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Acceleration-monitored coring revisited

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Abstract A measurement system is described for recording vertical accelerations of piston or gravity corers during penetration. The system consists of acceleration, tilt, and absolute pressure sensors. Double integration of the acceleration signal during the penetration time gives the maximum penetration depth of the core. This value, when compared with the total length of recovered core allows quantification of core compaction or core loss. The system was used successfully on 13 gravity and piston corers during *RV Polarstern* cruise XI/4 to Antarctica. In most cases the recovered core length is less than the total core penetration, with a maximum core compaction of 30%. A general increase of core compaction or core loss with core length can be observed.

Introduction

It is commonly known in the marine geology community that recovered deep-sea sediment cores do not necessarily reflect in situ sedimentary sequences. On the contrary, the core recovered is more or less disturbed by well-known processes such as core compaction and selective coring (e.g. Buckley et al. 1994; Bouma and Boerma 1968; McCoy 1985; Lebel et al. 1982; Parker and Sills 1990; Seyb et al. 1977, among others). The degree of disturbance or core shortening depends on the core type used. Generally gravity cores experience a larger amount of core shortening than do piston cores. The simplest ways to quantify the amount of core shortening is to record mud marks on the outside of the core barrel and compare penetration depth with the length of the recovered core. However, the existence of mud marks depends on the sediment type cored, which means that they are not always present or upper parts are very soft and washed away. Mud mark recordings in the station log of a core station are also certainly not done on a routine basis and by no means reported in publications interpreting investigations on the recovered core.

With the high-resolution dating methods now available, quantitative paleooceanographic and climatic studies are quite common. In those cases core compaction plays an increasingly important role because it introduces an undescribed and unquantified error in the interpretation. The physical processes of core shortening and selective coring have been described qualitatively by Weaver and Schultheiss (1983), and measurements like those of Parker and Sills (1990) support the general physical ideas and observations. Geotechnical experiments made about 30 years ago (Preslan 1969; Dayal et al. 1973) demonstrated the technological feasibility of monitoring the penetration of a deep-sea sediment core with an acceleration sensor and an analog data logger. These geotechnical studies mostly focused on deriving geotechnical properties such as sediment shear strength from the deceleration of a coring device penetrating sediments. For unknown reasons, however, the marine geology community has only just now picked up these ideas to use them in a routine way for every core taken, although acceleration measurements are technically feasible now at low cost.

In this paper we describe an acceleration sensor package mounted in the core head to monitor the penetration process of a deep-sea gravity or piston core. Integrating acceleration twice yields total core displacement from impact until the core comes to a complete stop. Total displacement when compared to the total core length recovered is a measure of core shortening and/or selective coring, an extremely valuable indicator for the core quality. Because only acceleration is measured, however, it is not possible to distinguish between the two processes, causing core loss, nor it is possible to identify the core segment where shortening or selective coring has occurred. After presenting the technical details of the sensor package, we discuss the signals seen on

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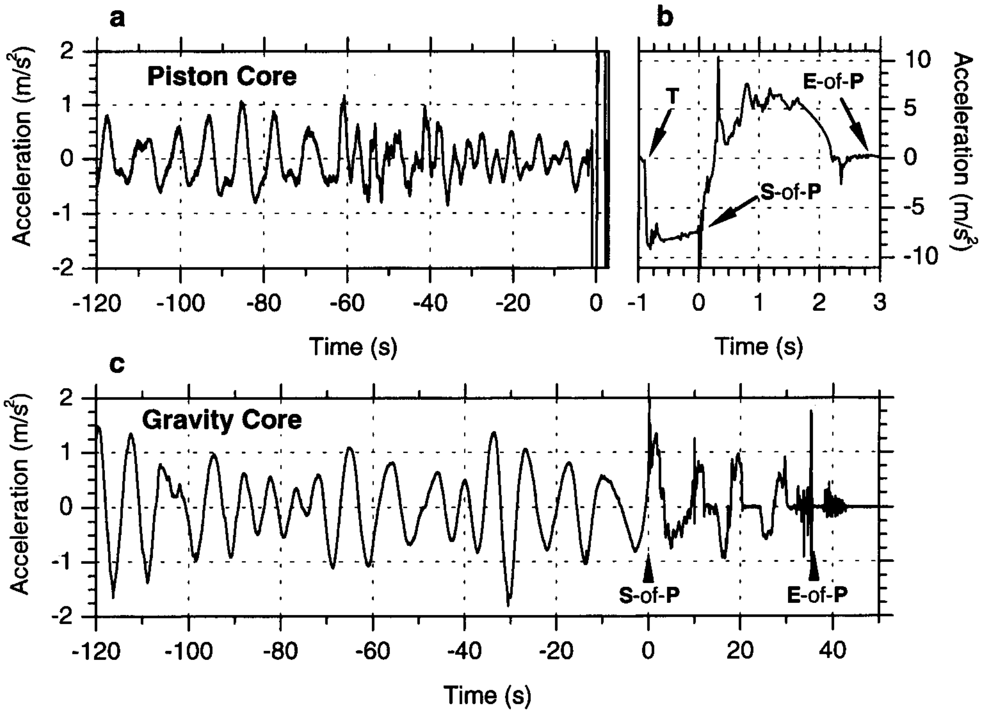


Fig. 2 Vertical acceleration of a 15-m-long piston (top left and top right) and 15-m-long gravity core (bottom) before and during penetration into the sea floor. The prepenetration record shows very clearly the ship's heave as a low-frequency signal with periods in the range of about 10 s. **b** The instant (marked with a T) when the trigger core hits the bottom and the free fall period of the piston core begins. The start of the penetration (marked with S-of-P) is easily identifiable on the record of the piston (**b**) and gravity core (**c**). While the piston core penetrates within a short time period, the gravity core takes about 35 s until it comes to rest. It is remarkable how much the penetration of the gravity core is dominated by the low-frequency heave of the ship

experience ship heave with accelerations up to ±2 m s^{-2} and periods in the range of about 10 s. Due to the attached trigger core, the piston core record also shows higher frequency components. In Fig. 2b the moment (*T*) when the trigger weight hits the sea floor ($t = -0.9$ s) is clearly marked by a sudden change in acceleration; the piston core accelerates during the free fall to a peak value of almost −9 m s^{-2}. Deceleration at impact is almost 10 m s^{-2}. After only 2.8 s the core comes to a complete stop (end of penetration, E-of-P). A completely different acceleration history is exhibited by the gravity core (Fig. 2c). The start of penetration is easily identifiable (start of penetration, S-of-P); in contrast to the piston core, it takes about 35 s until the gravity core completely stops. However, the ship's heave dominates the penetration with significant time periods of zero acceleration during penetration.

Our experience from 13 deployments of the system reveals that in all cases the exact moment of penetration was easily identified, as it is marked either with a peak in acceleration or a sudden change in the frequency of the acceleration signal. Sensors and the data logger worked well, although a larger memory will be needed for piston core measurements to sample the very short penetration time span with a frequency of at least 100 Hz. Additional recording of horizontal accelerations in a few coring stations show that they are of minor importance and can be neglected.

Results

All measurements presented were made during the ANTXI/4 expedition (1994) on *RV Polarstern* in the southeast Atlantic and southeast Indian Ocean as well as close to the Antarctic continent. Details of the cruise and the exact locations of the cores can be found in the cruise report (Kuhn 1999). During the cruise, 13 successful measurements on piston (8) and gravity (5) cores were made. The lithology of the cores recovered ranged from hemipelagic muds to diatomeceous ooze. Unfortunately the complete acceleration measuring system was lost, together with the piston core, in mid-cruise when the piston core superpenetrated and the weak link between wire and piston eventually failed.

Gravity corer

Figure 3 shows a typical record obtained with a 15-m-long gravity corer (core PS2561-1) during penetration. The acceleration record (Fig. 2c) before penetration shows clearly the long period heave of the ship that is still present on the penetration record once the core cutter has entered the sediment. Integration of acceleration during penetration (Fig. 3a) gives the velocity during penetration (Fig. 3b), showing clearly the highly variable penetration speed due to ship heave. Therefore, the penetration process is by no means continuous. There are time intervals on the order of seconds in which the core comes to a complete stop and even an instance in the early part of the penetration in which negative velocities indicate that the core was almost completely pulled out of the sediment by about 1.6 m again. Integrating the velocity record once more yields the penetration depth as a function of time, which allows plots of penetration as a function of time (see Fig. 3c). Therefore the acceleration record. The penetration record itself and the details of interpretation are demonstrated on records from a piston and a gravity core. Included is also an attempt to correlate sediment physical properties and the acceleration signals during penetration. Finally all successful penetration depth measurements are compared with the core recovered.

Instrumentation and data processing

The detailed analysis of the published penetration data by Preslan (1969) helped immensely in selecting the appropriate components of the sensor package that are suitable for the measurements. Our design philosophy was to use as many off-the-shelf components and/or modules as possible to minimize development time and cost. To prevent the sensor package from damage during core deployment and recovery, the pressure case containing the sensor package had to be integrated into the weight stand head. This constraint and a target maximum deployment depth of 6000 m resulted in a stainless steel pressure case, 190 mm long, with an outer diameter of 110 mm and an inner diameter of 80 mm. A hole in the weight stand large enough to house the pressure case allowed the complete integration of the system. Bolts fix the pressure case to the weight stand to prevent relative motion.

Figure 1 shows all the sensors used. The primary sensor is a static vertical acceleration sensor with sufficient sensitivity and a high shock tolerance. This is especially important due to the occurrence of high peak accelerations during core recovery and deployment. The tilt sensor provides an additional record of the penetration process but is less important, as we show later. Monitoring the hydrostatic pressure increase during penetration is a direct way of deriving total displacement. However, all pressure sensors capable of measuring absolute pressures at full ocean depth lack the resolution needed at the high sampling rates required by the fast penetration speed of a piston core. Therefore, the integrated pressure sensor provides only a rough estimate of total core displacement but serves as a vital trigger to start data storage and an extremely valuable constraint for the acceleration-derived total penetration depth. All analog signals had to be amplified and fed through an antialiasing filter before being digitized and stored. The monitoring process was under complete control of a small data logger that incorporated a CPU, an A/D converter, and solid-state memory. The complete system is powered by a 9-V battery. Table 1 provides details.

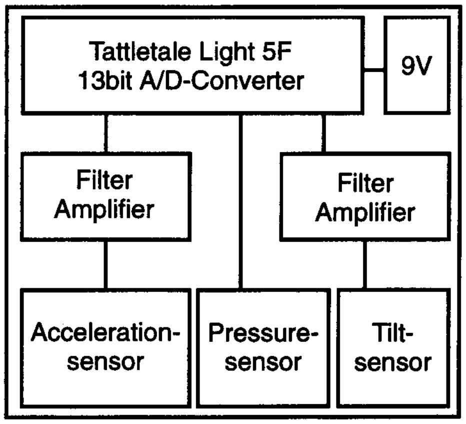


Fig. 1 Block diagram of the acceleration measuring system

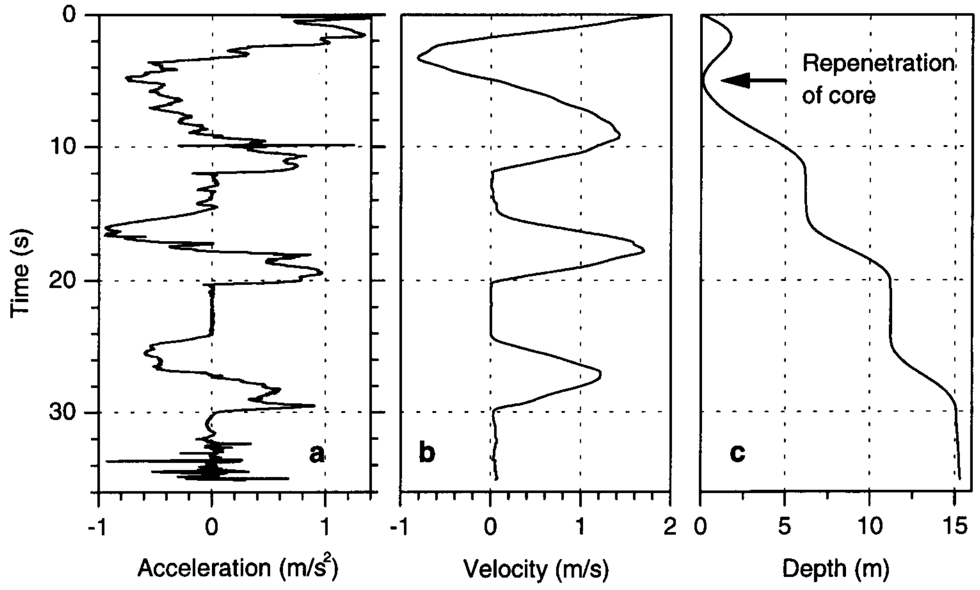
Before the core is lowered into the water, the depth threshold level at which the system will start to store data in memory has to be set via a RS232 link to the data logger. The depth level was always about 100–200 m higher than the actual water depth at the core site. After the setup and start of the system in the laboratory, the pressure case is installed into the core weight stand. The data logger interrogates the pressure sensor at a low frequency (0.1 Hz) to monitor depth while the core is lowered to the sea floor. Once the preset depth level has been reached, the logger starts to acquire and store data from all sensors at a software selectable rate, normally at 50 Hz. In that way, available memory is sufficiently large to store all relevant data just before and during penetration of the core. When the memory is full, the logger stops and the data are retrieved via an RS232 link to a computer once the core is on deck. The complete memory is dumped to a computer hard disk, and the raw data are processed using calibration constants supplied by the vendors of the sensors. The next step consists of finding the exact time window in which penetration occurred. After this data window has been extracted to a separate data file, the static acceleration due to the ambient gravity field of the earth is removed by averaging the constant acceleration in a time window immediately following core penetration. Due to the sometimes nonvertical penetration of the core, the static acceleration value has to be corrected with the help of the International Gravity Formula (Lowrie 1997), which allows calculating the earth's gravity for any given latitude. In general, all inclinations were less than 7° from vertical.

Figure 2 shows typical acceleration records before and during penetration of a piston and a gravity core. The coring devices used consist of a 2-t weight stand and a 15-m-long core barrel with an inside diameter of 125 mm (gravity core) or 90 mm (piston core). Time (t = 0) in Fig. 2a–c coincides with the start of the penetration process. All measurements shown are vertical accelerations only. Orientation of the z axis is positive downwards, with positive values being decelerations. In the water column (time <0) both cores

Table 1 Technical specifications of sensors and data logger

Module	Range	Resolution
Vertical acceleration	±3 g	0.001 g
Tilt	±20°	0.5″
Pressure	400 bar	±0.05 bar
Datalogger	13 bit A/D resolution	512 kB memory
TattleTale Lite 5	50 Hz sample rate	29 min total storage

Fig. 3 Vertical acceleration, penetration velocity, and penetration depth for a 15-m-long gravity core PS2561-2. Integration of acceleration during penetration (marked time window of **a**) gives penetration velocity, shown in **b**. Double integration of acceleration during the penetration time window gives the penetration depth of the core cutter as a function of penetration time. The maximum penetration depth of the core cutter is 15.3 m, whereas the length of the recovered core is only 11.53 m



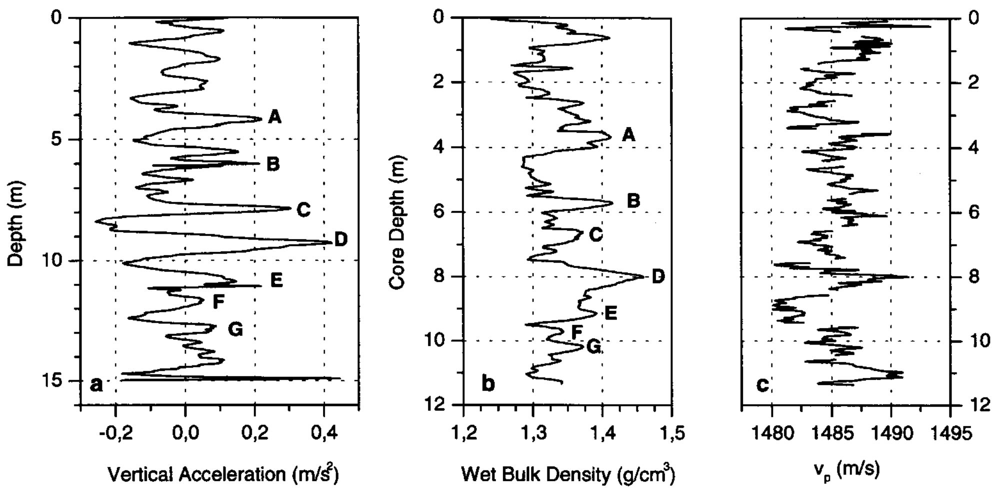
this depth section could have been cored twice. The maximum penetration depth of the core cutter is 15.3 m below the sea floor, whereas the length of the recovered core is only 11.53 m. That means that core shortening is almost 25%, although the depth at which core material is missing is unknown.

Deceleration of the corer is closely related to sediment shear strength, which in turn is directly coupled to porosity and density. An attempt to correlate deceleration during penetration and sediment physical properties is shown in Fig. 4a–c. High values in deceleration are associated with a sudden increase of wet bulk density. Based on the penetration versus time record shown in Fig. 3c, the deceleration of the core is mapped into a deceleration versus depth relationship (Fig. 4a). Long period accelerations less than 0.75 Hz caused by the ship heave (see Fig. 3a–c) had to be removed for comparison of accelerations with wet bulk densities (Fig. 4b) and p-wave velocities (Fig. 4c). Sediment physical property measurements were made on cores in the laboratory with a multisensor track, comparable to the one described by Weber et al. (1997). Large deceleration peaks in the uppermost meter of the penetration history (Fig. 4a) have been omitted to allow a better comparison among the three data sets. It is important to keep in mind that the depth scales of the acceleration and the physical properties are not identical. Letters indicate a possible correlation of deceleration peaks and wet bulk density. Plotting these, Fig. 5 indicates that the core compaction or core loss is largest in the lowermost part of the core due to increasing liner friction with the amount of core recovered.

Piston corer

The acceleration record for a piston corer is fundamentally different from the one obtained with a gravity corer (Fig. 2a and b). It shows vertical acceleration, penetration velocity, and penetration depth during the

Fig. 4 Vertical acceleration and sediment physical properties of the recovered gravity core PS2561-2 as a function of depth. Low frequency accelerations less than 0.75 Hz caused by the ship heave (Fig. 3a–c) had to be removed before comparison of accelerations with wet bulk densities (**b**) and -wave velocities (**c**). Letters indicate a possible correlation of deceleration and wet bulk density peaks



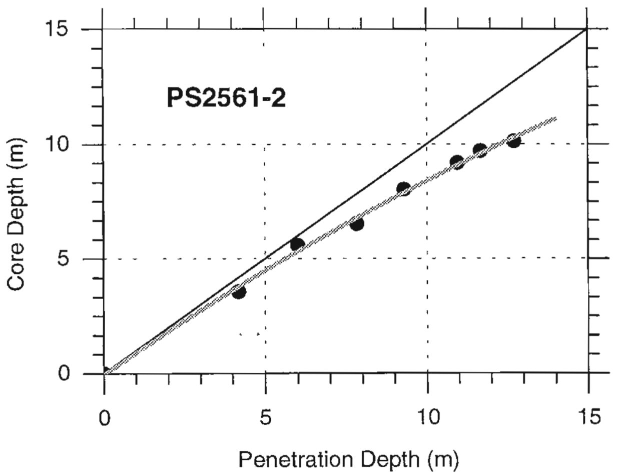


Fig. 5 Correlation of deceleration and wet bulk density peaks (see Fig. 4a, b) in order to quantify the amount of core compaction

penetration process of a 15-m-long piston core (PS2595-1) before and during penetration. Integration of acceleration during penetration (time window from 0 to 2.3 s in Fig. 6a) gives the penetration velocity, (Fig. 6b). Double integration of acceleration during the penetration time window gives the penetration depth of the core cutter as function of penetration time (Fig. 6c). It is remarkable that the piston corer penetrates the sediment with a speed of about 8 m s^{-1}, which is considerably higher than in the case of a gravity core where the penetration speed is entirely controlled by the maximum speed of the winch. Due to the lack of a direct coupling to the ship's heave through the wire, the deceleration rises fairly smoothly and reaches a maximum value 1.5 s after penetration. In this example the maximum penetration depth of the core cutter is 11.9 m, whereas the length of the recovered core is only 9.51 m and thus shorter by almost 20%.

Superimposed on the general acceleration pattern in Fig. 6a are small changes of deceleration that are associated with varying sediment properties with depth. If one removes the general trend in deceleration by subtracting a second-order polynomial, one can clearly identify depth intervals with peak values (see Fig. 7a). As in the case of a gravity core, these signals are most likely associated with porosity (or wet bulk density) changes. Core logs of wet bulk densities and acoustic velocities (Fig. 7b, c) measured in the same way as on a gravity core are shown for correlation, which is indicated by uppercase letters in Fig. 7. Two prominent peaks in deceleration are easily correlated with major changes in wet bulk density or acoustic velocity. However, correlation of minor peaks is not as unambiguous as in the case of the gravity core. Plotting the correlated depths (Fig. 8), the core compaction most likely increases linearly with depth.

Interpretation of pressure data

As mentioned earlier, absolute pressure was also recorded during penetration of the cores. The relatively low pressure resolution equivalent to a depth interval of 0.5 m does not allow derivation of the precise penetration history from pressure measurements alone. However, they are extremely valuable in constraining the double integration of the measured accelerations. Figure 9 shows a comparison of acceleration and pressure-derived penetration records for three cores. It is remarkable how well the two completely independent measurements agree, supporting the method used to calculate penetration history from acceleration values.

Conclusion

The data presented show clearly that it is possible to derive the total penetration depth of a gravity or piston

Fig. 6 Vertical acceleration, penetration velocity, and penetration depth during the penetration process of a 15-m-long piston core PS2595-1 during penetration. The integration of the acceleration during penetration (time window of 0–2.3 s in **a**) gives the penetration velocity, shown in **b**. Double integration of the acceleration during the penetration time window gives the penetration depth of the core cutter as function of penetration time. The maximum penetration depth of the core cutter is 11.9 m whereas the length of the recovered core is only 9.51 m

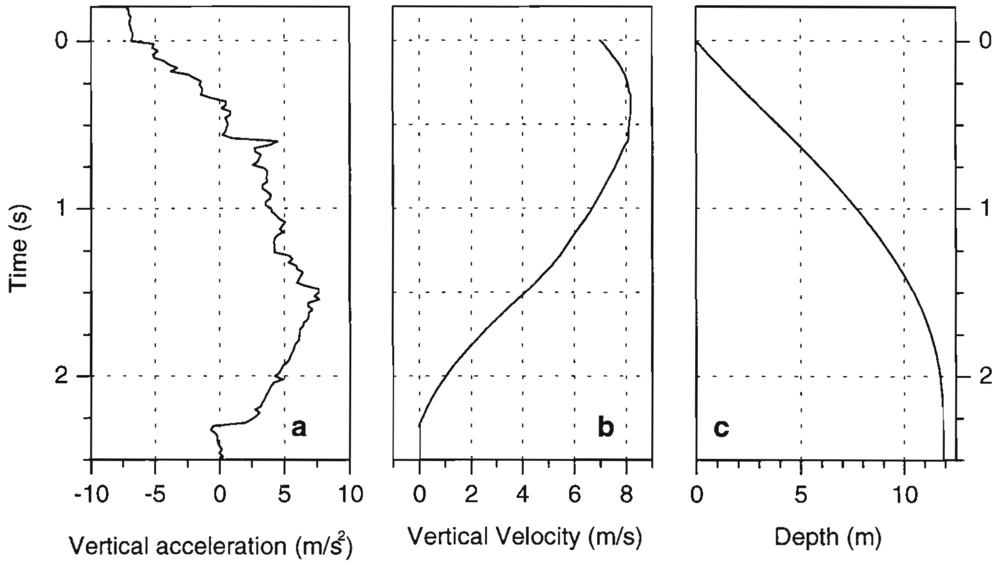
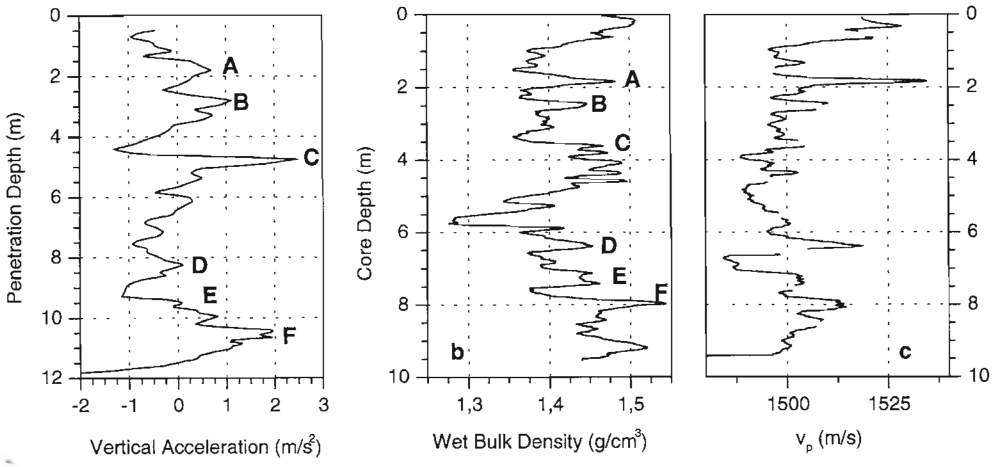


Fig. 7 Vertical acceleration and sediment physical properties of the recovered piston core PS2595-1 as a function of depth. The low-frequency change of acceleration with penetration time (and depth) has been removed by subtracting a quadratic polynomial from the penetration record (see Fig. 6a) to clarify any correlation. Letters indicate a possible correlation of deceleration and wet bulk density peaks. Due to the very short penetration time and the maximum acceleration sampling rate of 50 Hz, a detailed correlation of some of the acceleration peaks with significant changes in physical properties is very difficult



corer from acceleration measurements. The system used is fairly simple, easy to install in a core head, and easy to operate. As only off-the-shelf components were used, the price for one system is well below US$3000.

The results of all 13 successful measurements are summarized in Fig. 10. In all but two cases, the core is shorter than the penetration depth clearly quantifying the well-known fact that a recovered core has been subjected, more or less, to compression or core loss. The figure also supports the assumption that core compaction or core loss is proportional to penetration depth. In general, core distortion is more severe for gravity cores than for piston cores, but it is not possible to quantify this observation from the limited number of measurements available and the variable sea conditions and sediment environments encountered. Changes in deceleration during penetration are most likely caused by changes in sediment physical properties. A correlation of both records may be helpful in deciphering down core compaction as the examples demonstrate. Deriving sediment physical properties from deceleration is potentially possible, but many more penetration records at higher sample rates will be necessary in order to gain experience in predicting physical properties from deceleration processes.

The increasing interest in long cores for paleoclimatic studies and the capabilities of taking long cores with modern research vessels demand a detailed monitoring

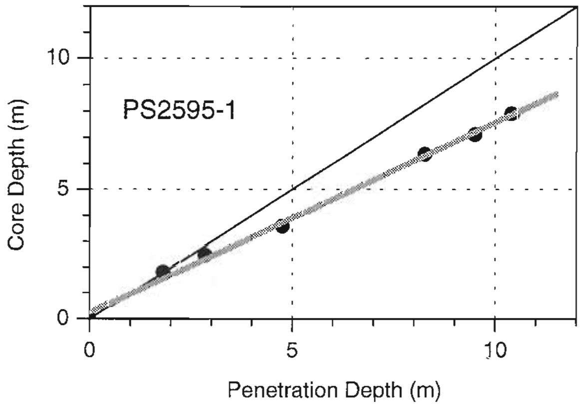


Fig. 8 Correlation of deceleration and wet bulk density peaks in order to quantify the amount of core compaction

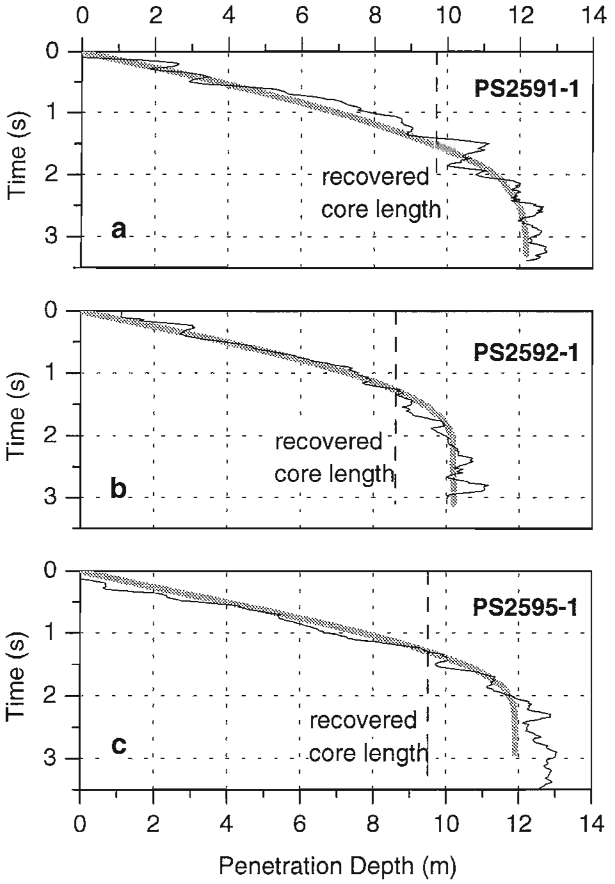


Fig. 9 Comparison of acceleration (solid line) and pressure-derived (heavy gray line) penetration depth for three cores. Both data sets agree remarkably well, supporting the validity of the method used

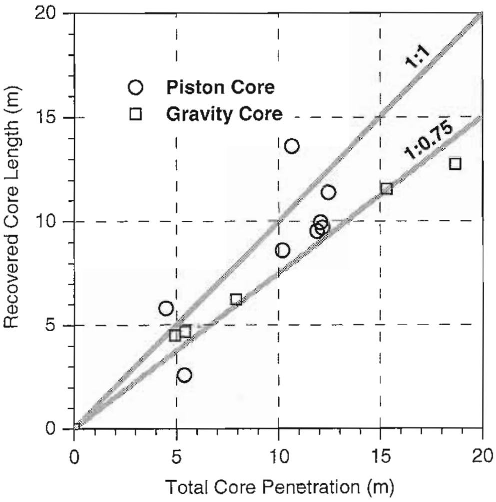


Fig. 10 Comparison of recovered core length and calculated total penetration, based on acceleration measurements during coring operation. The complete data set of 10 individual measurements supports the fact that core loss or core compression is much larger for gravity cores than for piston cores

of core recovery. Only measurements like the ones presented in this paper will help to establish sound criteria to assess the quality of a recovered core, which in turn will strongly support all interpretations based on core samples. The paper demonstrates that systems like the one used are technically feasible without extensive costs and minimal interference within the standard coring procedures. What is needed now is a strong interest and support from the marine geology community to further improve the technology used and to broaden the knowledge and data base.

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