New techniques in sediment core analysis: an introduction

R. GUY ROTHWELL[1] & FRANK R. RACK[2]

[1]*National Oceanography Centre, Empress Dock, Southampton SO14 3ZH, UK (e-mail: rgr@noc.soton.ac.uk)*

[2]*Joint Oceanographic Institutions, 1201 New York Avenue, NW, Suite 400, Washington, DC 20005, USA*

Abstract: Marine sediment cores are the fundamental data source for information on seabed character, depositional history and environmental change. They provide raw data for a wide range of research including studies of global climate change, palaeoceanography, slope stability, oil exploration, pollution assessment and control, and sea-floor surveys for laying cables, pipelines and siting of sea-floor structures. During the last three decades, a varied suite of new technologies have been developed to analyse cores, often non-destructively, to produce high-quality, closely spaced, co-located downcore measurements, characterizing sediment physical properties, geochemistry and composition in unprecedented detail. Distributions of a variety of palaeoenvironmentally significant proxies can now be logged at decadal and, in some cases, even annual or subannual scales, allowing detailed insights into the history of climate and associated environmental change. These advances have had a profound effect on many aspects of the Earth Sciences, particularly palaeoceanography. In this paper, we review recent advances in analytical and logging technology, and their application to the analysis of sediment cores. Developments in providing access to core data and associated datasets, and data-mining technology, in order to integrate and interpret new and legacy datasets within the wider context of sea-floor studies, are also discussed. Despite the great advances in this field, however, challenges remain, particularly in the development of standard measurement and calibration methodologies and in the development of data analysis methods. New data visualization tools and techniques need to be developed to optimize the interpretation process and maximize scientific value. Amplified collaboration environments and tools are needed in order to capitalize on our analysis and interpretation capability of large, multi-parameter datasets. Sophisticated, yet simple to use, searchable Internet databases, with universal access and secure long-term funding, and data products resulting in user-defined data-mining query and display, so far pioneered in the USA and Australia, provide robust models for efficient and effective core data stewardship.

Sea-floor sediment cores are the fundamental data source for information on seabed character, depositional history and environmental change. Research into global climate change, slope stability, oil exploration, pollution assessment and control, surveying for laying telecommunications cables and offshore pipelines all rely on data obtained from marine sediment cores and samples (Table 1). Important oceanographic and earth science disciplines such as palaeoceanography rely on core material to determine past climate changes and changes in ocean circulation. Models of past climate changes can only be validated by examining the past record preserved in marine sediment and ice cores, and such records allow us to understand the past and predict the future world.

References to marine sediments occur in Ancient Greek and Roman texts, but it was not until 1773 that the first recorded sediment was recovered from the deep sea. In that year 'fine soft blue clay' was sampled with the first recorded deep-sea sounding made by Captain John Phipps on HMS *Racehorse* in 1250 m water depth on the southern margin of the Vøring Plateau north of Norway. Forty-five years later in 1818, Sir John Ross recovered 2.7 kg (6 lbs) of greenish mud from the floor of Baffin Bay, offshore Canada, using a deep-sea grab. This recovery from 1920 m water depth represents one of the first recorded successful substantial deep-sea sediment recoveries. In 1851 the first functioning submarine telegraph cable was laid across the Straits of Dover and the advent of submarine cable laying as a new means of intercontinental communication led to a rapid growth in the collection of deep-sea soundings and samples. However, it was not until the *Challenger* expedition of 1872–1876 that enough deep-sea samples were recovered to produce the first global sea-floor sediment map. Victorian intellectual curiosity led Sir Charles Wyville Thomson, Professor of Natural History at Edinburgh University, and his Canadian-born

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Table 1. *End users of core and sea-floor sample data*

Scientific research	Industry-related research	Training
Research into environmental change	Sea-floor mapping and surveys (ground truth)	Undergraduate, postgraduate and professional training
Palaeoceanographic research	Hydrocarbon exploration	
Studies of slope stability	National resource assessment	
Geochemical studies	Pollution control and assessment	
Geochronological studies	Environmental protection and monitoring	
Studies of sedimentary processes and dynamics	Surveying for laying submarine cables, pipelines and siting sea-floor structures	
Benthic surveys	Studies of acoustic response and defence applications	
Biological and productivity studies		

student John Murray to conceive an oceanographic expedition of global extent. They successfully persuaded the Royal Society to back such a voyage and the British Navy provided HMS *Challenger*, a three-masted square-rigged wooden ship of 2300 tons displacement and some 226 feet long overall, for the purpose. The *Challenger* expedition was the first large-scale expedition devoted to oceanography. During its 4-year voyage, the ship recovered a large number of sea-floor samples from 362 observing stations, spaced at uniform intervals, along the cruise track, which spanned 128 000 km. The initial analysis of these samples was made by John Murray who edited the *Challenger* reports following Wyville Thomson's death in 1882. In 1891, with his co-worker A.F. Renard, he published the milestone *Challenger* report on 'Deep-sea Deposits', the first comprehensive volume on sediments of the deep-sea floor (Murray & Renard 1891). This volume introduced many descriptive terms still used today such as '*Globigerina* ooze' and 'red clay', and provided a firm basis for further deep-ocean sediment studies.

A fundamental step forward in the recovery and investigation of deep-sea sediments was the invention of the gravity corer by German researchers. This allowed recovery of longer continuous sections of sediment, although these were generally restricted to 1–2 m in length. Gravity corers were used to collect several 2 m-long cores on the German South Polar expedition (1901–1903) and these were described by E. Philippi in 1910. These cores provided the first evidence that some deep-water sediments were stratified. From 1925 to 1938, Germany ran a number of oceanographic expeditions using the ship *Meteor*, which recovered several 1 m-long cores from the South Atlantic and Indian oceans. Wolfgang Schott used these cores to demonstrate changes in foraminifer species with depth, initiating the new field of palaeoceanography. The Swedish Deep Sea *Albatross* expedition of 1947–1949 saw another fundamental advance in the recovery of deep-sea sediments by deploying a new kind of coring device developed by Börje Kullenberg, a marine geologist working in Gothenburg, Sweden. This was the piston corer, an innovative modification of the traditional gravity corer, in which the coring tube fell past a stationary piston at the end of the wire. This mechanism expelled water from the falling tube above the piston admitting sediment from below. This allowed retrieval of much longer (typically 10 m long or more) and much less disturbed sediment cores. Acquisition of long piston cores made possible the study of Pleistocene ocean history and initiated the era of modern deep-sea sampling. Although other types of corer have been developed, piston coring still forms one of the main methods for sampling the deep-sea sedimentary record. Sizing up of this design has led to the development of giant piston corers, now capable of obtaining sediment cores of up to 60 m in length. In 1990, the French vessel *Marion Dufresne* obtained a 54 m-long piston core covering 4 Ma of sedimentation from the Indian Ocean – one of the longest piston cores so far recovered. However, it is only within recent years that we have understood the mechanics of coring process, especially in the taking of long piston cores. Thouveny *et al.* (2000) demonstrated through magnetic susceptibility measurements of sediment fabric and sedimentation rate studies of long piston cores from the Portuguese margin that the sequence recovered in some, if not all, long piston cores can appear up to 1.5–2 times longer when compared to the same sequence recovered by conventional piston cores on the same site. This is due to syringing or oversampling of the sediments in the upper portion of the core resulting from cable rebound that causes upward piston acceleration and a microfabric rotation to the vertical during the coring process. Skinner & McCave (2003) studied the coring mechanism from a soil mechanics perspective and confirmed that the upper 5–25 m of long piston cores are affected by such oversampling. They suggested that to get the least deformed record for stratigraphic analysis, a large diameter (D_c of *c.* 20–30 cm) square-barrel gravity corer for the top 10–12 m of the sediment section should be combined with a cylindrical piston corer for below -10 m sub-bottom.

The capability to routinely acquire long, undisturbed marine sediment sections has provided a major impetus to palaeoceanographic research and to the development of associated international core collection programmes. One of the best known of these is the IMAGES (International Marine Past Global Changes Study) programme, a global project, running since 1995, which organizes cruises to collect long piston cores specifically to gain greater understanding of the mechanisms and consequences of climatic change. Eleven international IMAGES coring cruises were completed between 1995 and 2003, collecting in total 11.5 km of core. As part of the programme, in 1996 IMAGES created a technical standing committee (called 'New Techologies in Sediment Imaging') to research new data acquisition tools and relationships with proxies.

The advent of the Deep Sea Drilling Project (DSDP) in 1968 took deep-sea sampling technology further and heralded a new era in the exploration of the deep-ocean sedimentary record. Using the dynamically position drillship *Glomar Challenger,* DSDP set out to recover long geological time duration continuous or semi-continuous sediment records from the world ocean. Prior to DSDP, the global inventory of cores containing pre-Quaternary sediments was less than 100. DSDP and its successor, the Ocean Drilling Program (ODP) which began drilling operations in 1985 using a new drillship with improved capabilities, *JOIDES Resolution*, have led to major advances in our understanding of Earth's history, the processes of plate tectonics, and the Earth's crustal structure and composition. The Ocean Drilling Program collected a little over 222 km of core from January 1985 to September 2003, which are stored at a number of repositories in the USA and at Bremen, Germany. Recently, international deep-sea drilling has embarked on a new phase with the advent of the Integrated Ocean Drilling Program (IODP, to run from 2003 to 2013), which builds upon the success of ODP and DSDP but expands the research of these programmes by using several drilling vessels, including riser, riserless and mission-specific platforms to achieve specific research goals. Specific research areas within IODP are the deep biosphere, environmental change, and solid earth studies and geodynamics (IODP 2001). Within IODP, the USA will continue to deploy a riserless vessel for 2-month drilling legs around the world. In addition, a riser vessel, *Chikyu*, supplied and operated by Japan, will provide a platform for long-term expeditions at specific locations. Mission-specific platforms for drilling in ice-covered and shallow-water regions will be operated by the European Consortium for Ocean Research Drilling (ECORD) as part of IODP. The first ever drill sites drilled through the ice-covered Arctic Ocean, implemented as part of the IODP programme, found evidence of a warm, ice-free Arctic during the Palaeocene–Eocene Thermal Maximum some 55 Ma ago, a precursor of conditions that may return in a greenhouse world of 2100 (Kerr 2004), a graphic example of how studies of cored marine sediments from the past can be used to predict conditions in a future world.

The great growth in core collection over the last five decades and the ever-increasing need to extract more high-resolution information from cores has led to the development of a range of often non-invasive, non-destructive, core-logging and imaging techniques (Table 2). These techniques provide researchers with automated instruments that can continuously and rapidly characterize sediments downcore in terms of their density, physical, magnetic, optical, geochemical and acoustic properties, providing far more measurements than ever could be reasonably obtained using traditional invasive analytical methods. Such logging instruments when used at sea provide immediate characterization of sediment properties, allowing cost-effective use of expensive sea time and almost immediate guides for stratigraphic correlation and further sampling. Although non-destructive core-logging techniques can, in some instances, be less precise than conventional laboratory analyses (for instance, X-ray fluorescence (XRF) data derived from XRF core scanners compared to destructive laboratory XRF analysis), this

Table 2. *Scientific applications of established and emerging non-destructive techniques for investigating sediment cores*

Technique	Instrument	Property measured	Example applications	Key references
Porosity logging	GRAPE (Gamma Ray Attenuation Porosity Evaluator)	bulk density	• porosity evaluation • water content	Evans (1965)
Multi-sensor core logging (MSCL)	Standard configuration MSCL (Geotek MSCL-S)	gamma ray attenuation	• measurement of sediment bulk density • stratigraphic correlation between cores • porosity measurement • measurement of water content	Schultheiss & Weaver (1992) Gunn & Best (1998) Best & Gunn (1999) Kayen *et al.* (1999)
		P-wave velocity	• seismic correlation • stratigraphic correlation • construction of synthetic seismograms • core quality assessment • determination of grain-size variations	
		magnetic susceptibility	• terrigenous material indicator • stratigraphic correlation between cores • turbidite identification and correlation • glacial–interglacial climatic cycle studies	
		electrical resistivity	• grain-size-related lithological information	
	Vertical MSCL (GEOTEK MSCL-V)	magnetic susceptibility (loop only) P-wave velocity gamma ray attenuation electrical resistivity	– see above – used to study properties of the sediment–water interface	
	XYZ MSCL (Geotek MSCL-XYZ)	magnetic susceptibility	– see above	
		spectrophotometry	• quantification of sediment lightness and sediment colour variability • determination and identification of palaeoclimatic cycles and events • detection and quantification of small-scale variability	
		natural gamma	• determination of lithological character • radioactive mineral determination and study • stratigraphic correlation	

Digital imaging	Film-based and digital cameras Signal processing of images Geotek GEOSCAN III colour imaging system Thermal imaging infrared cameras	visual spectrum photography temperature anomalies	• visual core description • colourimetry • compositional and mineralogical studies • determination of oxidation states • identification of gas hydrate and voids in cores and estimation of their volume • lithological characterization	Merrill & Beck(1995) Nederbragt & Thurow (2004) Nederbragt *et al.* (2006) Rogerson *et al.* (2006) Ford *et al.* (2003)
Non-imaging optical systems	Computer analysis of high-resolution images of cut core surfaces	grey reflectance	• identification of glacial–interglacial climate cycles • preliminary stratigraphies • productivity studies	Bond *et al.* (1992) Balsam *et al.* (1999)
	Commercial spectrophotometers and spectroradiometers	quantitative colour Munsell colour visible and NIR spectral reflectance	• recording small-scale variability • palaeoclimate studies • mineralogical and geochemical studies	Chapman & Shackleton (1998) Giosan *et al.* (2002) Helmke *et al.* (2002) Jarrard & Vanden Berg (2006)
	OSU reflectance spectroscopy logger (SCAT – split core analysis track)	UV, V, NIR spectral reflectance	• lithological characterization • identification of oxidation state	Mix *et al.* (1992, 1995) Ortiz *et al.* (1999*a*, *b*)
X-ray fluorescence core scanners	CORTEX core scanner	element concentrations from Al–U	• identification of geochemical variability downcore • identification and application of palaeoenvironmental proxies • identification and characterization of climatic deterioration • temporal variability in productivity (e.g. variation in Ba) • bed provenance and correlation • identification of chronostratigraphic markers • identification and characterization of volcanic ash and ice-rafted debris • identification and characterization of palaeosols in lake and delta cores • variability in redox-related element mobilization and relocation within sediments • distribution of industrial contaminants and their diagenetic relocation (e.g. arsenic and heavy metals)	Jansen *et al.* (1998) Zolitschka *et al.* (2001) Richter *et al.* (2006)

Table 2. *Continued*

Technique	Instrument	Property measured	Example applications	Key references
X-ray fluorescence core scanners (*cont.*)	ITRAX core scanner	element concentrations from Si–U	– see above	Croudace *et al.* (2006)
		digital X-radiography	• examination and identification of sedimentary structures • quantification of bioturbation • identification of dropstones and gas bubbles	
	Eagle µProbe	element concentrations from Al–U	– see above	Haschke (2006)
X-ray computed tomography	Medical-type petrophysical CT scanners	3D X-radiography of sediments	• sediment fabric studies • petrophysical characterization • granulometry • porosity and permeability studies • structure and density of sediments • determination of fracture and fissure patterns in rocks and consolidated sediments • characterization of slump and mass failure deposits • study of bubble formation and migration • characterization of methane hydrates	Hainsworth & Aylmore (1983) Petrovic *et al.* (1982) Vinegar (1986) Wellington & Vinegar (1987)
	Self-shielded portable petrophysical scanners	3D X-radiography of sediments	– see above	Freifeld *et al.* (2006)
Magnetic resonance imaging	Nuclear magnetic resonance laboratory instruments Schlumberger Combinable Magnetic Resonance Tool	Images of nuclear spin density or magnetic resonance relaxation times	• characterization of porosity, permeability and pore-size distribution • determination of sedimentary structures and heterogeneity • evaluation of fluid flow characteristics • growth habit studies of interparticle ice and methane hydrate	Osment *et al.* (1990) Kleinberg (1996) Kleinberg (1999) Chen & Song (2002) Chen *et al.* (2006) Kleinberg (2006)
Confocal macro/microscopy	Confocal scanning laser macroscope/microscope	Laser imagery over a wide range of fields of view and magnifications	• rapid imaging of cores and identification of areas of interest • sediment microfabric and microfossil examination • microscale mineralogical analysis • discrimination of compositional data through reflectance or fluorescence spectroscopy	Dixon *et al.* (1995) Ribes *et al.* (2006)

disadvantage is offset by statistical advantages derived from gaining far larger numbers of point data measurements and constantly improving processing techniques that improve the signal to noise ratio. Other advantages are rapidity of acquisition of datasets and relative lack of operator effort compared to laboratory analysis. These automated or semi-automated logging techniques have evolved rapidly and have been reviewed in a series of reports and papers. In July 1997, the French Research Institute for the Exploitation of the Sea (IFREMER), Brest, organized a Core Logging Workshop, under the auspices of the EU-funded CORSAIRES European Concerted Action (1996–1997), which reviewed developments in a wide range of logging methods (Auffret 1997). Shortly afterwards, the IMAGES standing committee on 'New Techologies in Sediment Imaging' produced an interim report surveying emerging trends in non-destructive measurements for the geosciences (Rack 1998). This was followed by a benchmark paper by Ortiz & Rack (1999) on non-invasive sediment monitoring methods reviewing current and future tools for high-resolution climate studies. Since then, development of established and new core analysis technologies and identification of detailed proxies for physical, geochemical and environmental processes have continued apace. In 2001, under the sponsorship of the Japan Agency for Marine Earth Science and Technology (JAMSTEC) and their programme Ocean Drilling in the 21st Century (OD21), a community workshop on 'Advances in Coring, Drilling and Non-Invasive Measurement Technologies for Palaeoceanographic Investigations: A Community Discussion on the State of the Art' was held at ICPVII (7th International Conference on Paleoceanography) in Sapporo, Japan. This workshop, supported by JOI/ODP and the IMAGES programme, was convened specifically to discuss calibration issues, data handling and how non-invasive measurements be best used to develop sedimentological and palaeoceanographic proxies. In September 2003, the community met again at Southampton Oceanography Centre, UK, to review current developments in core logging and imaging. In this paper we review current developments in established and emerging technologies for sediment core research, particularly those in recent years.

The development of core-logging systems

During the last three decades, the development of non-destructive core-logging techniques has revolutionized our capability to analyse sediment properties and gain insights of environmental, geochemical and physical processes through characterization of detailed proxies. Previously researchers had to extrapolate using low-resolution data of variable quality, but the development of high-resolution core-logging systems means that scientists today can rapidly acquire a wealth of high-quality, co-located, closely spaced measurements that provide details of downcore variability at centimetre, millimetre and, even, micrometre scales. Such technology makes it possible to discriminate environmental and climatic variability at sub-Milankovitch, millennial, centennial, decadal and, even, subdecadal timescales. At the same time, our ability to visualize sediment in two or three dimensions has increased markedly with the development of new generation digital cameras, high-resolution digital X-radiography, three-dimensional X-radiography (CT scanning), magnetic resonance imaging, confocal laser macro/microscopes and wavelength-specific visualization. Another major advance is the capability to recover cores and preserve cores at *in situ* pressures, allowing study of subsurface biota and clathrates under real subsurface conditions, providing unprecedented insights into the deep biosphere and methane diagenesis and clathrate stability.

Early (post World War II) studies of physical properties of marine sediments were aimed at addressing engineering requirements for designing sea-floor structures and platforms or to support military research or geophysical mapping. Consequently, such studies tended to concentrate on parameters such as index properties and sediment shear strength to understand sediment consolidation and its response to loading, or determining the acoustic properties of sediments and their interaction with sound waves. Bulk sediment properties were routinely studied during the early DSDP legs, but the resulting data were often compromised due to poor sample recovery, drilling-induced core disturbance and poor stratigraphic resolution. However, as early as 1979, Mayer demonstrated in cores from the equatorial Pacific that changes in key physical properties, specifically saturated bulk density and porosity, related to changes in carbonate content and hence to climate variability (Mayer 1979). During the 1980s DSDP/ODP drilling technology improved significantly. The development of the Hydraulic Piston Corer (HPC) and the Advanced Piston Corer (APC) as standard ODP drilling technology (Storms *et al.* 1983; Deep Sea Drilling Project 1984) improved core recovery and reduced core disturbance considerably, making continuous logging a realistic option for ODP cores. The first stratigraphic application of magnetic susceptibility measurements, to determine changes in magnetic mineral concentrations and interpretation of variability in palaeoenvironmental terms, was made by Bloemendal (1983), soon after the introduction of the HPC, on cores from DSDP Site 514 in the SE Atlantic. Since then there has been rapid expansion in this type of investigation, with progress from discrete low field magnetic susceptibility measurements made on samples removed from cores and stored for measurement in small plastic cubes, to continuous palaeomagnetic profiling made directly from the surface of split sediment cores or using long U-channel samples.

The possible near real-time availability of detailed continuous physical property logs has allowed detailed stratigraphic correlation of sequentially recovered cores whilst still at sea. On ODP Leg 138, non-invasive sediment logging was used to monitor core recovery and the contained stratigraphy from multiple drill holes to ensure full recovery of the target sequence (Hagelberg *et al.* 1992, 1995). Intercomparison of GRAPE (Gamma Ray Attenuation Porosity Evaluator), diffuse reflectance and P-wave measurements, obtained through automated logging, allowed all cores in each drill hole to be placed on a new depth scale in their correct stratigraphic position, producing a composite section that allowed drillers to recover potentially missing sequences. This strategy repeated at other ODP sites has produced high-quality data allowing detailed core log integration and the development of an orbitally tuned timescale for much of Tertiary time.

Present-day researchers have available a varied suite of technologically advanced, often non-destructive, core-logging and imaging techniques to extract maximum environmental information from marine sediment records (Table 2). Several of new core imaging technologies that have emerged in the last decade (e.g. X-ray computed tomography, magnetic resonance imaging, confocal microscopy) were originally developed for, and have long-standing, medical applications.

Historical development of core-logging systems

The development of core-logging can be traced back to the 1940s with the first use of wireline logging in boreholes. Pointecorvo (1941) first used gamma-ray attenuation to estimate sediment density in logging oil wells. Similar methods were applied to soils by Bernhard & Chasek (1955). In the 1950s and 1960s, the Schlumberger Well Surveying Corporation (now Schlumberger Ltd) pioneered wireline logging of boreholes with the development of their Formation Density Logger, a gamma-ray-based wireline density logging tool. One of the first core-logging systems that logged actual core on an automated track was the GRAPE system developed by Evans (1965). This instrument compared the attenuation of gamma rays through a core section with that through an aluminium standard, to make incremental measurements of bulk density downcore. The absorption and scattering of gamma rays by elements in the sediment is determined by the mass absorption coefficient, which is a function of an element's atomic number to mass ratio (Z/A). Most elements found in deep-sea sediments have a Z/A of *c.* 0.5, but hydrogen found within sea water has a Z/A of *c.* 1, allowing porosity to be evaluated. The GRAPE logger was used from DSDP Leg 1 and continues in use today. An automated track for making automated incremental core physical property measurements was permanently installed on the ODP drillship *JOIDES Resolution*. Over time, other sensors were added to this track. Schultheiss & McPhail (1989) added a means of characterizing compressional sound-wave velocity (P-wave) on ODP Leg 108. This provided data useful for seismic and stratigraphic correlation, as well as for constructing synthetic seismograms and useful data for assessing quality of uncut cores. On ODP Leg 115, Robinson (1993) used a loop sensor to measure magnetic susceptibility, a very useful indicator of terrigenous material with applications in correlation, provenance and climatic studies. These new sensors and applications resulted in a multi-sensor logging track that was the precursor to modern systems.

Modern core-logging systems

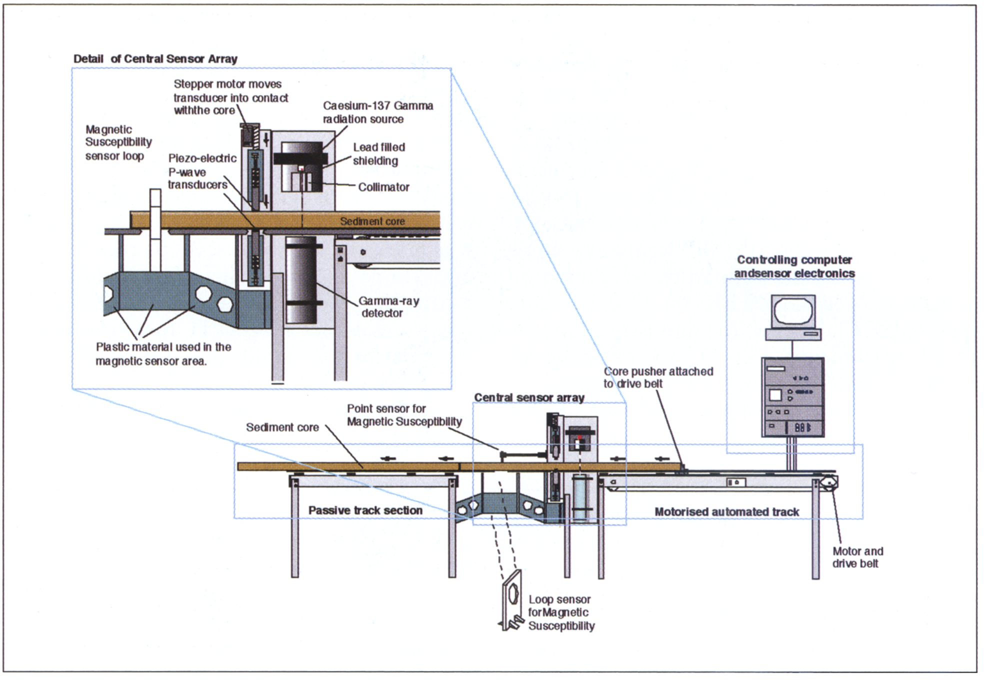
The development of automated core-logging systems over the last four decades has been rapid and such instruments are now in routine use. Most types now make measurements on whole or split sediment cores of specific physical or chemical parameters and the resolution of measurement has moved continually higher, producing rapidly acquired high-quality data. Common types in use include multi-sensor core loggers, acoustic logging systems and elemental scanners.

Multi-sensor core loggers

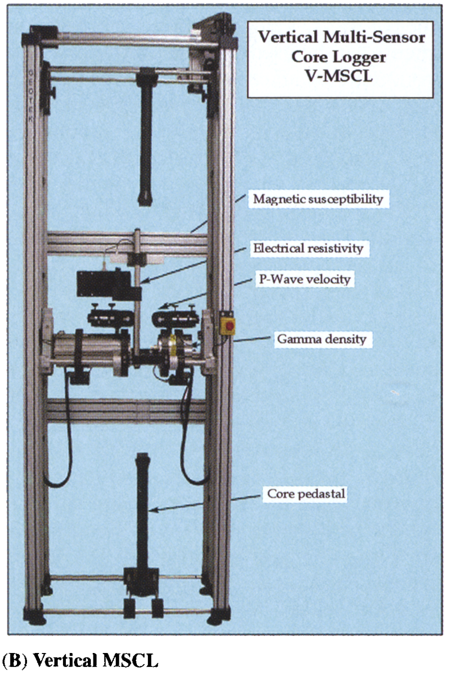
Automated tracks, as used on DSDP/ODP, provided ready and convenient platforms for a variety of non-destructive sensors and logging tools for physical property measurement leading to the commercial development of multi-sensor core loggers. Modern multi-sensor core loggers (Weaver & Schultheiss 1990; Schultheiss & Weaver 1992; Gunn & Best 1998) produce routine, high-quality incremental measurements of gamma-ray attenuation bulk density, P-wave velocity, natural gamma and magnetic susceptibility, and are capable of resolving subtle changes in sediment properties of geological significance. The GEOTEK multi-sensor core logger (MSCL) is now the industry standard with 84 instruments (Fig. 1), operating worldwide by June 2005. The range of parameters that can be measured using the standard logger configuration includes P-wave velocity, wet bulk density (via gamma attenuation method), magnetic susceptibility, electrical resistivity, colour imaging and gamma spectroscopy. Typically, the MSCL can log material at rates of $12\,\mathrm{m\,h^{-1}}$ and at sampling intervals of down to 1 mm. It can analyse either whole or split cores, which for magnetic susceptibility measurements has advantages both ways as point-sensor magnetic susceptibility measurements provide high spatial resolution, while the whole-core magnetic susceptibility loop sensor has a higher signal to noise ratio and so is better for measuring sediments with low magnetic susceptibility (Gunn & Best 1998; Ortiz & Rack 1999). A major improvement in recent years is the replacement of the P-wave transducer mechanism, which previously rose and fell to couple with the sediment after each incremental core movement with a roller mechanism (acoustic rolling contact – ARC – transducers). This provides better sediment contact, and improves the consistency of the acoustic coupling between the core liner and the transducer during the logging process. This arrangement improves data quality and consistency, and removes the necessity and inconvenience of using coupling fluids (previously sprayed water) which eliminates data dropouts caused by operator error. Additional sensors currently in development for multi-sensor loggers include radar scattering (for determining water content), ultraviolet, visible and infrared spectroscopy (for mineralogy), permeameters (for measuring permeability), high-frequency acoustic imaging (for porosity and grain size) and X-ray imaging (for determining sediment structure). A configuration that can log cores vertically (called MSCL-V) has been developed by GEOTEK and is designed for cases where the properties of the sediment–water interface need to be studied, or for installation in laboratories or ships where available space is limited (Fig. 1). In this system a sensor platform moves, under motor power, either in manual or computer control along the complete vertical length of the core section. The normal logging direction is from top to bottom. The sensor platform normally contains the systems required for measuring P-wave velocity, gamma density and magnetic susceptibility. Another recent innovation is an *XYZ* logging system on which several split-core sections can be laid out on a frame and magnetic susceptibility, using a Bartington point sensor, natural gamma and spectrophotometer spectral measurements can be made incrementally and automatically over successive core sections (Fig. 1). This system can be set up and left to run overnight enabling greater core throughput and data collection with time. The collection of large amounts of core in many present-day coring programmes and the necessity to analyse these quickly, often with limited manpower, means that core loggers that can automatically analyse several core sections and run unattended overnight offer great advantages in cost-effective and time-efficient data collection. Such instruments are a major innovation in data acquisition.

The data collected by multi-sensor core loggers can be related to sediment character in a number of ways. Velocity–density/porosity measurements can be used to infer lithology in many environments as siliceous, calcareous and terrigenous sediments group into specific fields when P-wave velocity is plotted against bulk density (Hamilton 1976; Ortiz & Rack 1999, fig. 5). Weber *et al.* (1997) and Weber (1998) used acoustic impedance (the product of bulk density and P-wave velocity) as a grain-size estimator in carbonate-free sediments. P-wave data also allow identification of grain-size variation through acoustic properties, being particularly useful in identifying sand and silt interbeds. However, core-logging measurements of physical properties differ considerably from *in situ* values due to pressure reduction, porosity rebound, and changes in sediment rigidity due to release of overburden pressure and temperature changes during core recovery. Indeed, density variations may relate to changes in grain size and packing rather than changes in lithology, as demonstrated by Rack *et al.* (1996) and Rack (1997) from ODP sites 909 (Fram Strait, Arctic Ocean) and 980 (Feni Drift, Rockall, NE Atlantic) where peaks in density correlated with increased ice volume, through increased delivery of poorly sorted ice-rafted debris to the seabed.

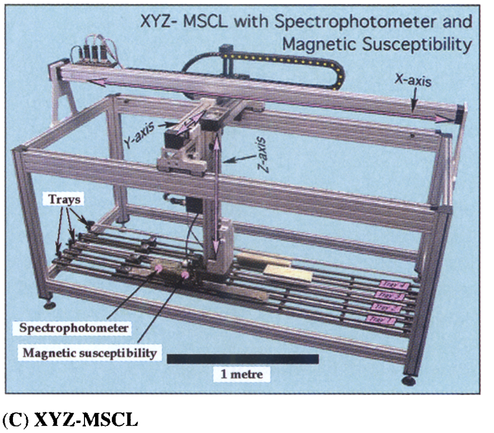
One property now routinely measured using multi-sensor loggers is magnetic susceptibility, which relates to sediment composition. Sediment



(A) MSCL – Standard configuration



(B) Vertical MSCL



(C) XYZ-MSCL

Fig. 1. The Geotek multi-sensor core logger, shown in its current three configurations. The standard configuration (**A**) can measure sediment bulk density through gamma-ray attenuation, P-wave velocity, magnetic susceptibility and electrical resistivity. The vertical configuration (**B**) is used where there are space constraints or a need to study properties of the sediment–water interface. The *XYZ* multi-sensor core logger (**C**) is a repository tool that allows automated measurement of a number of sections on unattended runs.

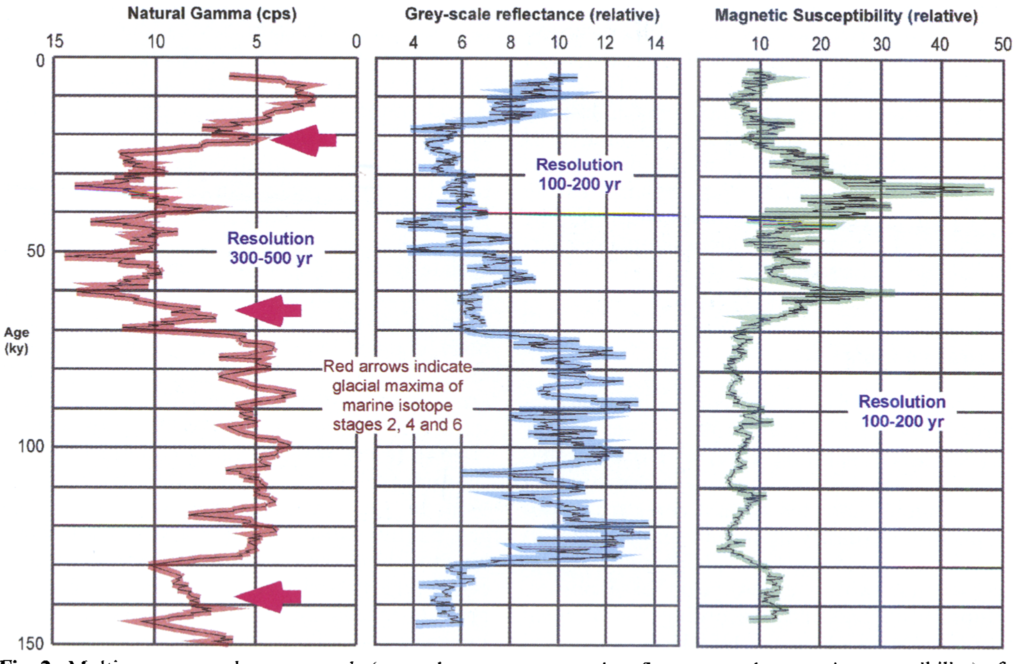


Fig. 2. Multi-sensor core logger records (natural gamma, grey-scale reflectance and magnetic susceptibility) of the last 150 ka (MIS 1–6) of archived half-core from DSDP Site 594. The site is located at latitude 45 °S, SW Pacific Ocean, east of the South Island of New Zealand. The site lies just south of the Subtropical Front, at a water depth of 1000 m beneath north-flowing Antarctic Intermediate Water. During glacial periods, a mountain ice cap developed on the Southern Alps and melt waters delivered abundant terrigenous mud to Site 594. As first described by Nelson *et al.* (1985), alternations in the core between biopelagic carbonate and terrigenous mud therefore record a striking climate cyclicity. Geophysical scanning, especially the natural gamma record (cf. Carter & Gammon 2004), confirms the macroscopic lithological pattern but provides a far higher resolution climate record, at centennial scale for the datasets shown and at decadal scale for the colour imagery (not shown). The core scans were performed at the West Coast Core Repository at Scripps Institute of Oceanography, USA, using a GEOTEK MSCL-*XYZ* system, which, after loading, is capable of unsupervised collection of data from a full 10 m-long DSDP or ODP core.

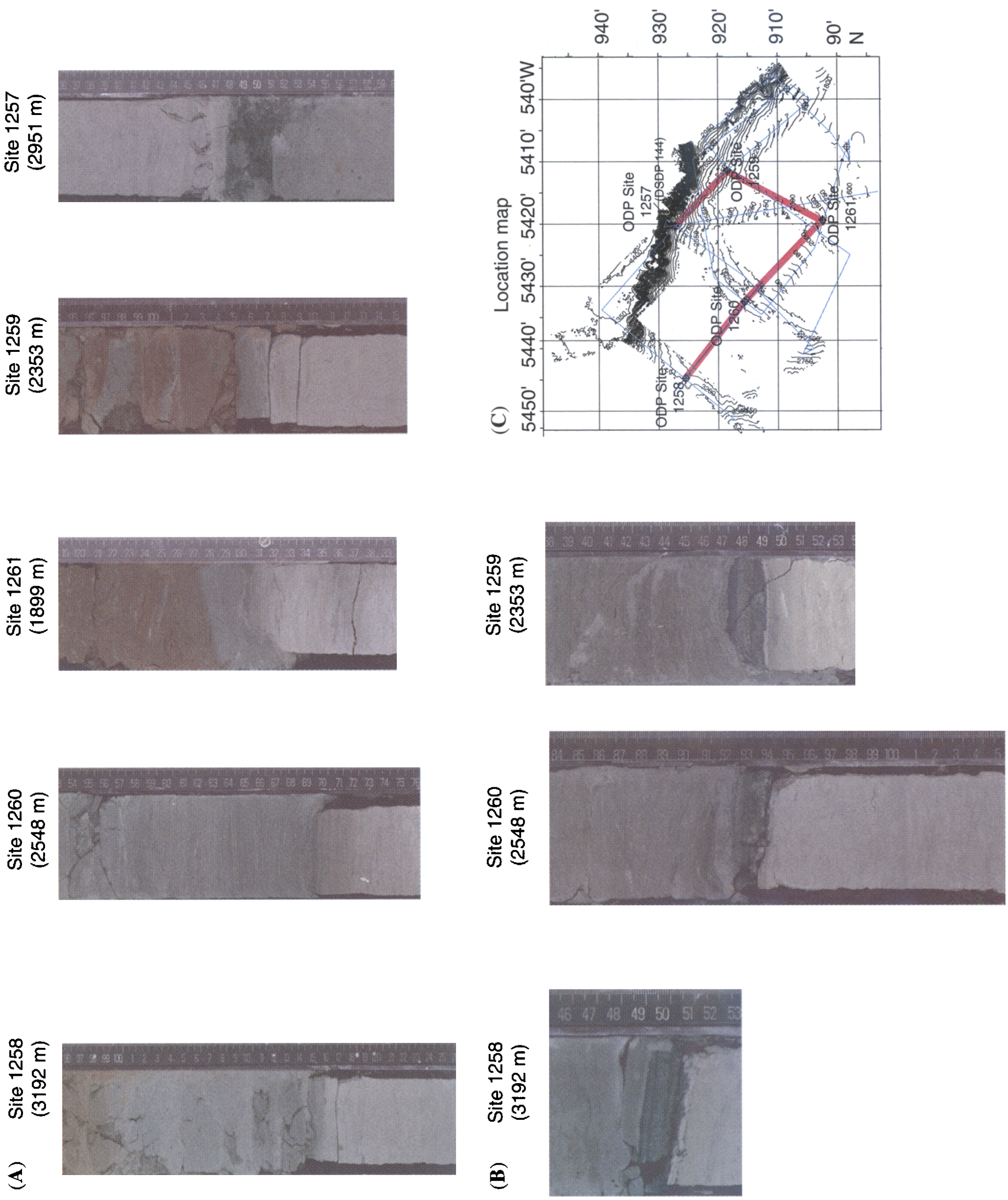
containing abundant ferro- or paramagnetic minerals (e.g. magnetite, pyrrhotite, hematite, olivine, biotite, pyrite, and iron-oxide-stained rock and mineral fragments) show high magnetic susceptibility, whilst biogenic material, such as calcite and silica, and quartz and feldspar show low or even negative magnetic susceptibility values (Robinson 1993). Relative changes in magnetic susceptibility and absolute values can thus be important parameters relating to sediment provenance, palaeoclimate, bottom-water flow conditions and regional stratigraphy (Fig. 2). Chi & Mienert (1996) and other authors have demonstrated the value of GRAPE density and magnetic susceptibility in identifying Heinrich Events in marine sediments, and the importance of these parameters in reconstructing climatic changes and related events in the Late Pleistocene.

Most stratigraphic applications of MSCL logs rely on the relative values of logged parameters for detecting geological events. However, absolute MSCL parameters are also of great potential value. Measurement of sediment bulk density and P-wave velocity downcore using multi-sensor core loggers allows acoustic impedance to be calculated from the product of velocity and density. These data are important for quantifying sound propagation through the sea floor and reverberation modelling (Best & Gunn 1999). However, there are difficulties in using absolute parameter values measured using MSCL logging. Gerland & Villinger (1995) and Weber *et al.* (1997) show that gamma density MSCL measurements must be calibrated to give meaningful results as they are susceptible to significant instrument errors. Best & Gunn (1999) proposed using a short length (*c.* 24 cm) stepped aluminium core placed in a water-filled sealed section of standard piston core liner as a standard calibration tool for the MSCL to simply quantify systematic errors during MSCL logging and intercalibrating MSCLs at different laboratories. Aluminium is chosen as its density ($2.70\,g\,cm^{-3}$) is not too dissimilar to quartz ($2.65\,g\,cm^{-3}$) and calcite ($2.71\,g\,cm^{-3}$), both common minerals in marine sediments. The steps in the block simulate different porosity sediments.

Digital imaging

Sediment cores can be difficult to photograph, particularly if the core surface is wet and/or uneven. After splitting cores can oxidize and change colour, losing important information on their original character. Even if cores are photographed immediately after splitting using traditional film-based cameras, the emulsion dyes may change within a few years of exposure, compromising accurate recording for archival purposes (Merrill & Beck 1995). However, digital images preserve accurate colour data indefinitely, allowing quantitative study of what is often an ephemeral physical property long after the cores were collected. The wide availability of affordable digital cameras and application of digital imaging to traditional film-based techniques (visual spectrum photography, X-radiography) means that images can now be rapidly acquired, stored and distributed electronically, and analysed using universal data-processing/data-mining tools. The visible spectrum of light (400–700 nm) is used for visual core description where sedimentary structures, bioturbation, layer thickness, textures and fractures are recorded. It is also used for colorimetry, where colour values are quantitatively recorded (e.g. colour space, x, y, Y; $L^*a^*b^*$, Munsell notation) by spectrophotometers that are either hand-held or integrated into an automated logging tool. Traditional film-based systems (particularly transparencies) have high sharpness and can record and reproduce a wide range of colours. The relative sensitivities (speeds) of the photosensitive layers are balanced, such that properly colour-balanced images result when scenes illuminated by the reference scene illuminant are photographed. With digital imaging, the image is captured using a digital camera, the signal processed (typically on a computer workstation), and the image formed and displayed on a video monitor. The spectral power distribution of a colour stimulus is generally a product of the spectral power distribution of a light source and the spectral reflectance of an object (as a function of wavelength). Several digital imaging systems are now in use. The Geotek GEOSCAN III calibrated colour core imaging system collects digital images using a line-scan camera linked to the MSCL core conveyor stepper motor to generate synchronous output of image data. These resulting image data can then be integrated with other MSCL data, making it possible to carry out a wide range of statistical and multivariate analyses. Individual interference filters in front of each of the three CCD (charge-coupled device) line arrays within the camera body, coupled with appropriate calibration protocols, ensures that colour from each CCD array is calibrated and non-overlapping. High-resolution images are created that can be analysed in terms of three colour components, irrespective of the time, place or the MSCL system used. In this way, image data from institutions around the world can be compared and combined without the need for reference to Munsell colour charts and ensures laboratory intercalibration. During ODP Leg 207, the Palaeocene–Eocene and Cretaceous–Tertiary boundary were drilled on the Demerara Rise, western Altantic (Erbacher *et al.* 2004). Both these important boundaries have dramatic lithological expression at the sites drilled (Fig. 3). The Palaeocene–Eocene (P–E) boundary occurs at the base of an approximately 30 cm-thick greenish clay bed that is an unique lithology at each site where it is present. The clay may record the shoaling of the calcium carbonate compensation depth following the P–E boundary event and is thought to coincide with the benthic foraminifera extinction event and a carbon isotopic excursion

Fig. 3. (**A**) Close-up photographs of the Palaeocene–Eocene (P–E) boundary drilled at five drill sites on ODP Leg 207. The boundary occurs at the base of an approximately 30 cm-thick greenish clay bed that is a unique lithology at each drill site. The clay layer is thought to record the shoaling of the CCD following the P–E transition and is thought to coincide with a benthic foraminifera extinction event and a carbon isotope excursion. (**B**) Core photographs of the Cretaceous–Tertiary (K–T) boundary as drilled at three drill sites on ODP Leg 207. The boundary is marked by an ejecta layer, just under 2 cm thick, composed of normally graded green spherules, interpreted as ejecta from the K–T Yucatan bolide impact. Both the P–E and the K–T boundaries can be identified and correlated at the drill sites using core images due to their consistent lithological character. (**C**) Map showing the locations of the Leg 207 drill sites on the Demerara Rise, offshore of Suriname. Water depths are given in metres. From Shipboard Scientific Party (2004 in Erbacher *et al.* 2004).


(A)
Site 1257
(2951 m)
Site 1259
(2353 m)
Site 1261
(1899 m)
Site 1260
(2548 m)
Site 1258
(3192 m)
(B)
Site 1259
(2353 m)
Site 1260
(2548 m)
Site 1258
(3192 m)
(C)
Location map
5450'
5440'
5430'
5420'
5410'
540'W
940'
930'
920'
910'
90'
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ODP Site
1257
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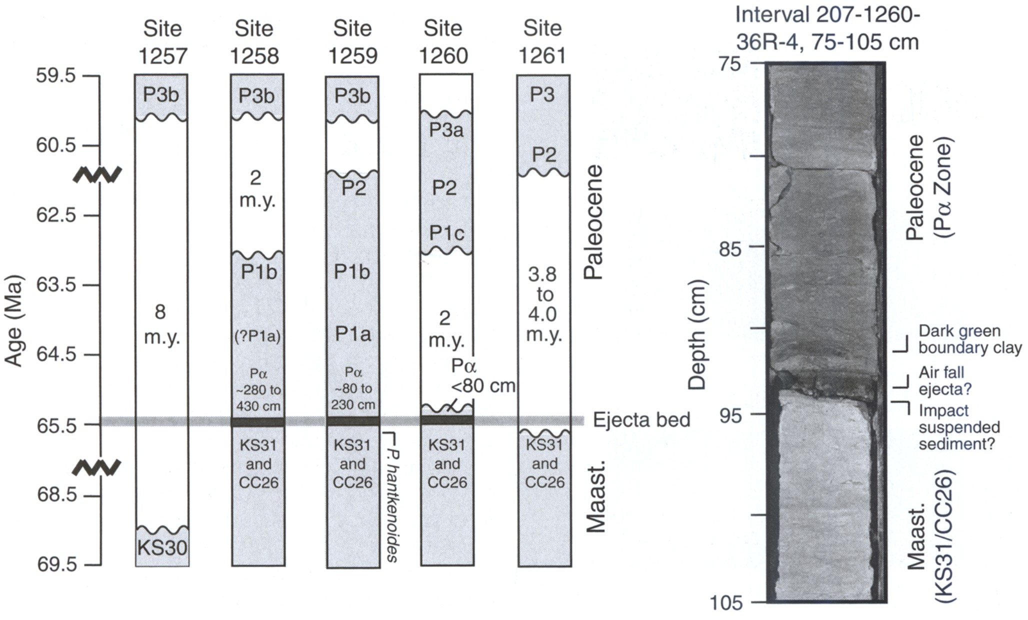


Fig. 4. The Cretaceous–Tertiary (Late Maastrichtian–Danian) boundary at Site 1260 drilled on ODP Leg 207 with interpretation. Cretaceous and Palaeogene planktonic foraminiferal zones are also shown for drill sites 1257–1261, across the K–T boundary. From Shipboard Scientific Party (2004 in Erbacher *et al.* 2004).

(Erbacher *et al.* 2004). The Cretaceous–Tertiary boundary (K–T) also shows a remarkably consistent character at the three sites where it was drilled (Fig. 3). The boundary is marked by an ejecta layer, just under 2 cm thick, composed of normally graded green spherules, interpreted as ejecta material from the K–T Yucatan bolide impact (Fig. 4). Both the P–E and K–T boundaries can be correlated at the ODP Leg 207 drill sites using core images due to their consistent lithological character.

Colour has been shown to be a highly diagnostic property of marine sediments. Lightness is a robust indicator of certain sediment components such as carbonate, iron-bearing minerals (e.g. goethite, hematite, pyrite), free iron and clay. Colour can also give information on the oxidation state of iron (e.g. Mix *et al.* 1995; Giosan *et al.* 2002). Rogerson *et al.* (2006) demonstrate the potential of colour logging in developing an initial chronostratigraphic model for a high-resolution record from the late Quaternary using a core from the western Gulf of Cadiz (SW Spain). Nederbragt *et al.* (2006) discuss methods for extracting calibrated colour values from digital images of sediment core surfaces, which can be correlated with geochemical composition. In the carbonate-poor laminated sediments studied, total organic carbon had the dominant effect on colour (Nederbragt *et al.* 2006).

A recent development in imaging sediment cores is the application of infrared (IR) thermal imaging. On ODP Leg 201, a Thermacam thermal imaging IR camera was used to image methane hydrate on immediately recovered core from the Peru margin (D'Hondt *et al.* 2003; Ford *et al.* 2003). This was the first time IR cameras were used to identify gas hydrate prior to its dissociation, which usually occurs rapidly due to pressure release and temperature increase. Hydrate dissociation is an endothermic process, creating a negative temperature anomaly (cold anomaly, on average 4 °C cooler) that can be rapidly imaged using an IR camera (Ford *et al.* 2003). Hydrate volume could be estimated from the processed images. In addition, voids in the sediment could be detected as warm anomalies. Another development of IR imaging also explored on ODP Leg 201 was its possible use in lithological characterization of ambient-temperature cores, due to slight variation in thermal emission properties reflecting differences in sediment composition or water content. Dissociation of the hydrate resulting in the creation of gas expansion voids caused increased variability in resistivity, P-wave velocity and natural gamma-ray emission logs. Although the data produced

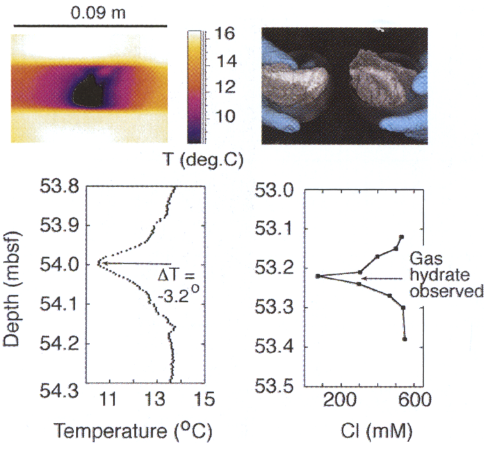


Fig. 5. The relationship between a thermal anomaly in a core containing clathrate, from the Cascadia continental margin, offshore Oregon, drilled during ODP Leg 204, and chloride concentration anomalies. From Shipboard Scientific Party (2003 in Tréhu *et al.* 2003).

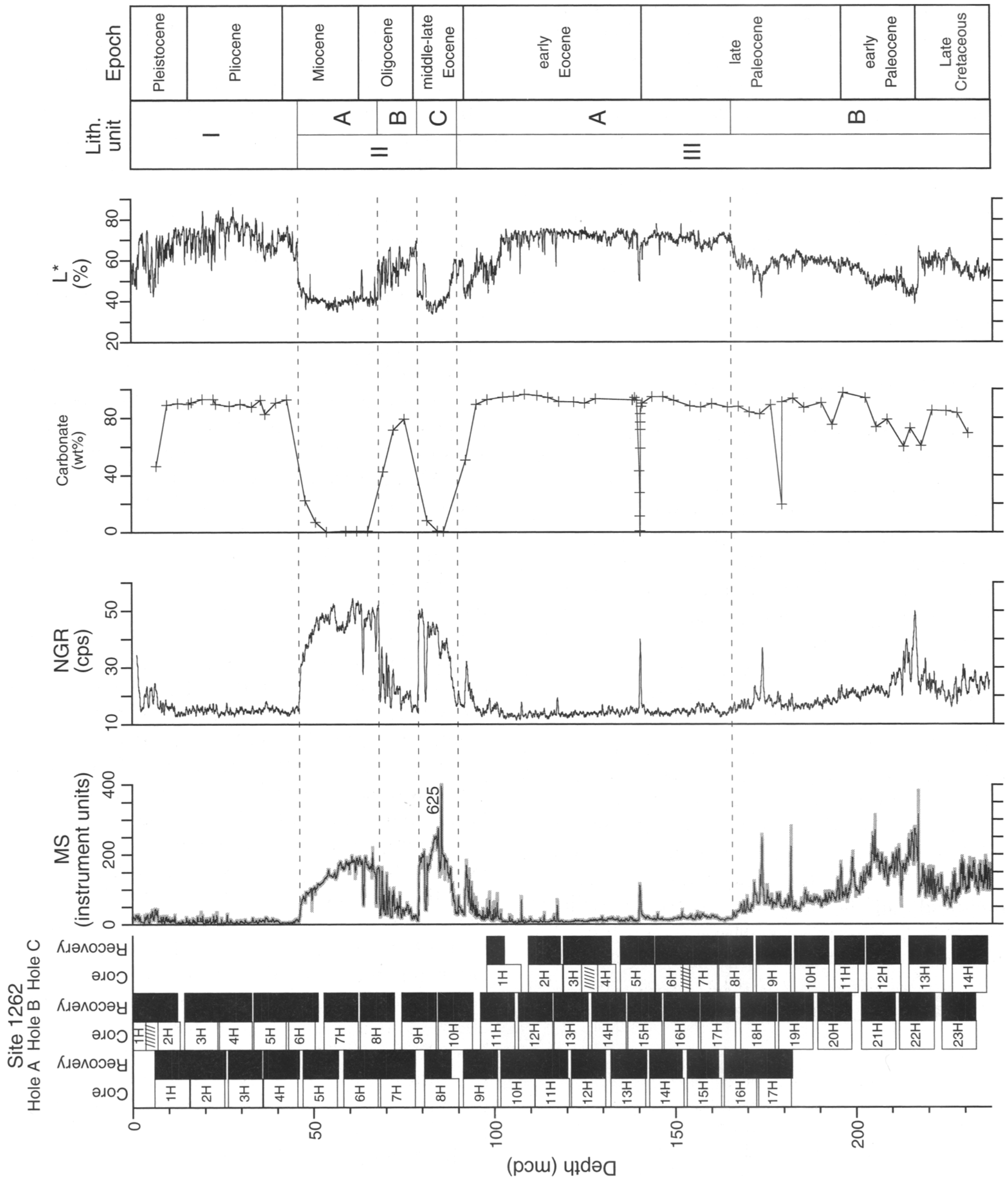
are essentially qualitative, careful monitoring of core-handling times and ambient temperature, integration of the IR camera with a logging track, standardization of image analysis software and quantitative treatment of emissivity differences between different sediment types would make a more quantitative method (Ford *et al.* 2003). During ODP Leg 204, extensive use was made of IR cameras immediately after core retrieval to determine the distribution and texture of gas hydrates recovered from the Cascadia continental margin, offshore Oregon (Tréhu *et al.* 2003). Thermal anomalies recorded by the IR imaging camera provided a robust record of gas hydrate distribution that could be calibrated using estimates of *in situ* gas hydrate concentration determined from pressure core samples and chloride concentration anomalies (Fig. 5). Infrared imaging of hydrate-bearing core seems a valuable potential tool for gas hydrate identification and quantification.

Non-imaging optical systems

A great deal of useful scientific information can also be gathered from split sediment cores using non-imaging optical systems. These include grey reflectance measurements and diffuse spectral reflectance analysis. Grey reflectance analysis reduces information from a black and white core photograph to a single downcore profile with relative intensities ranging from 0 (pure white) to 255 (black). Grey reflectance changes in deep-sea sediments are commonly related to variations in the calcium carbonate/detrital ratio, which in Plio-Pleistocene pelagic sequences are often broadly related to productivity variations during glacial–interglacial climatic cycles. Such measurements have been calibrated by oxygen isotope analysis and micropalaeontological studies, providing a useful, rapidly acquired, chronological tool (Broecker *et al.* 1990; Bond *et al.* 1992) that can be acquired using relatively simple instrumentation. Greyscale (lightness) has been successfully used for developing preliminary stratigraphies on long sediment cores, particularly those collected during the Ocean Drilling Program (e.g. Ortiz *et al.* 1999*a*, *b*; Grutzner *et al.* 2002) (Fig. 6).

Sediment colour is a major indicator of composition and detailed quantitative colour data, showing character and variability beyond that assessable with the naked eye, can be collected by modern spectroscopy instruments. These include commercially available spectrophotometers, such as those produced by Minolta (the CM-2002 and CM-2022 models are the most commonly used in core analysis). These compact hand-held instruments combine measurement, data-processing and display functions in a single unit, and are ideally suited for laboratory and shipboard use. The data can be displayed in a variety of ways, graphically as spectral reflectance or colour difference, numerical absolute and/or difference values for standard defined colour spaces, or as Munsell notation. When attached to jigs or tracks to allow incremental measurement downcore, colour variation related to climate variability on scales as small as 1 cm have been documented (e.g. Chapman & Shackleton 1998). The Geotek XYZ-MSCL, where a spectrometer is a standard sensor, allows automated collection of such data (Fig. 1).

Reflectance spectroscopy has been widely used in mineralogical and geochemical studies (e.g. Hunt 1977; Gaffey 1986) and has been applied to deep-sea sediments by Chester & Elderfield (1966), Barranco *et al.* (1989) and others. Oregon State University (OSU) have developed an automated reflectance spectroscopy logger to measure diffuse reflectance spectra in the ultraviolet, visible and near-infrared bands on split sediment cores (Mix *et al.* 1992, 1995). Measurement of wet sediments and split-core surface roughness will affect reflectance, but water effects can be minimized by careful selection of the wavelengths studied and scraping with glass slides will mitigate roughness effects (Mix *et al.* 1992). Use of the OSU reflectance


Epoch
Pleistocene
Pliocene
Miocene
Oligocene
middle-late Eocene
early Eocene
late Paleocene
early Paleocene
Late Cretaceous
Lith. unit
I
II
III
A
B
C
L* (%)
Carbonate (wt%)
NGR (cps)
MS (instrument units)
625
Site 1262
Hole A
Hole B
Hole C
Recovery
Core
Depth (mcd)

spectroscopy logger on ODP Leg 138 proved the technique as a tool for rapid, non-intrusive characterization of major lithologies and sediment oxidation state (Mix *et al.* 1992, 1995). A second-generation logger, examining a wider frequency band and with an improved signal-to-noise ratio, was used on some subsequent ODP legs (e.g. Shipboard Scientific Party 1997; Ortiz *et al.* 1999*a*, *b*). Visible light spectroscopy, through providing quantitative measurement of optical lightness, has been used for determining carbonate content of marine sediments (Balsam *et al.* 1999), and spectral data have been used to estimate concentrations of opal, organic carbon, chlorite and hematite (Balsam & Deaton 1991, 1996; Deaton & Balsam 1991). Sediment mineralogy based on visible and near-IR reflectance spectroscopy is discussed by Jarrard & Vanden Berg (2006).

X-ray fluorescence core scanners

A major innovation in the last decade has been the development of X-ray fluorescence (XRF) core scanners allowing rapid collection of high-resolution continuous downcore records of element distributions. In XRF analysis, sediment is excited by incident X-radiation that causes electrons to be ejected from inner atomic shells. The resulting vacancies are subsequently filled by electrons falling back from the outer shells, and the surplus energy (i.e. the energy difference between the vacant inner and the outer shells) is emitted as a pulse of X-radiation (Jenkins & De Vries 1970). Atoms of specific elements will emit characteristic energy and wavelength spectra allowing recognition and estimation of element abundance. Elemental variations determined by XRF core scanners can be used for inferring environmental changes, diagenetic processes and pollutant inputs, and can assist in sediment correlation and process studies. A number of XRF core scanners have now been developed.

The Netherlands Institute of Sea Research (NIOZ), Texel, The Netherlands, developed the first scanner of this type in 1988 (Jansen *et al.* 1998). This core scanner made measurements on split sediment cores and was containerized to allow sea-going use. A modified version of this XRF core scanner was installed at the University of Bremen in 1997, and a second-generation core scanner, the AVATECH XRF core scanner, has been operational at both NIOZ and Bremen since 2002 (Richter *et al.* 2006). Röntgenanalytik Messtechnik GmbH, of Taunusstein, Germany, have also produced a XRF core scanner, known as the Eagle μProbe (see Haschke 2006). In this instrument the incident X-rays are focused by a polycapillary lens to irradiate a very small area of the core allowing very high-resolution measurement with typical spot sizes in the range 30–50 μm. Another instrument is the ITRAX core scanner, manufactured by Cox Analytical Systems of Gothenberg, Sweden (see Croudace *et al.* 2006), which also uses capillary optics in the form of a flat glass waveguide to focus the incident X-radiation in order to achieve a very small step size (down to 100 μm). In addition to element profiling, the ITRAX core scanner can also acquire very high-resolution continuous digital X-radiographic images through the centre of the split cores.

Conventional laboratory XRF analysis requires samples to be homogeneous, dry and have a flat smooth surface. These requirements cannot be met when analysing split sediment cores. Cut core surfaces, even when very carefully cut, will have topography and variation in grain size will cause surface roughness. Sediment compositional variability, water content, and textural and porosity changes all mean that XRF logging using core scanners will be semi-quantitative at best. Light element ($Z < Si$) measurement is often compromised by attenuation of excited X-rays in the air gap between the X-ray detector and the core surface. However, XRF scanning of marine sediment cores has allowed discrimination of even decadal, annual and subannual environmental changes. For example, Haug *et al.* (2003) used the Eagle μProbe (see Haschke 2006) to measure Ti in sediments from the Cariaco Basin, offshore Venezuela, at subannual resolution. Titanium was used as proxy for terrigenous sediment delivery to the basin from surrounding watersheds, hence providing an index of hinterland rainfall, with lower Ti reflecting lower precipitation resulting in lower river runoff. The resulting data identified three periods of drought, each lasting for a decade or less, coincident in time with the three phases of Maya city abandonment around 810, 860 and 910 AD previously identified on archaeological evidence. Whatever social stresses were responsible for the

Fig. 6. Lithostratigraphic composite for ODP Site 1262 (Walvis Ridge, SE Atlantic) showing how the variation in properties measured by non-destructive core-logging can be used to distinguish lithostratigraphic units, in this case, magnetic susceptibility (MS), natural gamma radiation (NGR), carbonate content and lightness (L^*). Note how lightness (together with magnetic susceptibility and natural gamma) clearly distinguishes the boundary between lithostratigraphic units IIIA and IIIB and the Cretaceous–Tertiary boundary. From Shipboard Scientific Party (2004 in Zachos *et al.* 2004).

collapse of Mayan civilization, repeated prolonged regional droughts seem implicated as a probable underlying cause.

Within an oceanic setting, much research using XRF core scanning has concentrated on palaeoceanographic studies (e.g. Jahn *et al.* 2003; Kuhlmann *et al.* 2004; Lamy *et al.* 2004; and others), although the technique also has value in lithostratigraphic analysis and provenance studies of allochthonous beds (Rothwell *et al.* 2006) and studies of diagenetic processes (Thomson *et al.* 2006). In the North Atlantic, the Ca/Fe ratio offers a good proxy for discriminating glacial–interglacial cycles as pelagic sediments deposited during interglacials have higher carbonate contents than those deposited during glacials (Balsam & McCoy 1987). Hence, downcore major element XRF records can rapidly provide preliminary stratigraphies by showing the relative abundance of biogenic carbonate and clay, respectively (Richter *et al.* 2006). Inter-element relationships can also be useful for discriminating multiple sources for some elements if present. For example, the Sr/Ca ratio can show the relative contribution of aragonite to particular sediments, as aragonite generally has high Sr and calcite low Sr (Thomson *et al.* 2004; Richter *et al.* 2006). The Si/Al ratios can show the relative contributions of terrigenous-derived Si compared to biogenic opal. When Al data are poor, such as where it is at the limit of detection, then Ti or Rb can be used as suitable detrital divisors (Rothwell *et al.* 2006).

X-ray computed tomography/digital X-ray imaging

The opacity of sediments hides their internal structure, processes that have occurred or may be occurring within them, and their response to stresses and other natural processes. This limits our understanding of important natural processes, such as sediment deposition, post-formational geochemical and physical alteration, bioturbation, dewatering and consolidation, erosion, in-sediment gas-bubble formation and migration, stress and failure, and many other phenomena. X-ray computer tomography (3D X-radiography or CT scanning) provides multi-dimensional real-time imaging of the structure of solid objects and can produce digital images (Fig. 7). Outside of its well-known medical uses, it is increasingly being used as a research tool for dendrochronology, archaeology and oceanography. Since the dataset is three dimensional, images can be visualized for any plane. Resolutions down to 100 μm are now readily available and promise to provide unparalleled insights into core structure, physical properties and, hence, sedimentary processes.

Commercially available models specifically made for scanning rock or sediment cores have become increasingly affordable in recent years. CT scanners have been used by the oil industry since 1980, and CT scanning is now standard procedure in North America in the analysis of borehole samples, and rock and sediment cores, with a number of institutions having CT scanners specifically for geological research. A substantial body of literature has now been published resulting from CT scan analyses of sediments and rocks. These cover diverse applications including fabric studies, granulometry, porosity and permeability studies of source and reservoir rocks; structure and density of ice and cohesive muds; mineral assemblages in rocks, sediments and placer deposits; hydrocarbon contamination in soils; fracture and fissure patterns in rocks and consolidated sediments; composition of deep-sea polymetallic nodules; characterization of slump and mass failure deposits; and pollutant migration in cores and characterization of methane hydrate in marine sediments.

Until recently, most CT work on sediment cores has been performed using medical-type CT scanners, which were originally designed for imaging the human body and not optimized for core characterization. Such CT scanners are expensive, are generally non-portable (although tractor-trailer mounted units exist), and have high maintenance and installation costs (having large footprints and requiring lead-lined rooms). Recently, however, smaller specifically petrophysical CT scanners have been developed, some of which are self-shielded; negating the necessity of specially constructed lead-lined rooms. Freifeld *et al.* (2006) have designed and built a portable CT imaging system specifically for imaging whole-round cores at the drilling site. In this instrument core is loaded vertically and rotated about its vertical axis, and the X-ray source and detector move within a shielded horizontal gantry over the core. Careful design of the radiological shielding minimizes the size and weight of the instrument, resulting in a much smaller footprint than conventional systems and complete portability. Power consumption is low.

The recent availability of smaller self-shielded CT scanners, specifically designed for imaging core, with their lower capital and maintenance costs compared to conventional medical-type scanners, makes this technology more affordable than ever before. As a result such systems are likely to come into routine use to provide extremely fine-scale density analysis.

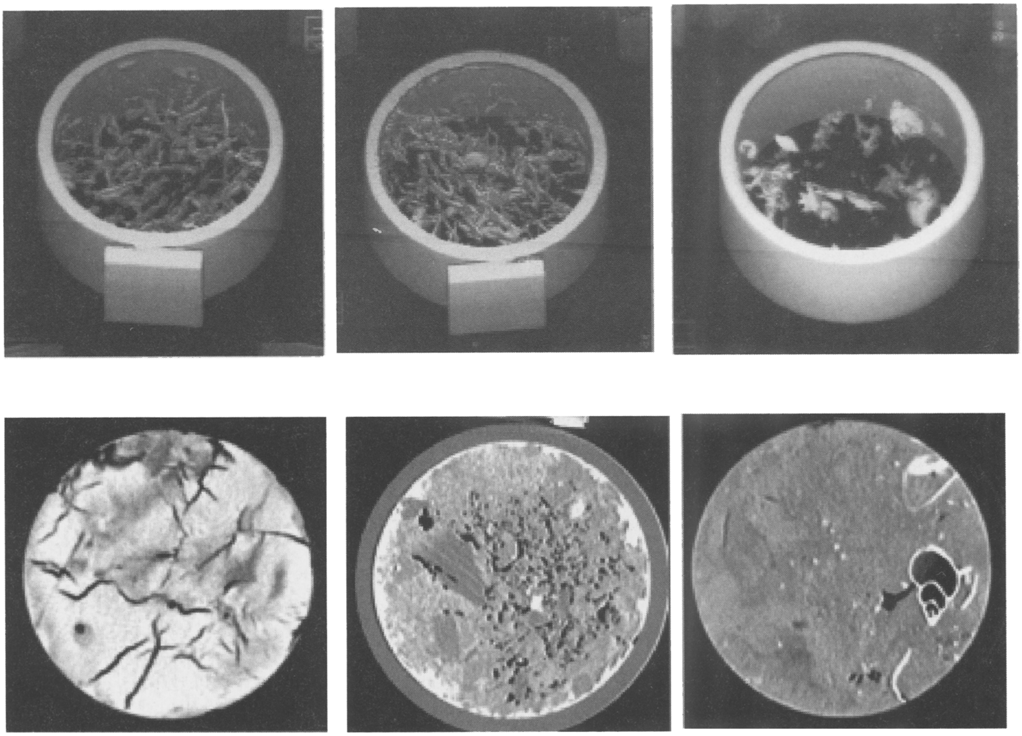


Fig. 7. X-ray CT images of a pressure-sealed gassy sediment core taken from Dibden Bay, Southampton Water, UK. The top three pictures image, in three dimensions, gas bubbles and worm tubes by bandpass filtering grey levels. The bottom three images are 2D image slices through the core and show crack-like gas bubbles in mud, subspherical bubbles in sand and gas trapped in gastropod shells. Gas, probably methane, appears as black, calcium carbonate as white, and other minerals as intermediate grey levels. These images show the wealth of detail that can be revealed by both 2- and 3D X-radiography. (Reproduced courtesy of Dr A. Best, National Oceanography Centre, Southampton, partially adapted from Best *et al.* 2004.)

Nuclear magnetic resonance/magnetic resonance imaging (NMR/MRI)

Nuclear magnetic resonance (NMR), also known as magnetic resonance imaging (MRI), is another investigative technique borrowed from medical imaging technology. NMR is increasingly being used to investigate physical properties, particularly porosity and pore-size distribution, of cored sediments. Within the hydrocarbon industry, NMR is now widely used to characterize porosity of source rocks and, hence, evaluate the productive potential of hydrocarbon reservoirs (Kleinberg 1996, 2006).

Magnetic resonance imaging most frequently relies on the relaxation properties of excited hydrogen nuclei in water or inter-pore fluids. When the object to be imaged is placed in a powerful, uniform magnetic field, the spins of the atomic nuclei with non-zero spin numbers within the material all align in one of two opposite directions: parallel to the magnetic field or anti-parallel. MRI systems generate images of nuclear spin density or magnetic resonance relaxation times (i.e. the return of spinning nuclei to a lower energy state). The SPRITE (Single Point Ramped Imaging with T_1 Enhancement) MRI technique (Balcom *et al.* 1996; Chen *et al.* 2006) can produce images related to porosity, pore-size distribution, internal sediment structures and heterogeneity. Such data are essential for evaluating fluid flow characteristics in reservoir rocks. Kleinberg (2006) demonstrates how the technique can be used to quantify frozen and unfrozen phases in interparticle spaces and to understand the growth habit of ice and methane hydrate (clathrate) within sediment.

Confocal macro/microscopy

Confocal microscopy is an imaging technique that uses a laser as the light source that is tightly focused through a slit or pin-hole aperture, limiting the depth of field to a single plane. By varying the focal point, multiple images of different surface planes can be combined to produce a sharply focused, three-dimensional (3D) computer image of the object. Filters can be used to modify both the incident and reflected laser light, and these can be used to discriminate compositional data through reflectance or fluorescence spectroscopy. Although this technology was developed for medical application, a system specifically adapted for imaging rock and sediment has been produced (the confocal scanning laser Macroscope/Microscope, abbreviated cslM/m; Dixon *et al.* 1995). This instrument offers a range of fields of view and magnifications and can image samples ranging in size from 25 × 25 μm up to 7.5 × 7.5 cm in under 10 s using reflected light or photoluminescence as contrast mechanisms (Ribes *et al.* 2006). With this instrument, the sample can be rapidly surveyed in macroscope mode providing a photoluminesence overview image and areas of interest identified which can then be viewed in microscope mode to provide ultra-high-resolution images, resolving submillimetric features within the sediment. This instrument offers great potential for rapidly imaging core sections in low-resolution macroscope mode (similar to taking traditional core photographs) with the option of using the high-resolution microscope for sediment microfossil and microfabric examination, and microscale mineralogical analysis (Ribes *et al.* 2006). Indeed, an imaging survey of ODP cores has shown that the instrument can be used in fluorescence response mode to discriminate between different sediment types and to describe the distribution, and discriminate the relative percentage, of microfossils in sediments (Ribes *et al.* 2006).

Chemical fossils (biomarkers) and molecular stratigraphy

During the last two decades discovery of biologically derived chemical markers (biomarkers) within marine sediment cores has led to remarkable advances in understanding past environmental changes. Biomarkers are organic compounds of known biological origin (primarily lipids, alkenones, and, for higher plants, *n*-alkanes, *n*-alkanols, *n*-alkanoic acids and wax esters) commonly preserved in marine sediments that can be used to develop proxy records of environmental change. Both marine and terrestrial plants biosynthesize molecules that are in some cases highly source-specific. On death of the source organism, some of these molecules, which are resistant to degradation, are transferred to sediment sinks and preserved as chemical fossils. Currently, the most well-defined and well-studied lipid biomarkers are a series of long-chain unsaturated ethyl and methyl ketones, known as alkenones (see Herbert 2004 for a review). These are principally produced in the modern ocean by two species of widely distributed coccolithophorid algae, *Emiliana huxleyi* (which can make up 60–80% of coccolithophore assemblages) and *Gephyrocapsa oceanica*. The function of alkenones in the source cell is poorly understood but may regulate membrane fluidity at different temperatures; however, they are clearly a physiological response to growth temperature. The overall degree of unsaturation in alkenones synthesized by these coccolithophores varies inversely with water temperature (Brassell *et al.* 1986). Alkenones are resistant to degradation within sediments and can survive for long temporal spans (several tens of Ma). Further, alkenones survive during long-term core storage (Sikes *et al.* 1991). Alkenones are usually measured by gas chromatography coupled with a suitable detector, typically a flame ionization detector (GC–FID) or mass spectrometer (GC–MS). Variation in the proportion of di-, tri- and tetraunsaturated alkenones in sediments is quantified as an alkenone unsaturation index, termed U^{k}_{37} or $U^{k'}_{37}$ (Brassell *et al.* 1986). Culture experiments have shown that there is a linear relation between U^{k}_{37} and growth temperature; and analysis of core tops and comparison with sea-surface temperatures (SST) in many parts of the world ocean has resulted in a universal and relatively robust calibration at least for typical open ocean regimes (Müller *et al.* 1998). However, analysis of alkenones may give temperature values for the water depth at which the source organisms lived rather than true SST. Even so, alkenone thermometry has become an important and widely used tool by palaeoceanographers and SST records have now been constructed for temporal spans from years to hundreds of kiloyears (ka). Recent work by Cacho *et al.* (1999, 2002) demonstrates how alkenone records can provide astonishingly detailed records of the pervasive nature of millennial events within the late Quaternary regional climate of Europe and the North Atlantic. Western Mediterranean Sea alkenone records show all the millennial-scale features seen in Greenland ice cores over the last 50 ka as conspicuous SST changes, with some changing as quickly as 6 °C per century (Cacho *et al.* 2002).

Biomarkers from higher plants and terrestrial sources also occur in marine sediments, particularly in areas with high fluvial input, or areas of open ocean where aeolian terrestrial inputs can be greater than pelagic ones (Pagani *et al.* 2000).

These biomarkers can give insights to hinterland vegetation from which palaeoclimatic changes can be inferred (Pancost & Boot 2004). Indeed, the often large hinterland areas that contribute sediments to offshore basins, the high sampling resolution possible and the long temporal records often available means that marine sediments can provide a better assessment of continental climate change than comparable terrestrial sites, such as peats and lake sediments (Pancost & Boot 2004). Measurement of carbon isotopic composition of sedimentary organic carbon can also distinguish that derived from different, yet isotopically definable, sources – marine plankton and vascular plants (Degens 1969).

Recovery and analysis of core at *in situ* pressure

In the last two decades two particular aspects of the subsea-floor sedimentary environment have been recognized as being of global importance. The first is the widespread occurrence of clathrates (gas hydrates) in marine sediments in some areas of the world. Gas hydrates occur both in Arctic regions affected by permafrost and in marine subsurface sediments in the polar regions (shallow water) and in continental slope sediments (deep water), where pressure and temperature conditions combine to make them stable (Kvenvolden 1993, 1998). Gas hydrate is a crystalline solid with a simple structure, consisting of gas molecules (usually methane) each of which is surrounded by a 'cage' of water molecules (Sloan 1990). In appearance, gas hydrate looks very much like water ice (Fig. 5). Methane hydrate is stable in ocean-floor sediments at water depths greater than 300 m and, where it occurs, it is known to cement loose sediments in a surface layer of up to several hundred metres thick. Gas hydrates within sediments store immense quantities of concentrated methane, with major implications for potential future energy resources and climate. Release of methane from the clathrate reservoir, perhaps due to sea-level change-related sediment unloading, may contribute to significant global warming and, hence, may control long-term climate change (Kvenvolden 1988; Paull *et al.* 1991; Harvey & Huang 1995; Kennett *et al.* 2003; and others). Within subsea-floor sediments, gas hydrate occurs within interparticle pores and cements sediment grains. It therefore can have a significant effect on sediment strength and its formation and breakdown may influence the occurrence and location of submarine landslides (e.g. Kayen & Lee 1993). Such landslides may release methane into the atmosphere, affecting global climate. When drilled, pressure release results in rapid dissociation of gas hydrate resulting in a frothy sediment of mousse-like appearance. As a result the study of gas hydrates has been hampered by lack of a way of recovering and preserving hydrate-bearing core at *in situ* pressure.

The second feature of subsea-floor sedimentary environments to be recognized, of critical importance in the past two decades, is the deep biosphere (Parkes *et al.* 1994, 2000; Schippers *et al.* 2005). Living and diverse bacteria adapted to high-pressure, often high-temperature, regimes exist within sediments hundreds of metres below the sea floor, to depths of at least 850 m below the seabed. The extent and importance of this remarkable microbial habitat, which may account for perhaps 10% of total global biomass, has only been recently recognized. Indeed, Whitman *et al.* (1998) estimated that deep marine sediments may contain over 60% of global bacterial biomass, making the subsea floor the largest bacterial habitat on Earth. The deep biosphere may play a major role in the global cycling of elements and form a significant reservoir of organic carbon. These obligate barophilic bacteria may not survive depressurization during the coring process. Yet, their diversity and remarkable adaptation to a highly extreme environment makes deep biosphere microbes of great biotechnological potential if means to recover and culture them are developed. Recently, the European-funded HYACE (HYdrate Autoclave Coring Equipment) project, and its successor HYACINTH (Deployment of HYACe tools In New Tests on Hydrates), have developed a pressure corer designed to recover cores in liners at *in situ* pressure and transfer them to pressure vessels (Schultheiss *et al.* 2006). As a result, subsamples can now be taken from cores and transferred to chambers, all at *in situ* pressures, where intrusive measurements and experiments can be made. The HYACINTH system has already been used on ODP Leg 204, allowing core containing gas hydrate to be logged at *in situ* pressure in the laboratory (Tréhu *et al.* 2003; Schultheiss *et al.* 2006). Further, during the HYACINTH project, new subsampling equipment was developed to allow further biological, chemical, geophysical and geotechnical investigations at *in situ* pressures in the future.

Developing global accessibility to sea-floor samples and core data

The huge numbers of sediment cores now acquired globally and the immense corpus of data, much of it high resolution, collected from these cores necessitates a means of making cores and the data from them accessible to the wider scientific community. After cores have been analysed for the purpose for which they were taken, cores and sea-floor samples are normally stored under controlled conditions to ensure optimum preservation for further use. As new measurement techniques and instrumentation become available, and new concepts evolve, existing cores can be re-sampled to add to the knowledge base. The financial and scientific investment in collecting and storing cores is considerable, and stored cores provide a legacy of continuing scientific usefulness and importance. Secondary usage of cores and core-derived data, after the primary data collection requirement has been served, enables cost-effective use and maximizes the scientific return on the cost of core collection.

The problem of providing accessibility to large sediment sample archives has been long recognized in the USA. As early as 1977, several oceanographic research institutions got together in a collaborative effort to help researchers locate marine sediment and rock material for further analysis. Today, 20 oceanographic institutions (mainly US-based, but including repositories in the UK, Canada and Germany) make up this effort, submitting core data to the 'Index of Marine and Lacustrine Geological Samples' at the US National Geophysical Data Centre (NGDC)/World Data Centre A for Marine Geology and Geophysics, at Boulder, CO (see Moore & Habermann 2006). This database currently holds information on nearly 157 000 sea-floor cores, grabs, dredges and drill samples, and can be searched through the Internet. The database is searchable by any parameter or combination of parameters. Inventories, data listings, data in digital form and plots by station/lithology/texture are available. Samples are normally available for further scientific study, on request, from the participating institution. The importance of the 'Index of Marine and Lacustrine Geological Samples' and the service its provides to the international marine science community was recognized by a resolution of the International Oceanographic Commission (IOC) Committee on International Data & Information Exchange (IODE) passed by the IOC in 1994, which states:

> The IOC Committee on International Oceanographic Data and Information Exchange, recognizing the importance of analyses deriving from ocean sediment cores to studies of past climates and to palaeoceanography, being concerned with the diminishing amount of sample material and with the difficulty in locating material available for analysis ....
>
> Noting the need to identify, catalogue and curate all such remaining material so these materials can be fully utilized for analyses beyond those for which the samples were collected originally ....
>
> Encourages Member States to locate and catalog marine sediment cores available for sampling and analysis and contribute information (meta-data) about these cores to the Index to Marine Geological Samples database maintained by WDC-A-MGG; ....
>
> Urges Member States to establish procedures to provide access to these cores for sampling. (International Oceanographic Commission (IOC) Committee on International Data & Information Exchange (IODE) Resolution IODE-XIV.2, 1994: published on the Internet at http://www.ngdc.noaa.gov/mgg/curator/ioc_resolution.HTML.)

NGDC is developing the Index to create common cross-reference to additional data held in its archives. These include a full suite of DSDP core data, around 70 000 pages of scanned cruise reports, more than 50 000 core photographs, 7500 core X-radiographs, 20 000 sea-floor photographs, 14 000 pages of paper documents, and 5000 pages of core logs and text descriptions (Moore & Habermann 2006). Thus, the Index is developing into a valuable comprehensive data resource for the global marine and earth science community. Planned importation of the Index into centre-wide geospatial database systems will allow implementation of standard quality assessment tools, as well as their integration into desktop and Internet mapping applications. This standards-based interoperable agenda promotes global use of the archived data and ensures its continuing value to the worldwide scientific community (Moore & Habermann 2006). Representatives from institutions that submit metadata and data to the Index meet about every 2 years to hear facility presentations, discuss common issues of interest, such as core-based research projects and facility information systems, and hold round-table discussions on information needs and strategies for co-operation. The 'Index' therefore also provides a valuable forum for idea exchange and discussions on core curation and analysis (Mix *et al.* 2003). The long-term funding and commitment to develop the Index and its robust data service provision, with its inherent networking amongst curators and associated community, provides an excellent model for data infrastructure for Europe and other countries.

Within the ODP, and successor IODP projects, an online relational data management system called JANUS has been implemented. The database includes palaeontological, lithostratigraphic, chemical, physical, sedimentological and geophysical data for sediments and rocks collected during these programmes. The central JANUS database consists of more than 450 oracle tables divided into 25 subject areas that can be accessed, queried and visualized through a number of different tools (Mithal & Becker 2006). Data can be extracted using commercial applications such as SQL*Plus and Microsoft Access.

Core metadata and core-derived data can be stored, as in the Index or JANUS, and made accessible through the Internet worldwide. However, an important development is the ability to mine existing datasets in order to effectively integrate diverse core-related and other sea-floor data collected over decades in order to provide ocean-bottom information at many spatial scales. A major innovation in this respect is the development of dbSEABED – an information-processing system for marine substrates originally developed at the Ocean Science Institute, University of Sydney, and used to provide thematic sea-floor maps of the Australian Maritime Region based on data collected from over 275 000 attributed sample sites. DbSEABED is a unique, versatile and detailed information-processing system. It works through data mining, with modules devoted to extraction of diverse geological attributes, linguistic parsing of geological descriptions (e.g. core logs, photographs, descriptions, etc.) and on calculation of some parameters (see Jenkins *et al.* 2006). In order to preserve spatial resolution of original sampling campaigns, it deals in point data, although polygon and poly-line data types are also used. The structure is such that new attributes and new datasets are readily added. DbSEABED is now operated by a number of co-operating institutions in the USA and Australia, who import, integrate, process and display regional datasets under a common format and software set-up. They share data, code and innovations. The dbSEABED database structure currently holds in excess of 1×10^6 attributed sea-floor describing sites worldwide with over 400 000 of these within US waters. Processing of the data from US sites to produce multi-parameter thematic maps forms the usSEABED project run by the United States Geological Survey (USGS) (Williams *et al.* 2003). Data mining, through software such as dbSEABED, maximizes the benefits of legacy data and provides a model for efficient and effective exploitation of core-based and related datasets.

Data visualization and amplified collaboration environments

The rapid development of core analysis and data-mining techniques, and the high degree of collaboration between scientific and technological specialists in present-day core-based programmes and research projects, requires development of new data visualization methods and amplified collaboration environments. A recent innovation in data visualization is the Geowall project (www.geowall.org). This has developed 3D scientific visualization tools to aid (principally stereoscopic projection) in the understanding of spatial relationships. Although stereoscopic projection is not new for 3D visualization, the Geowall consortium has developed for the first time a low-cost, portable system that broadens the use of virtual reality visualization and associated tools in Earth Science research and education. A basic system consists of a desktop computer (running MacOS, Linux or Windows) with a fast graphics card, two projectors and a screen. The projected image is polarized using filters within the projectors. If the image is perceived through 3D polarized glasses, then a near-true 3D image is observed (passive stereo). GeoWall visualization systems are now widely used in educational and research institutions.

A related development to GeoWall is CoreWall (www.corewall.org), an integrated visualization tool for studying sediment cores developed through collaboration by the University of Illinois at Chicago's Electronic Visualization Laboratory, the US National Lacustrine Core Repository (LacCore) at the University of Minnesota and the Integrated Ocean Drilling Program (IODP). CoreWall uses high-resolution tiled LCD displays to show images of core sections along with discrete data streams of measured parameters downcore and nested images, allowing rapid multi-disciplinary interpretation (Fig. 8). CoreWall users can link to databases of core images and sensor logs, and

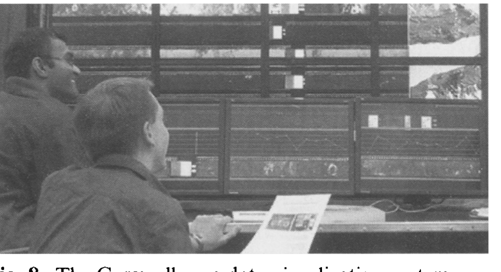


Fig. 8. The Corewall core data visualization system. Corewall uses high-resolution tiled LCD displays to show images of core sections along with discrete data streams of measured parameters downcore and nested images, allowing rapid multi-disciplinary interpretation. Corewall users can also link and download data from remote databases, allowing access to dispersed datasets for interpretation. Sophisticated data visualization tools like Corewall will lead to the development of amplified collaboration environments for core analysis. (Reproduced courtesy of Arun Roa and the Corewall Consortium).

fetch data from remote CoreWall repositories. Links to the ODP JANUS database at Texas A&M University are anticipated in the future. A prototype desktop application for CoreWall has also been developed that uses a single computer to drive four LCD panels and a single screen GeoWall display. Using this system, high-resolution core images and sensor data can be examined together with stereoscopic visualizations (Rao *et al.* 2004, 2005).

Conclusions

Our capability to extract multi-parameter high-resolution data, including important and varied palaeoenvironmental proxies, has increased dramatically during the last two decades and the impact on marine geology, particularly palaeoceanography, has been profound. A variety of non-destructive logging technologies now allow rapid acquisition of high-resolution physical property, geochemical and compositional data, providing considerable savings in time, cost and effort normally required to collect such data by more traditional laboratory means. Variation in palaeoenvironmental proxies can now be examined at decadal and, in some cases, annual and, even subannual scales, allowing unprecedented insights into the history of climate and associated environmental change.

X-ray fluorescence core scanning, 3D X-radiography, visual spectrum, infrared and ultraviolet spectral reflectance, confocal macro/microscopy, magnetic resonance imaging and developments in molecular stratigraphy all promise to provide powerful tools for 21st century geoscientists to gain greater understanding of the Earth and its history in unprecedented detail. However, challenges remain, both in the development of standard measurement and calibration methodologies and in the development of data analysis methods. New data visualization tools and techniques need to be developed to optimize the interpretation process and maximize scientific value. In order to provide an adequate interpretation infrastructure necessary for the analysis and collation of multi-parameter datasets new amplified collaboration environments and tools need to be developed. In addition, data archiving and data-mining software needs to be developed and maintained at 'state-of-the-art' level in order to integrate and interpret new and legacy datasets within the wider context of sea-floor studies. Equally important is the need to make core data and associated datasets and products accessible to, and easily searchable for, the worldwide scientific community. Sophisticated, yet simple to use, searchable Internet databases, with universal access and secure long-term funding, and data products resulting from user-defined data-mining query and display, all so far pioneered in the USA and Australia, provide robust models for efficient and effective core data stewardship.

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