Origin of well-rounded gravels in glacial deposits from Brøggerhalvøya, northwest Spitsbergen: potential problems caused by sediment reworking in the glacial environment

DAVID HUDDART, MATTHEW R. BENNETT, MICHAEL J. HAMBREY, NEIL F. GLASSER and KEVIN CRAWFORD

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Well-rounded gravels are described from moraine-mound complexes, diamicton forefields and modern englacial thrusts at the margins of four glaciers on the northern side of Brøggerhalvøya, northwest Spitsbergen. Their shape characteristics are compared with modern and fossil glacigenic, modern beach and Early Weichselian beach gravels from this peninsula. The best discriminators of the well-rounded gravels have been found to be the percentage-frequency roundness histograms, the roundness mid-point and roundness range diagrams and the sphericity-roundness plots. It is concluded that the gravels have been derived by englacial thrusting from Early Weichselian or last interglacial beaches in the inner parts of the fjord and in the low level cirques when sea level reached at least 50 m a.s.l. and deposited the beach gravels. The discrimination between gravel in basal diamictons, proglacial outwash and modern beaches is difficult as the reworking has resulted in little particle shape change. The potential major problem caused by reworking in the glacial environment is emphasised, especially when clast shape comparisons from modern environments to older sediments are used.

David Huddart, School of Education and Community Studies, I. M. Marsh Campus, Liverpool John Moores University, Barkhill Road, Liverpool L17 6BD, U.K.; Matthew R. Bennett, School of Earth and Environmental Sciences, University of Greenwich, Medway Towns Campus, Pembroke, Chatham Maritime, Kent ME4 4AW, U.K.; Michael J. Hambrey*, Neil Glasser and Kevin Crawford†, School of Biological and Earth Sciences, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, U.K.

Introduction

The shape of clasts in sedimentary environments is commonly used to help infer the processes of deposition. As part of a wider project concerned with moraine formation and sedimentation at high-arctic, polythermal glaciers (Hambrey & Huddart 1995; Huddart & Hambrey 1996; Bennett et al. 1996a and b; Hambrey et al. 1997) data on clast shape from a range of glacial facies of known origin was routinely collected. This data-set of 172 samples from these polythermal glaciers adds to the growing reference material on clast shape which can be used to aid the interpretation of sediments of unknown origin and was reported in Bennett et al. (1997). During the data collection, a facies consisting of very well-sorted and rounded pebble/cobble gravels was

recorded on the forefields of glaciers on the northern side of Brøggerhalvøya (Fig. 1). The gravels are visually distinctive (Fig. 2A and B) and different from any other facies sampled. They are colloquially described as "egg gravels" (Bennett et al. 1997) but they are referred throughout this paper as well-rounded gravels. The aim of this paper is to demonstrate the distinctive nature of this facies and offer an explanation for its formation and incorporation into both modern and Neoglacial maxima glacigenic sediments in the investigated area.

Morphological occurrence of the well-rounded gravels

The well-rounded gravels occur in three morphological settings within the glacier forefields of Brøggerhalvøya: (1) as pods within the moraine-mound complexes which mark the Neoglacial maxima; (2) as distinct ridges trending across flat, diamicton and gravel forefields; and (3) within

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* now at the Centre for Glaciology, Institute of Geography and Earth Sciences, University of Wales, Aberystwyth, Ceredigion Sy 23 3DB, U.K.

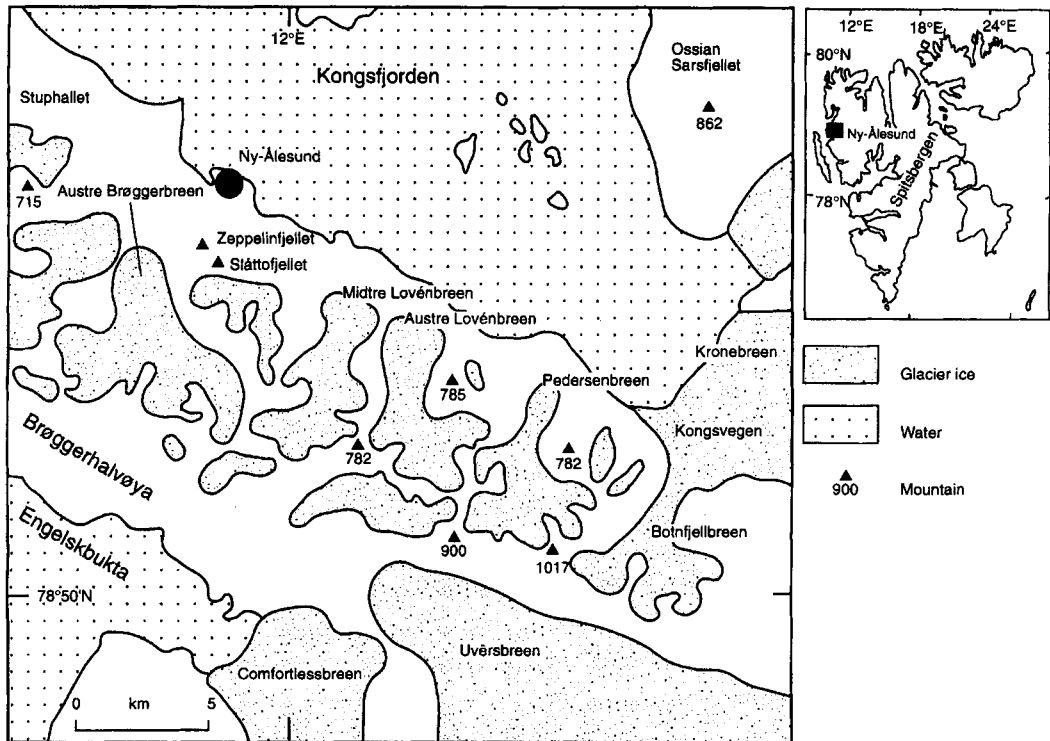† now at Liverpool Hope University, Hope Park, Liverpool L16 9JD, U.K.

Fig. 1. Location of the high-arctic valley glaciers in this study. Altitudes are in metres above sea level.

englacial thrusts outcropping on the glacier sur-
face. Within the moraine-mound complexes well-
rounded gravels can be found as pods, up to 10 m
across (Fig. 2A), within the diamicton which is
the dominant facies within the moraine com-
plexes. The moraine-mound complexes have been
interpreted as the product of englacial and
proglacial thrusting in response to flow compres-
sion at a polythermal ice margin (Sollid & Sørbel
1988; Hambrey & Huddart 1995; Bennett et al.
1996a; Huddart & Hambrey 1996; Hambrey et al.
1997). Freezing on of subglacial sediment leads to
its incorporation as sediment rafts within englacial
thrusts, which subsequently melt out as undis-
turbed sediment blocks, a process which can be
seen operating at the contemporary ice margin. A
range of different sedimentary facies may be
incorporated into moraine-mounds, including
basal diamictons, glaciofluvial sediments, glacio-
marine fjord sediments and well-rounded gravels,
although the dominant facies is usually basal
diamicton.

The well-rounded gravels also outcrop as linear
ridges on the glacier forefields, particularly at
Midtre Lovénbreen and Austre Brøggerbreen. The
ridges can be traced as continuous ridges over
50 m and up to 0.5 m high (Fig. 3C) and they have
been shown to cut through small esker ridges (Fig.
3A and B). They cut unconformably through
diamicton, glaciofluvial gravel and supraglacial
sediment and are interpreted as an expression of
linear thrusts which elevated the well-rounded
gravels within a former ice margin (Bennett et al.
1996a; Hambrey et al., 1997). Modern examples
of this process can be seen at the margins of
Midtre Lovénbreen, Austre Brøggerbreen and
Botnfjellbreen (Fig. 4A) where well-rounded
gravels are melting out from linear, englacial
thrusts (Fig. 4B). The sediment forms an ice-
cored, ridge morphology, and as the ice slowly
melts out, the ridge maintains its integrity as a
continuous feature.

The occurrence of well-rounded gravels in this
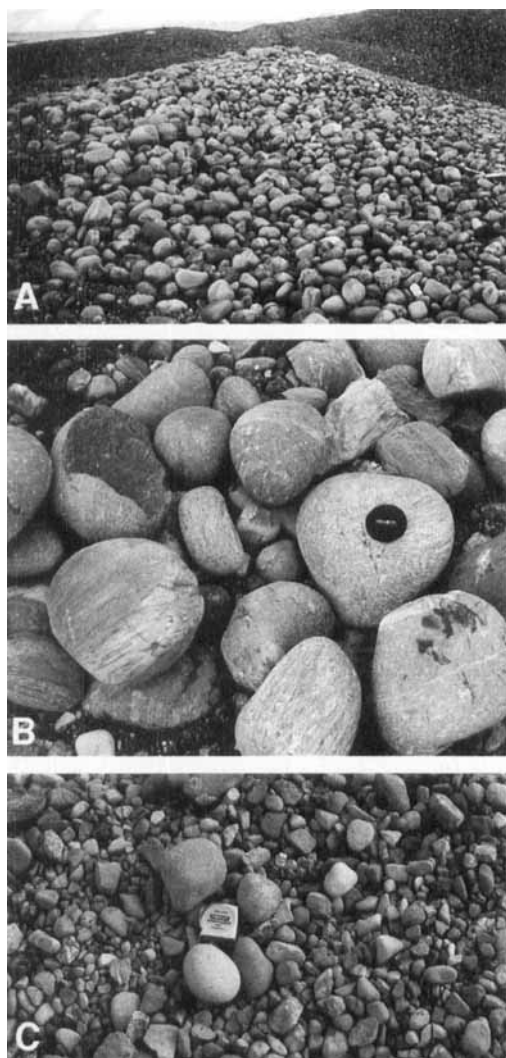environment is therefore linked to thrusting within

Fig. 2. Well-rounded gravels and raised beach gravels. A. Well-rounded gravels, Midtre Lovénbreen. The gravels are largely composed of augen gneiss. Scale shown by spade. B. Well-sorted and rounded cobble gravels, Midtre Lovénbreen. C. Raised beach gravel at 50 m a.s.l. at Stuphallet. One location for Early Weichselian beach gravel samples in the particle shape diagrams.

process involving ice, or subglacial or englacial fluvial transport. Alternatively, the sediments could be eroded from pre-existing sediments, such as a fluvial or marine gravel, over which the glacier was advancing. In an attempt to explore the origin of these gravels, their clast shape characteristics have been investigated and compared with clast shapes typical of the range of sedimentary environments encountered on Brøggerhalvøya. These include subglacial diamicton, subglacial esker, sandur, modern beach and Early Weichselian beach.

Clast shape analysis and data

Samples containing 50 clasts were collected from each sedimentary facies encountered in the proglacial, subglacial and ice-marginal zones of the glaciers. In addition, modern beach gravels were sampled from the shore of Kongsfjorden and from Early Weichselian beaches (at 50 m a.s.l.) outside the maximum Weichselian ice limit at Stuphallet (Fig. 2C) on Brøggerhalvøya described by Miller (1982), Miller et al. (1989) and Lehman & Forman (1992). A total of 172 samples (8600 clasts) were collected. For each clast the following information was obtained: (1) the length of the three orthogonal axes (a, b and c), and (2) a visual estimate of particle roundness recorded both as a Powers' (1953) roundness class and as a Krumbein (1941) roundness number in order to record the full spectrum of variation within each roundness class (very angular 0.0–0.17; angular 0.17–0.25; subangular 0.25–0.35; subrounded 0.35–0.49; rounded 0.49–0.7; well rounded 0.7–1.0). The data is analysed in detail in Bennett et al. (1997), but here we focus on the characteristics of the well-rounded gravels.

The well-rounded gravels can be distinguished on the basis of particle roundness from all the samples, except the Early Weichselian beaches (Fig. 5). This point is reinforced in Fig. 6 which shows the mean and range in roundness values for a number of typical samples. This plot shows that there is a lack of distinction in roundness for most of the subglacial facies, as noted by Bennett et al. (1997). For example, basal diamictons cannot be distinguished from glaciofluvial deposits, including esker gravels. They can, however, be distinguished from supraglacial sediments which are significantly more angular as would be
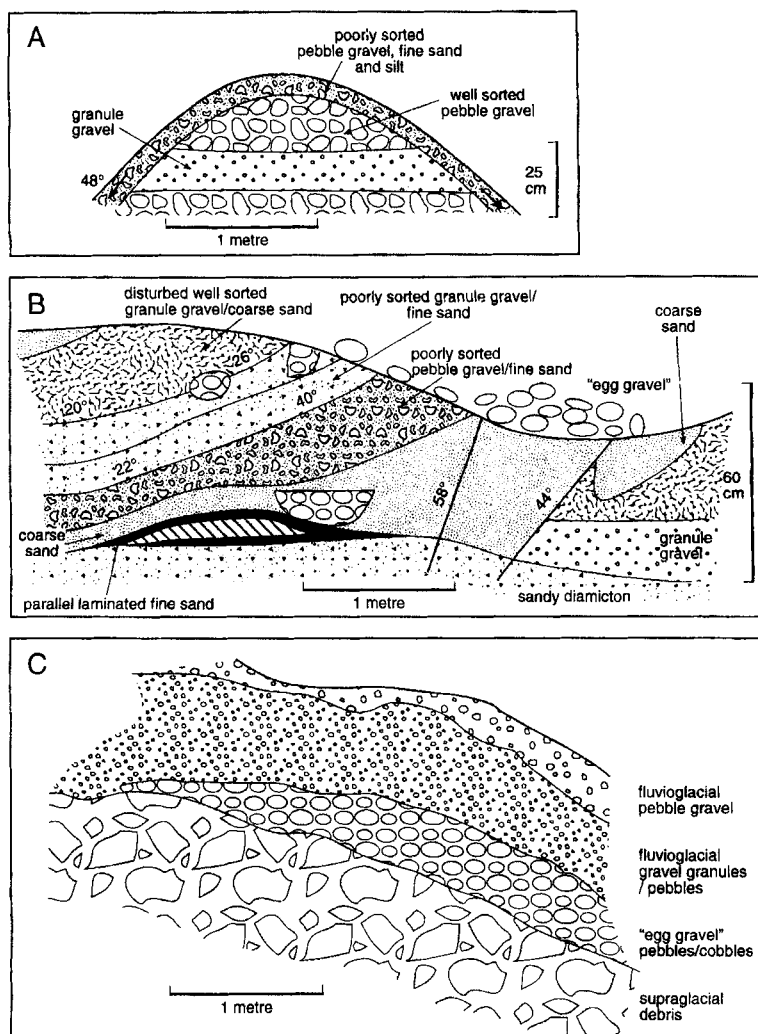
glacier ice which elevates basal debris into an englacial and supraglacial position within the glacier. The origin of this sediment therefore must represent a subglacial or englacial facies and could be derived from a subglacial or englacial

Fig. 3. Thrusts cutting through the Midtre Lovénbreen forefield. A. Small esker and its stratigraphy. B. Esker sediments cut through by thrusting at a high angle which brings well-rounded gravels to the surface in places. C. Well-rounded gravels within glaciofluvial and supraglacial sediment.

expected (Boulton 1978; Benn & Ballantyne 1994). The subglacial facies is also very similar to modern beach sediments which is not surprising since the beach sediments are largely reworked from basal diamictons and outwash sediments. However, the modern beach samples are very distinct from the Early Weichselian raised beach gravels sampled, which are similar in roundness to the well-rounded gravels. Co-variant plots of roundness and sphericity reinforce the similarities between well-rounded gravels and the Early Weichselian raised beach gravels and their mutual distinction from the other facies sampled, which are indistinguishable on this type of plot (Fig. 7).

Discussion

There are three major points which need discussion. These are the origin of the well-rounded gravels, the greater roundness of the Early Weichselian raised beach gravels with respect to modern beach gravels, and the importance of sediment re-working and the potential problems that this can cause in the correct interpretation of a glacial sedimentary facies.

The origin of the well-rounded gravels

Clues as to the origin of these sedimentologically distinctive, well-rounded gravels have largely

Fig. 4. Thrusts and well-rounded gravels at Midtre Lovénbreen. A. Thrusting in an ice frontal location. Most of the gravel is glaciofluvial in origin but some is well-rounded gravel, as in Fig. 4B.

B. Well-rounded gravel from a thrust ridge, similar to Fig. 4A. Note the angular, supraglacial sediment adjacent to the thrust ridge.

come from the clast characteristic work. It has been shown that they occur within the moraine mounds, in the recent glacier forefields and as modern englacial thrusts in all of the valley glaciers on the north side of Brøggerhalvøya, from Austre Brøggerbreen in the west, to Botnfjellbreen in the east (Fig. 1). None have yet been observed at any of the glaciers on the south side of this peninsula, despite sedimentological work on these glaciers (Hambrey & Huddart, 1995; Huddart & Hambrey 1996). Their current morphological expression is the result of thrusting

from a subglacial position, followed by subsequent meltout from the ice. The clast shape data presented in this paper suggest that the most likely source for these well-rounded gravels is Early Weichselian beaches which are currently found on Brøggerhalvøya but to the west of the glaciers investigated.

However, Brossard & Joly (1986) attributed the occurrence of well-rounded gravels at Midtre Lovénbreen to a subglacial meltwater network. This seems unlikely as the clast-shape data presented above for esker gravels at Midtre
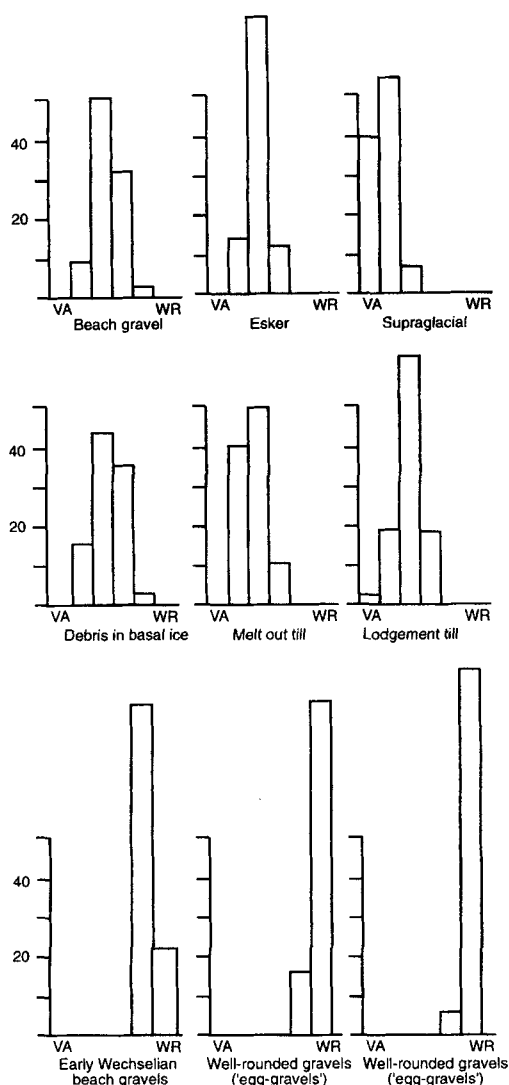
Fig. 5. Percentage frequency histograms of roundness class (very angular, angular, subangular, subrounded, rounded and well-rounded) for well-rounded gravels, Early Weichselian beach gravels, modern beach gravel and some of the glacial facies sampled. Each sample contains 50 clasts.

and Moign (1974) there are reports of another beach at 80–85 m at the base of Slattôfjell, between Austre and Midtre Lovénbreen (Fig. 1). As the Late Weichselian marine limit occurs at 45 m on Brøggerhalvøya (Forman & Miller 1984; Forman et al. 1987), it is likely that the higher beach noted by these authors indicates at least an age as old as the last interglacial, possibly the Leinstranda Interglacial, or episode C (Eemian) of Miller (1982) and Miller et al. (1989). This interglacial has been correlated with isotope substage 5e at approximately 122,000 ± 6000 BP (Martinsson et al. 1987). The higher beach samples for clast-shape analysis reported here came from an altitude of 50 m a.s.l. (measured by altimeter), outside the supposed Weichselian ice limits, although this limit is still debated. Hence these beach gravels are likely to be Early Weichselian in age (Episode B of Miller et al. (1989). Forman & Miller (1984) suggested that beaches between 44 m–55 m should be tentatively correlated with sea levels in the period 60–160 ka, and Miller et al. (1989) suggested an age of 70 ± 10 ka. The age in the latter paper was based on a radiocarbon date of >62.5 ka on intact collagen from whalebone preserved in frozen Episode B littoral sediments and in addition two U-series dates on bone from this level indicate an age of about 70 ka. Miller et al. (1989) also state that the glaciation preceding Episode B was smaller than the one preceding Episode C, yet the former is interpreted to have been regional in character. However, this is still debated, as are the ice limits for the Late Weichselian. Yet an age of 70 ka for the initial deposition of the well-rounded gravels would explain their localised occurrence and their presence in all the thrust moraine-mound complexes on the northern side of Brøggerhalvøya. The well-rounded gravels in the glacial sediments could nevertheless be reworked also from beach gravels from the older Episode C in the inner parts of Kongsfjorden. The fact that the well-rounded gravels have not been located on the southern side of the peninsula might indicate a difference in glacier accumulation and glacier growth during the Late Weichselian and/or the Little Ice Age and be evidence of localised events concentrated on the northern side of the peninsula. It equally well could be that further work on the south side might yet locate such well-rounded gravels. Further work on the significance of the well-rounded gravel distribution needs to be carried out and cannot be considered here.
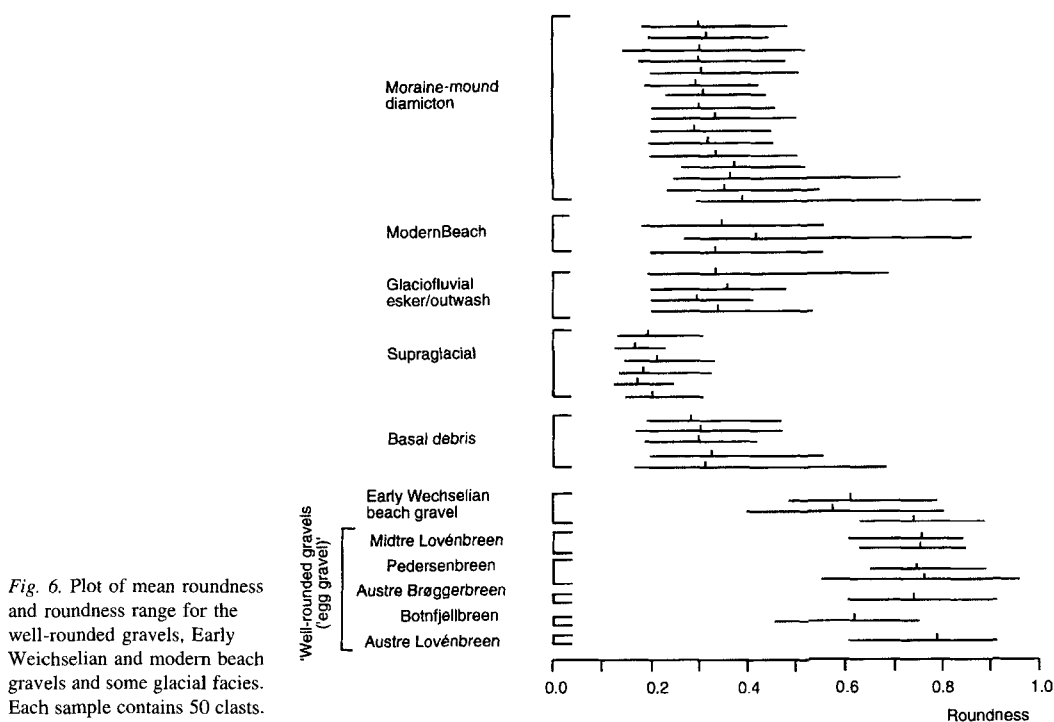
Lovénbreen, Pedersenbreen and Comfortlessbreen do not possess such high roundness values. A derivation from an Early Weichselian or Eemian raised beach seems much more plausible. High beaches are present on the peninsula. For example, Lefauconnier (1987) noted a beach at 83 m at the foot of Zeppelinfjellet, east of Austre Brøggerbreen (Fig.1), and in Barbaroux (1966)

Fig. 6. Plot of mean roundness and roundness range for the well-rounded gravels, Early Weichselian and modern beach gravels and some glacial facies. Each sample contains 50 clasts.

Greater roundness of the Early Weichselian raised beach gravels and well-rounded gravels compared to modern beach gravel

The greater roundness of the well-rounded gravels and the Early Weichselian raised beach gravels compared with that of the contemporary beach gravels may reflect the greater time availability for marine attrition during that time period, or to greater wave energy associated with a deeper, wider, ice-free fjord during this period. The Early Weichselian beach gravels sampled as a control from 50 m a.s.l. are not quite as rounded as the well-rounded gravels, except for the Botnfjellb-reen sample, and it is possible that these less-round gravels are slightly younger in age, and lower in altitude. The modern beach gravels have been shown to be derived from basal diamictons and outwash sediments from the glaciers around Kongsfjorden and from basal debris transported by icebergs from Kronebreen-Kongsvegen which often subsequently melt on the beaches on the south side of the fjord.

The importance of sediment reworking and the problems this can cause in the correct interpretation of glacial facies

Sediment reworking has not been fully considered as a problem in the interpretation of glacial facies in the past but it has to be taken into consideration before the correct history of a sediment is fully understood. The example of the well-rounded gravels illustrates that an obvious, anomalous sediment type within the glacial facies will be easily recognised and interpreted, but some sediments which might not be so markedly different would be difficult to recognise, or would have remained unrecognised. For example, if the glaciers advanced over the proglacial outwash and modern beaches around Kongsfjorden, they would incorporate sediment from these environments which would be difficult to accurately place in the correct, original sedimentary facies. It is doubtful if clast shape characteristics would allow such subtle distinctions. In clast shape studies, there-fore, these sediments would have the potential to
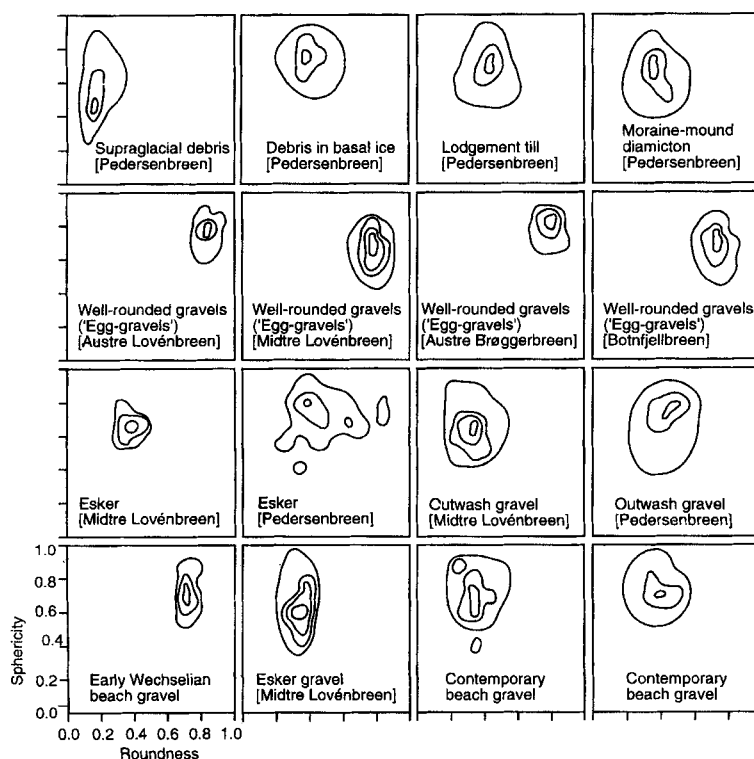
Fig. 7. Sphericity versus roundness plots for the well-rounded gravels and other sampled facies. Point densities are contoured at 1, 3, 5 and 7% per 100% area. Each sample contains 50 clasts.

bias the results and possibly limit their usefulness in such circumstances. This work from Brøgger-halvøya acts as a warning wherever clast shape comparisons are made to a modern glacial environment from unknown sediments. In the Pleistocene, where there could have been multiple reworking and recycling of glacial, glaciofluvial and marine sediments, the task of differentiating sediments based on clast shape characteristics becomes very difficult. Kirkbride (1995) reinforces this point in discussing particle shape evolution where he stresses that "great caution must therefore be used in discriminating between different glacial environments solely upon particle shape and roundness."

In general the possible inheritance of clast shape characteristics from earlier deposits (reworking) presents a difficult problem which calls for careful interpretation of results. It may not always be evident that the problem exists, although Fisher & Bridgland (1986) suggested that the occurrence of a bimodal or polymodal distribution of morphological indices may suggest

that reworking has occurred. Dreimanis (1976) too recognised that local reworking of older strata in deformation till may completely dominate an assemblage, obscuring a smaller regional component and therefore hindering interpretation.

Nevertheless, despite the cautionary warning with regard to the interpretation of reworked sediments, the value of clast shape as a discriminator of depositional environments has proved to be important in deciding the likely origin of these gravels.

Conclusions

The morphological expression of well-rounded gravels associated with high-arctic valley glaciers in Spitsbergen has suggested that they were formed by englacial thrusting of subglacial sediment, followed by melting out to form moraine-mound complexes, or smaller thrust ridges. Clast shape data from these well-rounded

gravels, from modern glacial and beach environments, and from Early Weichselian beaches, suggests that the well-rounded gravels are not associated with any of the glacial facies and were most likely to have originated on a high energy beach in an ice-free fjord over a long period of time, probably well in excess of ten thousand years. This was likely to be during the period 70–125 ka when sea levels ranged from 50 to 80 m a.s.l. (Miller et al. 1989). The best discriminators for the well-rounded gravels are the roundness histogram, the mean roundness and the roundness range diagrams and the plots of sphericity versus roundness. The modern beach gravels cannot be distinguished from the basal diamictons and outwash sediments from which they have been reworked comparatively recently. Reworking is potentially a major problem when clast shape comparisons to modern glacial environments are made from older unknown sediments. The types of reworking problems outlined in this paper must always be considered as likely in a glacial sequence and that the correct interpretation based solely on clast shape studies is often difficult.

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