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A new automated nondestructive system for high resolution multi-sensor core logging of open sediment cores

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Abstract A new system for logging the geophysical properties of marine sediment cores allows both whole cores and split cores to be measured in a nondestructive fashion. The current sensor configuration measures compressional (P) wave velocity (500 kHz), bulk density (using gamma-ray attenuation), and magnetic susceptibility at user-defined sample intervals down the core. Split-core logging gives more reliable results than whole core logging as it mostly eliminates core-slumping effects that can lead to spurious results; it also gives higher resolution magnetic susceptibility readings.

Introduction

Nondestructive logging of marine cores began in the early 1960s, measuring bulk density using gamma-ray attenuation (Evans 1965; Preiss 1968). Further developments brought a degree of automation (Boyce 1973) and continuous compressional (P) wave velocity logging was introduced in the mid-1980s (Schultheiss and McPhail 1989). The first fully automated and integrated multi-sensor core logging system (Schultheiss and Weaver 1992) included compressional (P) wave velocity, gamma density, and magnetic susceptibility sensors for use on whole cores. Automated, nondestructive core logging is now standard practice on the Ocean Drilling Program. Velocity and density data may be used to create synthetic seismograms for comparison with seismic profiles; magnetic susceptibility data may be used to identify palaeoclimatic events that are not easily detected through visual inspection of the cores (e.g., Robinson 1990; Chi and Mienert 1996). The data may also be compared with those collected from downhole wireline logs and provide a helpful cross-reference for checking data integrity. In general, core log data represent an important source of quantitative information for a wide range of geological and environmental studies.

Whole core loggers are designed primarily to record the geophysical properties of unconsolidated, marine sediment cores, although they also have the potential to log both consolidated sediment and hard rock cores. Unconsolidated marine sediment cores are generally collected in rigid plastic or polycarbonate liners typically with wall thicknesses of about 3 mm. The liners preserve original sedimentary structures as much as possible (Weaver and Schultheiss 1983), and in many respects also assist in the core logging. For example, P-wave logging of whole cores is quite straightforward as the transducers slide along the smooth outer wall of the liner and can be held in contact by a simple spring mechanism (Schultheiss and McPhail 1989). However, it is common practice to split marine sediment cores in a longitudinal direction soon after they are brought ashore, or even while at sea, after the whole core logging has been performed. One half is archived, and the other is used for conducting various sedimentological, geochemical, and geotechnical, analyses that involve some destruction to the core material. Split cores cannot be relogged via conventional whole core logging technology, and hence the need for a dedicated split core logger. Moreover, some marine cores have been split without first being logged. Their archive halves reside in core repositories around the world and make up a sizable source of potentialy useful data. However, we must treat retrospective logging data with some caution, as it is difficult to quatify the effects of long term storage on cores.

Split core logger

The split core logger is a development of the whole core logging system described by Schultheiss and Weaver (1992). The split core logger can measure compressional

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(P) wave velocity, bulk density (using gamma-ray attenuation), and magnetic susceptibility at a user-defined sample interval down the length of the core (typically at 1-, 2-, or 4-cm intervals, but others are possible). The system comprises four main units: (1) a central sensor array, (2) a motorized track for feeding the core past the stationary sensors, (3) an electronics interface for controlling the sensor settings and for passing data to the logging computer, and (4) the logging computer (a PC) that runs specially written software for controlling sensor operations and the track while recording the data on hard disk (Figs. 1 and 2). Cores are moved along the track by a core pusher attached to a drive belt that is operated by a stepper motor with low-ratio gears.

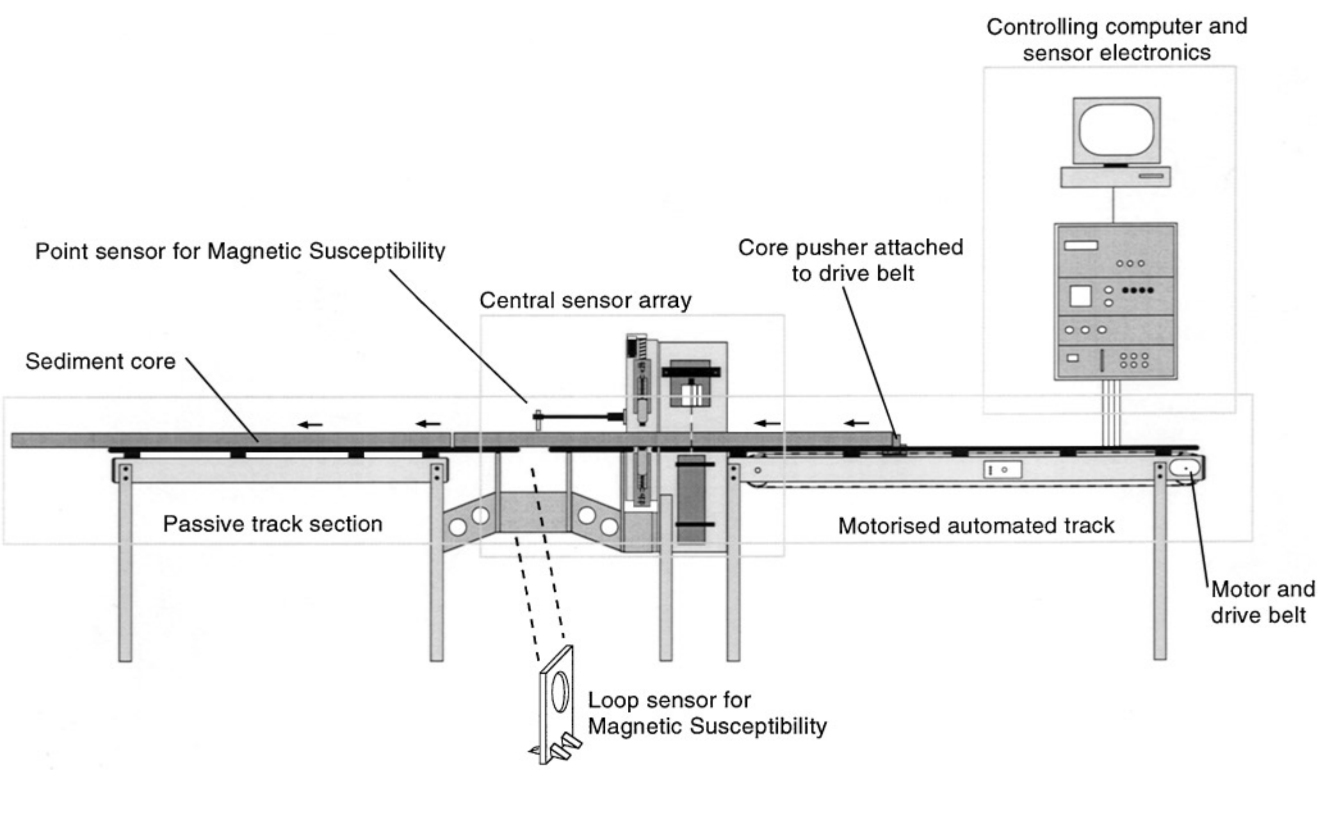
Some preparation of cores is required for split core logging. Once split in the longitudinal direction using a special cutting device, the exposed sediment surface is protected from dehydration and contamination by a thin polythene film that is placed down the length of the core. It is then ready for logging.

P-wave velocity

Velocity measurements are made using a simple transmission geometry with two vertically mounted compressional wave transducers located on opposite sides of the core. The active element in each transducer is a thickness-mode 500-kHz piezoelectric crystal mounted in epoxy resin and housed within a stainless steel sliding cylinder. The diameter of the active face of each transducer is 2 cm. The most critical aspect of these measurements is the acoustic coupling between the transducer faces and the core. For whole marine cores, which are generally encased in a polycarbonate liner, the transducer–liner contacts remain fairly constant down the length of the core; the transducer faces are wetted to improve the acoustic coupling. For split cores, while the lower transducer is in contact with the liner, the upper transducer is in contact with the polythene film on top of the sediment; again, water is used to maintain good acoustic coupling.

The main technological innovation is the design of the P-wave sensor system. First, the transducers are mounted vertically so that they can be brought into contact with the upper sediment surface (duly protected by a polythene film) and the core liner beneath. This arrangement also provides additional benefits in terms of data quality. Second, due to the often compliant nature of marine sediments, the upper transducer is designed to move in and out of contact with the sediment surface at each sample point; the spring-loaded, lower transducer remains in constant contact with the liner beneath. This enables the split core to be moved freely past the transducers before the next measurement is made. A simple spring-loaded transducer system like the one used on the original whole core logger (Schultheiss and McPhail 1989) would not work on split cores as it would tend to cause rucking of the soft sediment.

Fig. 1 The new split core logger showing the central sensor array, the motorized track, the control interface, and the logging computer. The whole system is approximately 4 m long. Note the interchangeable magnetic susceptibility loop and point sensors



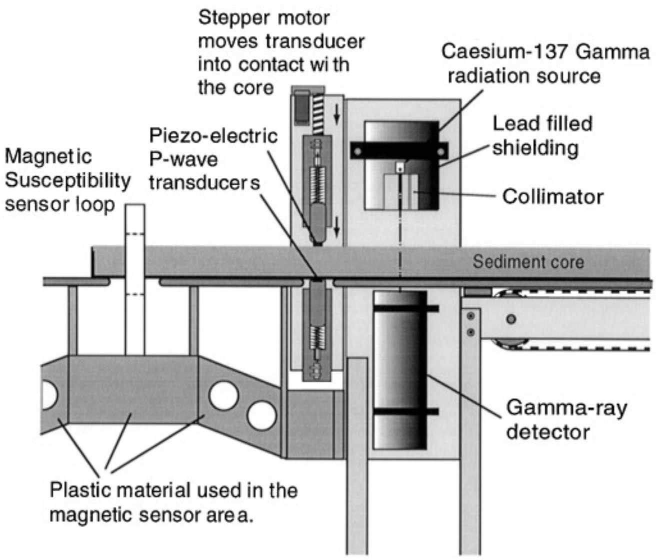


Fig. 2 Detail of the sensor array showing the vertically mounted P-wave transducers, gamma-ray source, and detector. The magnetic susceptibility loop sensor is shown. The detector is approximately 100 cm high

The transmitter sends a 500-kHz pulse through the core at a repetition rate of 1 kHz. The pulse is then detected at the receiver and amplified using automatic gain control. An automated system is used to detect and measure the travel time of the first negative excursion of the received waveform that falls within preset amplitude thresholds. Travel time is measured to a precision of 50 ns.

Core thickness is measured by two rectilinear displacement transducers attached to the P-wave transducer housings. Displacements can be measured to a precision of 0.1 mm. They are calibrated by bringing the P-wave transducer faces into contact with a solid block of known thickness (e.g., an aluminum block), and setting the displacement to zero. Both transducers have 3 cm of free travel so that they can compensate for variations in core thickness. The lower transducer is held against the liner surface also by a simple spring mechanism. The upper transducer is suspended within the housing by a simple spring mechanism; as the transducer housing continues to move down after the transducer face has come into contact with the sediment surface, progressively more of the transducer weight is taken by the sediment. The firmness of the transducer–sediment contact can be increased by adding weights to the transducer assembly. It is important that the transducer loading is adjusted to suit the stiffness of the sediment; correct adjustment will leave shallow (< 0.5 mm) transducer footprints on the sediment surface after logging.

The velocity, V_p, is calculated using

$$V_p = \frac{(d_C + d_R - d_L)}{(t_R - t_L)} \tag{1}$$

where d_C is the calibration block thickness, d_R the recorded displacement, d_L the total liner thickness, t_R the recorded pulse travel time, and t_L the pulse delay time. The latter includes the travel time through the liner and through the transducer faces, the delay caused by the automatic picking (the recorded time is for a point on the waveform that is one cycle after its true onset time, which can be considered to be constant as a narrow frequency band is used), and the small time delay in the system circuitry (also a constant). Hence, the pulse delay time must be recalculated after any change in liner thickness. It is calculated from the measured travel time through a section of whole core liner (the same sort as the ones containing the sediment) filled with distilled water. Standard tables (e.g., Kaye and Laby 1986) are used to obtain the velocity of distilled water at the logging temperature. Core liner thickness is measured directly on several sections of liner (taking an average value) or is taken from the manufacturer's specifications. The thicknesses of the core liners used to date varied typically by less than $\pm$ 0.1 mm.

When logging cores it is important to periodically wet the transducer faces. If they become totally dry, there is poor acoustic coupling and recorded signal amplitude, which may result in the wrong delay time being picked by the automated system. In practice, we found that there only has to be some water present at the contacts for good coupling to be maintained (i.e., the whole transducer surface does not have to be wet). For split core sections, it is usually sufficient to spray the upper polythene film with water and to wet the lower transducer before logging commences. With the above proviso, tests show that the measured velocity is fairly insensitive to the exact degree of coupling (i.e., amount of water present). However, as expected, the amplitude of the signal is extremely sensitive to the coupling and for this reason, the logger cannot be used for accurate attenuation measurements in its standard mode of operation. Signal amplitude is recorded, however, and it may sometimes give a useful indication of relative sediment attenuation where the data are good, but this is a matter for interpretation.

The only other major cause for spurious readings is sediment slumping in the core liner. This results in air gaps being formed between the liner and the sediment, and this cannot be accounted for in the standard velocity calculations (air gap thicknesses are unknown). One advantage of split core logging is that this problem is seldom encountered (see Fig. 3).

The sediment temperature is recorded using a thermocouple probe placed to one end of the section during logging. It is then possible to correct the logged velocities to sea-floor temperature, for example, by using empirical formulae for the speed of sound in seawater (e.g., Wang and Zhu 1995) and a sediment velocity model (e.g., Wyllie et al. 1956; Wood 1941).

Bulk density

The split core logger uses the standard and well-documented technique of gamma-ray attenuation to

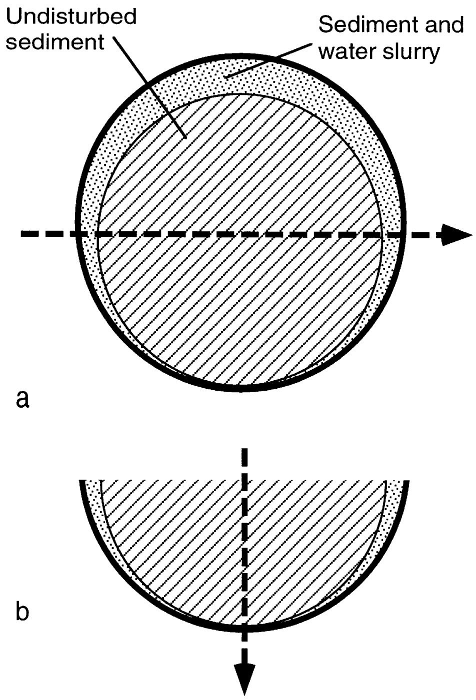


Fig. 3 **(a)** Cross-section through a typical marine sediment core showing the effect of sediment slumping, which is mostly eliminated during split core logging (**b**)

derive sediment bulk densities (e.g., Boyce 1973, 1976; Evans 1965, 1970; Preiss 1968; Gerland and Villinger 1995, Weber et al. 1997). This method has the advantage of being wholly nondestructive to the core, but does require stringent health and safety guidelines to be followed in the use of the gamma radiation source (414 MBq cesium-137).

The setup is illustrated in Figs. 1 and 2. The radiation source, housed in a lead container, is located above the core and the detector (a scintillation counter) is positioned below the core in the vertical plane. Gamma rays are switched on by opening a small window at the base of the lead shielding. There are two aperture sizes giving collimated beams of 2 mm or 5 mm diameter.

The system works by counting the number of scintillations over a given length of time, thus giving the count rate. As the source emits radiation in a random fashion, increasing the detection time improves the accuracy of the measurement. Detector count times of 2 or 5 s proved to be the best compromise between logging time and count rate stability, with the 5-s count time providing more stable results.

Bulk density, ρ (g/cm^3), is calculated from (Evans 1965):

$$\rho = \frac{1}{\mu d} \ln\left(\frac{I_0}{I}\right) \tag{2}$$

where I is the intensity of the gamma beam received at the detector after passing through the air gap, the core liner, and the sediment itself (cps), I_0 is the intensity of the gamma beam after passing through the air gap and the appropriate thickness of core liner (cps), μ is the Compton mass attenuation coefficient of the sediment (cm^2/g), and d is the thickness of the sediment (cm). This equation assumes a linear effect for gamma rays passing through materials, that attenuation in air is negligible, and that the beam is perfectly collimated.

The main problem with this technique is that not all materials have the same Compton mass attenuation coefficient, a characteristic that depends on the electron density of the material. While most sediment-forming minerals have similar values, water has a relatively high electron density. Given that water typically constitutes up to 60% of a marine sediment by volume, this effect can lead to bulk density errors of $\pm 10\%$. One solution is to use a Compton mass attenuation coefficient for a hypothetical sediment of porosity 50% ($\mu = 0.0795$ cm^2/g); this leads to a maximum bulk density error of $\pm 1\%$ for most marine sediments (Gerland and Villinger 1995). Another method is to determine the actual porosity of the measured sediment through an iterative process (Whitmarsh 1971) and to assign the correct Compton mass attenuation coefficients to the water and solid components. Both these techniques require some assumptions about the mineralogy of the sediment.

As with the other sensors, the whole operation is automated by the controlling computer. Sediment thickness is measured by the displacement transducers, as described previously. For this reason, the best results are obtained when the sampling points for the P-wave and gamma density measurements coincide; as the P-wave and gamma density systems are spaced 44 cm apart along the core, only sampling intervals of 1, 2, or 4 cm will achieve this.

Magnetic susceptibility

Magnetic susceptibility is a dimensionless parameter and is simply a measurement of how easily a substance can be magnetized (Dearing 1994). Specifically, the volume susceptibility κ is defined as:

$$\kappa = \frac{M}{H} \tag{3}$$

where M is the magnetization per unit volume induced by applying a magnetic field H to a material. Susceptibility can also be expressed as mass susceptibility (χ) by dividing the volume susceptibility by the material density. It is common practice to use volume susceptibility in marine sediments because variations in density between sediments are relatively small.

Volume magnetic susceptibility is a measurement of the concentration per unit volume of magnetizable material. Diamagnetic materials have negative values of κ, paramagnetic materials have small positive values of κ, and antiferromagnetic, ferrimagnetic, and ferromagnetic materials have small, medium, and large positive κ values, respectively. The total magnetic susceptibility of a sediment is therefore the sum of the susceptibilities of its constituent minerals (Carmichael 1982).

The split core logger uses a point sensor for split cores or a loop sensor for whole cores as described in Dearing (1994). The point sensor is mounted on an arm extending from the P-wave system and is moved into and out of contact with the sediment surface together with the P-wave transducers. The loop sensor remains stationary as the core is moved through it. Both sensors create a low-frequency (0.46 kHz) magnetic field and measure the magnetization of the material lying within it. The detectors output readings of magnetic susceptibility either in SI or in cgs units. The SI scale is generally used and gives units in multiples of 10^{-5} (e.g., a reading of 50 corresponds to a magnetic susceptibility of 50×10^{-5}). Strictly speaking, volume susceptibility measurements made with the above sensors should be normalized in the form of mass specific susceptibility; this takes into account the differing sample sizes and densities. This is not done in practice because, first, marine sediments exhibit relatively small variations in density, and second, core thickness changes by only a small amount down the length of a core in most cases. The sensor (either loop or point) is mounted between two main track sections in such a way that no magnetic or metallic components come close to it (Figs. 1 and 2).

The whole core loop sensor (internal diameter 14 cm) takes an average reading over a 28-cm length of core and is capable of admitting most common core sizes. It is calibrated by the manufacturer using a stable iron oxide, in this case for a standard sample diameter of 13 cm. Hence, there is a systematic error for whole cores deviating from this diameter, although most interest in magnetic susceptibility is in the relative values (e.g., for use in evaluating Milankovich cycles). Therefore, this system measures an apparent magnetic susceptibility in most cases.

By contrast, the point sensor receives 50% of its signal from the upper 3 mm of sediment with a maximum diameter of influence of 2 cm. Therefore, the point sensor gives much better resolution than the loop sensor. Unfortunately, it cannot detect through plastic core liners and, hence, cannot be used on whole cores. It is also calibrated by the manufacturer.

The manufacturer claims a linear deviation of less than 1% over the full scale (0–9999×10^{-5}) and an equipment precision of better than 1% for the loop sensor and better than 5% for the point sensor (Dearing 1994). The manufacturers quote a measurement precision of $\pm 0.01\%$ under ideal conditions. The absolute accuracy is more difficult to define and depends on temperature fluctuations and vibrations that may cause instrument drift. We use a 1-s measurement interval for the point sensor, as recommended by the manufacturer. A 10-s measurement interval is recommended when using the loop sensor on low-susceptibility (less than 50×10^{-5}) materials. We find that recorded values tend to fall in the range -10×10^{-5} to 900×10^{-5} (SI) for typical marine sediments.

Comparison of whole core and split core measurements

One advantage of split core logging is that it drastically reduces effects due to core slumping (Fig. 3). Boyce (1976) described the problem of measuring velocity and gamma density through a whole core section. Sediment slumping or sediment slurry is especially common in the upper parts of the core liner. This is caused by the facts that the softest, most unconsolidated sediments occur at the sediment–water interface and that they also have to travel the furthest up the core barrel when cored. As they move up the core barrel, a sediment and water slurry is formed. Figure 4 shows velocity and density data collected on

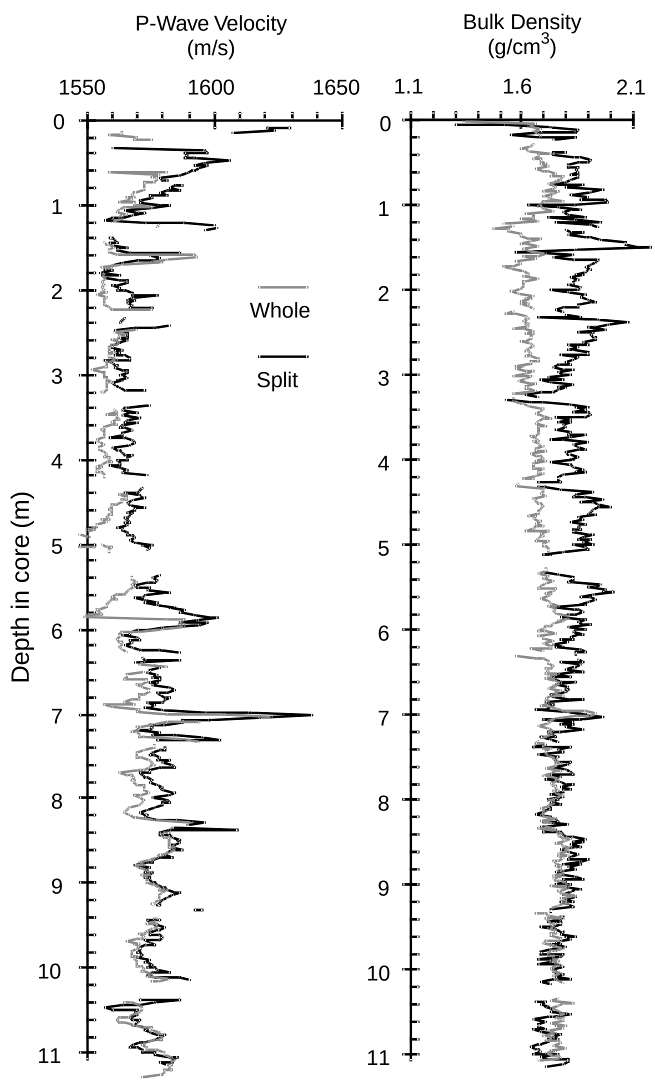


Fig. 4 P-wave velocity and gamma density data collected with the new core logger on the same core when whole (grey line) and when split (solid line). The effect of sediment slumping in the liner can be seen clearly towards the upper part of the core section, where it tends to predominate. The apparent velocity and density are much lower in the whole core than in the split core in this region; the whole core results are spurious as the calculations assume that the sediments fill the liner when in fact they do not

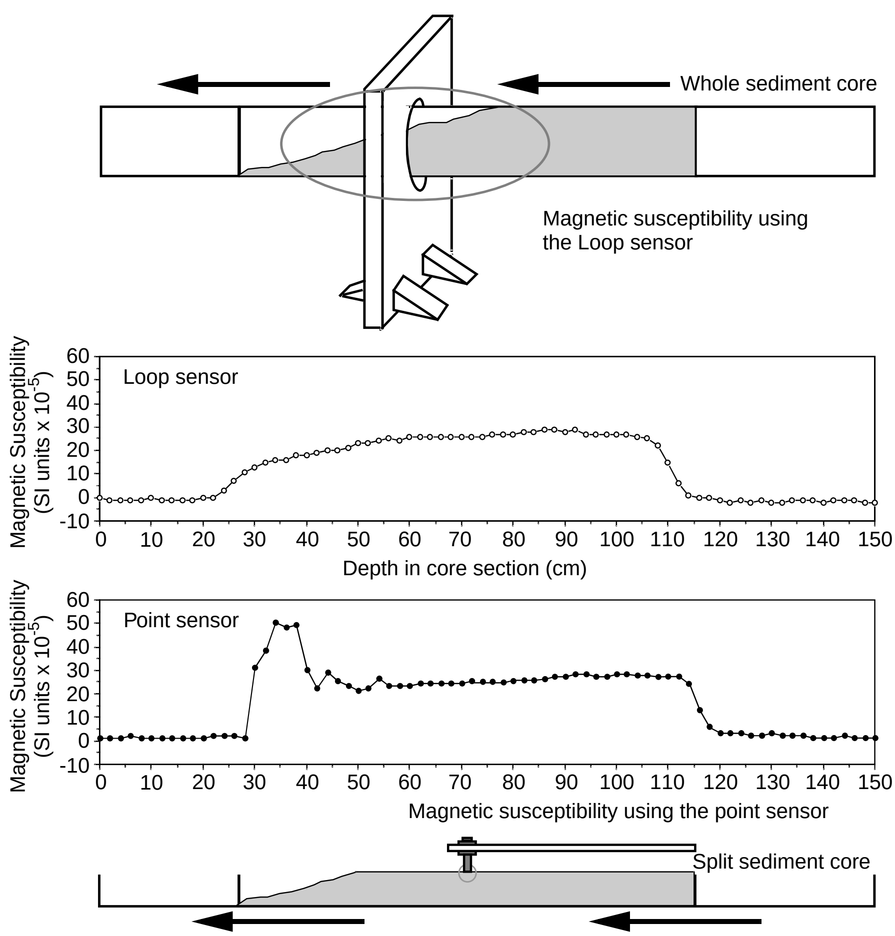
a partly slumped core when whole and when split; it clearly shows lower velocity and density values in the whole core (especially density) than in the split core in the slumped/slurry regions.

While the resolution of the P-wave and density sensors is the same for both systems, that of the magnetic susceptibility point sensor is much better than that for the loop sensor. Figure 5 shows the effect of slumping and resolution on the loop and point sensor magnetic susceptibility readings. The loop sensor readings show spuriously low values in the slumped region due to the sample volume change and also in the adjacent region of intact sediment due to its signal averaging over a larger portion of the core (Bloemendal et al. 1988) than for the point sensor. Conversely, the point sensor shows constant values for the undisturbed part of the core, and spurious values for the disturbed part, most likely due to poor contact with the irregular sediment surface. The increased resolution of the magnetic susceptibility system will be of added benefit for detailed stratigraphic interpretations.

The high accuracy and resolution of the split core logging measurements allow detailed studies to be carried out, such as the effect of core aging, as illustrated in Figure 6. Here, two separate data sets were collected on a North Atlantic core (mainly turbidite sediments) that was stored under ideal conditions after collection (4°C). It was logged once immediately after collection, then again 14 months later. The major effect on core deterioration is drying, which will occur more rapidly in high permeability sands and silts than in less permeable clays. Hence, we would expect to see more pronounced changes in the coarser sediments at the base of each turbidite layer than in the finer sediments. The results in this particular case show significant changes in velocity (at 4.5-m depth) and density (e.g., at 2.4-m depth), but these discrepancies do not correspond to the sand and silt layers. This may indicate that there is no appreciable aging of this core after 14 months. However, the variations observed could be a result of factors not related to age, such as handling disturbance. At the same time a significant proportion of the data appear unaffected. Clearly, more work is needed to quantify the effects of core aging.

At Southampton Oceanography Centre marine sediment cores are stored inside D-tubes at a constant temperature of 4°C, considered to be ideal storage conditions. Marine sediment cores stored in this manner (formerly at the Institute of Oceanographic Sciences, Surrey, England, and now at Southampton Oceanography Centre) showed no visible signs of deterioration (cracking and shrinkage)

Fig. 5 Comparison of whole core and split core magnetic susceptibility measurements. The loop sensor gives lower resolution readings than the point sensor as it averages over a core length of about 28 cm as opposed to 2 cm for the point sensor. Both sets of results are spurious in the slumped region, but the intact sediment region is better represented by the point sensor



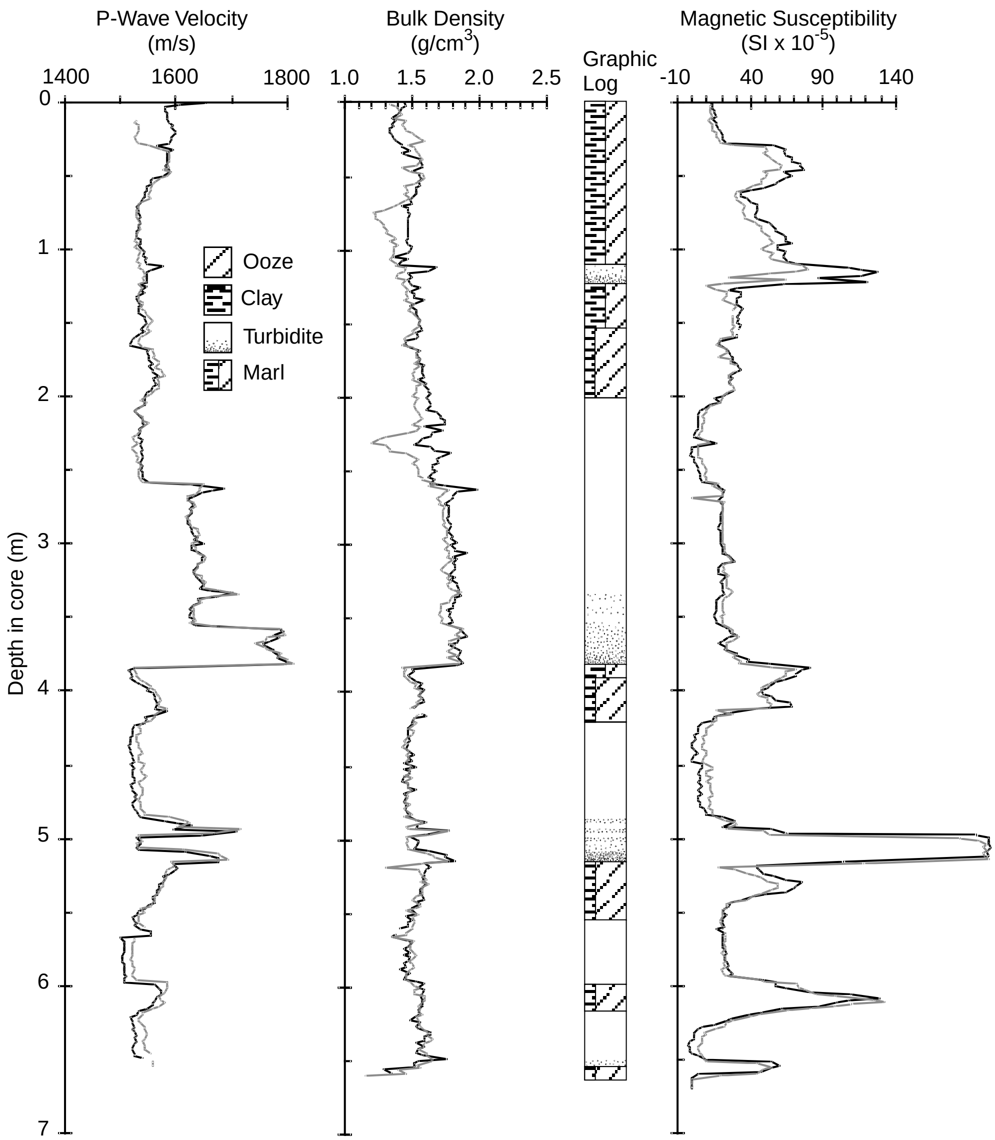


Fig. 6 Results for a North Atlantic split core logged soon after collection (solid line) and again after 14 months in cold storage at 4°C (grey line)

after 10 years, although cores stored for up to 20 years do show these signs of aging.

Conclusions

The new core logger measures P-wave velocity, bulk density, and magnetic susceptibility as a function of core depth. It enables archived split cores to be logged as well as whole cores, which gives much greater flexibility to core analysis programs. Moreover, split core logging gives more reliable readings than whole core logging as it eliminates most sediment slumping/slurry effects. It also gives higher resolution magnetic susceptibility values, which will be of value to paleoclimate studies and high-resolution stratigraphy in general.

The modular design of the logger enables new sensors to be added, such as full-color imaging and electrical resistivity, which are currently under development.

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