ELSEVIER

Marine Geology 229 (2006) 101 – 112

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.com/locate/margeo

The hydrostatic corer *Selcore*—a tool for sediment sampling and geophysical site characterization

Yngve Kristoffersen [a],*, Eldar Lien [b], Kjetil Festervoll [c], Sigurd Ree [d],
Kåre Åardahl [e], Øyvind Hosøy [b]

[a] *Department of Earth Science, University of Bergen, N-5007, Bergen, Norway*
[b] *Selantic AS, Kokstadflaten 19, N-5257 Bergen, Norway*
[c] *Statoil, P.O. Box 7200, N-5020 Bergen, Norway*
[d] *Lerumveien 16, N-5178 Loddefjord, Norway*
[e] *N-6740 Selje, Norway*

Received 23 July 2005; received in revised form 13 February 2006; accepted 15 February 2006

Abstract

Hydrostatic energy is used to power an active device for sediment sampling and geophysical site characterization. In the *Selcore* design, a steel tank with built-in drive unit constitutes the core head. The difference between ambient water pressure and atmospheric pressure in the tank provides the energy. The *Selcore* prototype enters the seabed as a gravity corer and automatically shifts into pile driving mode with up to 52 duty cycles without the need for an external trigger mechanism. The corer has operated in water depths from 300 to 3500 m. Operation at depths shallower than 300 m including on dry land can be facilitated using auxiliary water pressure. Penetration and recovery is generally more than two times the performance of a gravity corer of equivalent weight. The added utilization of hydrostatic energy has particular advantage in cases of relatively high shear strength sediments as well as attempts to core shallow bedrock below a sediment cover. *Selcore* has potential as a seabed seismic hammer source and initial land tests show good signal repeatability. Estimates of sediment thickness and seismic velocity obtained from the inversion and interpretation of the dominant Rayleigh surface waves corresponds closely to the shallow borehole stratigraphy at a land test site.

Keywords: sediment corer; hydrostatic energy; high shear strength sediments; seismic hammer source

---

1. Introduction

Conventional seabed sediment sampling devices such as the gravity corer and the piston corer are driven into the seabed by the kinetic energy of the corer released from a short distance (<10 m) above bottom (Hopkins, 1964). Tools lowered from the surface through the water column can exploit the large energy potential represented by the difference between ambient hydrostatic pressure and atmospheric pressure in a sealed reservoir. The ambient pressure at a water depth typical of outer continental shelf and upper slope settings (500 m) is about 50 bar.

The first designs of a sediment coring apparatus using hydrostatic power to drive the sampling tube into the seabed released all the energy in a single burst

---

* Corresponding author. Tel.: +47 47318446; fax: +47 55583660.
E-mail address: yngve.kristoffersen@geo.uib.no
(Y. Kristoffersen).

0025-3227/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.margeo.2006.02.007

(Hough, 1939; Petterson and Kullenberg, 1940). In spite of the large amount of energy available, the maximum length of the recovered sediment cores was limited by the length of travel of the piston to about 2 m. Sediment disturbance was a problem due to the violent implosion when the piston was released. Another application of the hydrostatic pressure differential was the Sysoev-Kudinov corer (Bezrukov and Petelin, 1960). As the cutting edge touched the seabed, a valve opened passage for water between the closed top of the core barrel and a container with the same volume of air at atmospheric pressure. The resulting pressure differential between the interior of the core barrel and the water column assisted driving the corer into the seabed. The device was reported to have recovered cores up to 33.5 m length (Lisitzin, 1972), but did not perform well in firm sediments and was not routinely used.

Rosfelder (1966) and Rosfelder and Marshall (1967) outlined a number of ideas where controlled hydrostatic pressure could be used to drive a sampling tube into the seabed. Here again, core length was limited to the length of the drive cylinder. A recent application of the principle has been reported by Smits (1990). A different approach is to exploit hydrostatic energy to drive a motor (Brooke and Gilbert, 1968). Selwyn and McCoy (1981) designed a hydrostatic motor to repeatedly lift a set of core head weights which were then released to free fall 0.33 m and ram the core barrel into the sediment like a pile driver. In a single trial with more than 60 lift cycles, they successfully recovered a 2-m section of well indurated marl, but no further development of the device has been reported.

Fig. 1. The hydrostatic corer *Selcore* I (left) and *Selcore* II (right).

In the design presented here, a steel tank containing air at atmospheric pressure constitutes the core head (Fig. 1). Inside the tank is a cyclic drive unit that lifts the tank and lets it free fall back to rest in each duty cycle. After initial penetration as a gravity corer, hydrostatic energy is engaged to drive the core barrel farther into the sediment in a pile driving mode. The total energy available for penetration in the pile driver mode depends on the volume of the reservoir and is four times the initial gravitational energy for the prototype corers presented here. The hammering action of the free falling tank also generates seismic energy which can be utilized for local engineering studies at the coring site. A hydrostatic sediment corer design named *Selcore* (Fig. 1) has been developed jointly by Selantic Industrier A/S (now Selantic AS) and the University of Bergen with the support of Elf Aquitaine Norway (now TotalFinaElf Exploration Norge AS). The device has been successfully tested in a range of environments in the World‘s oceans down to 3500 m water depth. *Selcore* was first used commercially in a seabed survey for the planned pipe line from the Troll field in the North Sea to Mongstad on the coast of western Norway by Statoil in April 1993. *Selcore* comes in two versions; *Selcore* I (weight in air 800 kg) and *Selcore* II (1750 kg).

2. The *Selcore* operating principle

Selcore (Fig. 1) enters the seabed like a regular gravity corer and achieves its initial penetration by its kinetic energy. As further progress of the corer is retarded by resistive forces encountered by the penetrating core barrel, *Selcore* automatically enters a pile driving mode where the mass of the pressure tank serves as the hammer head. The driving mechanism is housed in a stainless steel pressure tank initially filled with air at atmospheric pressure. The volume of the reservoir relative to an internal drive cylinder determines the maximum number of duty cycles. When *Selcore* is recovered, the reservoir is drained at the rail before landing the corer on deck. This simple task constitutes the only difference in handling *Selcore* vs. handling a conventional gravity corer.

The *Selcore* I head (800 kg in air) is dimensioned for about 52 duty cycles with a cycling time of 2 s. The minimum water depth for unassisted operation of the hydrostatic corer is ca. 300 m. This pressure differential threshold is required to overcome the combined forces from friction of the cylinder seals and the lift necessary to raise the tank for each duty cycle. *Selcore* can operate on land by connecting a high-pressure hose to the inlet valve to generate the necessary pressure differential.

3. Results

3.1. Sediment sampling

We have tested the performance of the hydrostatic corer *Selcore* with respect to penetration, recovery and core quality in a number of different sediment types. The recovered sediment cores were split and undrained shear strength was measured at 1–5 cm intervals by a falling cone apparatus (Geonor). Drained shear strength was determined from an average of three falling cone measurements made on well stirred material from a 3-cm section of the core half placed in a beaker with convex-shaped bottom. Sediment deformation was inspected by X-ray photography of 12-mm thick, 8 × 20 cm slices cut along the center of the core.

3.1.1. Cohesive sediments with low to moderately high shear strength

Silty clay was the dominant lithology in core An9306 (Fig. 2A) recovered by *Selcore* I in 2500 m water depth on the Antarctic continental margin (Forsberg et al., 2003). Total penetration of the 18 m-long core barrel (11.7 cm diameter outer diameter) was more than 15 m with a recovery of 12.5 m (< 80%). The increase of shear strength vs. depth was about twice that of deep sea sediments (Silva et al., 1976) with variations due to intervals of silty sand as well as variations (20%) in carbonate content. Another example is recovery of silty clay from Nordfjord, western Norway, in three coring attempts with *Selcore* I (Fig. 2A). Penetration was 15–16 m including 0.35–0.85 m of a high shear strength silt layer at the bottom of the cores. The acoustic record from the 3.5 kHz ORE echosounder (1 ms pulse length) indicate a depth of 14.8 m to the top of the silt layer at the site of core 91-01 assuming a velocity of 1600 m/s. Total recovery at the site was 53–64%. The shear strength was uniformly low in the silty clay with local maxima < 10 kPa in the upper and lower parts of the core and a near tenfold increase in a bottom layer of pure silt (Fig. 2, core Nordfjord 91-01).

Sediments at the shelf edge and upper continental slope (water depths 800–1600 m) off western Norway (63° N) are characterized by a diamicton (Møre diamicton) which is a poorly sorted homogenous silty, sandy clay where the average grain size distribution is 55% clay, 29% silt, 15% sand and 1% gravel (Jansen et al., 1983). This lithology was sampled by *Selcore* I outside the Storegga slide scar. A gravity corer with a core head weight of 500 kg and the same barrel diameter as *Selcore* 1 was also used (Fig. 2, cores GC 92-4 and GC 92-5). *Selcore* I penetrated ca. 13 m on the continental slope, but recovery was only 4.5 m, while the gravity corer penetrated 5 m with a recovery ratio of 0.5. The shear strength is <20 kPa and the gradient of shear strength increase with depth is about twice that of deep sea sediments (Silva et al., 1976; Futterer et al., 1992).

3.1.2. High shear strength diamicton

Exposures of the Møre diamicton within the Storegga slide scar (water depth 505 m) have shear strengths up to 200 kPa with large lateral variation between cores from the same locality (Fig. 2B, cores SEL 92-03 thorough SEL 92-06). This is not unexpected as the upper part of the original stratigraphy has been removed by mass wasting. While core recovery is only 40–50% except for SEL92-4, the deeper penetration obtained by the hydrostatic hammer action of *Selcore* I about doubles the amount of recovered core.

3.1.3. Non-cohesive sediments: sand and gravel

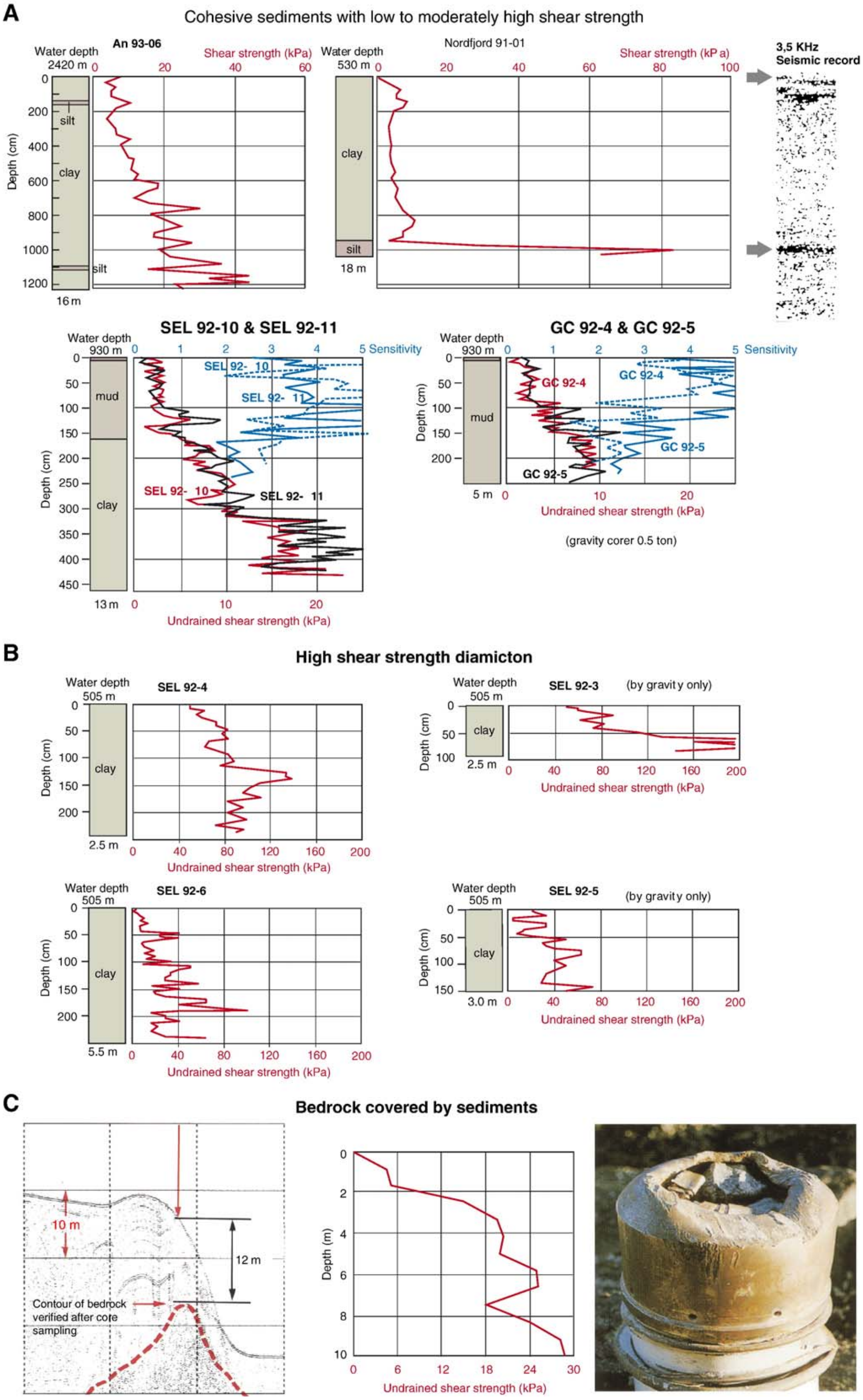
The performance of the hydrostatic corer in sand and gravel was tested from the dock at the port of Nordfjordeid, western Norway. *Selcore* I was dropped from a mobile crane and allowed to free fall from 8 m into a seabed of sand and gravel at 10 m water depth. A seawater pump generated the necessary pressure to operate *Selcore* I in pile driving mode. *Selcore* I was allowed to run for more than 200 cycles and penetrated ca. 6 m of sand and gravel section with 50% recovery. When used as a gravity corer the penetration was 3 m with ca. 35% recovery.

3.1.4. Bedrock covered by sediments

The larger version *Selcore* II was used for geotechnical mapping of the Troll-Mongstad pipe line corridor off the west coast of Norway. In this configuration the weight of the tank and drive unit is ca. 1750 kg. The core cutter was deformed by the impact and filled with pieces of fresh granite recovered from the top of bedrock overlain by 12 m of silty clay (Fig. 2C).

3.1.5. The hydrostatic corer vs. the gravity corer

Data on penetration and recovery for a gravity corer with core head weight of ca. 1 ton (in air) and the


A
Cohesive sediments with low to moderately high shear strength
An 93-06
Water depth 2420 m
Shear strength (kPa)
0 20 40 60
Depth (cm)
0 200 400 600 800 1000 1200
silt
clay
silt
16 m
Nordfjord 91-01
Water depth 530 m
Shear strength (kPa)
0 20 40 60 80 100
clay
silt
18 m
3,5 KHz Seismic record
SEL 92-10 & SEL 92-11
Water depth 930 m
0 1 2 3 4 5 Sensitivity
SEL 92- 10
SEL 92- 11
mud
clay
Depth (cm)
0 50 100 150 200 250 300 350 400 450
SEL 92- 10
SEL 92- 11
13 m
0 10 20
Undrained shear strength (kPa)
GC 92-4 & GC 92-5
Water depth 930 m
0 1 2 3 4 5 Sensitivity
GC 92-4
GC 92-4
mud
GC 92-5
GC 92-5
Depth (cm)
0 50 100 150 200
5 m
0 10 20
Undrained shear strength (kPa)
(gravity corer 0.5 ton)
B
High shear strength diamicton
SEL 92-4
Water depth 505 m
clay
Depth (cm)
0 50 100 150 200
2.5 m
0 40 80 120 160 200
Undrained shear strength (kPa)
SEL 92-3 (by gravity only)
Water depth 505 m
clay
Depth (cm)
0 50 100
2.5 m
0 40 80 120 160 200
Undrained shear strength (kPa)
SEL 92-6
Water depth 505 m
clay
Depth (cm)
0 50 100 150 200
5.5 m
0 40 80 120 160 200
Undrained shear strength (kPa)
SEL 92-5 (by gravity only)
Water depth 505 m
clay
Depth (cm)
0 50 100 150
3.0 m
0 40 80 120 160 200
Undrained shear strength (kPa)
C
Bedrock covered by sediments
10 m
12 m
Contour of bedrock verified after core sampling
Depth (m)
0 2 4 6 8 10
0 6 12 18 24 30
Undrained shear strength (kPa)

hydrostatic corer (*Selcore* I, ca. 0.8 ton) are plotted in Fig. 3. Unfortunately, no direct field effort has been tailored to compare the hydrostatic corer with a pure gravity corer of the same weight. However, coring attempts made with comparable tools at the same station suggest that the total length of core material obtained can be more than two times the core length obtained by the single impact of an equivalent gravity corer (Fig. 2B, cores SEL92-03 through SEL92-06) while in other cases the difference appears smaller (Table 1, coring sites NP94-19, NP94-27, NP94-37 and NP94-39). How much material *Selcore* collects during the initial gravity penetration stage is not known. The longest core obtained by *Selcore* I to date is 12.45 m with 16 m of penetration (Forsberg et al., 2003) on the continental slope in the Weddell Sea, Antarctica (Figs. 2 and 3, core An93-06).

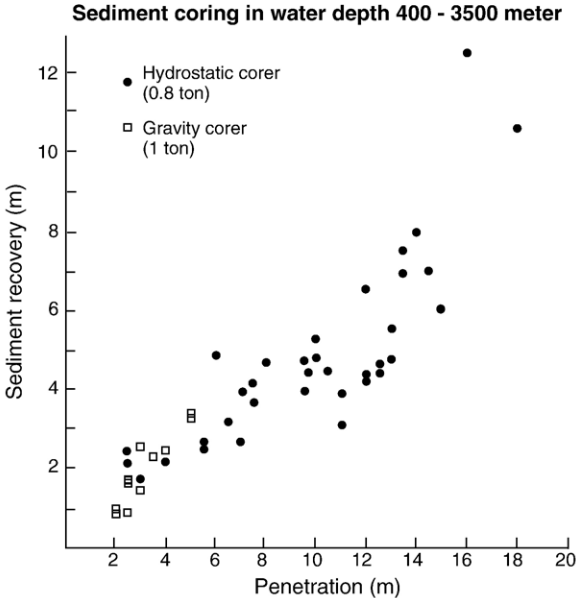


Fig. 3. Plot of penetration and recovery for sediment cores taken by the hydrostatic corer *Selcore* I (0.8 ton in air) and by a gravity corer (ca. 1 ton in air) from the continental slope north of Svalbard (Solheim and Forsberg (1996) and from unpublished sea trials from the continental margin west of the Storegga Slide scar, and from Nordfjord, western Norway (internal report No. 00011224/992 of Selantic Industrier A/S, now Selantic AS). The database is tabulated in Table 1.

3.2. Selcore as seismic source

A hydrostatic hammer on the seabed can serve as a seismic source for local marine geophysical site investigations. We have carried out an initial test on land using the hydrostatic corer as a seismic hammer source (Festervoll, 2003). *Selcore* I was mounted on a 0.5 m × 0.5 m steel plate next to a borehole less than 50 m from the modern beach at Grødeland, about 40 km south of Stavanger, Norway. The borehole penetrates 124.5 m of Middle- and Late Pleistocene tills, glacio-marine and marine deposits (Janocko et al., 1997). The water table at the site was observed to be about 0.3 m below the surface. The signals from impacts of *Selcore* I was recorded by a 150 m long array of 3-component geophones planted at 2 m intervals (Fig. 4). The observed energy was in the frequency band 15–35 Hz with a peak at about 28 Hz (Fig. 4). Lighter falling weights such as the Bison Elastic Wave Generator (114 kg) also have a peak frequency of about 28 Hz (Miller et al., 1992). For comparison, the spectrum of the wave field generated by an electric cap at 1 m depth in a water filled hole next to the position of *Selcore* I is also shown in Fig. 4 (insert). The repeatability of the seismic signal generated by *Selcore* I was assessed by forming a reference trace (Fig. 5) from the average of nine shots to compare with the actual trace from individual shots (field file #20), all recorded by the same channel. This comparison shows differences are minimal, suggesting good shot to shot repeatability (Fig. 5).

4. Interpretation and discussion

4.1. Geotechnical aspects and performance of the hydrostatic sediment corer

The penetration of a pipe or a pile into the seabed depends on the available energy, the diameter of the pipe or pile and the physical properties of the sediments. Total penetration is a function of the sum of the integrated mobilized friction between the outside of the core barrel and the end resistance, while sediment

Fig. 2. Comparison of recovery, lithology and geotechnical parameters for sediment cores representing different regimes of shear strength versus depth collected by *Selcore* (SEL) and by standard gravity corer (GC). Core locations are listed in Table 1. (A) Data for *Selcore* An 93-06 are from Forsberg et al. (2003) and for Nordfjord 9101 from unpublished Internal Report No. 00011224/992 of Selantic Industrier A/S (now Selantic AS). Cores SEL 92-10, SEL 92-11, GC 92-4 and GC 92-5 were recovered from the upper continental slope west of the Storegga slide scar. (B) *Selcore* cores SEL 92-3 through SEL 92-6 were raised from within the Storegga slide scar. All cores were recovered using *Selcore* I. Note cores SEL92-3 and SEL92-5 penetrated only by the initial gravity impact. (C) Bedrock from the Troll-Mongstad pipeline investigations was recovered in the core catcher of the larger (1.75 ton) version *Selcore* II (C). Results of shear strength and sensitivity measurements are shown as continuous lines connecting discrete measurements.

Table1
List of position, water depth, penetration and sediment recovery of cores used in this study

Core	Location	Water depth (m)	Penetration (m)	Recovery (m)
Selcore				
An93-06	69°13.4′S, 01°03′W	2420	16.0	12.5
Nordfj.91-01	61°52.25′N, 05°45.00′E	530	18.0	10.6
Nordfj.91-02	61°52.05′N, 05°45.30′E	510	14.0	7.8
Nordfj.91-03	61°52.05′N, 05°45.30′E	510	14.0	7.98
NP94-1SC	77°15.23N, 09°05.45′E	2084	15.0	6.0
NP94-19SC	81°30.44N, 22°09.35′E	912	7.0	4.0
NP94-20SC	81°56.45′N, 21°13.62′E	3500	3.0	1.78
NP94-21SC	81°44.99′N, 21°54.87′E	3380	9.5	4.8
NP94-22SC1	82°25.68′N, 38°39.97′E	2276	14.5	7.0
NP94-22SC2	82°25.32′N, 38°31.82′E	2256	13.0	4.8
NP94-27SC	81°12.79′N, 39°45.99′E	516	2.5	2.10
NP94-28SC1	81°11.60′N, 39°47.24′E	533	9.7	4.5
NP94-28SC2	81°11.60′N, 39°46.78′E	532	6.0	4.9
NP94-28SC3	81°11.53′N, 39°44.90′E	527	10.5	4.5
NP94-28SC4	81°11.87′N, 39°46.52′E	527	10.0	4.82
NP94-32SC	80°58.33′N, 43°56.96′E	493	7.5	3.70
NP94-37SC1	80°38.11′N, 41°50.16′E	425	7.0	2.70
NP94-37SC2	80°38.14′N, 41°50.35′E	426	4.0	2.20
NP94-38SC1	80°57.99′N, 40°36.26′E	594	12.0	6.5
NP94-38SC2	80°57.80′N, 40°37.08′E	598	13.5	6.9
NP94-39SC	81°25.60′N, 27°37.57′E	881	10.0	4.75
NP94-41SC	80°47.10′N, 29°26.25′E	473	8.0	4.70
NP94-43SC	80°41.94′N, 06°45.57′E	825	13.0	5.5
NP94-44SC	80°24.29′N, 06°40.42′E	614	6.5	3.2
NP94-45SC	80°11.18′N, 07°17.74′E	558	7.5	4.2
NP94-46SC	80°00.33′N, 09°02.29′E	491	5.5	2.65
NP94-47SC	80°31.48′N, 11°08.02′E	851	12.5	4.7
NP94-50SC	80°09.08′N, 17°07.15′E	453	10.0	5.3
NP94-51SC1	80°21.34′N, 16°17.97′E	399	9.5	4.0
NP94-51SC2	80°21.47′N, 16°17.94′E	400	13.5	7.5
SEL92-04	62°46.04′N, 03°59.98′E	505	2.5	2.45
SEL92-06	62°45.96′N, 03°59.93′E	505	5.5	2.5
SEL92-07	62°41.37′N, 03°01.01′E	496	11.0	3.95
SEL92-08	62°41.38′N, 03°00.98′E	496	11.0	3.15
SEL92-09	63°04.99′N, 02°39.89′E	929	12.5	4.4
SEL92-10	63°05.05′N, 02°39.85′E	930	12.0	4.3
SEL92-11	63°04.97′N, 02°39.79′E	930	12.0	4.4
Gravity corer				
GC92-4	63°05.01′N, 02°39.90′E	929	5.0	2.15
GC92-5	63°05.06′N, 02°39.83′E	930	5.0	2.5
NP94-19GC	81°30.33′N, 22°10.39′E	847	5.0	3.65
NP94-23GC	82°06.30′N, 39°29.17′E	1016	5.0	3.4
NP94-26GC3	81°30.82′N, 38°50.62′E	448	2.5	1.68
NP94-26GC4	81°30.85′N, 38°50.70′E	453	2.0	1.05
NP94-27GC	81°12.73′N, 39°45.93′E	516	3.0	2.57
NP94-29GC	81°09.00′N, 39°09.54′E	442	2.5	1.75
NP94-30GC	81°09.12′N, 41°27.96′E	463	2.0	0.9
NP94-31GC	80°59.70′N, 43°57.62′E	502	5.0	3.25
NP94-37GC	80°38.09′N, 41°49.94′E	425	3.5	2.30
NP94-39GC	81°25.98′N, 27°36.77′E	922	4.0	2.5
SEL92-03[a]	62°46.00′N, 04°00.07′E	505	2.5	0.93
SEL92-05[a]	62°45.98′N, 03°59.91′E	505	3.0	1.5

Core An9306 is from Forsberg et al. (2003), cores recovered at sites NP94-xx from Solheim and Forsberg (1996), and cores from sites designated SEL92-xx and GC92-xx from unpublished Internal Report No. 00011224/992 of Selantic Industrier A/S (now Selantic AS).

[a] *Selcore* used as a regular gravity corer.

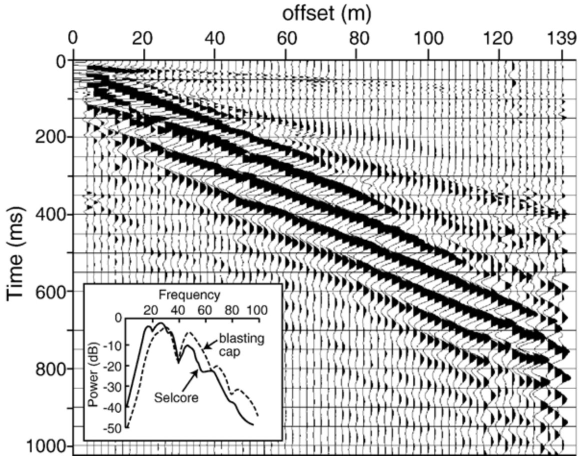


Fig. 4. Signals (time versus offset) recorded on vertical component geophones (14 Hz) from impact of *Selcore* I on a 50 cm × 50 cm steel plate (2 cm thick) on the ground at the site of the Grødeland borehole. Insert shows amplitude spectrum of signals at 8–16 m offset (solid line) as well as the frequency content of the wave field from an electric cap (dashed line) fired at 1 m depth in a water filled hole next to *Selcore.* Modified from Festervoll (2003).

recovery is related to the integrated mobilized friction between the inside of the core liner and the sediment sample relative to the end-bearing capacity of the sediments in front of the core cutter (de Nicola and Randolph, 1997; Skinner and McCave, 2003). Although the data base is limited, the hydrostatic corer appears to penetrate cohesive sediments twice the penetration of a gravity corer of similar weight and barrel dimensions (Figs. 2 and 3). The terminal velocity of *Selcore* II free falling into the seabed is calculated from accelerometer measurements to be 7.5 m/s. The added kinetic energy from 52 duty cycles of 1.6 kNm each amounts to three times this maximum free fall energy. However, since the core barrel comes to rest between each impact of the tank, part of the hydrostatic energy is lost due to viscous effects at each impact as well as the additional resistance arising from the difference between static and dynamic shear strength. Consider a soil profile where the undrained shear strength has a value of 2 kPa at the seabed and increases 4 kPa/m depth (i.e. SEL 92-10 and -11, Fig. 2). The resistive force per unit area of the core barrel is the undrained shear strength times a skin friction factor (α) set to 0.35 (Meyerhof, 1976). Penetration as a pure gravity corer from 6 to 12 m sub-bottom would require an additional three times the energy consumed in the first 6 m below the seabed, assuming full sediment recovery and more if only partial recovery. If *Selcore* penetrated the first 6 m as a gravity corer, the estimated additional penetration by hydrostatic energy would be in the range of 3–8 m for limiting values of $\alpha=1$ representing static friction and $\alpha=0.35$ for dynamic friction.

Selcore has the same potential for sediment recovery as any gravity corer until it comes to rest and the pile driving mode starts. While total penetration of *Selcore* is greater than a gravity corer, there is a tendency for a greater degree of stratigraphic undersampling throughout the extended depth range (Fig. 3). Although the deepest penetrations (>16 m) yielded 78% and 60% recovery, values for recovered section for most of the cores with penetration of 8–15 m sub-bottom appear to be in the range 35–57%, excluding extreme values (one high and one low) from the data (Fig. 3). Observations of full-scale instrumented piles have revealed the complexities of calculating the resistance of piles to compressive loads, and a soil mechanics approach combined with empirical methods are commonly used (Tomlinson, 1994). A schematic load–settlement curve for *Selcore* is outlined in Fig. 6 following Tomlinson (1994, p. 100) and Fleming et al. (1992, p. 340). When the tank impacts the core barrel, the load exceeds the initial elastic behaviour of the core barrel–soil system and at point A the maximum skin friction (limiting value of shear stress) along the outside of the entire core barrel has been mobilized. The movement required is only of the order of 0.1 cm (0.3–1% of the barrel diameter). After the barrel head has moved another 1–2 cm (10–20% of the base diameter), the additional resistance at the base and inside of the barrel is fully mobilised and penetration is achieved without further increase of the load. The skin friction becomes reduced (strain softening) after a few centimetres of relative motion

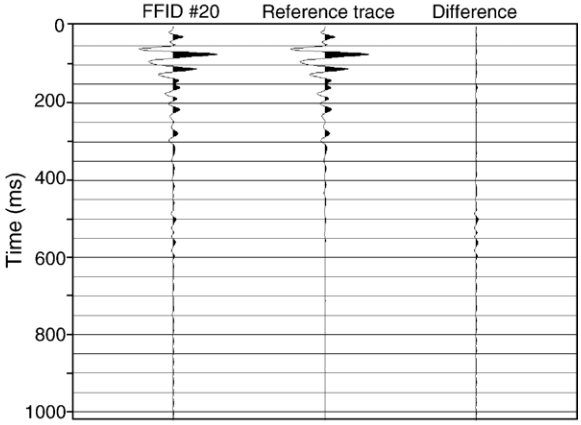


Fig. 5. Source repeatability measured as the difference between the signal of an individual shot (FFID #20) with respect to a reference trace formed by averaging the signal from nine consecutive shots recorded at the same geophone (vertical component). Data from Festervoll (2003).

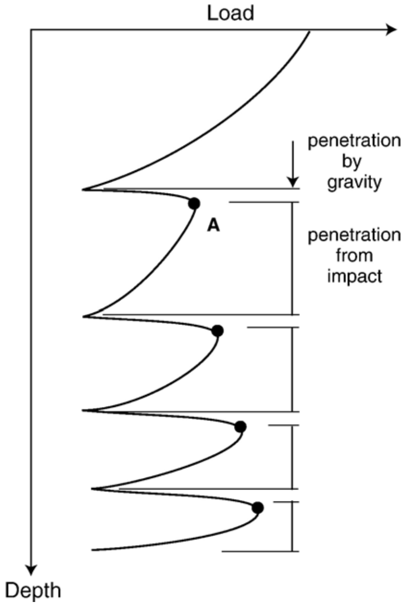


Fig. 6. Schematic diagram for impulse versus penetration adapted from Tomlinson (1994, p. 100). The skin friction between the core barrel and the sediment is fully mobilized at point A from increased compressive load during the impact of the free-falling *Selcore* tank. Conditions at the sediment/core liner interface will in principle be similar, but actual sediment entry into the core liner will depend on the bearing capacity of the soil in front of the core cutter.

between the core barrel and the sediment; a reduction by a factor of two may take place particularly in soft, lightly overconsolidated clays (Chandler and Martins, 1982). Karlsrud and Haugen (1984) have investigated the stress distribution during penetration of a 5-m-long instrumented steel pile in overconsolidated clay. The pore and lithostatic pressures built up during the downward displacement are of the order of 3–7 times the vane shear strength. Most remarkable is that the pore pressure is close to the total earth pressure and therefore the effective horizontal stresses along the pile become rather small. Sediments will enter a downward moving core barrel as outlined by Skinner and McCave (2003) for the gravity corer. However, since extended penetration of *Selcore* is achieved incrementally and not by continuous motion of the core barrel, we attribute added entry deficit to the fact that the static friction to be overcome at each duty cycle is larger than its dynamic value (Tomlinson, 1994). The sediment volume is also subject to downward acceleration at each impact which adds to the resistive force to be counter balanced by the bearing capacity if more material is to enter the core barrel. In the cases of very short cores, Emery and Dietz (1941) and Emery and Hulsemann (1964) report no apparent differences between recovery in gravity cores and hammered cores. In these cases, the length of the core was found to be directly proportional to the depth of penetration.

Sediment recovery by the hydrostatic core may be improved by implementation of a piston which is stationary with reference to the seabed. However, recurrent elastic rebound in the wire holding the piston is a concern.

4.2. Sediment core quality

Selcore as a pile driver with repeated large downward core barrel accelerations may degrade the geotechnical quality of the sampled material. Our preliminary assessment of core quality includes proxy indicators such as X-ray inspection for visual deformation and estimates of the sensitivity and volumetric strain. Sensitivity which is the ratio of undrained to drained shear strength may be a crude indicator of sediment disturbance.

Visual comparison of sediment deformation in cores taken by *Selcore* I and a gravity corer appears inconclusive. X-ray photos of 12 mm thick sediment slabs of cores taken at the same locality at the shelf edge sometimes show bent layering in the gravity cores and not in cores taken by *Selcore* I or vice a versa (Fig. 7). While these examples are insufficient to draw firm conclusions, they suggest that the additional deformation

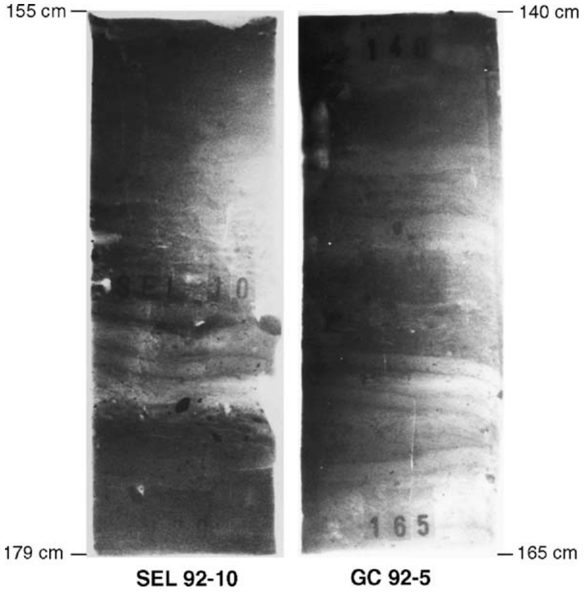


Fig. 7. X-ray photographs of 12-mm-thick sediment slabs from *Selcore* I (SEL 92-10) and a gravity core (GC 92-5) cut normal to the bedding along the center of the core. The cores were recovered at the same locality at the shelf edge west of the Storegga slide scar.

imposed during the pile-driving mode is minor at least in the cases considered here. An added uncertainty is that the specific core intervals may not necessarily represent identical true stratigraphic levels if entry deficits during penetration for some reason were different in the two cases (Parker and Sills, 1990). No significant deformations were observed in laminated sequences intercalated with layers of indurated salt sampled by *Selcore* II in the Dead Sea (Heim et al., 1997). On the other hand, sediments sampled by hammer sampling in the East Shetland Basin site show disturbed and bent layering in about 30% of the cases as examined from X-ray photographs (Schjetne and Brylawski, 1980).

While fluctuations are considerable, the overall down-core variation in sensitivity is broadly similar for sediments recovered by a gravity corer and *Selcore* I in the vicinity of the Storegga slide scar (Fig. 2A). Andresen and Kolstad (1979) suggested the relative change in volumetric strain during consolidation tests as a proxy indicator for geotechnical sample quality. Triaxial uniform compression (CAU) tests and direct simple shear (DSS) tests carried out by the Norwegian Geotechnical Institute on behalf of Statoil on *Selcore* II samples recovered from the Troll-Mongstad pipe line corridor in 1993 show relative changes in volumetric strain in the range 2.1–4.3%. These estimates fall into the category of fair sample quality. More recent work considers relative change in pore volume as a more reliable geotechnical quality indicator (Lunne et al., 1998). On the other hand, measurements of undrained shear strength on wire line hammered samples from geotechnical drill holes in the North Sea appear to show values that are 20–50% lower than those measured on sediments recovered by a push-in tool (Schjetne and Brylawski, 1980).

4.3. Selcore—a tool for geophysical site characterization

A downward directed vertical impulsive force generates maximum P-wave energy in the same direction and vertically polarized shear waves with maximum amplitude at about 45° from the normal (Kähler and Meissner, 1983). The two wave types combine to generate vertically polarized (Rayleigh) surface waves which are dispersive in a layered medium. The wave field generated from the impact of *Selcore* I (Fig. 4) is dominated by surface waves and elliptic retrograde particle motion indicates predominantly Rayleigh waves. The dispersion curve for the fundamental wave mode is mainly influenced by the acoustic properties of sediments to a depth of 1–2 wave lengths, i.e. few tens of meters (Ritzwoller and Levshin, 2002). Rayleigh wave phase velocities were determined using the f–k approach of Gabriels et al. (1987) and inverted for velocity versus depth following Lokshtanov et al. (1991). The calculated theoretical dispersion is most sensitive to changes in shear wave velocity, thickness and density of the upper layer, but less influenced by changes in compressional velocity (Xia et al., 1999). Best fit to the data is obtained using an upper layer thickness of 12 m with a shear wave velocity greater than 240 m/s (Fig. 8A). This shear-wave velocity estimate for the unconsolidated upper sediments suggests sand as the dominant lithology (Fig. 8B, right graph) since corresponding velocities for clays are <70% of this value at 5–10 m depth (Hamilton, 1979). These geophysical results from the *Selcore* test at the Grødeland drill site compare well with the bore hole stratigraphy (Fig. 8B, left) which show a transition at 12 m depth from predominantly sand to a 29-m-thick section of diamicton consisting of sorted gravel (Fig. 8B). However, near the surface we find a 2.3-m-thick section of matrix supported diamicton with an uppermost unit of cobbly beach sediment (Janocko et al., 1997). The latter sediments were not readily resolved by the inversion (Fig. 8A).

4.4. Selcore perspectives

Selcore can recover sediment and also obtain a geophysical data set from the site by deriving compressional and shear wave velocities as well as an estimate of the shear strength of the upper 10–15 m of sub-bottom sediments.

An experimental set-up for geophysical measurements would include a cable with equally spaced self erecting three-component geophones trailing *Selcore* and deployed on the bottom from a slowly moving vessel. The recording system may either be self contained and activated by acceleration levels or data is routed to the surface via a conducting cable. *Selcore* free-falls the last few meters into the seabed and start hammering while sediments are recovered. Alternatively, if only used as a seismic source, it could hammer a few times at each location before being pulled up above the bottom and moved to the next shot point with the recording cable in tow.

Another application would be to derive estimates of shear strength versus depth. *Selcore* is essentially a dynamic penetrometer and could be instrumented by a small transducer mounted on the core barrel to monitor incremental penetration for each duty cycle to obtain estimates of shear strength over the interval of

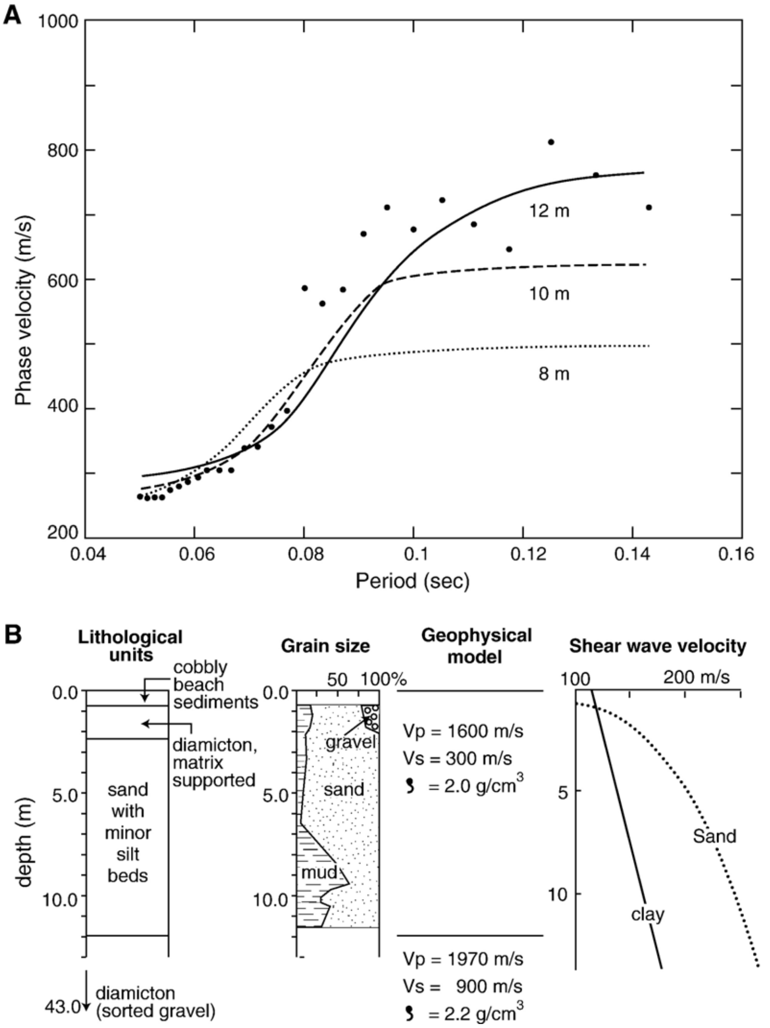


Fig. 8. Comparison of geophysical results obtained with *Selcore* as seismic source and geological core data (Janocko et al., 1997) from the same site. (A) Rayleigh phase velocity versus frequency (dots) derived form the shot file in Fig. 4 compared with theoretical dispersion curves for various layer thicknesses. Modified from Festervoll (2003). (B) Drill hole stratigraphy and down-hole grain size distribution for the uppermost sediments at the Grødeland drill site (from Janocko et al., 1997) compared with best fitting geophysical model derived from the Rayleigh wave analysis in (A) (after Festervoll, 2003). Data on compressional and shear wave velocities in marine sediments (lower right panel) are from Hamilton (1979).

penetration. Other attachments could be electrodes for vertical resistivity profiling during penetration.

Improving sediment recovery by *Selcore* is a concern. We have considered the feasibility of injecting a lubricant along the inside of the core liner to reduce friction. An initial test was carried out using a modified gravity corer where the core head was connected to the barrel via a hydraulic cylinder filled with polymer mud. Mud pressure was generated from compression of the cylinder by the force transmitted from the retarding core barrel to the core head during penetration. The lubricant was sprayed onto the inner wall of the core liner through an annular nozzle located behind the iris of the core catcher. The test comprised eight cores in soft cohesive Holocene mud. Recovery increased from 30% to 50% in conventional gravity coring attempts to about 75% with mud lubrication, but the results still leaves full recovery to be desired.

5. Conclusions

Hydrostatic energy gained by descent through the water column provides opportunities for design of active sediment sampling devices. A hydrostatic corer may first penetrate the sub-bottom sediments by its inertia as a free falling gravity corer and subsequently enter into a pile driving mode as the resistance met by the core barrel pass a threshold value. The energy for ramming the core barrel into the sediment is thereafter provided by the pressure difference between initial atmospheric pressure (1 bar) inside the core head tank and ambient water pressure at the seabed. Although, the total hydrostatic energy available at any water depth is much greater than a single impact of the equivalent gravity corer, significant energy is lost to overcome static friction between the sediment and the core barrel at the beginning of each duty cycle. The fact that static skin friction is greater than its dynamic value also implies lower sediment recovery for incremental penetration in the pile driving mode.

The *Selcore* design comprise a tank and drive assembly which rams the top of the core barrel over 50 times with a 2-s duty cycle. The corer can operate unassisted in water depths greater than 300 m. Operation at shallower depths including operation on dry land is achieved by using auxiliary water pressure. *Selcore* I (800 kg in air) has operated down to 3500 m water depth and achieved a penetration of 18 m and a maximum recovery of 12.5 m (78%) in fine grained sediments. In general, *Selcore* may achieve more than two times the penetration of a gravity corer of equivalent weight, but relative core deficit tends to increase with increasing penetration. The added utilization of hydrostatic energy has particular advantage in cases of relatively high shear strength sediments.

A preliminary land test of *Selcore* I as a seismic source for future local marine geoengineering studies has been carried out with respect to energy level, frequency and repeatability of the source signal. Rayleigh-type surface waves (15–35 Hz) dominate. Repeatability of the source signal appears good. Lithologic prediction based on inversion of Rayleigh wave phase velocities compares well with the observed bore hole stratigraphy at the site.

Acknowledgements

Instrument development takes ideas, enthusiasm, persistence, money and a realistic perspective. The second, third and fourth of these factors varied dramatically with time, while the last one grew steadily. Development of *Selcore* would not have been possible without the support of Elf Aquitaine Norway and the understanding of company representatives S. Sørensen, O. Minsås, N. Deschaux and P. Broissard. University of Bergen provided ship time for sea trials and we are grateful to the captains and crew of research vessel *Håkon Mosby* for their effort and positive attitudes at all times. The effort of P. Kiviranta, P. Berg, and P. Winson contributed to move the development forward, and we benefited from discussions with C.F. Forsberg, A. Solheim and A. Grantz on corer performance. The Norwegian Geotechnical Institute kindly permitted us to quote the results of geotechnical measurements on samples taken by *Selcore* II during a Troll-Mongstad pipe line survey. We thank Art Grantz for comments to the manuscript.

References

Andresen, A., Kolstad, P., 1979. The NGI 54 mm sampler for undisturbed sampling of clays and representative sampling of coarser materials. Norw. Geotech. Instit. Publ., vol. 130.

Bezrukov, P.L., Petelin, V.P., 1960. Outline on collection and simple working instruments for marine sediments. Tr. Inst. Okeanol. Akad. Nauk, USSR 44, 81–112 (in Russian).

Brooke, J., Gilbert, R.L.G., 1968. The development of the Bedford institute deep-sea drill. Deep-Sea Res. 15, 483–490.

Chandler, R.J., Martins, J.P., 1982. An experimental study of skin friction around piles in clay. Gèotechnique 32, 119–132.

de Nicola, A., Randolph, M.F., 1997. The plugging behaviour of driven and jacked piles in sand. Geotechnique 47, 841–856.

Emery, K.O., Dietz, R.S., 1941. Gravity coring instrument and mechanics of sediment coring. Bull. Geol. Soc. Am. 52, 1658–1714.

Emery, K.O., Hulsemann, J., 1964. Shortening of sediment cores collected in open- barrel gravity cores. Sedimentology 3, 144–154.

Festervoll, K., 2003. Impulsive overflatekilder for seismisk prospektering. Cand. Scient. thesis, Department of Earth Science, University of Bergen. 140 pp.

Fleming, W.G.K., Weltman, A.J., Randolph, M.F., Elson, W.K., 1992. Piling Engineering, 2nd edition. Blackie & Son, Ltd., London, p. 347.

Forsberg, C.F., Løvlie, R., Jansen, E., Solheim, A., Sejrup, H.P., Lie, H.E., 2003. A 1.3 Myr paleoceanographic record form the continental margin off Dronning Maud Land, Antarctica. Palaeogeogr. Palaeoclimatol. Palaeoecol. 198, 223–235.

Futterer, D.K., et al., 1992. ARCTIC '91: The Expedition ARK-VIII/3 of RV "Polarstern" in 1991. Berichte zur Polarforschung, vol. 107. 267 pp.

Gabriels, P., Schneider, R., Nolet, G., 1987. In situ measurements of shear wave velocity in sediments with higher-mode Rayleigh waves. Geophys. Prospect. 35, 187–196.

Hamilton, E.F., 1979. V_p/V_s and Poisson's ratios in marine sediments and rocks. J. Acoust. Soc. Am. 64, 1093–1100.

Heim, C., Nowaczyk, N.R., Negendank, J.F.W., 1997. Near east desertification: evidence from the dead sea. Naturwissenschaften 84, 398–401.

Hopkins, T.L., 1964. A survey of marine bottom samplers. In: Sears, M. (Ed.), Progress in Oceanography, vol. 2, pp. 215–255.

Hough, J.L., 1939. Bottom sampling apparatus. Recent marine sediments: a symposium. Amer. Assoc. Petroleum Geol., Tulsa, Oklahoma (1955), pp. 631–634.

Janocko, J., Landvik, J.Y., Larsen, E., Sejrup, H.P., 1997. Stratigraphy and sedimentology of Middle to Upper Pleistocene sediments in the new Grødeland borehole at Jæren, SW Norway. Nor. Geol. Tidsskr. 77, 87–100.

Jansen, E., Sejrup, H.P., Fjæran, T., Hald, M., Holtedahl, H., Skarbø, O., 1983. Late Weichselian paleoceanography of the southeastern Norwegian Sea. Nor. Geol. Tidsskr. 63, 117–146.

Kähler, S., Meissner, R., 1983. Radiation and receiver pattern of shear and compressional waves as a function of Poisson's ratio. Geophys. Prospect. 31, 421–435.

Karlsrud, K., Haugen, T., 1984. Feltforsøk med instrumentert stålrørspel i overkonsolidert leire. Norw. Geotech. Inst. Publ. 153, 1–6.

Lisitzin, A.P., 1972. Sedimentation in the World Ocean. In: Rodolfo, K.S. (Ed.), Society of Econom. Paleontol. and Mineral., Spec. Publ., vol. 17.

Lokshtanov, D.E., Ruud, B.O., Husebye, E.S., 1991. The upper crust low velocity layer; a Rayleigh (Rg) phase velocity study from SE Norway. Terra Nova 3, 49–56.

Lunne, T., Berre, T., Strandvik, S., 1998. Sample disturbance effects in deep water soil investigations. Proceedings SUT conference on Soil Investigation and Foundation Behaviour, London Sept. 1998, pp. 199–220.

Meyerhof, G.G., 1976. Bearing capacity and settlement of pile foundations. Proc. ASCE, J. Soil Mech. Found. Div. 102, 197–228.

Miller, R.D., Pullan, S.E., Steeples, D.W., Hunter, J.A., 1992. Field comparison of shallow seismic sources near Houston, Texas. Geophysics 57, 693–709.

Parker, W.R., Sills, G.C., 1990. Observation of core penetration and sample entry during gravity coring. Mar. Geophys. Res. 12, 101–107.

Petterson, H., Kullenberg, B., 1940. A vacuum core-sampler for deep-sea sediments. Nature 145, 306.

Ritzwoller, M.H., Levshin, A.L., 2002. Estimating shallow shear velocities with marine multicomponent data. Geophysics 67, 1991–2004.

Rosfelder, A.F., 1966. Hydrostatic actuation of deep-sea instruments. J. Ocean Technol. 1, 53–63.

Rosfelder, A.M., Marshall, N.F., 1967. Obtaining large, undisturbed, and orientated samples in deep water. Proceedings International Research Conference on Marine Geotechnique, University of Urbana. Illinois Press, pp. 243–263.

Schjetne, K., Brylawski, E., 1980. Offshore soil sampling in the North Sea. Norw. Geotech. Inst. Publ. 130, 1–18.

Selwyn, S., McCoy, F.W., 1981. The hydrostatic motor: utilization of hydrostatic pressure differentials in the deep sea. Geo Mar. Lett. 1, 233–236.

Silva, A.J., Hollister, C.D., Laine, E.P., Beverly, B.E., 1976. Geotechnical properties of deep sea sediments: Bermuda Rise. Mar. Geotechnol. 1, 1995–2232.

Skinner, L.C., McCave, I.N., 2003. Analysis and modelling of gravity- and piston coring based on soil mechanics. Mar. Geol. 199, 181–204.

Smits, F.P., 1990. A seabed sediment sampler for ocean waste disposal. Geotechnical Engineering of Ocean Waste Disposal. ASTM STP, vol. 1087, pp. 87–94.

Solheim, A., Forsberg, C.F., 1996. Norwegian Polar Institute's cruise to the northern margin of Svalbard and the Barents Sea 25/7–2/9, 1994: Marine geology/geophysics and physical oceanography. Norsk Polarinstitutt Report No. 92, 66 pp.

Tomlinson, M.J., 1994. Pile Design and Construction Practice. E & FN SPON, London. 403 pp.

Xia, J., Miller, R.D., Park, C.B., 1999. Estimation of shear-wave velocity by inversion of Rayleigh waves. Geophysics 64, 691–700.