seven samples were taken from 13 cores (see Table 2). Each sample consisted of the sediment pellet itself and the immediately surrounding matrix. The matrix and the pellet samples were analysed separately using coarse fraction mineralogy, determination of organic content, scanning electron microscopy, grain size analysis, and grain shape analysis. The matrix was then compared to the pellet sediment to determine the likelihood that they had similar or different origins.

The grain shape was classified according to RUSSELL and TAYLOR (1937). Radiographs of the cores were examined for signs of postdepositional submarine processes such as slumping and bottom currents in the area of the sediment pellets. The results obtained from the study of the pellet sediments were compared to studies of dispersed and aggregated sediment found on the surface of sea ice collected during the 1987 *Polarstern*

ARK IV/3 cruise (WOLLENBURG, in preparation) and to sediment found in Barents Sea icebergs during the 1989 *Polarstern* ARK VI/I cruise. Finally, the mineralogy and organic content of the pellet sediments were compared to the geology and biology of the Siberian, Barents, Norwegian and Greenland shelves to assess potential source areas.

RESULTS

Sediment pellets from the Nansen Basin and the Greenland Sea are up to 2 cm in diameter. This is an order of magnitude larger than pellets previously found in sediment cores. Pellets examined in this study were generally variable in shape.

Grain size

Seafloor sediment pellet samples. The individual grains in the sediment pellets are mostly medium- to coarse-grained; the predominant range for both areas is 63–250 μm, with a mean range of 125–250 μm (Fig. 4a). The grain size of the pellet sediments recovered from the Greenland Sea is slightly finer than that of pellet sediments from the Nansen Basin: while grain sizes between 60 and 1000 μm are present in both areas, sizes of 40–63 μm are found only in the Greenland Sea samples. The pellet sediments from the Nansen Basin tend to be more homogeneous (less variability in grain size from pellet to pellet). Certain pellet sediment samples from both areas show no size similarity to their immediately surrounding matrix sediments (regression coefficient (r^2) between the pellet and the matrix = 0.14–0.27), while other samples show strong similarity (r^2 = 0.97–1.00) (Fig. 4b). The mean r^2 value for the two areas is nearly identical: 0.64 in the Nansen Basin and 0.65 in the Greenland Sea, which indicates that the possibility that the pellets originated in the same manner as their matrix is weak for both areas. The mean grain size of the matrix sediments is the same as or coarser than the pellet sediments in both areas.

The sediment pellets recovered from the Norwegian Sea, while being the same size, have significantly finer grains than those discussed above (Fig. 4a). While 70% of the samples have grains up to 1000 μm, as do the Nansen Basin and Greenland Sea samples, 60% of these Norwegian Sea samples also include grains less than 4 μm in size. The predominant grain size range for sediment pellets in this area is 125–250 μm, the mean being 63–125 μm. The pellet/matrix similarity is approximately the same as for the Nansen Basin samples: r^2 values range from 0.16 to 0.96, the mean being 0.59, also indicating that the pellets may not have formed in the same manner as their surrounding matrix (Fig. 4b). Mean grain sizes of the matrix show no trend in being coarser or finer than their pellet counterparts.

GKG 15/050-2, 23 cm. A different type of sediment pellet was found in the Greenland Sea at 23 cm depth in core 15/050-2. The pellets are much larger than the aforementioned sediment pellets (Fig. 5); while pellets discussed above have sizes of <1–2 cm, those from GKG 15/050-2, 23 cm are up to 5 cm in diameter. The *grain* size of pellets from this layer is also significantly coarser: grains larger than 2000 μm were found in all the pellet sediments sampled; the mean grain size is 250–500 μm. Unlike the other pellet sediments, these have no specific one or two modes; instead, grains with sizes of 125–250, 250–500 and 500–1000 μm make up most of each pellet in roughly equal amounts. One pellet from GKG 15/050-2, 23 cm has a single pebble measuring 1.7 cm at its core.

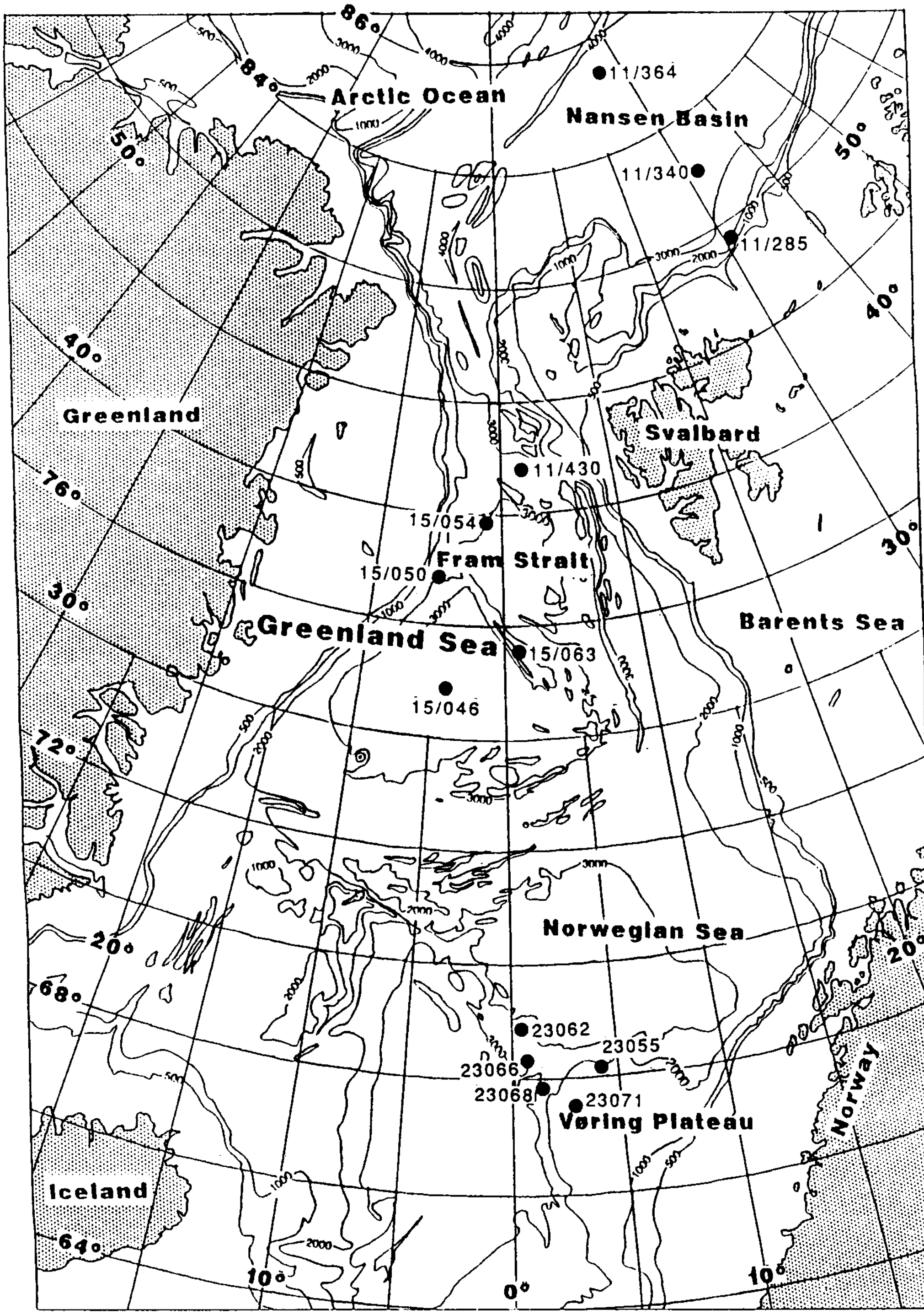

Fig. 3. Location of cores studied. Base map courtesy of S. Rumohr.

Table 2. Core locations and depths of samples

Location	Core	Latitude (N)	Longitude	Water depth (m)	Sample depth (cm)
Nansen Basin	11/285-11	81°38.2′	31°23.2′E	2301	251
	11/340-15	82°56.5′	32°05.2′E	3752	27
	11/364-2	85°21.8′	26°12.9′E	3646	184
					225
Greenland Sea	11/430-8	78°44.8′	01°52.8′E	2557	88
					125
					131
	15/046-2	74°57.6′	04°01.3′W	3586	10
					11
	15/050-2	76°47.6′	05°23.7′W	1638	11
					23
	15/054-5	77°45.5′	00°59.9′W	3075	26
	15/054-6	77°46.0′	00°58.8′E	3118	306
					342
	15/063-1	75°31.3′	00°49.4′E	1730	15
Norwegian Sea	23055-3	68°25.4′	04°01.3′E	2311	382
	23062-1	68°43.7′	00°10.1′E	2244	253
	23066-3	68°15.2′	01°00.4′E	2795	521
					640
	23068-3	67°50.0′	01°30.3′E	2230	533
	23071-3	67°05.1′	02°54.5′E	1308	253

Iceberg sediment samples. Due to the difficulty and danger of sampling icebergs, only two sediment samples were recovered for this project. One of these samples, approximately 15 cm in diameter, was roughly spheroidal in shape and contained interstitial ice, indicating that it may have been in the process of being consolidated. The sediment found in the icebergs is predominantly coarse-grained; the mean is 1000 μm. One sample does not contain any sediment finer than 250 μm.

Sea ice surface sediments. Samples of dispersed sediment collected from the sea ice surface in the Nansen Basin are very similar in grain size to aggregated sediments collected at the same time (Fig. 4a). These sediments are much finer than the sediment found in seafloor pellets. No grains are larger than 500 μm and the mean grain size is only 10–20 μm.

Grain roundness

Seafloor sediment pellet samples. Studies of grains from the Greenland Sea and the Nansen Basin show no strong tendency toward roundedness or angularity in pellet sediments from either area (Fig. 4a). The pellet sediments from the Nansen Basin are slightly more angular than those from the Greenland Sea, but not significantly so: the mean shape for the Nansen Basin is subrounded to subangular, while that for the Greenland Sea is subrounded. When compared to their immediately surrounding matrix, pellets sediments from both areas have only 1–2% well-rounded grains and 20% angular grains and show mean r^2 values of 0.61 (Greenland Sea) and 0.81 (Nansen Basin), indicating that the pellets in the Nansen Basin may have formed in the same manner as their surrounding matrix; this possibility is weaker for the Greenland Sea (Fig. 4b).

Pellet sediments from the Norwegian Sea are somewhat more rounded than their counterparts in the Greenland Sea and the Nansen Basin. The similarity of pellet particle shape to matrix particle shape in the Norwegian Sea samples is relatively strong (mean r^2 value = 0.73), indicating that it is possible that the pellets formed in a similar manner as their surrounding matrix.

GKG 15/050-2, 23 cm. The predominantly coarse-grained pellet sediments from GKG 15/050-2, 23 cm are most similar to the predominantly fine-grained Norwegian Sea pellet sediments in terms of grain shape (Fig. 4a). While less than 20% of the grains from this core fall into the "angular" categories, fully half fall into the "rounded" categories. The mean shape is rounded to subrounded.

Iceberg sediment samples. More than half of the sediments recovered from icebergs fall into the "angular" categories. The mean shape is subangular to subrounded. This may indicate that the sediments are from the supraglacial environment (see Table 1).

Sea ice surface sediments. Although grains of both dispersed and aggregated sea ice surface sediments have a mean shape of subrounded to subangular, as do most of the pellet sediments, the distribution of the shapes of these grains is more variable than those in the pellet sediments.

Pellet composition

Seafloor sediment pellet samples. While all samples contain primarily quartz, there are distinct mineralogical differences among the pellet sediment samples from the Norwegian and Greenland Seas and those of the Nansen Basin (Fig. 4c). The maximum amount of quartz per sample in all three areas is 90–95%. However, the minimum amount decreases from 85% in the Norwegian Sea to 60% in the Nansen Basin to only 3% in the Greenland Sea. The opposite pattern emerges for the amount of rock fragments, increasing from 3% in the Norwegian Sea to 35% in the Nansen Basin and to 80% in the Greenland Sea. Biogenic matter was composed almost exclusively of *Neogloboquadrina pachyderma* sin., and ranged from <1% of the sample in the Nansen Basin, to 0–7% in the Norwegian Sea, and 15% in the Greenland Sea. Feldspar, pyroxene and mica are 0–1% in all three areas. The r^2 values for mean pellet/matrix similarities is 0.56 for the Greenland Sea samples, 0.81 for those from the Nansen Basin, and 0.99 for those from the Norwegian Sea, indicating that the possibility that the pellets were formed in the same manner as their surrounding matrix is very strong for the Norwegian Sea, strong for the Nansen Basin, and weak for the Greenland Sea (Fig. 4b).

Analysis revealed that sediment pellets found in the same layer were markedly different from one another compositionally. This fact favours incorporation into glaciers and later deposition by icebergs over the more uniform incorporation into sea ice.

GKG 15/050-2, 23 cm. Although they were recovered from the Greenland Sea, the pellet sediments from this layer compositionally closely resemble the pellet sediments

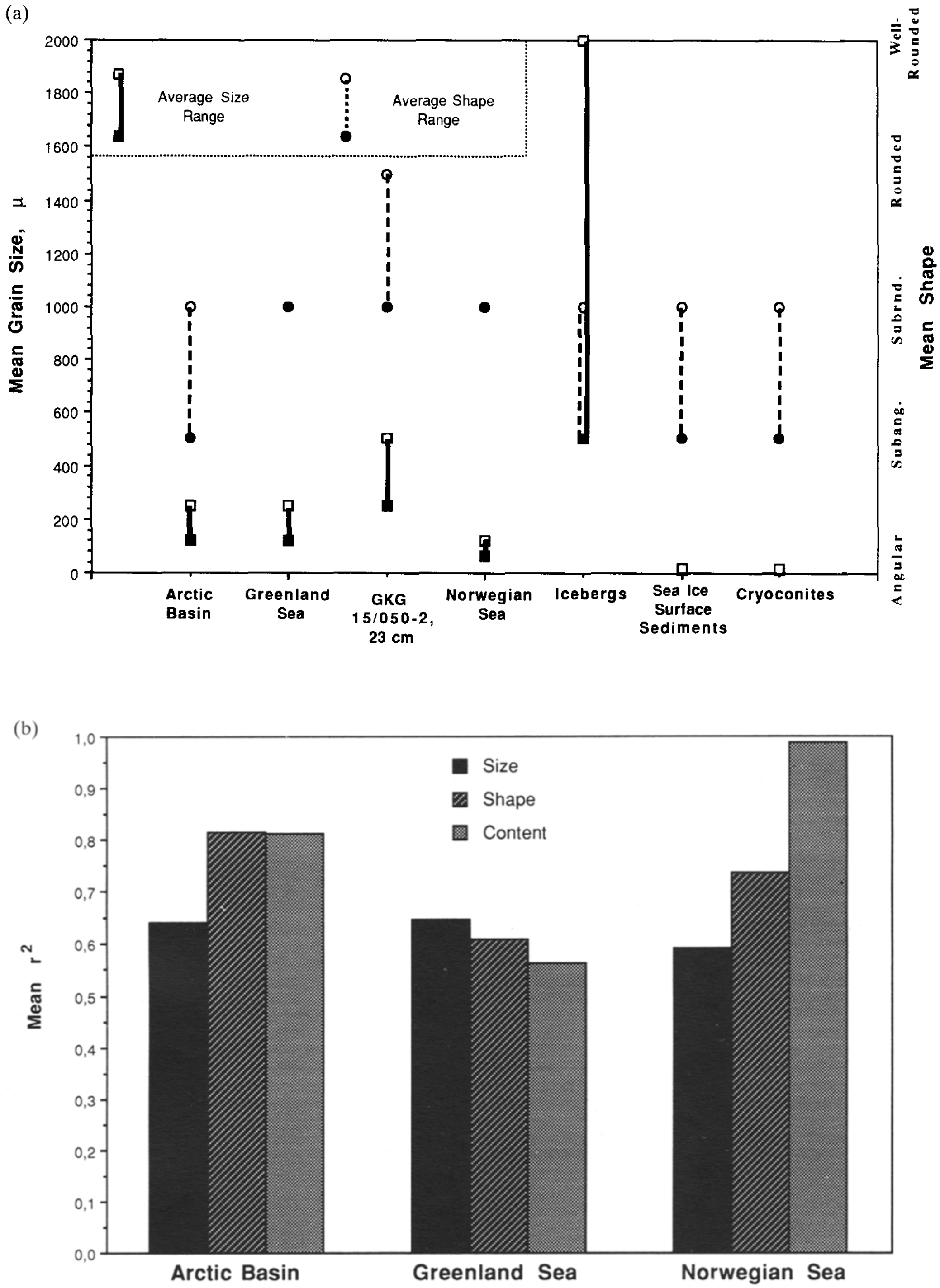

Fig. 4. Summary of results from investigations of sediment pellets, iceberg sediments, sea ice surface sediments and cryoconites. (a) Mean size and shape. (b) Mean pellet/matrix similarity. (c) Mean composition.

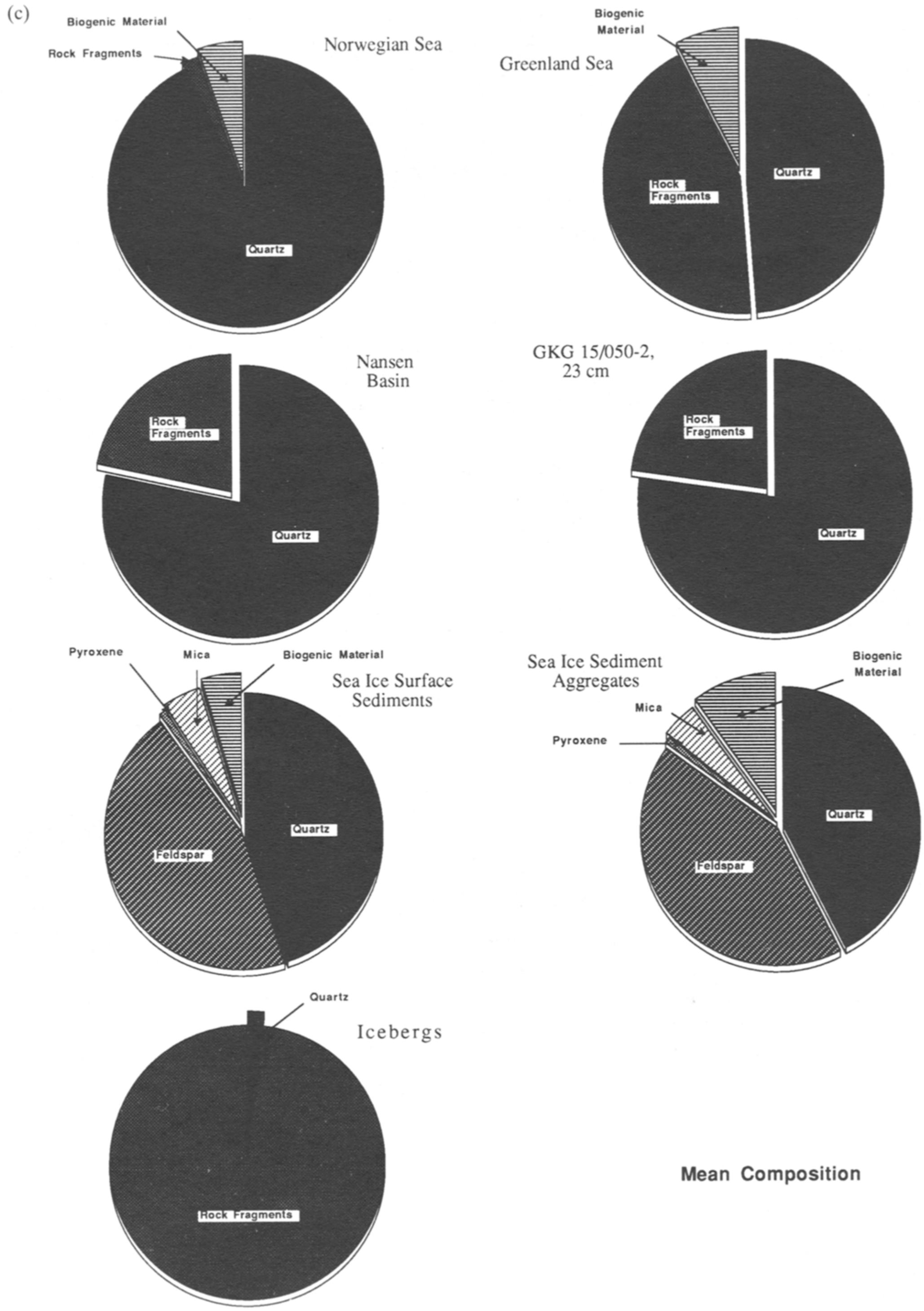

Fig. 4. *Continued.*

from the Nansen Basin (Fig. 4c). In fact, the difference between the GKG 15/050-2, 23 cm pellet sediments and others from the Greenland Sea is so great that it is clear that they are not related. As with the sediment pellet samples, the amounts of feldspar, pyroxene, and mica are 0–1%.

Iceberg sediment samples. The sediments recovered from the Barents Sea icebergs are compositionally very different from any of the aforementioned sediments (Fig. 4c). Quartz grains make up 5% of the samples, while rock fragments account for the rest. There is no feldspar, pyroxene, or mica.

Sea ice surface sediments. Unlike that of sediment pellet sediments, the mineralogy of the sea ice surface sediments is not dominated by quartz (Fig. 4c). Instead, feldspar and quartz combined make up about half of these samples. There is more mica, up to 10% of a sample, but about as much (0–1%) pyroxene in the surface sediments. Rock fragments are much rarer, accounting for <1%.

The amount of biogenic matter is the only criterion in which dispersed sea ice surface sediments differ from the aggregates: dispersed sediments contain 1–10% while aggregates have 5–20%. Thus the biogenic content of sediment pellet sediments is roughly similar to the dispersed sediments and somewhat lower than that of the aggregates.

Rock fragment lithology

Rock fragments in all pellet samples include dark shales and clay-, sand-, and siltstones. Granites, sandstones, and dark crystalline rocks (possibly amphibolites or gabbros) make up the samples from GKG 15/050-2, 23 cm.

Biogenic matter

No pollen or spores were found in the sediment pellets. Planktonic foraminfera make up most of the biogenic matter and all species found come from the marine environment. *Neogloboquadrina pachyderma* is the predominant life form; the warm-water dextral variation occurs in only one sediment pellet and one of the matrix samples. *Cassidulina teretis* also occurs in two of the matrix (none of the sediment pellet) samples: this bottom-dwelling benthic foraminifer is also an indicator of cold (<2°C) conditions. *Cassidulina teretis* lives at water depths of 700–1500 m (MACKENSEN and HALD, 1988), indicating that these matrix samples, and possibly the associated pellet samples, were deposited in the shelf/slope environment and were later eroded and re-deposited in the deep sea.X

Examination of core X-rays

Seafloor sediment pellet samples. X-ray plates made from the cores from the Greenland and Norwegian Seas and the Nansen Basin were examined to determine if postdepositional processes such as slumping and bottom currents (1) had occurred in the areas of the sediment pellet samples; (2) were instrumental in their formation; or (3) had, through winnowing, led to pellet-enriched horizons. Of the 37 pellets taken out of the cores, only four (two from core 11/364 and one each from 15/046 and 15/054) appear to have been affected by bottom currents or slumping (Fig. 6). This does not necessarily mean that these four pellets were *not* formed in sea ice or icebergs, only that submarine processes are also possible. In all other samples, postdepositional processes can be ruled out as a method of sediment pellet formation because no evidence of these processes can be seen in the neighbourhood of the pellets. The radiograph of core 23068 shows a pellet that has made a crater-like deformation in the sediment layer beneath it, clear evidence that it was dropped to the sea floor (see HARLAND *et al.*, 1966; PIPER, 1976).

Also observed in the X-rays are numerous associations of pellets with dropstones (Fig. 7). One of these is from core 15/054, which also shows evidence of bottom currents. The syndeposition of pellets with dropstones strengthens the possibility that the pellets have a similar (i.e. ice-rafted) origin.

GKG 15/050-2, 23 cm. The radiographs (Fig. 5b) indicate no sediment finer than sand in the matrix near the pellets. Several centimetre thick layers of sand- to gravel-sized sediment appear both above and below the pellet layer.

SEM results

Two pellets each from the Nansen Basin and the Greenland and Norwegian Seas were fractured after drying and then examined for internal structural features with a scanning electron microscope (SEM). Only one pellet has indistinct banding; the others are structureless. Pellets from GKG 15/050-2, 23 cm were too large for SEM study; normal microscopy did not reveal any structures in these pellets.

DISCUSSION

Origin of sediment pellets

The grain size of the pellet sediments and textural evidence in the X-rays allow us to rule out a submarine (i.e. bottom current or slumping) origin of the pellets. It also appears unlikely that the sediment pellets described in this study are fecal pellets. While fecal pellets are usually packed with coccoliths (see BROMLEY, 1990), SEM investigations show that the sediment pellets contain very few coccoliths: some of the sediment pellets have no skeletal matter whatsoever. Fecal pellets tend to decompose when they reach the ocean bottom (KENNETT, 1982). Since the sedimentation rate in the Arctic Ocean is about 1–3 cm ky^{-1} (CLARK *et al.*, 1980), a fecal pellet would have sufficient time to decompose before it is buried by other sediments. The cold water on the Arctic seafloor may hinder disintegration, but clearly not longer than the time required for burial (see WILLE, 1988). Fecal pellets are usually uniform in size and are often rounded (GOLDSTEIN, 1983), whereas the sediment pellets are of varying sizes and often angular. In addition, fecal pellets are usually much smaller (<1 mm; see NÖTHIG and VON BODUNGEN, 1989), although they can also reach centimetre size. If the pellets were fecal pellets that had formed *in situ* as the deposits of burrowing organisms the pellets would occur in association with evidence for bioturbation (see BROMLEY, 1990). Most pellets studied here are not found in bioturbated areas.

Table 3. Characteristics of studied sediments in relation to the tendency of these sediments to have originated in sea ice or icebergs

Parameter	Nansen Basin	Greenland Sea	GKG 15/050-2, 23 cm	Norwegian Sea
Grain size	Iceberg	Iceberg	Iceberg	Iceberg
Grain shape	Iceberg	?	?	?
Mineralogy and rock fragment lithology	?	Iceberg(?)	?	?
Biogenic matter	—	Iceberg	—	Iceberg

Comparison of results with idealized grain parameters (Table 3; see also ANDERSON, 1981) indicates that the sediment pellets are more likely to have come from iceberg than sea ice rafting. Looking first at grain size, it is clear that sediments in pellets found in the sediment cores and those on the modern sea ice surface are not texturally related. Modern sea ice surface sediments consist primarily of clay and silt while seafloor sediment pellets are composed of sand with some silt and very rare clay (Fig. 8). Although coarse-grained sediment has been seen on sea ice (cf. PRESTWICH, 1886; STEFANSSON, 1921; BROCHWICZ-LEWINSKI and RUDOWSKI, 1976; DALLAND, 1976; DIONNE, 1976; MOIGN, 1976; VANNEY and DANGEARD, 1976; GILBERT, 1990), nothing resembling coarse-grained aggregates has yet been seen on sea ice. In addition, when coarse-grained sediments are present on sea ice they are apparently always accompanied by fine-grained sediments (see KNIGHT and DALRYMPLE, 1976). This size difference points to an iceberg origin for seafloor sediment pellets, assuming that sea ice and iceberg sediment incorporation processes were essen-

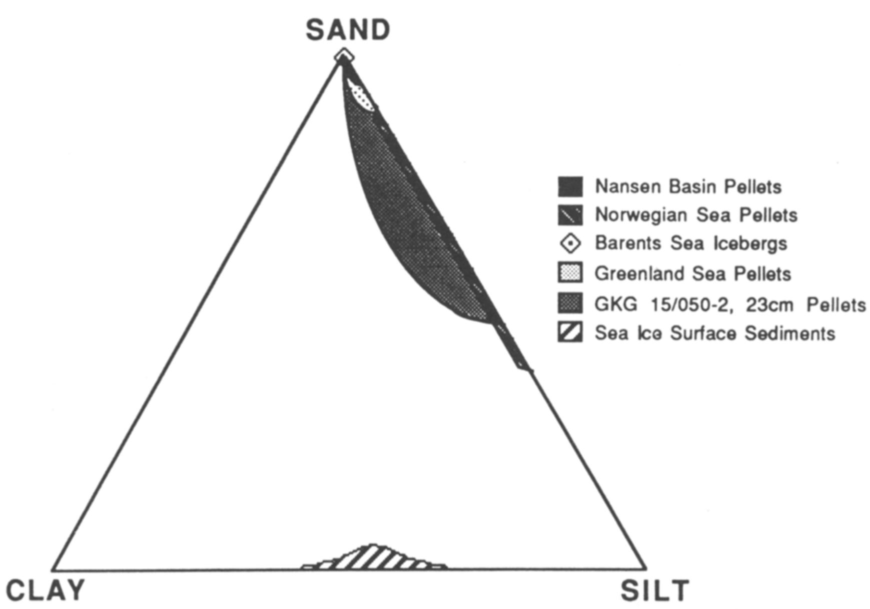

Fig. 8. Ternary diagram of distribution of all sediments investigated.

tially the same in the past as they are now. However, it is also possible that sea ice sediments were coarser-grained in the past or that the pellets are depositions of coarse-grained sea ice sediments which have not been found on the ice surface to this date.

While iceberg sediments can be rounded or angular, sea ice sediments today are predominantly rounded. Angular grains would point to an iceberg origin while rounded ones would not decide in either direction. Most sediment pellet grains studied are subrounded to rounded in shape, thereby leaving the question of their origin unanswered.

The matrix between the sediment pellets contains dropstones that consist of either grayish silt/sandstones or crystalline and metamorphic rocks. Coal and chalk dropstones are also found (BISCHOF *et al.*, 1990; HENRICH, 1990 and unpublished data). These lithologies, which were also found in the sediment pellets, crop out on the Norwegian (BUGGE *et al.*, 1984) and Barents Sea shelves (ELVERHØI and LAURITZEN, 1984), the Scandinavian craton, in the North and Baltic Seas and in the lands surrounding these seas (ZIEGLER, 1982). These areas have been covered by ice sheets in the past and represent potential iceberg sources.

All biogenic matter found within the pellets consists of planktonic marine foraminifera. These could be entrained by either sea ice or icebergs from the continental shelves. The presence of *C. teretis* (preferred water depth 700–1500 m) within a few of the matrices may indicate that the matrix sediments were redeposited in the deep ocean.

It is apparent from Table 3 that the sediment pellets from all three areas most probably have an iceberg-derived origin and represent an accumulation of relatively fine-grained (sand-size or smaller) sediment quarried by a glacier. An exception is the layer of unusually coarse-grained sediments found in rounded pellets from GKG 15/050-2, 23 cm. These pellets may have come from a winnowed till or moraine. We have not found any other deposits similar to these sediment pellets, although it is possible that they are related to till balls (see GOLDSCHMIDT, submitted).

Correlation with other studies

Several studies of the matrix have been made for the cores examined in the present study. It was found that pellets were compositionally similar to the matrix in terms of:

(1) low amounts of coal and chert and high amounts of siltstones in cores from the Nansen Basin (BISCHOF *et al.*, 1990; M. KUBISCH, personal communication, 1990);

(2) peaks in quartz and low amounts of mica and $CaCO_3$ in cores from the eastern Arctic Ocean (PAGELS, unpublished);

(3) peaks in the amount of coarse material (KÖHLER and SPIELHAGEN, 1990) and peaks in silt- and claystones (ROBERT SPIELHAGEN, personal communication, 1989) in cores from Fram Strait;

(4) the absence of coccoliths in cores from the eastern Arctic Basin (BAUMANN, 1990; NOWACZYK and BAUMANN, 1992);

(5) the presence of glacial and deglacial sediments determined from oxygen isotopic analyses and the presence of dropstones in cores from the Norwegian Sea (HENRICH *et al.*, 1989; HENRICH, 1990).

If the hypothesis that pellets were deposited by icebergs is correct, it is possible that the sediments surrounding the pellets were also deposited by icebergs.

Formation environment

Although this analysis indicates that the sediment pellets are likely to be rafted by icebergs, there are some difficulties in reconstructing the formation environment:

Biogenic material. Many of the pellets contain marine planktonic foraminifera. If the pellets were formed within or on the surface of glaciers, these foraminifera could only get into the pellet sediment if the sediment were exposed on the face of the glacier that was washed with sea water before an iceberg calved. Yet this exposed sediment would almost certainly be lost during calving or soon after and would not cling to the berg through its numerous overturnings on its journey to the deep ocean. Tabular bergs, shortly before melting, could be low enough for waves to wash over them, possibly bringing foraminifera into sediments that had accumulated on the berg surface (see Dowdeswell, 1989). These processes would probably lead to the presence of foramifera only on the pellet surface.

It is more likely that the planktonic foraminifera are evidence that the pellets represent sediment entrained when glaciers overran the continental shelf. However, under these circumstances it is curious that benthic species were not also entrained.

Consolidation process. If pellets are to survive intact the kilometres-long drop through the water column and burial on the sea floor, they must be somewhat consolidated. The consolidation need not be extreme: fecal pellets have been known to fall intact to the deep ocean bottom (see Bruland and Silver, 1981). Several different processes that may consolidate sediment in sea ice and glacial ice are known. These include: freezing (frozen clumps of sediment could remain frozen in the cold Arctic waters until they reach the seafloor); sun-drying (Dionne and Laverdiere, 1972; Brochwicz-Lewinski and Rudowski, 1976; Gilbert, personal communication, 1990); glacial shearing (Ovenshine, 1970); freeze-thaw processes (Czeratski and Frese, 1958; Chamberlain and Gow, 1978; Chamberlain, 1989); and salt-desiccation (see Bettenay, 1962; Dare-Edwards, 1982; Wasson, 1983). Whether these last two processes can occur for sand-sized sediments in or near the ocean is unclear: while they may occur in the sediment pellets discussed here, they are more likely to consolidate the finer sediments found in modern sea ice aggregates.

Another possibility, that the pellets represent sediment that had been consolidated before it was incorporated into sea or glacial ice, exists. The sediment pellets may be derived from tills or moraines that were compacted when overridden by a glacier (see Elverhøi *et al.*, 1990).

A note on terminology

During review of this paper a debate over the properness of the terms "sediment pellets" vs "sediment clasts" vs "mud clasts" arose. Most of the controversy centers on the possible confusion that would arise if sediment pellets were confused with fecal pellets or if "sediment clasts" were confused with normal clasts. After careful consideration we have decided to stay with sediment pellets, with the stipulation that the name is not carelessly shortened to pellets, which might cause confusion with fecal pellets. They cannot be called clasts because a clast can consist of one grain (a dropstone, for example); clasts are usually considered to *be* particles, not to *consist* of particles (see Allaby and Allaby, 1990). Pellets, on the other hand, are usually an aggregate of grains. "Mud clasts", as mentioned in the introduction, is not possible because the presence of pure mud is implied. "Mud pellets" and "clay pellets" can exist as a subset of sediment pellets as long as only mud or clay are present in the samples under discussion.

If the term "sediment pellets" causes too much confusion with "fecal pellets", one alternative is "sediment aggregates". This term is vague, but a modifier such as "cryogenic" may help to separate the aggregates under discussion from others with different origins and environments (cf. RUST and NANSON, 1989). Another possibility is "sediment peloids"; if one argues that "pellets" connotes fecal pellets, "peloids" can be used for "structureless grains resembling pellets whch cannot be shown to be of faecal origin" (ALLABY and ALLABY, 1990; see also BATHURST, 1971; TOMKEIFF *et al.*, 1983). The term "till pellets" has been in use for about a quarter century (see review in ANDERSON, 1981); refusal to allow "sediment pellets" in terminology would lead to reconsideration of the term "till pellets".

CONCLUSIONS

Sediment pellets found in the Nansen Basin and the Greenland and Norwegian Seas are much larger than pellets discussed in previous studies. They are most likely deposited by overturning or melting icebergs rather than sea ice, because the pellet sediments are much coarser and have different mineralogies than sediment observed on sea ice today. Pellets found in the same layer are usually compositionally different, which also suggests incorporation into glaciers rather than into sea ice. The pellets may be aggregated prior to inclusion in the glacier or may form when freeze-thaw processes or desiccation consolidates sediments on/in ice. The consolidated pellets must be cohesive enough to survive a drop of several kilometres through the water column. However, it is difficult to reconstruct a formation environment that would allow for incorporation of planktonic marine foraminifera within sediment pellets and the exclusion of all other species. Unusually large and coarse-grained sediment pellets found in one layer in GKG 15/050-2 are probably from a winnowed till or morainal deposit. They may be related to till balls (GOLDSCHMIDT, submitted).

It is still possible that pellets represent sediment entrained into sea ice by processes different than those that predominate today. If sediment pellets were actually deposited by sea ice, then

(1) the sea ice was sediment-rich, having formed in a shelf or nearshore environment;

(2) it was probably multi-year ice so that concentration of sediment at the ice surface could take place during melting;

(3) sediment entrainment processes into sea ice were different than they are today, incorporating coarser grains than in modern sea ice; and

(4) pellet deposition areas, indicating the positions where sea ice melted or was disturbed, may delineate the ice drift path and zone of maximum ice extent in the past.

It appears unlikely that the sediment pellets are formed by submarine processes. The pellet sediments are quite coarse-grained and are generally not associated with disturbances such as slumps or contourites from near-bottom currents. The pellets are probably not fecal pellets, which would have a different biogenic makeup and which would in all likelihood disintegrate during their roughly 1000-year exposure on the ocean bottom surface.

Once the formation environment for sediment pellets is refined, their occurrence in sediment cores may become an important paleoenvironmental indicator. For example, if the sediment pellets are found to represent subglacial deposits picked up by the glaciers on continental shelves, then their presence in sediment cores would indicate not only the existence of such tidewater glaciers on continental shelves, but also the paleodrift pattern and maximum drift extent of icebergs calved from this particular environment.

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