

APPENDIX II: SHIPBOARD SCIENTIFIC PROCEDURES

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INTRODUCTION

The original Core Description Manual, which is used aboard the drilling vessel *Glomar Challenger* in carrying out the programs of the Deep Sea Drilling Project is an extensive and detailed work representing the cumulative efforts of many individuals, notably those of the JOIDES Advisory Panel on Sedimentary Petrology and the JOIDES Advisory Panel on Paleontology and Biostratigraphy. The JOIDES Advisory Panels on Well Logging, Interstitial Water, Heat Flow, Paleomagnetism, Igneous and Metamorphic Petrology, and Information Handling have also contributed to the original compilation. Working with these groups have been many other individuals.

The Core Description Manual performs a threefold purpose: that of briefly informing participants in the Project about the facilities available to them; that of defining the laboratory procedures to be followed in order to achieve a measure of uniformity in core description and investigation; and, thirdly, as a source of reference material, particularly for the paleontologists.

The purpose of the present presentation is to place in the public domain a short account of the facilities of the drilling vessel, *Glomar Challenger*, the operations carried out at sea, and the procedures followed in the shipboard laboratory for describing the core materials recovered. Experience has shown us that the details of laboratory procedures vary from cruise leg to cruise leg, as experience is gained and techniques are refined. There would appear then to be little value to the general reader in spelling out in detail techniques followed for a particular procedure. However, it is clearly important

to the understanding of the Initial Reports that the reader should have a general knowledge of the procedures followed on board ship, the basis for the various methods used and, where necessary, the limitations or inadequacy of these methods. The following contribution has been prepared with this in mind.

A large part of the reference material which appears in the biostratigraphic section of the Core Description Manual is unpublished material supplied through the generosity of many recognized authorities on the various fossil groups. It is therefore not possible for us to present this information in detail here. The paleontological content of this summary is, therefore, limited to a statement of the time-stratigraphic framework drawn up by the JOIDES Advisory Panel of Paleontology and Biostratigraphy and within which the shipboard paleontologists have worked when preparing their descriptions.

THE GLOMAR CHALLENGER AND HER CAPABILITIES

The vessel used in the Deep Sea Drilling Project, *Glomar Challenger*, is a specially designed drilling vessel having a length of 400 feet, beam of 65 feet, and draft of 20 feet. She is a completely self-sustaining unit carrying sufficient fuel, water and stores to enable her to remain working at sea for 90 days without replenishing. On site, she is capable of handling drill string lengths of up to 22,500 feet (6860 meters), her performance generally being limited to a maximum water depth of 20,000 feet (6096 meters) and a maximum penetration into the sea bed of 2500 (762 meters). The drilling propulsion and positioning equipment

are diesel-electric powered, and the twin screws give her a cruising speed between sites in excess of 12 knots. Special features of her design particularly valuable for deep-sea drilling include a dynamic positioning equipment with a computerized control system, a tank stabilizing system, and satellite navigation equipment.

Dynamic Positioning

Glomar Challenger is the largest commercial vessel afloat to be equipped with dynamic positioning. The positioning system employs four tunnel thrusters, two in the bow and two aft, each of which is capable of producing 17,000 pounds of thrust. The tunnel thrusters are mounted transversely and, operated in conjunction with the ship's main screws, they enable her to move in any direction. While on site, four hydrophones are extended below the hull. They continually receive signals transmitted from a sonar beacon implanted on the ocean floor. The signals are fed into a computer, which on the basis of the delay times of the arriving signals calculates the position of the ship relative to the beacon. The computer automatically controls the thrusters and main propulsion unit to maintain the ship's heading and location over the hole. The dynamic positioning system has both computerized and manual controls. Experience so far, has shown that under normal operating conditions it is easily possible to maintain the ship within 80 feet (24 meters) of the desired location for periods as long as six days.

Stabilizing System

The gyroscopically controlled tank stabilizing system is located amidships. This system substantially reduces the vessel's motion. Experience has shown that vessel roll or pitch is not a problem, provided the roll or pitch does not exceed 5 degrees half amplitude and if the period of the roll or pitch is not short. To date, the vessel motion has not been the determining factor in drilling being curtailed due to weather conditions.

Satellite Navigation System

The satellite navigation system is an ITT Model 4007AB; this is one of the first commercially available navigation instruments to offer all weather world-wide operation. It provides the ship with access to the precise navigational information which is continuously transmitted from the satellites of the U.S. Navy Navigation Satellite System (NNSS).

This system consists of four satellites in polar orbit, tracking stations, injection stations and a computing center. The tracking network tracks every pass of every satellite and measures the doppler shift very precisely. These data are transmitted to the computing center where they are used as the basis for computation of predicted satellite orbital information. The orbital information is transmitted to the satellite by the injection

stations and is normally updated several times each day. The NNS System is operated by the Navy Astronautics group headquartered at Point Mugu, California. The system's satellites continuously retransmit the orbital information back to the ship on ultra stable carrier frequencies. The user remains completely passive and merely receives the transmitted signals. The Model 4007AB collects the orbital information, measures the doppler shift and makes this data available to be fed directly into a PDP 8S computer for position-fix computation. This system enables *Glomar Challenger* to fix her geographical position with accuracies better than one tenth of a nautical mile anywhere in the world, day or night, regardless of local weather conditions.

Drilling Equipment

Situated amidships is the 142 foot, Global Marine designed derrick, which has a hook load capacity of 1,000,000 pounds. Immediately forward of the derrick, is the automatic pipe racker, which can carry 23,000 feet (7010 meters) of drill pipe, with below-deck space for additional storage.

Office and Laboratory Facilities

In general, all living spaces and office and laboratory facilities are air conditioned and acoustically insulated. In addition to laboratory facilities, a library lounge, office space, drafting room, and electronics laboratory are available. Laboratory facilities are housed in a separate structure installed on the floor of the casing rack. The upper laboratory is at the same level as the rig floor and has access to the rig floor via a catwalk. This laboratory is designed for core receiving and general processing. It, therefore, contains equipment for X-radiography, GRAPE (Gamma-Ray Attenuation Porosity Evaluator), natural gamma, and sonic velocity measurements, and for splitting and describing core sections. On the bottom level of the laboratory structure, the paleontology and chemistry laboratories are situated with their appropriate equipment for handling micropaleontological samples and interstitial water chemistry. Running from the upper laboratory down through the laboratory structure into the core-storage area is an electrically driven dumbwaiter with access to both laboratories and to the storage area. This is used for the transportation of cores and supplies. Situated at an intermediate level are a photographic laboratory, a dark room, and a small laboratory for the preparation of thin sections. Eight refrigerated storage vans maintained at a temperature of about 3°C. are provided in the cargo hold of the ship for core storage. Cores are accumulated in these storage vans and then are off-loaded at convenient ports for shipment to the shore repositories on the East and West Coasts of the U.S.A. The vans are also used for temporary storage of samples while on board the vessel.

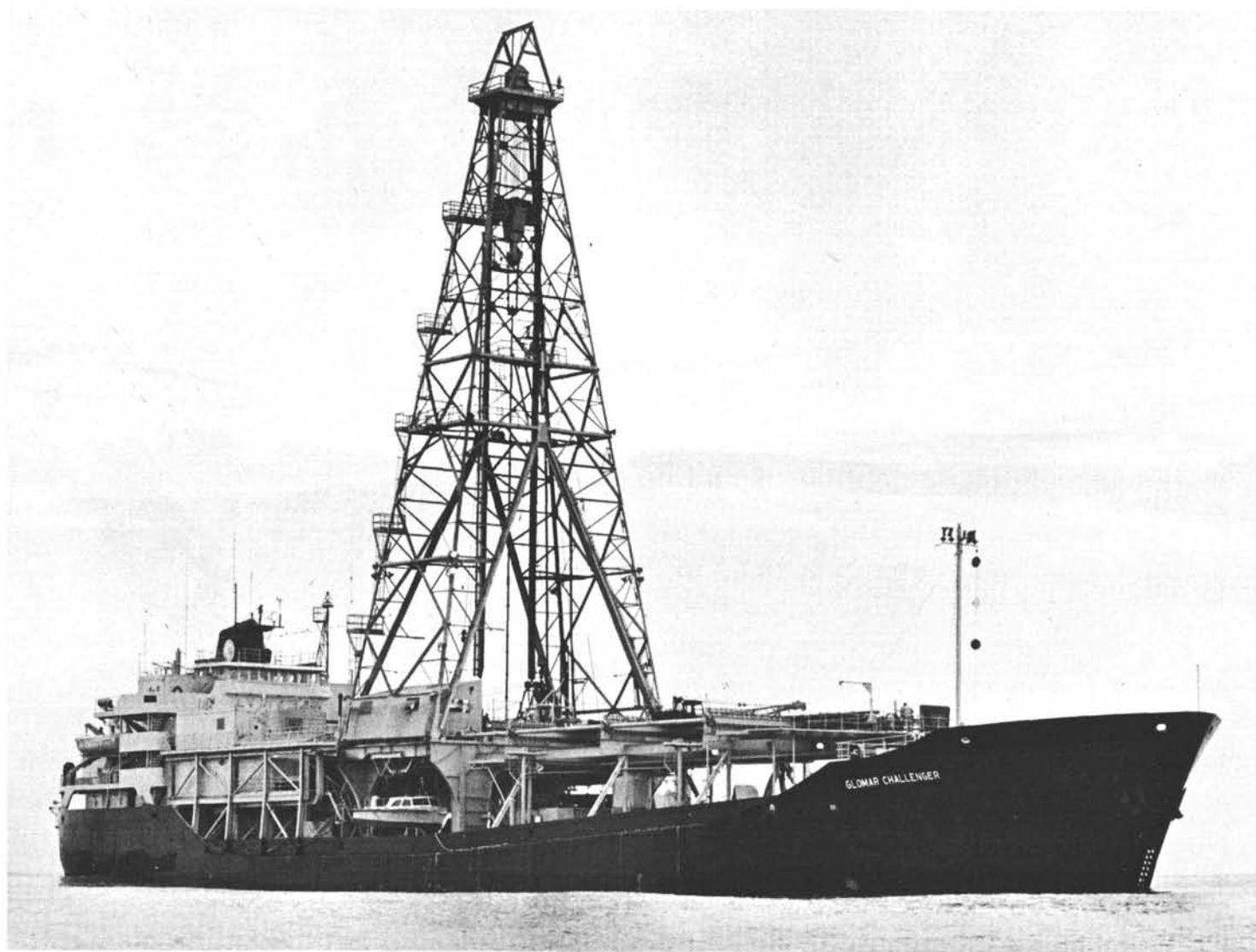


Plate 1.

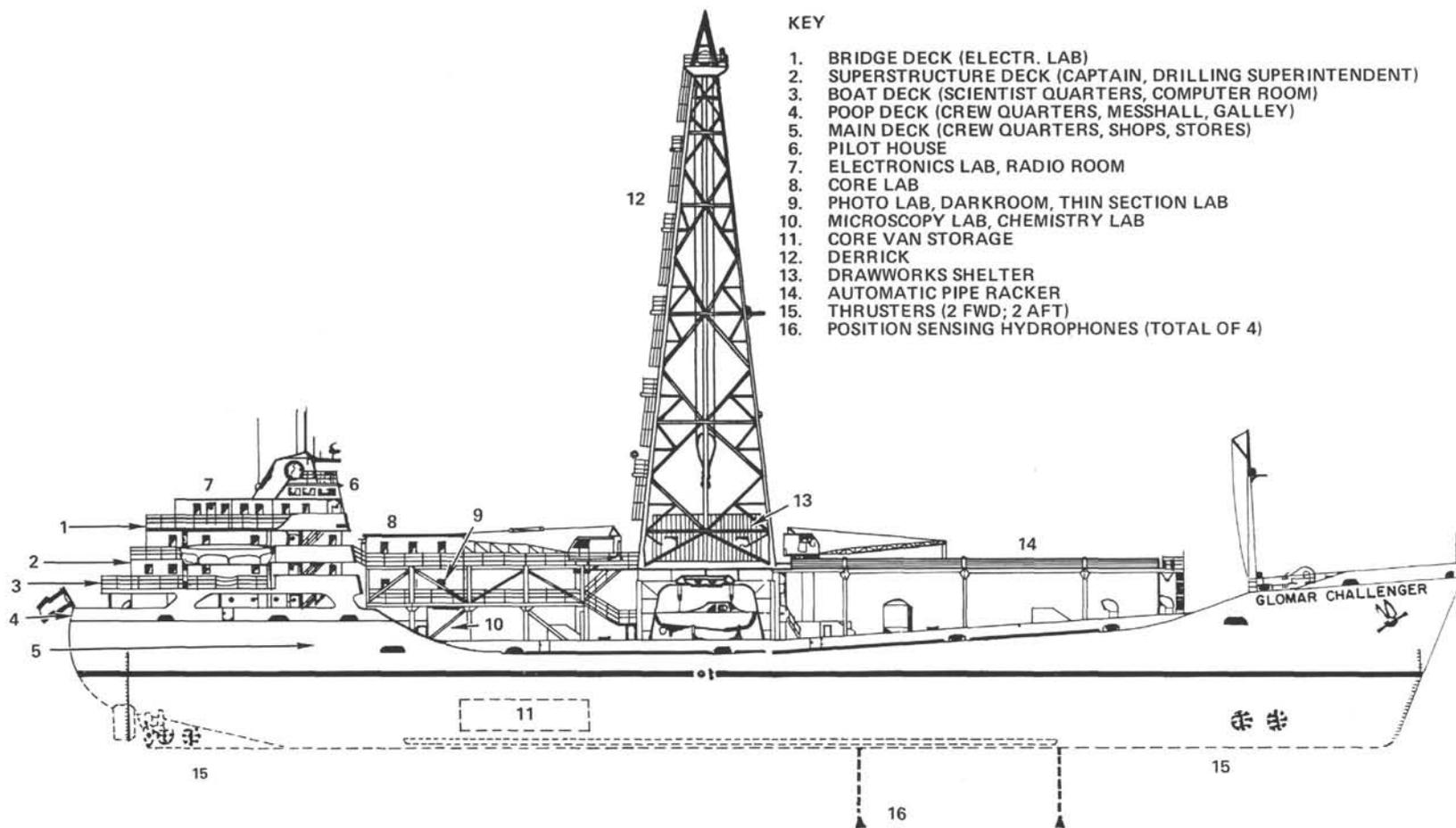


Figure 1. *Glomar Challenger*.

SHIP OPERATIONS

Underway Surveys

When cruising between drilling sites, oceanographic data are collected by a magnetometer and an air gun. A bottom profile is also taken with a precision depth recorder. The magnetometer utilized is a proton precession Varian 4970, the magnetic field values being presented in gammas on a direct readout of total field, accurate to within plus or minus one gamma. No attempt is made to process magnetometer data on board, although gross positive and negative magnetic anomalies may be identified. The seismic reflection profiler system uses a Bolt air gun with a modified Giffit oscillating blade recorder coupled to a hydrophone array for receiving.

Site Surveys

The proposed drilling sites have been selected by JOIDES Advisory Panels on the basis of information already available. The sites are then surveyed in detail by another, less expensive, vessel. Site surveys in the Atlantic Ocean have been conducted by the research vessel *Vema*, of Lamont-Doherty Geological Observatory and in the Pacific by the *R/V Argo*, of Scripps Institution of Oceanography. On arrival at the selected drilling site, a limited survey, specified by the shipboard scientists, is conducted to locate the optimum drilling location. These surveys are limited and directed specifically towards locating the best site. Immediately after the actual site is selected, a sonar beacon is lowered over the side and dropped to the bottom. The ship is then maintained on the selected station by the computer control system. Drilling operations can then commence.

Coring Equipment

Equipment from two major coring companies is used to give maximum flexibility in coring; tungsten carbide, diamond and milled cutter core bits are used. A variety of inner tube assemblies are available. These include non-rotating, rotating, and punch-type assemblies. The inner core barrel is lined with a plastic tube to assist in core handling and storage. The nominal sizes of the core cutting and bottom hole assembly are: hole diameter 9-1/4 inches; core diameter 2-1/2 inches; outer tube OD 8-1/4 inches; drill collar OD 8-1/4 inches; bumper sub OD 8-1/4 inches with a five foot stroke; and, drill pipe 5 inches OD, 19.5 pounds per foot grade.

Drilling and Coring

A power sub is used as the primary rotating system since the drill pipe can then be rotated at any height in the derrick, while the conventional kelly limits the drill pipe rotation to the length of the kelly above the rotary table. Standard wire line coring techniques are used. Coring is accomplished by dropping empty plastic

lined metal barrels through the drill string and after the core is cut recovering them with a half-inch sand line. Two sand line reels are situated on the derrick floor for this purpose. After recovery, the filled plastic liners are extracted from the core barrels and the core material is handed over to the scientific party for processing.

PROCEDURE FOR HANDLING CORES

The general procedure for handling cores is outlined in Figure 2, which is a simplified diagram showing the flow of core materials through the laboratories. The following notes are intended to amplify some of the procedures. Some of the processes which are not yet in general use are discussed here in more detail.

1. Core Cutting

Cores are received from the drill rig in clear 30 foot (9.1 meters) plastic liners, which are inscribed with longitudinal lines for orientation reference. Immediately after the core is received it is clearly labeled and sampled at the top and bottom before preliminary paleontological age determinations are made. These immediately provide useful information to guide future coring. The core is then cut into 150 centimeter lengths (sections) for processing. Each section is clearly labeled to show leg, site, core and section.

2. Core Section Weight - Bulk Density

The purpose of this procedure is to make a rough estimate of bulk density and core quality. The unopened 150 centimeter section of core is placed on a scale and weighed to the nearest 10 grams. The tare weight of an empty 150 centimeter core liner with plastic closures is then subtracted from the weight of the core section. For the purposes of this observation the assumption is made that the plastic liner and closures have a constant weight from one sample to another. The following simple calculation is then made to obtain an estimate of bulk density:

$$\text{Core section bulk density} = \frac{(\text{total core section weight}) - (\text{weight of liner \& closures})}{(\text{volume of plastic liner})}$$

Whenever the core section length is other than 150 centimeters an appropriate correction is made in the computation.

3. Core Radiography

In order to check core quality and to study minor structures and compositional differences, the core sections are X-rayed using a Faxitron X-ray machine. The unopened core sections are run through the Faxitron machine in a standard orientation and the X-radiographs are recorded on MP381 film, which is later processed in accordance with the manufacturer's instructions.

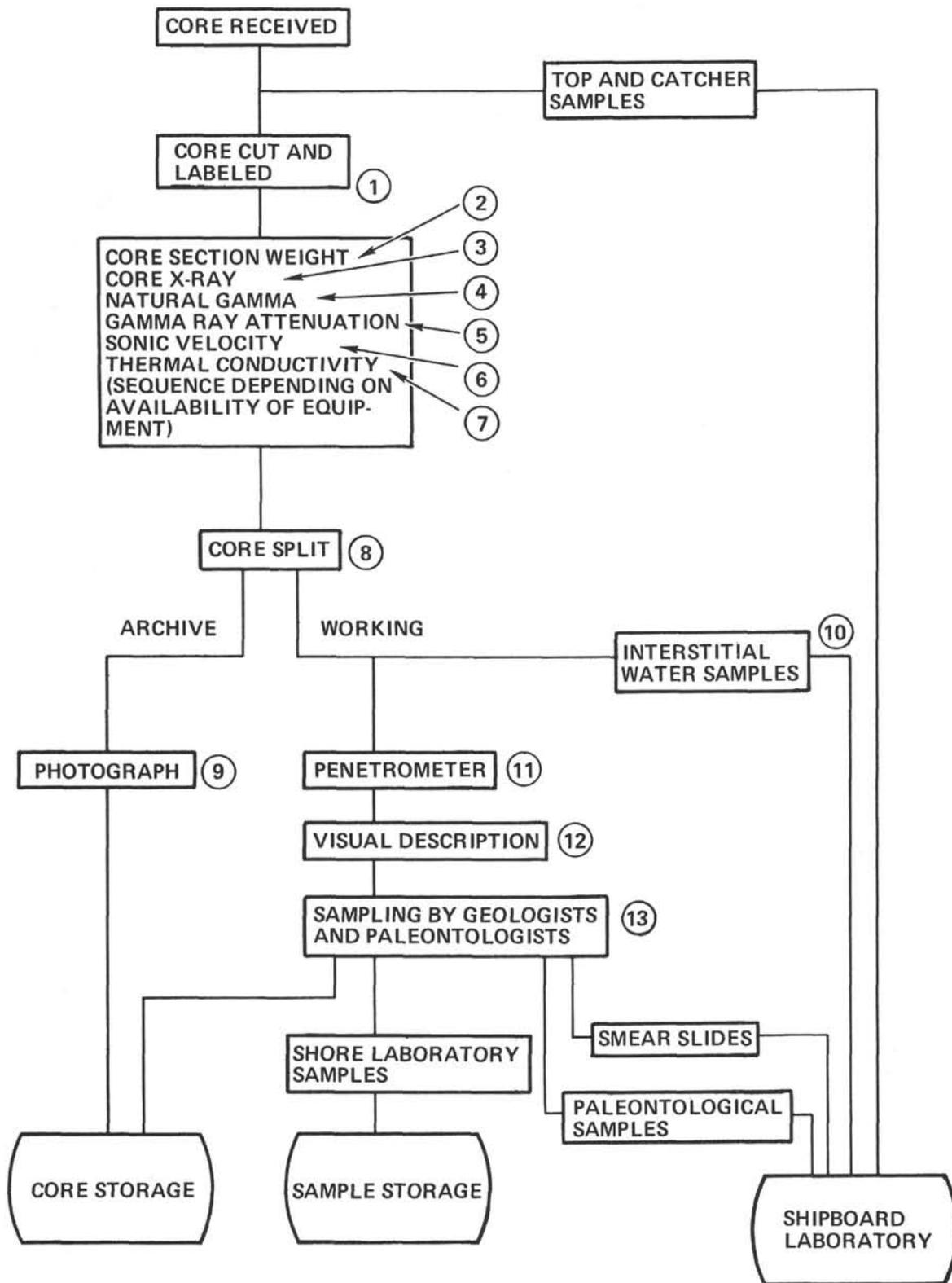


Figure 2. Block diagram of procedure for handling core materials. Numbers refer to paragraphs in the appropriate section of the text.

4. Natural Gamma Radiation Scanner

(H. B. Evans & J. A. Lucia)

Natural Gamma Radiation Measurements

Natural gamma radiation measurements provide a basic means of identifying lithology and lithologic variations, either in cores or in boreholes. The minerals giving rise to the gamma radiation include gamma-ray emitting isotopes of the uranium series, the thorium series, potassium minerals or phosphates. Diagnostic isotopes include U^{235} , Ra^{226} , Pb^{212} , Pb^{214} , K^{40} , Tl^{208} , Bi^{214} and Ra^{30} . Potassium contributes about half the total natural gamma-ray count in consolidated sedimentary rocks. The remainder can be attributed to uranium and thorium isotopes. Thus potassium-rich rocks are easily detected by gamma-ray measurements, exceptions occurring where the depositional environment has favored excessive accumulation of other radioactive minerals. Commonly, for example, the count rates obtained in fine-grained sediments are much higher than those in sandstones and carbonates tend to be particularly low in gamma-ray emitting isotopes.

In the equipment used on board ship only the total count rate is recorded; although, there is much to be gained from multichannel recording, where the total gamma-ray spectrum or the count rate contribution of individual isotopes can be recorded.

Applications to Deep Sea Sediments

A continuous, natural gamma-ray scan of deep sea sediments, in liners, obtained during the Deep Sea Drilling Project operations is desirable for a number of reasons. Continuous coring is carried out only on a limited basis; and, even where attempts are made to obtain continuous cores, in practice only partial recovery is possible. More often, intermittent coring and drilling are carried out since coring is expensive and time consuming. Therefore, the intermittent core segments which are obtained must be related to their proper vertical sequence or position in the geologic section drilled or cored. The most effective way, perhaps the only way, to affect this relationship between the core recovered and the geologic interval from which it was obtained is to scan the core segment with gamma-ray detectors, record the total count rate and/or gamma-ray spectra, and correlate these curves to a corresponding in-hole logging curve recorded over the total length of the hole. The logs, therefore, whether total count or spectra recording devices, are necessary to fill the gaps between core data and to place the core at its proper stratigraphic position. Because logging is considerably less expensive than coring, it is a reasonable substitute when some core is initially available to form a basis for log-lithology interpretation.

The natural gamma-ray scanner permits the marine geologist to extend meager information concerning

geologic and mineralogic characteristics of the core, recovered over the complete length of the geologic interval drilled, by making use of the relationship between the gamma-ray scan curve and the gamma-ray log. Features which may be obtained in this manner include lithology identification, stratigraphic properties such as bed definition, bedding sequences, and facies changes, plus information related to depositional processes where isotope identification is carried out.

Until now information concerning continuous, natural gamma-ray scans of relatively large sediment samples or core segments was extremely limited. Measurements suggest that, despite the relatively low counting rates encountered in gamma-ray measurements on deep sea sediments, sufficient differences exist between the samples low in radioactive minerals and those high in radioactive minerals to make scanning of cores for total gamma-ray count rate feasible, without introducing excessive counting times.

Some work has been done with discontinuous, collimated, pulse height analysis and spectra recording systems in identifying isotopes and lithology variations in deep sea sediment cores (Hori and Folsom, 1958) and with gamma-ray spectrometry in analyzing crushed mineral samples for uranium, thorium, and radium (Bunker and Bush, 1966). Gamma-ray spectroscopy has been used by the Marathon Oil Company (Denver Research Center), and probably by others, in defining stratigraphic intervals for correlation, which are difficult to detect by other methods.

Radioactivity measurements in red clays have been more revealing than resistivity measurements. Ocean bottom sediment radiation levels of potassium and uranium are relatively high; hence, the gamma-radiation of these sediments has proven to be a reliable lithology indicator, particularly when combined with in-hole, gamma-ray measurements.

Because of the increased sensitivity required to obtain good gamma-ray energy (spectra) definition, it is necessary to count a small core interval over a long period of time, advance the core, and repeat the measurement until the total core segment has been scanned on a step-by-step basis. Although the information obtained by this technique is preferable to total count rate measurements, the counting times are significantly increased. Hence, there would be a proportionate delay in handling core aboard ship. Because of the advantages inherent in this technique, it is hoped that gamma-ray spectroscopy and spectra analyses will be carried out on all core samples obtained during the deep sea drilling operations, even if it is necessary to make preliminary measurements aboard ship and conduct detailed analyses in the laboratory. While this delay is a disadvantage, the data obtained through core

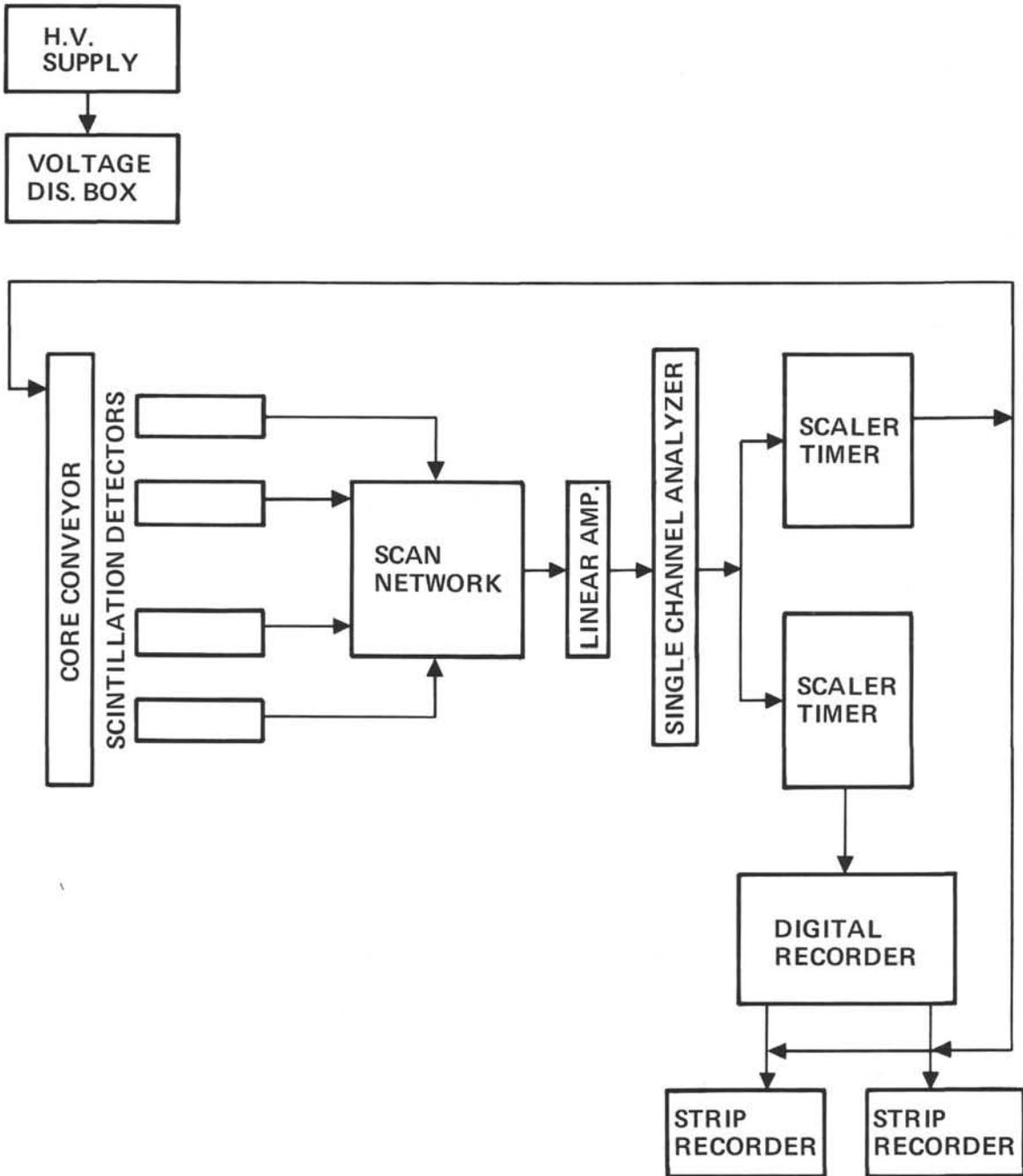


Figure 3. Gamma Core Scanning System

scan-log correlation may be one of the most powerful tools the marine geologist has available in interpreting the total geologic section.

Scan System

The natural gamma-ray scan system which is used by the Deep Sea Drilling Project is based on a design provided by the Marathon Oil Company (Denver Research Center). This is a multipurpose system consisting of: a) four shielded 3" x 3" scintillation detectors located 90 degrees apart in a plane normal to the direction of travel of the sample to be scanned; b) an incremental time-step sample transport mechanism; c) two dual-in input, single channel analyzers to accumulate total count rate; d) a multichannel analyzer to accumulate gamma-ray spectra from each of the four detectors; e) a timing unit to regulate both core transport activation and counting times; f) a digital to analog converter to supply the analog signal with the total count rate to g) two strip chart recorders. One recorder charts the count rate on a 1:1 correspondence with the core so that the recorded curve can be compared directly with the cored sample. The other recorder is scaled to the ratio of 5 centimeters of chart to 10 meters of core so the recorded curve can be compared directly with gamma-ray well logs. A printed tabulation of total count rate is also supplied. The core is advanced in increments adjustable from 1 inch to 6 inches per count interval, and counting times can be varied, but in general a 3 inch increment and a count time of 2-1/2 minutes per increment are used. Figure 3 is a block diagram of the total count rate system.

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5. Gamma-Ray Attenuation Density Scanner¹ (Hilton B. Evans and C. H. Cotterell)

Design, Development, and Evaluation

Summary

The Gamma-Ray Attenuation Density Scanner is designed to provide a continuous calculated porosity or liquid content from bulk density measurements in core

¹This system is frequently referred to by its trade name, GRAPE, an acronym for Gamma-Ray Attenuation Porosity Evaluator.

samples, encased sediments or other materials from 1 to 4-1/2 inches in diameter or thickness. The basis for this device is the equation for gamma-ray attenuation in an ideal slab absorber which is shown below:

$$I = I_0 e^{-\rho_B \mu d} \text{ or } \dots \dots \dots (1)$$

$$\rho_B = \frac{1}{\mu d} \ln [I_0/I] \dots \dots \dots (2)$$

Here I is the intensity of the gamma-ray beam which penetrates the absorber with no loss of energy,

I_0 is the source intensity,

ρ_B is the bulk density in gm/cm³,

μ is the mass absorption coefficient in cm²/gm, and

d is the thickness or diameter of the sample in centimeters.

In porous materials:

$$\rho_B = \rho_g (1-\phi) + \rho_f (\phi), \dots \dots \dots (3)$$

where ρ_g is the matrix or grain density,

ρ_f is the density of the fluid filling the pores, and

ϕ is the porosity (or liquid content in completely saturated samples) of the material.

Combining these two expressions in bulk density (2) and (3) results in an equation in which the general unknown parameters are the grain density, the absorption coefficient, and the fluid density. The equation for porosity or liquid content is:

$$\phi = \frac{\rho_g - \frac{\ln [I_0/I]}{\mu d}}{\rho_g - \rho_f} \dots \dots \dots (4)$$

Both the initial and the transmitted gamma-ray intensity (or count rate) can be measured.

For most geologic materials which are of interest, the absorption coefficient is constant (about 0.1 cm²/gm). The grain density and fluid density are variables which must be provided to evaluate equation (4) for porosity or liquid content. A reasonable value of grain density can be assigned to the common sedimentary rock types

(after visual examination of the sample) and a sufficiently accurate estimate of the fluid density is usually possible, since samples directly from a well are usually 80 to 100 per cent fluid saturated and laboratory or core storage samples are nearly dry (0 to 30 per cent).

Encased samples, particularly unconsolidated sea bottom sediments, may be partially gas saturated. However, the initial porosity or liquid content record can be corrected when the liquid contents have been determined by heating; furthermore, the samples can be rerun after drying to obtain the corrected curve using measured grain and fluid densities.

Bulk density is measured continuously by this device at various sample drive rates. Only the values for grain density and fluid density are supplied by the operator to make the porosity or liquid content calculation.

The measured sample density, computed porosity (or liquid content), and the measured sample diameter are recorded on a strip chart. Two recorders are used: one yields a chart scale which correlates directly to the sample, permitting a comparison of chart anomalies and sample characteristics; the second strip chart, records these data at the same depth scale used in recording the responses of the in-hole logging devices (5 centimeters of chart = 10 meters of hole logged) permitting a direct comparison between core scan data and log response.

Introduction

The objective which initiated the development of this gamma-ray attenuation device was to find more accurate and detailed knowledge of the porosity, density, and variations of density and porosity in sedimentary rocks. Because continuous density and porosity measurements along the length of the core was devised. Therefore, the principal technical advantage of this method is that variations in density and porosity encountered by a moving, pencil-sized gamma-ray beam are recorded continuously. Conventional core analysis methods yield only an average porosity for a given core piece or plug. Conventional measurements of density and porosity of unconsolidated sediments are not sufficiently accurate or detailed for quantitative application. Other advantages of the GRAPE system are accuracy, rapidity and, therefore, economy, very little sample preparation (limited to removal of mud or cuttings from the core surfaces), and the nondestructive nature of the measurement.

These core-derived porosities and bulk densities are useful in studying sediment deposition and diagenesis, evaluating physical properties of encased samples, and in estimating values of acoustic velocity and average density used in logging and geophysical exploration. Studies of this type, however, are not practical unless

rapid, simple methods for evaluating core porosity and density are available.

Basically, the gamma ray attenuation device consists of a variable speed drive system to move geologic material between a shielded gamma-ray source and a shielded scintillation detector, an optical caliper to measure the sample thickness, and an analog computer to calculate density and porosity (or water content) from the measured parameters. The complete system is shown in Figure 4. The individual components are identified.

Theoretical Considerations

The theoretical basis for this density-porosity device is a simple, idealized gamma-ray attenuation experiment. The source is a beam of parallel, monoenergetic gamma rays of intensity I_0 . The source gamma rays are incident on one face of a uniform slab absorber which has a thickness (d), a bulk density (ρ_B), and a mass attenuation coefficient (μ). Some of the gamma rays penetrate the absorber without energy loss. All other incident gamma rays are absorbed or scattered out of the direct beam. Either type of interaction results in a change of energy and/or a change in direction of travel of these gamma rays.

The intensity of the gamma-ray beam is altered within the slab absorber by one of three major attenuation processes. These processes are photoelectric absorption, Compton scattering and pair production (Evans, 1965). The process which is most effective in removing gamma rays from the incident beam depends upon the energy of the incident gamma rays. Compton collision or attenuation results when part or all of the incident gamma-ray energy is transferred to a free orbital electron of the absorbing material. When only part of the gamma-ray energy is lost, the direction of travel of the gamma-ray is changed. That is, scattering occurs. For most absorbers, the Compton process is the predominant means of gamma attenuation in the energy range 0.2 to about 4 MeV. Compton attenuation, therefore, is directly related to the number of electrons in the gamma-ray beam, and the number of source gamma rays which penetrate a given thickness of absorber depends upon the electron density of the absorber. In effect, the gamma-ray density device measures the number of electrons between the source and the detector.

If the intensity of the parallel beam of gamma rays which passes through the opposite face of the absorber with essentially no energy loss, as measured at a detector, is I , then

$$I = I_0 e^{-\mu \rho_B d} \dots \dots \dots (1)$$

$$\rho_B = \frac{1}{\mu d} \ln [I_0/I] \text{----- (2)}$$

The intensity of the gamma rays at the detector depends upon the geometry of the gamma-ray beam, on the energy of the source gamma rays, on the source intensity (I_0), and on the thickness (d), density (ρ_B), and attenuation properties (μ) of the absorber material (Evans, 1965).

Further, the Compton mass attenuation coefficient depends on the gamma-ray energy and the nature of the absorber.

The proper choice of gamma-ray energy insures that the mass attenuation coefficient of different materials are all about the same. The mass attenuation coefficients of aluminum, water, air, and a variety of minerals and rocks of different mineral composition do not differ greatly for gamma-ray energies between 0.2 and 3.0 MeV (Evans, 1965).

For a particular gamma-ray energy, in this energy range, the values of the attenuation coefficients of common materials are all about the same which reflects the near constancy of Z/A^1 in these materials. For elements having atomic numbers between 6 and 20, $Z/A = 0.487 \pm 0.013$, so that the attenuation coefficient (μ) is nearly constant for compounds of carbon, oxygen, sodium, aluminum, magnesium, calcium and silicon. Using a Ba^{133} source, for example, the measured attenuation coefficients of many geologic materials is approximately $0.1 \text{ cm}^2/\text{gm}$.

Therefore, use of a constant for the attenuation coefficient of geologic materials is justified providing the energy of the source gamma ray is within the specified energy interval. Sources which satisfy this requirement from a practical standpoint include Ba^{133} (0.3 to 0.36 MeV), Cs^{137} (0.662 MeV), and Co^{60} (1.17 to 1.33 MeV).

In some geologic materials, it is necessary to make corrections for variations in μ . That is, if the measured intensity I is related to the electron density through Compton scattering, bulk density measurements using this attenuation technique will not be accurate unless the ratio of electron density to bulk density:

$$\theta = \frac{\rho_e}{\rho_B}$$

is a constant. Corrections must be provided when the electron factor θ varies significantly (± 3 per cent or greater).

¹Ratio of the number of electrons per atom to the atomic weight of the absorber.

A convenient unit for θ is the number of electrons per cubic angstrom per unit density. This ratio is 0.303 for many common rocks and minerals, such as calcite, quartz, dolomite, and some clays which are composed of elements having atomic numbers in the 6 to 20 range where Z/A is approximately constant. Electron factors smaller than 0.303 occur in compounds containing heavy elements such as iron, barium and lead. Values of θ greater than 0.303 frequently occur in compounds rich in hydrogen such as water, petroleum and plastics. Calculated electron factors for minerals or liquids common in sedimentary rocks are reported in Table 1 (Harms and Choquette, 1965).

The number of electrons per unit volume for a number of minerals and liquids common in sedimentary rocks is shown in this table. The minerals are listed in three major groups, the silicates, the carbonates, and a miscellaneous group which includes some sulfates, sulfides, chlorides and a phosphate. A fourth group includes liquids that might commonly be encountered in the pore spaces of sedimentary rocks: water, a brine, and a variety of hydrocarbons.

The second column of Table 1 lists the electron density or number of electrons per cubic angstrom for each compound. Each compound scatters gamma rays in proportion to its electron density, thereby reducing the intensity of the collimated gamma-ray beam received by the detector. Among the minerals most common in sediments—those which are underlined in Table 1—silicates contain 0.758 to 0.802 electrons per cubic angstrom, carbonates 0.820 to 0.853, and other crystalline compounds 0.624 for halite to 0.905 for anhydrite. Less common minerals have a much greater range in number of electrons per unit volume, as shown in Table 1. These values for the number of electrons per cubic angstrom were derived from the composition and dimensions of unit cells for the minerals. The number of electrons per cubic angstrom for water, a brine, and some paraffinic and aromatic hydrocarbons ranges from 0.25 to 0.40. Values for these liquids were computed from specific gravity and composition.

Because it is generally more convenient to think of compounds in terms of their density rather than the number of electrons per unit volume, the third column of Table 1 lists densities in grams per cubic centimeter, a figure numerically equivalent to specific gravity. Column 4 of Table 1 lists the ratio of the number of electrons per cubic angstrom to density, and number (the electron factor) that indicates the degree of correspondence between number of electrons and density. The value of this ratio for many minerals approaches 0.303. The near constancy of this ratio reflects the preponderance of elements with atomic numbers of 6 to 20 within these compounds.

TABLE 1
Densities of Common Minerals and Liquids

See text for discussion. The minerals most common in sedimentary rocks are in italics. The corrected gamma-ray density is calculated by dividing electrons/ \AA^3 by 0.303.

	Compound	Electrons/ \AA^3	Density (g/cm ³)	Electrons/ \AA^3 Density	Corrected Gamma-Ray Density
Light	Halloysite <i>A1₂Si₂O₄(OH)₄ · 2 H₂O</i>	0.637	2.1 (?)	0.303	2.10
	<i>Montmorillonite</i> <i>A1₂Si₄O₁₀(OH)₂</i> (Na - 1 layer H ₂ O)	0.717	2.5 (?)	0.286	2.37
	Chlorite (average) <i>(Mg,A1)₅(Si,A1)₄O₁₀(OH)₈</i>	0.769	2.75	0.279	2.54
	<i>Orthoclase</i> <i>KA1Si₃O₈</i>	0.758	2.57	0.295	2.50
	<i>Albite</i> <i>NaA1Si₃O₈</i>	0.772	2.62	0.295	2.55
	Average	Anorthite <i>CaA1₂Si₂O₈</i>	0.820	2.76	0.297
<i>Kaolinite</i> <i>A1₂Si₂O₅(OH)₄</i>		0.793	2.65	0.300	2.62
<i>Montmorillonite</i> <i>A1₂Si₄O₁₀(OH)₂</i> (collapsed)		0.790	2.6 (?)	0.304	2.61
<i>Quartz (low)</i> <i>SiO₂</i>		0.802	2.65	0.303	2.65
Muscovite <i>KA1₂(A1Si₃)O₁₀(OH)₂</i>		0.846	2.76	0.307	2.79
Heavy	Diopside <i>CaMg(SiO₃)₂</i>	0.987	3.25	0.304	3.25
	Hypersthene <i>(Mg,Fe)SiO₃</i>	1.035	3.45	0.300	3.42
	Termolite <i>Ca₂H₂Mg₅(SiO₃)₈</i>	0.917	3.00	0.306	3.03
	Anthophyllite <i>Mg₇H₂(SiO₃)₈</i>	0.880	2.85	0.309	2.90

TABLE 1—Continued

	Compound	Electrons/A ⁰³	Density (g/cm ³)	$\frac{\text{Electrons/A}^{03}}{\text{Density}}$	Corrected Gamma-Ray Density
Carbonates	<i>Calcite</i> CaCO ₃	0.820	2.71	0.302	2.71
	<i>Dolomite</i> CaMg(CO ₃) ₂	0.853	2.82	0.303	2.82
	<i>Siderite</i> FeCO ₃	1.185	3.88	0.305	3.91
	<i>Aragonite</i> CaCO ₃	0.891	2.93	0.304	2.93
Miscellaneous Minerals	<i>Barite</i> BaSO ₄	1.208	4.5	0.268	3.98
	<i>Anhydrite</i> CaSO ₄	0.905	2.98	0.303	2.98
	<i>Gypsum</i> CaSO ₄ · 2H ₂ O	0.634	2.32	0.273	2.09
	<i>Halite</i> NaCl	0.624	2.16	0.288	2.06
	<i>Sylvite</i> KCl	0.578	1.99	0.290	1.91
	<i>Pyrite</i> FeS ₂	1.236	5.02	0.246	4.08
	<i>Galena</i> PbS	1.870	7.5	0.249	6.17
<i>Apatite</i> Ca ₁₀ (Cl,F) ₂ (PO ₄) ₆	0.960	3.17	0.303	3.17	

TABLE 1—Continued

Compound		Electrons/Å ³	Density (g/cm ³)	$\frac{\text{Electrons/Å}^3}{\text{Density}}$	Corrected Gamma-Ray Density
Liquids	Water H ₂ O	0.334	0.9982*	0.334	1.10
	Brine H ₂ O + NaCl (100,000 ppm NaCl)	0.354	1.071*	0.331	1.17
	n-Decane C ₁₀ H ₂₂	0.254	0.730*	0.348	0.84
	n-Hexadecane C ₁₆ H ₃₄	0.269	0.775*	0.347	0.89
	Benzene C ₆ H ₆	0.285	0.879*	0.325	0.94
	Toluene C ₆ H ₅ CH ₃	0.284	0.866*	0.329	0.94
	Naphthalene C ₁₀ H ₈	0.367	1.145*	0.320	1.21
	Anthracene C ₆ H ₄ (CH) ₂ C ₆ H ₄	0.398	1.250*	0.318	1.31

*20°C

The ratio of electrons per unit volume to density departs significantly from 0.303 in several instances. Smaller ratios are found in compounds containing heavier elements (barite, pyrite and galena) and in hydrated minerals (halloysite, expanded montmorillonite and gypsum). These lower ratios indicate fewer electrons per unit volume as compared to density, either because of the presence of heavy atoms where atomic weights exceed atomic numbers by a ratio larger than 2, or because of the water molecules which expand the lattice. Ratios larger than 0.303 are found for liquids which contain high proportions of hydrogen. Hydrogen affects the ratio in this fashion because the atomic number and the atomic weight are very nearly equal.

A relative density, correct in terms of electrons per unit volume, can be calculated from the data on Table 1. This corrected density is calculated simply by dividing the number of electrons per cubic angstrom by 0.303, and places all compounds on a scale relative to quartz and some other common silicates and carbonates. This corrected density is shown in column 5 of Table 1. In effect, all compounds are given a constant Compton attenuation coefficient of 0.100 cm²/gm by this approach, eliminating the attenuation coefficient as a variable in computing porosity (Evans, 1965). These are the densities used in the porosity computer.

The concept of "density phases" emerges from a consideration of Table 1. A "density phase" is defined here as all compounds having the same number of electrons per unit volume. All compounds having this same characteristic number of electrons per unit volume would cause identical intensity reduction by Compton scattering of a collimated gamma-ray beam. Thus, each such compound would cause identical effects in the gamma-ray porosity device. Compounds making up a single density phase have identical corrected densities.

Many common silicates could be considered for *practical* purposes as one density phase of 2.65, as shown by Table 1. For example, quartz, feldspar with a composition intermediate between albite and anorthite, kaolinite, and collapsed montmorillonite all have corrected densities of between 2.6 and 2.65. The potassium and sodium feldspars (orthoclase and albite), along with chlorite, have somewhat lower densities of 2.50 to 2.55. Hydrated clays, such as halloysite and expanded montmorillonite, have much lower densities. The pyroxenes and amphiboles of both orthorhombic and monoclinic crystal systems are much heavier and their densities commonly exceed 3.00. Each of these groups of compounds could be considered a density phase.

Of the common carbonate minerals, none is sufficiently similar in corrected density to be considered identical. The sulfate, sulfide, and chloride minerals of Table 1 each constitute a density phase, with the exception of gypsum and halite which are together a density phase.

Porous rocks contain two or more density phases. The density phases common in sedimentary rocks are: (1) average silicates—quartz, plagioclase feldspars of intermediate composition, most micas, and unhydrated clays; (2) light silicates—potassium and sodium feldspars such as orthoclase and albite, some micas, and slightly hydrated clays, (3) calcite, (4) dolomite, (5) anhydrite, (6) gypsum and halite, (7) gas-filled pores—air or gaseous hydrocarbons; and (8) liquid-filled pores—water or oil.

Analog Calculations

The actual attenuation system which approximates the ideal absorber is shown in Figure 5. The energy of the source gamma rays is fixed within certain limits. The gamma-ray beam is shielded and collimated to make it approximately parallel; and, a cylindrical or slabbed core sample replaces the uniform absorber. A Ba¹³³ source of 5 to 10 millicuries is generally used as a "monoenergetic" gamma-ray beam. A shielded, collimated scintillation detector is used to insure that the transmitted gamma rays are parallel and monoenergetic. Both the source and the detector collimation slits are 1/4 inch diameter cylindrical ports approximately 1-1/2 inches long. Figure 5 shows the relative position of the source and detector shields, the calipers, the drive carriage, and the liner or core holder.

If the absorber is porous, the bulk density (ρ_B) is related to the matrix density (ρ_G), the density of the fluid in the pore space (ρ_F), and the amount of pore space or porosity (ϕ) by the expression:

$$\rho_B = \rho_G (1 - \phi) + \phi \rho_F \dots \dots \dots (3)$$

Combining equations (2) and (3) gives

$$\frac{1}{\mu^d} \ln \left[\frac{I_0}{I} \right] = \rho_G (1 - \phi) + \phi \rho_F \quad \text{or}$$

$$\phi = \frac{\rho_G - \frac{1}{\mu^d} \ln \left[\frac{I_0}{I} \right]}{\rho_G - \rho_F} \dots \dots \dots (4)$$

Since I_0 , I , μ and d are easily measured and ρ_G and ρ_F of common geologic materials are not difficult to estimate with sufficient accuracy for this purpose, the porosity (or liquid content) of the material can be readily evaluated from equation (4).

It is convenient to use a small analog computer to make the porosity calculations at the same time the gamma-ray intensity and the sample thickness are measured. Standard diameter cylinders are used to calibrate the caliper. The sample thickness (d) from the caliper and

the countrate I from the detector are fed into the computer. The source intensity I_0 is nulled and values for ρ_G , ρ_F , and μ are set on the appropriate potentiometer.

In evaluating equation (4) the most convenient computational procedure is to consider μ a constant, $0.100 \text{ cm}^2/\text{gm}$, and use corrected grain densities for any sample components having electron factors in the range $0.294 \geq \theta \geq 0.312$.

The corrected grain densities are calculated from the following relationship:

$$\rho_{GC} = \frac{\theta_1}{\theta} \rho_{GL}, \text{-----} (5)$$

where θ_1 is the electron factor of the "abnormal" component, θ is the normal electron factor 0.303, and ρ_{GL} is the measured grain density of the component which required correction. The corrected densities are listed in Table 1.

Bulk density is directly measured by the GRAPE device through the determination of the scattering caused by the rock sample. This bulk density measurement corresponds to an evaluation of the number of electrons per unit volume and can be converted to an apparent density. If values for grain density and fluid density are assumed in equation (2) or (3), porosity can be calculated. If a rock contains two density phases, for example quartz and air-filled pores, the selection of grain density and fluid density is straightforward and a porosity can be directly calculated.

The assumptions made to solve equations (2) or (3) are somewhat more complex if three or more density phases are present in the rock sample. If, for example, the rock is a calcite-cemented quartz sandstone with air-filled pores, a grain density between quartz and calcite proportional to the relative abundances of the two minerals must be assumed before equations (2) or (3) can be solved. Similarly a quartz sandstone with pores saturated with both gas and a liquid requires the assumption that the fluid density is intermediate between those of the gas and the liquid, and is dependent upon the relative saturation.

Complexities in the mineralogy or the saturation have effects on the accuracy of density and porosity determinations. It is our experience that most sedimentary rock systems are sufficiently simple to allow quite accurate porosity determinations by the gamma-ray technique—after a brief examination of the rock samples by a geologist.

In summary, the gamma-ray attenuation device is applicable to geologic materials. Factors that make the application of this technique practical are the preponderance

of Compton scattering for gamma rays with the energy used, the close relationship of number of electrons per unit volume to density for most minerals common in sedimentary rocks, and the general accuracy with which a geologist or engineer can judge both grain and fluid densities in common sedimentary rocks.

The measured bulk density and sample thickness as well as the computed porosity or liquid content are recorded on a strip chart. Standard cores or empty liners are used to calibrate the detector-computer system. Because the core sample and the recorder chart are driven at the same speed, a direct comparison of the recorded parameters and the actual sample characteristics can be made (Evans, 1965; Harms and Choquette, 1965). In addition, a second strip chart records these parameters on a scale of 5 centimeters of chart to 10 meters of core. This scale is identical to the one used in recording well logs; therefore, a direct comparison of core parameters and well logs is possible.

When space is left between samples on the carriage bar, a small section on the ends of each sample is lost to the density-porosity computer because the response of the system is not immediate. The length of these sections depends on the time constant of the ratemeter, the drive speed and the condition of the ends of the sample but sections longer than 1/2 inch at either end are unusual. Difficulties due to response time characteristics can be avoided by leaving no space between samples, when the samples are small.

System Characteristics

Specifically, the GRAPE system was constructed for rapid porosity evaluation of cores in storage as well as core samples cut during exploration and development drilling, however, the device is quite versatile. Core samples 1 to 4-1/2 inches in diameter, conventional core plugs, slabbed core, encased, unconsolidated sediments, and other materials can be analyzed at drive speeds up to about 6 inches per minute. At this speed, some 200 feet of core can be analyzed in about 6 hours. The carriage handles 5-foot lengths of core or liner.

The 1/4-inch diameter collimating slits produce a gamma-ray beam which varies in size with the source utilized to the detector spacing (which, in turn, depends on the sample thickness), but the average beam diameter at the center of the spacing is slightly less than 1/2 inch. Inhomogeneities such as layers, inclusions, vugs and other minor features with dimensions which are not small compared with the beam diameter have a major influence on the calculated porosity. The sample can be rotated to change the beam path and rerun to alter the effect of vugs or nodules. The relation of the strip chart to the path of the beam penetrating the sample is then necessary for future reference.

The device is designed for use in either the field or the laboratory by one operator. The same operator can assemble or disassemble the device without assistance. Because the device is readily portable, it provides an inexpensive and rapid method of evaluating old or new core for porosity and density. This information is of immediate interest to the log analyst, the geologist, the geophysicist and the engineer in both exploration and reservoir evaluation.

The total error of the system, including statistical variations in source strength and electronic drift, is less than ± 1 per cent porosity at the 20-per cent porosity level. Errors due to poor choices of matrix density or fluid saturation for a particular sample are discussed elsewhere (Harms and Choquette, 1965).

Applications of the Attenuation Method

The gamma-ray technique yields a value for bulk density which may be applied to some geophysical problems. For example, a knowledge of bulk density or porosity and lithology allows the estimation of acoustic wave velocities. Values of bulk density can therefore be useful for interpreting effects seen on acoustic and density logs. Detailed knowledge of acoustic wave velocities can, of course, be applied to many general seismic problems.

Bulk density values readily obtained by the gamma-ray technique can also be useful in the interpretation of gravity data, and in determining the physical properties of encased geologic materials.

The proportions of two density phases within a rock sample can be analyzed if there is a reasonable contrast in grain density between the two phases and if the rock is non-porous. Several examples of this application of the gamma-ray technique can be pointed out.

It is possible to determine the proportion of kerogen in oil shales. Oil shale is non-porous, contains little water, and commonly is layered in a manner reflecting the per cent of kerogen. The kerogen has a density of about 1.10 and the rock matrix has a density that averages about 2.70. Since in an oil-shale core the corresponding trace records the per cent of kerogen, the kerogen layering is clearly recorded on the gamma-ray trace. Average values of the per cent of kerogen reported for an interval correspond reasonably well to the amount of oil recorded from the same interval (Evans, 1965; Harms and Choquette, 1965).

Variations of the gamma-ray trace recorded for a rock sample can be used simply to locate changes within the sample and to guide sampling procedure. In applications aimed at the determination of porosity, bulk density or compositions, assumptions concerning the grain density and fluid density are made that are based on

observation or experience. In cases where observation or experience can be used to only a limited degree as a guide to analysis, the variations in the gamma-ray trace can be employed to select material for more comprehensive or complicated types of analyses. Such a guide can be very important in optimizing the amount of information derived from these additional analyses.

An example may serve to illustrate this point. The cores are taken from a potential reservoir interval. Some knowledge of the porosity distribution within this reservoir is desired, but it is known that the mineralogy of the rock is complex and many density phases are represented. The core is run through the gamma-ray device using intelligent guesses for grain and fluid densities. The trace recorded for this core may show relatively little or a great deal of variation. It is common practice in the industry to take samples at one-foot intervals for porosity, density, permeability, and saturated determinations. When such a sampling program is compared to the gamma-ray trace, the sampling may be found to be entirely inadequate or much too complete, depending on the degree of heterogeneity expressed by the trace. The implications are obvious: in the one case, an inadequate representation of porosity and porosity variations is obtained; and, in the other case, the additional analyses represent an unwarranted expense. Obviously, the same reasoning applies to encased, unconsolidated sediments obtained in deep sea coring.

The basic assumption made in the use of the gamma-ray device as a sampling guide is that related rock materials made up of numerous density phases will not appear homogeneous to the device unless they are indeed alike. Although exceptions to this assumption can be found, such cases are extremely uncommon.

Samples are sometimes encased in metal or plastic containers and cannot be analyzed in conventional ways. Cores of modern sediments are commonly taken in aluminum or plastic tubing, and cores of unconsolidated or fractured reservoirs are taken in rubber sleeves, so that direct observation of the core material in an undisturbed state is impossible. Most of our experience has been with cores of Recent carbonate sediments encased in aluminum tubing and cores cut in rubber sleeves. The traces clearly locate areas of bubbles and liquid distribution (or content) porosity or compositional changes which can guide sampling. Such a trace preserves an important permanent record of the condition of the core material before it is disturbed by sampling or removal from confinement.

The GRAPE device can be adapted to determine density or locate density contrasts in pressure bombs or tubes subjected to elevated pressures and temperatures. For example, the existence of a fluid interface and the position of the interface in a pressure bomb can be

determined. Such information is valuable in establishing phase relationships. The bulk density or porosity of jacketed rock samples can be measured while the sample is subjected to elevated pressure. This information is useful for determining properties of rocks under various states of stress.

Conclusions

A rapid, accurate, and continuous method for measuring porosity or bulk density of cores from bore holes has been developed. The method is based on gamma-ray scattering. The principle technical advantage of this porosity measuring method is that variations in porosity encountered by a moving, pencil-sized gamma-ray beam are recorded continuously.

Excellent agreement exists between porosities and densities of common sedimentary rocks obtained by this method and other conventional methods. This agreement reflects two factors. First, Compton scattering, the collision of gamma rays with electrons within the measured material, is essential for the production of the energy of gamma-rays emitted by the source used in this device. Second, the number of electrons per unit volume is closely related to density for most minerals commonly found in sedimentary rocks. Therefore, the amount of Compton scattering can be used to accurately measure the bulk density of the rock sample penetrated by the gamma-ray beam.

Porous rocks contain two or more "density phases". A density phase is defined as one or more non-porous minerals or fluids having a characteristic number of electrons per unit volume. If a rock contains two density phases and the density of each phase is known, the volumetric proportions of each phase can be directly determined. If a rock contains three or more density phases, the determination of the proportions of each phase is more complicated, but it can be achieved if accurate average densities are assigned to the grains and to the fluids. This can commonly be done with enough precision to yield accurate porosities or fluid contents.

Porosity variations within sedimentary rocks reflect the factors controlling the development of porosity. Porosity variations are commonly more extreme and less predictable where controlled by cementation, solution or fracturing.

The GRAPE device can be applied to a variety of problems. These include saturation determination of components or front identification of recovery flood fluids in observation wells, in engineering geophysics problems, and, in the mining industry, as a means of measuring the ore content of drill core or rock samples on the surface or in hole. The principle application is to the determination of density and porosity and their variations within sedimentary rocks. However, the

results can also be applied to geophysical problems where values for bulk density are useful. The gamma-ray device can be used to analyze the composition of rocks under certain conditions. Traces derived from the gamma-ray device can be used simply as guides to sampling for further analyses. Samples encased in metal or plastic under normal or elevated pressures and temperatures can be analyzed without disturbing sample conditions. Directional properties of rocks can, in some situations, also be detected. The most important applications at present are to measuring the average porosity and porosity and density variations of sedimentary rocks and to developing guides for sampling.

Acknowledgements

Attention should be drawn to significant contributions to this work by C. H. Cotterell, who was responsible for development and testing of the device as an operating system, by I. D. Johnson, who designed the optical calipers and most of the basic electronic circuits of the ratemeter and drive system, and by J. E. Beitel, who assisted in the design, development, and testing, and also established operating procedures for the GRAPE system. Cotterell and Beitel also carried out the experimental porosity and absorption coefficient determinations. J. C. Harms and P. W. Choquette selected most of the minerals and rock samples for use in porosity, grain density and absorption coefficient measurements, and C. L. Sutula assisted in computing the electron density. Finally, the Marathon Oil Company should be acknowledged for granting permission to publish this section.

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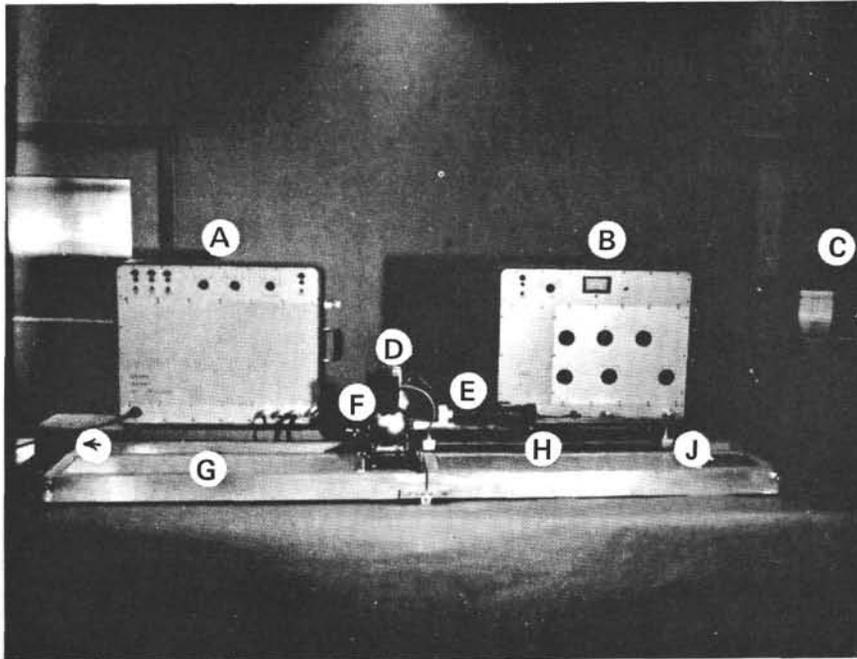


Figure 4. *The Complete GRAPE System (Single Recorder)*
Showing: A. Power Supply Case, B. Computer Case,
C. Strip Chart Recorder, D. Optical Caliper,
E. Core Sample, F. Source Shield (The
Detector Shield is Directly Behind The
Source Shield and Hidden by it), G. Main
Frame, H. Core Carriage, ←. Direction of
Core Travel, J. Vertical Centering Spacers.

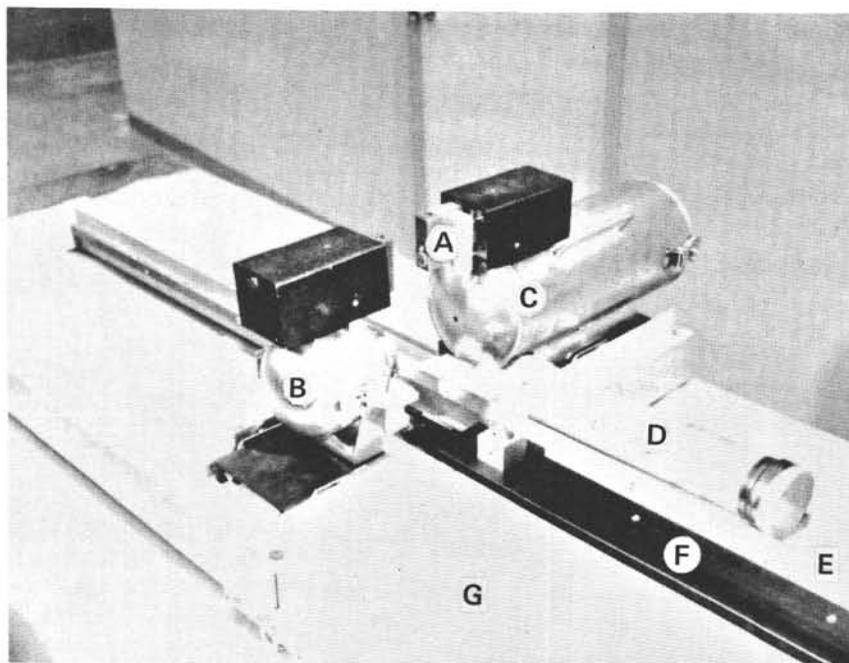


Figure 5. *Frame and Carriage Assembly*
A) Optical Caliper B) Source Shield
C) Detector Shield D) Core Sample
E) Carriage Bar F) Carriage Bed
G) Main Frame

General Information

Frame Section

The frame section is the measurement portion of the gamma-ray attenuation device. It consists of the source shield, detector shield, moving carriage and calipers (see Figure 5). The source shield contains the gamma-ray source capsule (either a Ba^{133} or Cs^{137} source of 1 to 10 millicurie is used). This shield is a lead sphere with an outer shell of steel for support. The source shield has a removable front with a 1/4 inch diameter hole for collimating the gamma-ray beam. The back of this shield is removed when the source is placed in the shield or removed from the shield.

The detector shield contains the crystal which is 1-1/2 inch diameter by 2 inches long, and a 2-inch photomultiplier tube (see Figure 5).

The carriage for the core consists of a bar for supporting the core and a bed which moves down a track between the source and detector (see Figure 5). The drive mechanism is controlled by a speed selector switch with positions 0.5 through 3.5 inches/minute. This varies the rate of travel of the carriage through the gamma-ray beam.

The optical caliper is in two sections. One section is located on top of the source shield, and the other is located on top of the detector shield (see Figure 5). Reflecting tape is located below these caliper sections. The principal of operation of these units is as follows: A light beam from a light source is reflected by the tape back to a photodiode in the caliper. The photodiode senses the light and moves forward until the side of the core blocks the reflected light. The sensing portion then holds in a position that allows only part of the light to be reflected. If the core diameter gets larger, the light is cut off and the caliper retracts until part of the light is again reflected. This system enables the calipers to follow both sides of the core. Because both of the trackers are connected electrically, a differential output voltage is applied to the computer and to the recorder. This voltage is calibrated to give the core diameter.

Power Supply and Controls

The power supply section contains the direct current power supplies for the stepper motors, the motor driver circuits, the caliper servomotors, the caliper lamps, and the photomultiplier tube. This case has the speed controls as well as the power supply switches.

Analog Computer

The analog computer case contains a special purpose computer designed to evaluate equation (3) in the first section of the Introduction. The computer operates on all of the input variables from the different sections

of the GRAPE device and uses them to evaluate the equation. The outputs from the computer and the caliper are recorded on strip chart recorders.

The computer case also contains the caliper servoamplifiers, the scintillation detector ratemeter and logarithmic amplifier, and the recorder calibration voltage network.

Recorders

The output from the computer is recorded on the paper strip charts of two 3-pen recorders. The three variables recorded are: 1) core diameter - red pen scaled 0-5 inches, 2) bulk density - green pen scaled 0-2.5 gm/cc or 1.0-3.5 gm/cc, 3) computed porosity - blue pen scaled 0-50 per cent with possibility of scaling from 0-100 per cent.

The chart drive of one recorder is driven by a stepper motor at the same rate the core samples move past the source and the detector. This recorder gives a *one to one* correlation between the strip chart record and the core. The second recorder is driven at a 200:1 reduction, yielding a chart curve that is comparable to a log recorded at 5 centimeters of chart per 10 meters of hole.

6. Sonic Velocity Measurements

General Considerations and Equipment

The objective of the sonic velocity measurements is to make continuous sound speed measurements along the core lengths in order to provide the basic information necessary for understanding the acoustic properties of the ocean bottom and their relationships to sedimentary properties and processes. The measurements are generally made at three places along each 150-centimeter core section using a pulse system capable of making sound speed measurements through a core liner with minimum disturbance to the sediment sample. The velocity profile for each core section is measured four hours after the core has been recovered. This allows this core to come to the ambient laboratory temperature. The measurements through the core liner are accomplished by using a specially designed transducer configuration that is coupled directly to the core liner. The transducer head is moved along the core liner to repeat the measurements at any desired interval. The transducer head is illustrated in Figure 7.

The pulse method involves measuring the travel time of a transmitted wave over a known path length. The technique employed for the sediment sound speed measurements differs from direct measurements of travel time in that sound speed is determined by comparing the travel time through the core sample to the travel time through a reference sample having a known sound speed. Distilled water is used as the reference

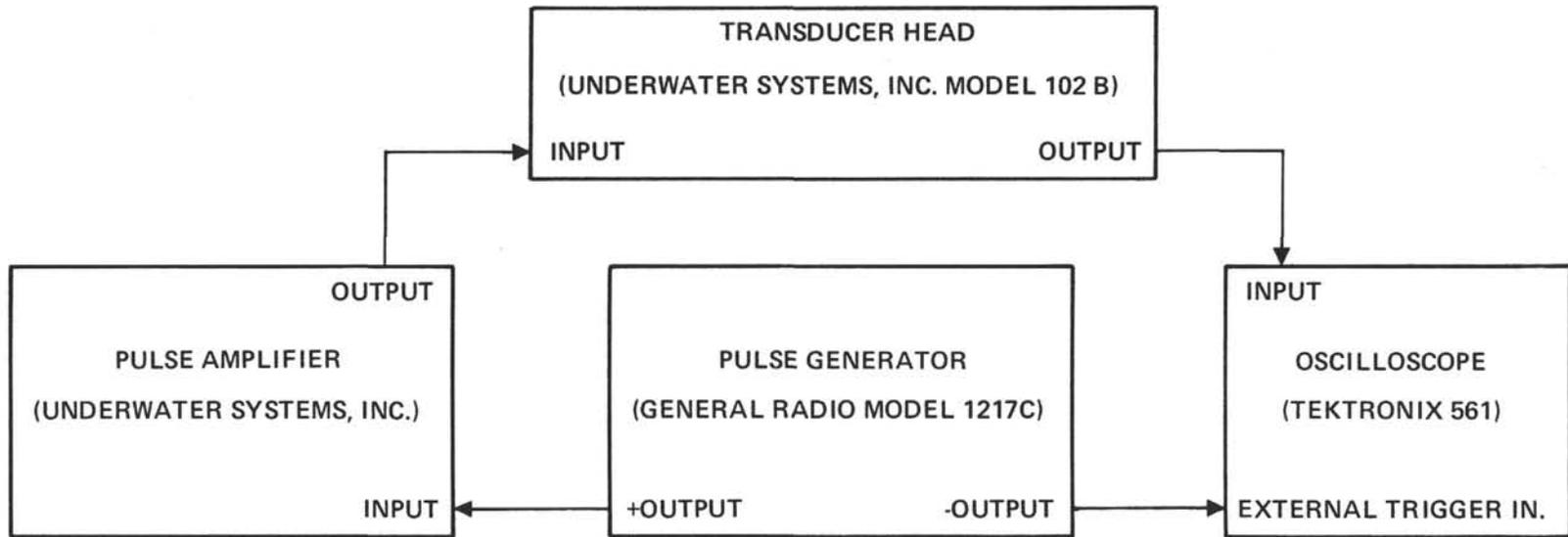
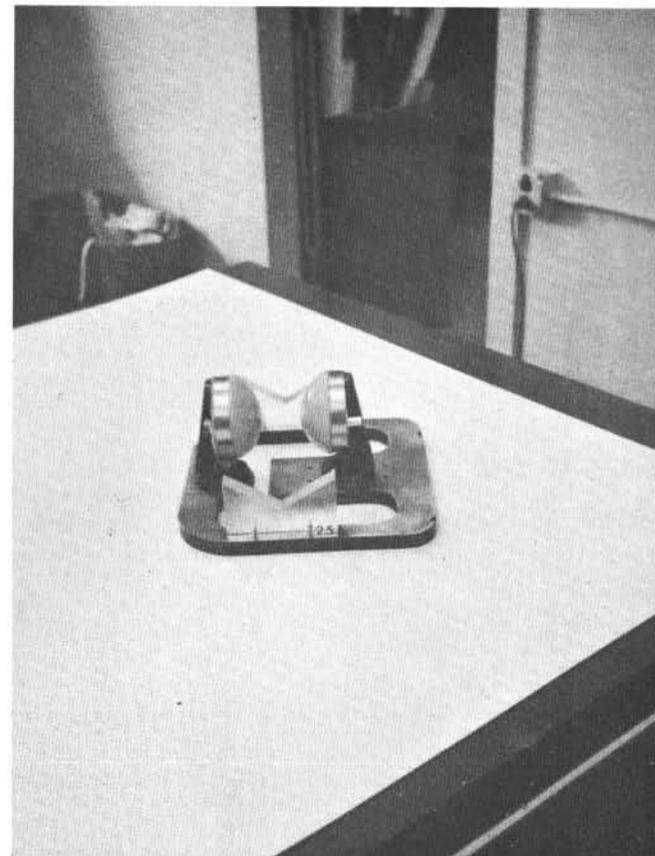


Figure 6. *Block Diagram of Sediment Velocimeter.*



**TRANSDUCER HEAD WITH
CORE LINER**



TRANSDUCER HEAD

Figure 7. Photos of transducer heads.

sample. The advantage of the comparison method is that it eliminates the need for absolute measurements of transit time.

The sediment velocimeter system is illustrated in a block diagram in Figure 7. Barium titanate transducers are excited to emit ultrasonic pulses in the compressional mode. A General Radio 1217C pulse generator, followed by an Underwater System, Inc. pulse amplifier, is used to excite the transmitting crystals at their natural resonant frequency of approximately 400 kHz. A 250 volt pulse of about 0.5 microsecond duration is used to obtain the sonic ring. The transmitted pulse is also used to trigger the sweep of a dual trace Tektronix 561 oscilloscope—with a 3A72 and a 3B3 plug-in unit—which is used to display the received signals.

Sound Speed Measurements Across the Diameter of the Core

The sediment sound speed across the diameter of the core (through the core liner) is determined by measuring the difference between the transmission time through the core sample and the transmission time through the reference distilled water sample. Before starting the sediment sound speed measurements, a series of tests are conducted to insure that the system is functioning properly. After completing the check-out procedure the first step in the actual measurement is to insert the reference sample into the transducer head. Both the reference and sediment sample liners should be kept moist when inserted into the transducer head to insure maximum coupling between the core liner and the transducers and to prevent damage to the membrane enclosing the transducer crystals. Either a soapy water solution or glycerine is used as the lubricant. The reference sample is contained in a core liner identical to the liners used for the core sections. The crystals in the transducer head are reciprocal, and either one can be used as the transmitter. The pulse repetition rate is adjusted so that reverberation from the preceding pulse has fully decayed prior to the next pulse.

After the reference sample is in the transducer head and the acoustic signals are transmitted, the delay time control, delay time multiplier, and sweep rate on the oscilloscope are adjusted so that one of the received pulses is conveniently expanded, in order that the desired portion of the wave train is displayed at the vertical center line of the oscilloscope. Generally, the third cycle of the wave train is used for the measurement. After the peak of the third cycle is aligned at the center of the oscilloscope face, the delay time and delay time multiplier settings are recorded in the data log book.

The reference sample is then removed from the transducer head and replaced by the core section. The

oscilloscope sweep rate and delay time multiplier should not be changed. The signal transmitted through the core sample is then aligned using the delay time control, so that the third cycle of the received wave train is at the center line of the oscilloscope. The delay time control setting is then recorded in the data log. It is important that the same portion of the reference and core sample wave train be used for making the travel time difference determination.

After completing the series of sediment sound speed measurements along the core section, the reference sample time measurement is repeated. The reference time measurement may be repeated more often if desired; however, this is not necessary unless the temperature in the laboratory is fluctuating rapidly during the course of the measurements. It is important that the temperature of the reference sample and the core sample be measured at the time the measurements are made. A thermometer is sealed in the reference sample, while the temperature of the core sample is determined by inserting a thermistor probe or small thermometer in the ends of the core section. The temperature measurement is essential, since both the reference and core sample velocities are a function of temperature.

The core liner surrounding the reference sample compensates for the contribution of the liner surrounding the core sample and the transmitter-receiver path length is fixed, so that the only difference between the two samples is in the sound speeds corresponding to the distilled water and sediment. The difference in travel times between the water and sediment is determined from the delay time settings and the difference then is used to compute sediment sound speed as follows:

$$T_w \cdot \frac{d}{C_w} - T_{e_w} = T_s \cdot \frac{d}{C_s} - T_{e_s}$$

where:

- C_s = sediment sound speed,
- C_w = sound speed of reference sample (distilled water),
- T_w = transit time through reference sample, including core liner, and electronic delay,
- T_s = transit time through sediment sample, core liner, and electronic delay,
- d = inside diameter of core liner,
- T_{e_w} = electronic delay time for reference sample, and
- T_{e_s} = electronic delay time for sediment sample.

Since

$$T_{e_w} = T_{e_s}, \text{ sediment sound speed is determined by}$$

$$C_s = \frac{C_w}{1 - C_w(T_w - T_s)}$$

Measurement Accuracy

The overall estimated accuracy for the measurement made across the diameter of the core depends on: (1) the accuracy to which C_w is known; (2) the accuracy in measuring $(T_w - T_s)$; (3) the accuracy in measuring the diameter of the core liner; (4) the oscilloscope incremental time delay error; and, (5) the difference in electronic delays associated with the reference and core sample measurements.

The estimated total error is determined by taking the square root of the sum of the squares of the individual errors. While it is difficult to assess the individual errors, the following factors should be considered: (1) C_w is known from Wilson's tables and is subject to error in determining the reference temperature and possible contamination of the distilled water; (2) the travel time difference $(T_w - T_s)$ can be measured with a maximum error of 0.02 microseconds; (3) the inside diameter of the core liner can be measured to 0.001 inch, although some error may result from possible variations in the thickness of the core liner; (4) there is a maximum oscilloscope incremental time delay error of 0.4 per cent, and, (5) the electronic delays for both the reference and sediment samples are equal. Considering these factors, the overall estimated accuracy is about 0.5 per cent.

7. Thermal Conductivity

Thermal conductivity measurements are made on one section of each core using a probe device. The procedures followed are essentially the same as those described by Van Herzen and Maxwell (1959).

Reference

Von Herzen, R. P. and Maxwell, A. E., 1959. Measurements of thermal conductivity of deep sea sediments by a needle probe methods. *J. Geophys. Res.* 64, 1557.

8. Core Splitting

A whole 150 centimeter core section is placed in the core cutting jig so that the core can be split longitudinally along an inscribed mark separating the identified sides of the core. A partial cut is made through both sides of the core liner with a circular saw mounted on the jig. Care is taken to avoid cutting through the plastic into the sediment since this might contaminate the sediment with a variety of plastic and other materials which are stuck to the cutting blade. After cutting partially through the plastic liner, a modified tile cutter is used to cut through the remaining thickness of plastic. This avoids cutting deeply into the core. After the core liner has been cut completely through on diametrically opposed longitudinal lines a coping saw fitted with a stainless steel piano wire blade is used to cut entirely through the sediment by drawing the

piano wire through the longitudinal cuts as if cutting cheese. After cutting through the unconsolidated sediment with the piano wire cutter, the two half sections are separated and, if necessary, the cut surface of the core is cleaned by scraping the sediment with a spatula. The sections are then designated working and archive halves, respectively. In order to protect them when they are not being processed, the core halves are stored in protective plastic tubing, D-shape in cross-section.

9. Core Photography

The photographic equipment in use aboard *Glomar Challenger* was especially designed to take pictures of core samples. The equipment consists of:

- (1) A ten-foot rubber belt conveyor and two 150-centimeter length core trays to transport the core samples into picture-taking position below the cameras.
- (2) Two cameras, one containing black and white film and one containing color film, set to continuously record 25-centimeter lengths of core sample.
- (3) An electronic flash strobe unit to supply the necessary light.
- (4) A dual relay and timer circuit to control the sequence of pictures taken.

The procedure then is to photograph a split half-section of core which is clearly identified with all the necessary numbers. The core is always positioned so that the camera travels from the top to bottom of the core section in fixed increments.

Aligned with the core sample is a 150-centimeter scale marked in centimeters with heavy markings each 25 centimeters. The scale is photographed along with the core section. The core camera tray is painted with an 18 per cent gray scale. A Kodak color scale is photographed along side each core section so that color reproduction can always be related to a standard, thereby making it possible for any color processing laboratory to produce the correct printed color temperature. Panatomic X and 5251 Kodak color negative film are the two films used. These are processed in the manner specified by the manufacturer, the black and white film being processed on board ship, using a Houston model BW-3510 film processor.

10. Procedure for Shipboard Sampling and Analysis of Interstitial Water in the Cores

The purpose of this operation is to preserve sediment and pore water samples for onshore laboratory studies of components of interstitial waters, and to make shipboard analyses of the more perishable components.

In a few cases prior to cutting the core it is drilled with an auger and any gases released are collected with a 20 cc vacutainer. About 200 milliliters of gas are collected

with a plastic syringe at the exit to the drill; this syringe is first quickly washed with some of the gas. This sample is injected into a 10-foot gas chromatography column.

Later, after splitting, three samples are taken from the core center for each 20 meters of sediment penetrated. A 2.5-centimeter diameter plastic syringe with the end cut off, and sharpened, or one of the plastic samplers provided, is driven 5 centimeters into the sediment. If the sediment is hard or brittle, an equivalent section is removed with a hammer and knife. One sample is immediately placed in a wide-mouthed bottle with Polyseal screw cap. Excess space in the bottle is filled with Saran Wrap enveloping moistened laboratory tissue (to maintain constant water vapor pressure in the bottle). The bottle is stored cool (not frozen) in a container in a refrigerated core van.

The second and third samples are extruded into the barrel of a specially designed passivated stainless steel squeezer (Manheim, 1966) which is placed in a hydraulic press and squeezed under 2,000 to 10,000 pounds pressure. During squeezing the pore water passes into a plastic syringe forcing the plunger before it, essentially prohibiting evaporation. The syringe is then capped with a millipore filtering attachment; 12 to 15 milliliters of fluid will often, but not always, be obtained.

About 0.6 milliliters of fluid is expressed through the syringe needle with half of this amount going into each of two evacuated glass stopcocks which have an enlarged center hold. These stopcocks are designed for a direct attachment to extraction lines for H/D and O^{18}/O^{16} analyses. In view of the later limited quantity the interstitial-water samples, it is extremely important to follow the correct sampling and storage procedures in order to avoid alteration of the original isotope content through evaporation, exchange or contamination.

An additional drop or two of fluid is expressed for salinity determination with a Goldberg hand refractometer, about 0.3 milliliters for gas analysis, and 1.2 milliliters for Eh, pH, S^{2-} , and Ca^{++} analysis with the U.C.L.A. electrochemical unit.

An additional 5 to 6 milliliters are fuse sealed in polyethylene tubing for later laboratory analysis of sodium, potassium, calcium, magnesium, strontium, chlorine, sulfate and iron, silicon, barium, boron, etc. in the ≥ 1 mg/l range. The remainder of the fluid is frozen in a polyethylene bottle with a nitrogen gas phase.

A fourth small sample from the core center is taken on a series of at least 4 cores from each of 4 or 5 holes for various carbon dioxide analyses. The objective is to take at least 20 of these samples per leg, such as seven from each of 3 or 4 holes top to bottom, or four from

each of 5 holes. Five milliliters of fluid squeezed from this sample is injected directly into a double glass stopcock for measurement of pCO_2 and total CO_2 (carbon dioxide) ashore. The sample is to be acidified with phosphoric acid, or one that does not contain sulphur. Subsequent to the carbon dioxide analysis, the water will be used to determine sulphur isotope ratios on the sulphates. Five milliliters of solution are also to be apportioned for carbon-isotope studies. Only rarely will the single sediment sample for the carbon dioxide studies provide the 10 milliliters required for the two aliquots (5 milliliters for total $CO_2 - pCO_2$ and 5 milliliters, for C-isotope). When more solution is required to achieve a total of 10 milliliters, the amount needed would be taken from the aliquot of the solution for major element analysis that is ordinarily frozen (that stored in the polyethylene bottle with a nitrogen atmosphere only). The removal of some of the latter solution must be done prior to freezing, and the two portions (that from the polyethylene bottle and that from squeezing the sample whose effluent is for carbon-dioxide analysis) must be mixed before the two 5-milliliter samples are apportioned.

Dense samples are squeezed in a similar manner with somewhat higher pressures and longer squeezing periods. If the volume of squeezed water is less than 2 cc, it may be necessary to duplicate the second sample, or reduce the scope of the analysis. If a sample has porosity but it is too lithified to be squeezed, such as, a metamorphic rock, it is preserved in a wide-mouthed bottle for future leaching to determine the chlorine content and possible other major constituents.

On each leg, four large samples are taken, one in each of 4 holes preferably at depths below 100 meters. Ideally, the samples should be fine grained and the least contaminated with drilling fluid. They should be large enough to yield a total of 100 to 125 cc of fluid on squeezing (probably 800 to 1000 grams) successive portions.

11. Penetrometer Measurements

This test is made to give a relative measure of induration of unlithified sediment. Its purpose is to supplement the core description made aboard ship, and it should not be considered a true measure of sediment strength. The instrument used here is the AP-210 penetrometer (Soil Test, Inc.) which consists of a test rod into which a standard needle can be mounted and which can be released under known loads by a clutch mechanism. Penetration of the needle into a sediment sample can be read on a four-inch diameter dial. The equipment comes with weights for penetration loads of 50 and 100 grams. The test follows the "Standard method of test for penetration of bituminous materials" (American Society for Testing and Materials Designation D-5-65).

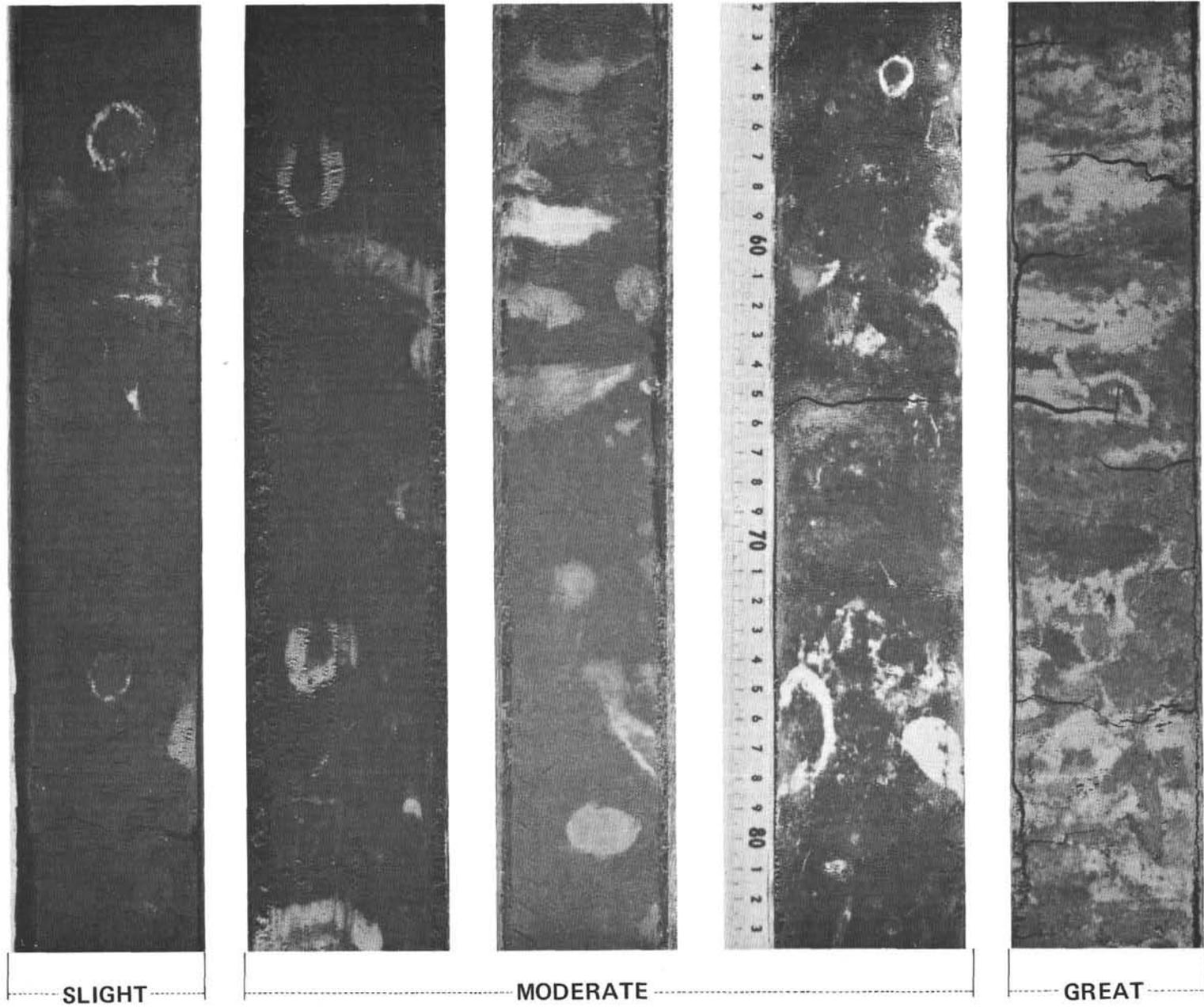


Plate 2. Degrees of mottling.

In measuring the induration of a core of uniform sediment, tests are made at 3 points on each core section (the same as those where sonic velocity measurements are made). However, if a variety of lithologies are present then the spacing of the tests is varied to give a better representation of these different lithologies.

12. Visual Core Descriptions

As soon as possible after splitting, a visual description of the split core is made. This is probably one of the more important records made aboard ship. Photographs certainly duplicate some aspects of this description, but the on-the-spot observations of trained geologists are invaluable. If the description is delayed, the colors of the core materials may change and, after many of the cruise legs, core materials do not reach the shore laboratories in time to be described before preparation of the initial report.

A free form of description is commonly followed which allows the geologists to make whatever observations they feel are most significant. However, particular attention is paid to such features as color, internal structures, and disturbances due to drilling, texture and composition of the core material. Color determinations are made as far as possible on the freshly split, wet core by comparison with the GSA rock and soil color charts under uniform lighting conditions by using daylight fluorescent illumination. Munsell Color Charts are also available.

Visual description of the minor structures is to some extent supplemented by the X-radiographs, and particular attention is paid to such things as: the nature of the bedding, disturbance of the core due to drilling, the presence or absence of mottling, etc. The degree of mottling (from slight, moderate, to great) is assigned according to the standards given in Plate 2.

When describing, in general terms, the texture of the core material, the Wentworth scale is commonly used. Any textural classification is, of course, superseded or supplemented by the results of the on-shore laboratory work on grain size analysis. In general, sediments are classified by texture according to the classification scheme devised by Shepard (1954).

The major components of the sediment composition, to the extent that these can be recognized with the naked eye, are described in general terms. These descriptions are supplemented by smear slide studies and later, on-shore studies of the coarse fraction composition and the overall X-ray mineralogy of the sediments. In general, the scientists have attempted to follow the compositional classification for marine sediments proposed by Olausson (1960).

13. Sampling

After a visual description of the cores has been made, they are sampled before being sent to the refrigerated core vans for storage. Because the cores, traveling in refrigerated storage on the *Glomar Challenger*, are only off-loaded at American ports, there is an extensive shipboard sampling program. On board ship, the samples are stored under refrigeration until the end of each cruise leg, when they are flown back to the mainland for further study in shore-based laboratories. These studies are then incorporated into the initial reports of the Project.

In dealing with soft sediments, larger samples are taken by means of a tube or syringe that can be packaged in a labeled vial with the sample. Smaller samples are taken with a scoop or knife. Every precaution is taken to avoid possible contamination. Hard sediments are sampled by breaking off pieces with a scoop, knife, spatula or hammer and they are packaged and labeled in the same manner as soft sediments. Igneous or metamorphic rocks are not sampled on board beyond a few small pieces which are taken for the preparation of thin sections.

The results of the visual core description and smear slide examination determine whether or not samples for particular purposes are taken and, to some extent, these results effect the size of those samples. Similarly, the spacing of samples is governed by the variability of lithological types cored. In long sections of uniform sediment, however, every attempt is made to obtain a reasonably representative and uniform coverage of samples.

The following table gives a list of the main types of samples, together with the purposes for which they are taken, and the approximate size of the samples. This list does not include the interstitial water samples or any samples, which may be taken for thin sectioning.

Type and Purpose	Sample Size
Grain size and coarse fraction	10 cc
Water content and carbon carbonate	2 cc
X-ray mineralogy	10 cc
Shipboard foraminiferal studies	2-10 cc, depending on the abundance of foraminifera
Shore-lab foraminiferal studies	2-10 cc, depending on the abundance of foraminifera
Shipboard radiolarian studies	1-10 cc, depending on the abundance of Radiolaria

Shore-lab radiolarian studies	1-10 cc, depending on the abundance of Radiolaria
Nannoplankton studies - Shipboard	1 cc
Nannoplankton studies - USGS, La Jolla	2 cc
Nannoplankton studies - Miami	2 cc

The grain size and coarse fraction samples are used for paleomagnetic studies prior to grain size analysis. For this reason, they are taken in oriented sample tubes, which are scribed in such a way that the vertical and horizontal axis within the core can be readily determined.

Samples taken for smear slide preparations are not recorded since the volume of material taken is trivial.

TIME STRATIGRAPHIC FRAMEWORK

Because a large number of paleontologists with different views are participating in the work leading to the initial core descriptions, the JOIDES Advisory Panel on Paleontology and Biostratigraphy recommended a scheme of period/system, epoch/series, age/stage classifications for uniform application in this work. It is probable that no worker will be happy with all of the details of this scheme—indeed, there was not unanimity among the members of the panel that formulated it. But it has been necessary to apply such a scheme uniformly in order that the contributions of diverse authors can be integrated into a coherent whole.

TIME STRATIGRAPHIC FRAMEWORK

			Stage	Bibliographic reference to the concept of the stratotype being applied for the purposes of this manual.	
CENOZOIC	QUATERNARY	PLEISTOCENE-RECENT	Calabrian	Gignoux, M., 1910. <i>Compt. Rend. Acad. Sci. Paris.</i> 150, 841. Gignoux, M., 1913. <i>Ann. Univ. Lyon.</i> 36. Gignoux, M., 1948. <i>Intern. Geol. Congr. 18th</i> (Report published 1950). Gignoux, M., 1952. <i>Congr. Geol. Intern. Compt. Rend. 19th</i> (Report published 1954). Gignoux, M., 1954. <i>Congr. Geol. Intern. Compt. Rend. 19th</i> p. 249. Selli, R., 1962. <i>Quaternaria.</i> 6, 391.	
			Astian	Astian: de Rouville, P. G., 1853. <i>Description geologique des environs de Montpellier.</i> Boehm (Montpellier), 185.	
	TERTIARY	PLIOCENE	Upper	Piacenzian	Piacenzian: Mayer-Eymar, C., 1858. <i>Verhandl. Schweig. Naturforsch. Ges.</i> 17-19 Aug. 1857. Pareto, L., 1865. <i>Bull. Soc. Geol. France.</i> (2), 22, 209. Gignoux, M., 1915. <i>Bull. Soc. Geol. France.</i> (4), 14, 338. Gignoux, M., 1924. <i>Boll. Soc. Geol. Ital.</i> 42, 368. di Napoli-Alliata, 1954. <i>Congr. Geol. Intern. Compt. Rend. 19th.</i> p. 229-234.
			Lower	Zanclian (A)*	Seguenza, G., 1868. <i>Bull. Soc. Geol. France.</i> (2) 25, 465. Baldacci, L., 1886. <i>Mem. Descrit. Carta Geol. Ital.</i> 1, 1. Ogniben, L., 1954. <i>Mem. 1st Geol. Mineral. Univ. Padova.</i> 18. Wezel, F. C., 1964. <i>Riv. Ital. Pal. Strat.</i> 70, 307.
	MIOCENE	Upper	Messinian	Mayer-Eymar, C., 1867. <i>Catologue systématique et descriptif des terrains tertiaires qui se trouvent au musée fédéral de Zurich.</i> (Zurich) 2, 13.	

*Capital letters in parentheses refer to "Notes on concepts of stages and other boundaries".

CENOZOIC	TERTIARY	MIOCENE		Upper	Tortonian (B)	Mayer-Eymar, C., 1858. <i>Verhandl. Schweiz. Naturforsch. Ges.</i> 17-19 Aug., 1857. Gino, G. F. et al., 1953. <i>Riv. Ital. Paleont. Mem.</i> 6, 7. Giannotti, A., 1953. <i>Riv. Ital. Pal. Strat.</i> Mem. VI, 168. Cita, M. B. et al., 1965. <i>Riv. Ital. Pal. Strat.</i> 71, 217.
		Middle	Langhian (C)	Pareto, L., 1865. <i>Bull. Soc. Geol. France.</i> (2) 22, 229. Cita, M. B. and Silva, I. P., 1960. <i>Intern. Geol. Congr. 21st, Copenhagen, 1960, Rep. Session, Norden.</i> 22, 39. Cita, M. B. and Elter, G., 1960. <i>Accad. Nazl. dei Lincei.</i> Ser. 8 (5), 29, 360.		
		Lower	Burdigalian	Girondian: Vigneaux, M., Magne, A. Weillon, M. and Moyes, J., 1954. <i>Compt. Rend. Acad. Sci. Paris.</i> 239, 818. Caralp, M. and Vigneaux, M., 1961. <i>Compt. Rend. Soc. Geol. France.</i> 140. Drooger, C. W., 1958. <i>83rd Congr. Soc. Sav., Sect. Sci.</i> p. 171.	Burdigalian: Deperet, C., 1892. <i>Compt. Rend. Soc. Geol. France.</i> (11), 145. Deperet, C., 1893. <i>Bull. Soc. Géol. France.</i> (3) 21, 263. Dollfus, 1909. <i>Bull. Serv. Carte Geol. France.</i> (124) 19, 380. Drooger, C. et al., 1955. <i>Koninkl. Ned. Akad. Wetenschap. Verslag Gewone Vergader. Afdel. Nat. Ser. 1</i> (2) 21, 1.	
			Aquitanian		Aquitanian: Mayer-Eymar, C., 1858. <i>Verhandl. Schweiz. Naturforsch. Ges.</i> 17-19 Aug., 1857, p. 188. Tournouer, R., 1862. <i>Bull. Soc. Geol. France.</i> Ser. 2, 19, 1035. Drooger, C. W. et al., 1955. <i>Koninkl. Ned. Akad. Wetenschap. Verslag Gewone Vergader. Afdel. Nat.</i> Szots, E., 1965. <i>Bull. Soc. Geol. France.</i> (7) 7, 743.	
		(E)		Bormidian	Pareto, L., 1865. <i>Bull. Soc. Geol. France.</i> (2) 22, 220. Lorenz, C., 1965. <i>Bull. Soc. Geol. France.</i> (7) 6, 192. Vervloet, C. C., 1966. <i>Stratigraphical and Micropaleontological Data on the Tertiary of Southern Piedmont (Northern Italy).</i> (Thesis) University Utrecht. Utrecht (Schotanus & Jens). Lorenz, L., 1964. <i>Bull. Soc. Geol. France.</i> Ser. 7, 6, 192.	
		OLIGOCENE		Chattian	Fuchs, T., 1894. <i>Jahresber. Ungar. Geol. Anstalt.</i> 10, 172. Gorges, J., 1952. <i>Abhandl. Hess. Landesametes Bodenforsch.</i> 4, 1. Hinsch, W., 1958. <i>Lexique Strat. Intern.</i> I 5hl. Anderson, H. J., 1961. <i>Meyniana.</i> 10, 118. Hubach, H., 1957. <i>Ber. Naturhist. Ges. Hannover.</i> 103.	
				Rupelian	Dumont, A., 1849. <i>Bull. Acad. Roy. Med. Belg.</i> (1) 16, 370. Batjes, A., 1958. <i>Inst. Roy. Sci. Nat. Belg. Bull. Mem.</i> 143.	
				Lattorfian	Mayer-Eymar, C., 1893. <i>Bull. Soc. Geol. France.</i> (3) 21, 8. Munier-Chalmas, E. and de Lapparent, A., 1893. <i>Bull. Soc. Geol. France.</i> 21, 478. von Koenen, A., 1893-1894. <i>Abhandl. Geol. Spec. Preussen.</i> 10, 1005. Krutzsich, W., and Lotsch, D., 1957. <i>Geologie.</i> 6, 476. Krutzsich, W. and Lotsch, D., 1958. <i>Ber. Deut. Geol. Ges.</i> 3, 99.	
		EOCENE	Upper	Priabonian	Priabonian: Munier-Chalmas, E. P. and de Lapparent, A., 1893. <i>Bull. Soc. Geol.</i>	

CENOZOIC	TERTIARY	EOCENE	UPPER	Bartonian	<i>France</i> . (3) 21, 471. Roveda, V., 1961. <i>Riv. Ital. Pal. Strat.</i> 67, 153. Fabiani, R., 1915. <i>Mem. 1st Geol. Mineral Univ. Padova</i> . 3, 1.	
				Priabonian	Bartonian: Mayer-Eymar, C., 1858. <i>Verhandl. Schweiz. Naturforsch. Ges.</i> 178. Prestwich, J., 1847. <i>Quart. J. Geol. Soc., London</i> . 3, 354. Prestwich, J., 1857. <i>Quart. J. Geol. Soc., London</i> . 13, 108. Curry, D., 1958. <i>Lexique Strat. Intern.</i> 1 3a 12.	
			Middle	(F)		
				Lutetian	de Lapparent, A., 1883. <i>Traite de Geologie</i> . 1st Ed., p. 989. Blondeau, A. and Curry, D., 1964. <i>Bull. Soc. Geol. France</i> . (7) 5, 275. Blondeau, A. et al., 1966. <i>Bull. Soc. Geol. France</i> . (7) 7, 200. Blondeau, A., 1964. <i>Mem. Bur. Rech. Geol. Min.</i> No. 28. 21.	
		Lower	Ypresian	Dumont, A., 1849. <i>Bull. Acad. Roy. Med. Belg.</i> (1) 16, 368. Kaasschieter, J. P. H., 1961. <i>Inst. Roy. Sci. Nat. Belg. Bull. Mem.</i> 147.		
			UPPER	Thanetian	Renevier, E., 1873. <i>Tableau des terrains sedimentaires (in 4°) et un texte explicatif</i> . Lausanne (G. Bridel). Renevier, E., 1897. <i>Chronogr. Geol.</i> Prestwich, J., 1852. <i>Quart. J. Geol. Soc., London</i> . 8, 235. Barr, F. T. and Berggren, W. A., 1965. <i>Stockholm Contrib. Geol.</i> (2) 13, 9.	
		PALEOCENE		LOWER	Montian	Dewalque, G., 1868. <i>Prodrome d'une description geologique de la Belgique</i> . p. 185. Cornet and Briart, 1866. <i>Bull. Acad. Roy. Med. Belg.</i> (2) 20, 757. Briart and Cornet, 1880. <i>Ann. Soc. Geol. Belg.</i> 7, 139. Rutot, A. and von den Broeck, E., 1885. <i>Ann. Soc. Roy. Malac. Belg.</i> 20, 108. Rutot, A. and von den Broeck, E., 1886. <i>Ann. Soc. Geol. Belg.</i> 13, 94. Rutot, A. and von den Broeck, E., 1887. <i>Bull. Soc. Geol. France</i> . (3) 15, 157. Marliere, R., 1955. <i>Ann. Soc. Geol. Belg.</i> 78, 297. Berggren, W. A., 1964. <i>Stockholm Contrib. Geol.</i> (5) 11, 135.
			Tertiary		Danian	Tertiary: de Grossouvre, A., 1897. <i>Bull. Soc. Geol. France</i> . Ser. 3, 25, 57. Loeblich, A. R., Jr. and Tappan, H., 1957. <i>U. S. Nat. Museum Bull.</i> 215, 173. Troelsen, J., 1957. <i>U. S. Nat. Museum Bull.</i> 125. Berggren, W. A., 1962. <i>Stockholm Contrib. Geol.</i> (2) 9, 103. Berggren, W. A., 1964. <i>Stockholm Contrib. Geol.</i> (5) 11, 103. Cretaceous: Eames, F. E. (in press), 1968. <i>J. Geol. Soc. India</i> . Desor, E., 1847. <i>Bull. Soc. Geol. France</i> . Ser. 2, 4, 179. Brotzen, F., 1959. <i>Sveriges Geol. Underokn Arsbok, Ser. C</i> . (571), 81 pp. Rasmussen, H. W., 1965. <i>Mededel. Geol. Sticht. N.S.</i> , (17), 33. (Supplemented by M. Meijer, <i>loc. cit.</i> , pp. 21-25).
		MESOZOIC	CRETACEOUS	Upper	Maestrichtian	Dumont, A., 1849. <i>Bull. Acad. Roy. Sci. Lettres, Beaux-Arts, Belgique</i> , 351. Hofker, J., 1966. <i>Paleontographica</i> . Supplement-Band 10, Atlas of Foraminifera, 5. Jeletzky, J., 1951. <i>Beih. Geol. Jahrb.</i> (1), 1.

MESOZOIC	CRETACEOUS	UPPER	Campanian (G)	Coquand, H., 1857. <i>Bull. Soc. Geol. France.</i> 749. Van Hinte, J., 1965. <i>Koninkl. Ned. Akad. Wetenschap. Proc. Ser. B.</i> (1) 68, 14. Marie, P., 1941. <i>Mem. Museum Nat. Hist. Nat. (Paris).</i> 12, 1.
			Santonian S.S. (H)	Coquand, H., 1857. <i>Bull. Soc. Geol. France.</i> 749. Seronie-Vivien, M., 1959. <i>Colloque sur le Crétacé Supérieur Français rendus de Congrès des Sociétés Savantes de Paris et des Départements, Comité des Travaux historiques et scientifiques, section des sciences, sous-section de géologie, tenu à Dijon.</i> Paris (Gauthier-Villars). pp. 581-582.
			Lower Santonian – Coniacian (I)	Coquand, H., 1857. <i>Bull. Soc. Geol. France.</i> 748. Seronie-Vivien, M., 1959. <i>Colloque sur le Crétacé Supérieur Français rendus de Congrès des Sociétés Savantes de Paris et des Départements, Comité des Travaux historiques et scientifiques, section des sciences, sous-section de géologie, tenu à Dijon.</i> Paris (Gauthier-Villars). p. 581. Schijfsma, E., 1946. <i>Medeskl. Geol. Sticht. Ser. C-V</i> (7), 1.
			Turonian	D'Orbigny, 1842. <i>Les Cephalopodes.</i> (Published by author) 622 pp. D'Orbigny, 1842. <i>Les Animaux Mollusques et Rarones.</i> (Published by author) 456 pp. Lacointre, 1959. <i>Colloque sur le Crétacé Supérieur Français rendus de Congrès des Sociétés Savantes de Paris et des Départements, Comité des Travaux historiques et scientifiques, section des sciences, sous-section de géologie, tenu à Dijon.</i> Paris (Gauthier-Villars). 415. Butt, A. A., 1966. <i>Micropaleontology.</i> (2) 12, 168.
			Cenomanian	D'Orbigny, 1842. <i>Les Cephalopodes.</i> (Published by author) 622 pp. D'Orbigny, 1842. <i>Les Animaux Mollusques et Rarones.</i> (Published by author) 256 pp. Marks, P., 1967. <i>Koninkl. Ned. Akad. Wetenschap., Proc., Ser. B.</i> (3) 7, 264.
	LOWER	Albian	Collignon, 1965. Rapport sur L'Etage Albian. In <i>Colloque sur le Crétacé Inferieur, Lyon. Mem. Bur. Rech. Geol. Min. (34)</i> (Lyon), 313. Casey, 1961. The stratigraphical paleontology of the Lower Greensand. <i>Paleontology.</i> 3, 487.	
		Aptian	Fabre-Taxy, Moullade, M. and Thomel, G., 1965. A-Les stratotypes de l'Aptien. In <i>Colloque sur le Crétacé Inferieur, Lyon. Mem. Bur. Rech. Geol. Min. (34)</i> , 173. Casey, R., 1961. The stratigraphical paleontology of the Lower Greensand. <i>Paleontology.</i> 3, 487.	
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		Hauterivian	Debelmas, J. and Thieuloy, J., 1965. E'tage Hauterivien. In <i>Colloque sur le Crétacé Inferieur, Lyon. Mem. Bur. Rech. Geol. Min. (34)</i> , 85.	
		Valanginian	Barbier, R. and Thieuloy, J., 1965. E'tage Valanginien. In <i>Colloque sur le Crétacé Inferieur, Lyon. Mem. Bur. Rech. Geol. Min. (34)</i> , 79.	

MESOZOIC	JURASSIC	UPPER	Berriasian	Busnardo, R., Hegaret, G. L. and Magne, J., 1965. Le stratotype du Berriasien. In Colloque sur le Crétacé Inferieur, Lyon. <i>Mem. Bur. Rech. Geol. Min.</i> (34) (Lyon), 5.	
			Tithonian	Enay, R., 1964. L'étage Tithonique. In Colloq. du Jurassique (Luxembourg, 1962). <i>Compt. Rend. Mem., Luxembourg.</i> 355.	
			Kimmeridgian	Ziegler, B., 1964. Das Untere Kimeridgien in Europa. In Colloque du Jurassique (Luxembourg, 1962). <i>Compt. Rend. Mem., Luxembourg.</i> 345.	
			Oxfordian	Callomon, J. H., 1964. Notes on the Callovian and Oxfordian Stages. In Colloque du Jurassique (Luxembourg, 1962). <i>Compt. Rend. Mem., Luxembourg.</i> 269. Enay, R. et al. (in press). Les Faunes Oxfordiennes d'Europe Meridionale. Essai de Zonation. In <i>Colloque International du Jurassique (Luxembourg, 1967).</i>	
		MIDDLE		Callovian	Callomon, J. H., 1964. Notes on the Callovian and Oxfordian Stages. In Colloque du Jurassique (Luxembourg, 1962). <i>Compt. Rend. Mem., Luxembourg.</i> 269.
				Bathonian	Cox, L. R. 1964. The type Bathonian. In Colloque du Jurassique (Luxembourg, 1962). <i>Compt. Rend. Mem., Luxembourg.</i> 265. Torrens, H. S. (in press). Standard zones of the Bathonian. In <i>Colloque International de Jurassique (Luxembourg, 1967).</i> Elmi, S., 1964. Précisions stratigraphiques sur la Bathonien supérieur du nord de l'Ardèche. In Colloque du Jurassique (Luxembourg, 1962). <i>Compt. Rend. Mem., Luxembourg.</i> 535.
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				Pleinsbachian	Geyer, O. F., 1964. Die typuslokalitat des Pliensbachian in Wurttemberg (Sudwer deutschland). In Colloque du Jurassique (Luxembourg, 1962). <i>Compt. Rend. Mem., Luxembourg.</i> 161.
				Sinemurian	Maubeuge, P. L., 1964. Quelques remarques a propos de l'Hettangien du Sinemurien et du Lotharingien. In Colloque du Jurassique (Luxembourg, 1962). <i>Compt. Rend. Mem., Luxembourg.</i> 127.
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NOTES ON CONCEPTS OF STAGE—
AND OTHER BOUNDARIES

- (A) Zancian is used in preference to Tabianian because the former has been shown to contain a better and more diverse marine fauna which can be used in regional stratigraphic correlation.
- (B) Tortonian is placed in the Upper Miocene because:
- 1) This was its original placement;
 - 2) Although subsequently placed in Middle Miocene, it has now been returned to its original position because the Langhian has been moved up from the top of the Lower Miocene into the Middle Miocene. The type Tortonian is subsequent to beds called “Elveziano” or “Tortonian of Vienna basin”, from which many species of Mollusca, especially, have been described as typical of the Middle Miocene. These “Vienna beds” are within the same stratigraphic interval as the beds of the Langhian (=Serravallian of Vervloet, 1966).
- (C) The Langhian is restricted, for the purposes of this Manual, to the beds included in the Cessole Formation, and excludes the older horizons included in the Langhian by Cita and Elter.

This essentially follows the usage of Pareto (1865), who directly referred only to the section north of Cessole, which commences with the Cessole Formation. This is in accordance with the results of the work carried out by Drooger and colleagues, who recommended that the first evolutionary appearance of the genus *Orbulina* occurs from the base of the Middle Miocene, which is a few meters above the base of the exposed Cessole Formation at Cessole.

This is supported by the fact that the base of the French stage Sallomacian (which falls within the Langhian Stage) has always been regarded by the French as the commencement of the Middle Miocene. (The name “Sallomacina” has two years’ priority over the term “Vindobonian”.) The beds included in the Langhian and Sallomacian Stages are also equivalent to the Badenian Stage of Reiss and Gvirtzman, which covers beds included in the Vindobonian from which virtually all the typical Middle Miocene molluscs were obtained.

- (D) The Girondian Stage (Vigneaux *et al.*, 1954) is coextensive with the Aquitanian and Burdigalian, and forms a stratigraphic unit well defined in terms of larger Foraminifera and Mollusca.
- (E) Regarding the position of the Oligocene-Miocene boundary, for the purposes of this Manual, the panel has accepted (by majority opinion) the base of the stratotype Aquitanian to represent the base

of the Neogene (Oligocene-Miocene boundary), as recommended by the Comité du Néogène Méditerranéen in 1959 (published 1960), 1961 (published 1964), 1964 (published 1966) and 1967 (in press), but not yet formally approved by the IUGS.

There is a radical dichotomy of opinion represented among the panel members, and the two viewpoints are explained below, labelled 1 and 2.

1. It has been recommended that the base of the stratotype Aquitanian should be taken as the base of the Miocene (and, therefore, the base of the Neogene). The following points apply:
 - (1) When originally proposed, the Bormidian was regarded as Miocene, and one of the latest publications (Lorenz, 1964), also regarded it as Miocene.
 - (2) The Bormidian is highly conglomeratic and rests directly upon the Triassic; normally it would not be considered suitable for a stratotype for a standard stage. There has been no indication whether any of the fossils recorded are derived or not (the pebbles of phyllites, schists, etc. obviously are derived). Some fossils were believed later to be Oligocene, but some have been found elsewhere *only* in beds of Miocene age. To the east of the area the Bormidian is cut out, and the overlying Aquitanian rests directly on nummulitic Oligocene (not present to the west) so that there is an unconformity at the base of the Bormidian—the Triassic underlying it in one area, and nummulitic Oligocene underlying it in another area.
 - (3) The European stage names on the Tertiary Chart prepared by this panel were all based upon marine megafossil faunas such as Mollusca, Echinoidea, larger Foraminifera, etc. (except for the Paleocene, which originally was based upon plant evidence). The evidence of plankton foraminifera, however important an asset it may be in the refinement of zonation within and correlation of these stages, did *not* enter into the primary definitions. It seems quite wrong *arbitrarily* to select one level of planktonic foraminiferal zonation to define the Miocene-Oligocene boundary; it remains but one part of a much larger field for synthesis. In any case, terms such as “Miocene” and “Oligocene” are time-stratigraphic units, and cannot be stratotyped. Consequently, the evidence of megafossils should be considered when attempting to find a suitable position

- for the Miocene-Oligocene boundary.
- (4) In the Marnes Blanches de Bernachon, which immediately and conformably underlie the stratotype Aquitanian, there are 7 species of Gastropoda, 9 species of bivalvia, and 20 species and 1 subspecies of Ostracoda, all of which occurred in the overlying Miocene faunas, but have not been found anywhere else in beds regarded as being of Oligocene age. There were a few Ostracoda having known long ranges, but *not a single* mollusc or ostracod previously known only from the Oligocene or from Oligocene and older beds. This fauna is to be regarded as Neogene and Miocene. In the same beds are found Miogypsina at a more advanced stage of evolution than those of the Eochattian of Bunde. These beds rest unconformably upon nummulitic Middle Oligocene.
- (5) In the Nordic Province of Northwestern Europe, the fauna of the Vierlander Stage, although originally regarded as Aquitanian, was later regarded by Kautsky (1925) as being of Burdigalian or even younger age. Consequently, in this Nordic province, there are *no* basal Miocene megafossil faunas at all available for comparison with the megafossil faunas of the stratotypes of the Chattian, Eochattian and Neochattian. Furthermore, it is evident that the top ends of the ranges of the megafossils in the stratotype Chattian are completely unknown since some of them may well (and probably do) range up into the basal Miocene age. If the basal Miocene age of much of the Eochattian-Neochattian succession were not realized, such extensions of ranges would never come to light.
- (6) With regard to the Eochattian-Neochattian succession it is perhaps significant that: (a) there are several common molluscan species in the Neochattian of which there is no sign in the Eochattian, and (b) there are three levels in the Eochattian at which derived Liassic ammonites occur.
- (7) The fauna of the Escornebéou beds as published by Butt (1966) was regarded by him (and Drooger) as late Oligocene ("Chattian"). Not only does this material contain derived material from at least two older levels, and not only do the beds in the area rest unconformably on the Cretaceous, but the faunas include good *Globigerinoides* which correlate the material with material *within* the type Aquitanian at the *oldest*. This material is therefore *younger* than the Neochattian.
- (8) Conclusions: The terms "Miocene" and "Oligocene" are time-stratigraphic units and cannot be stratotypified. Miocene faunas occur *beneath* the stratotype Aquitanian, and at Escornebéou (where they were called Oligocene). Much of the Eochattian-Neochattian succession can reasonably be regarded as basal Miocene. Useful levels of changes in planktonic foraminiferal faunas are certainly to be used to refine the time-limits within such successions of megafossil faunas occur, but any single one of these *alone* should *not* be taken to define a boundary such as "Miocene-Oligocene" without synthesizing the planktonic foraminiferal faunal evidence with that of the megafossils. Any attempt to take the "Miocene-Oligocene" boundary at the incoming of *Globigerinoides* (i.e., base of stratotype Aquitanian—would result in a large number of molluscan, echinoid, larger foraminiferal, etc. faunas having their ranges extended a very short distance down into the "Oligocene" (*sic*), which at level there is not only a very noticeable faunal change in many groups of fossils (justifiably taken as the Neogene-Paleogene boundary) but very often evidence of unconformity in the Alpine-Himalayan region (used in a broad sense). It seems to be highly undesirable to have a major faunal change occurring a short distance below one of relatively minor significance, and to use the latter rather than the former as a "Miocene-Oligocene" boundary.
2. The stratigraphic extent of the Bormidian can be shown in terms of planktonic foraminiferal zones to include much of the interval ascribed to the Eochattian and Neochattian of Northern Germany. The uppermost part of the Bormidian is approximately at the same level as the middle part of the Neochattian, and both are prior to the *Globigerinoides* datum which can be recognized at the base of the stratotype Aquitanian. This *Globigerinoides* datum, as expressed in the stratotype Aquitanian, was recommended in 1959 and reaffirmed in 1963 and 1967, by the Neogene Commission on Mediterranean Neogene as the horizon to be taken to mark the base of the Miocene. The base of the Bormidian falls within the upper part of the Eochattian succession, while the lower part of Eochattian succession has been correlated, Hubach

(1957), and Anderson (1961) with the type Kassel Sands representing the type Chattian. Therefore, there is a *prima facie* case for regarding the Bormidian as post-Chattian, but pre-Aquitanian. German workers have long regarded the successions seen at Kassel, Doberg and Astrup as being a single major lithological unit, and have considered them as Oligocene. However, where Beyrich (1854 and 1858) did not discuss the present exposure at Astrup, he did discuss the beds at Doberg which include both Eochattian and Neochattian. Therefore, in Beyrich's terminology, the term "Oligocene" should be applied, not only to the Kassel Sands, but also to the succession at Doberg. *Miogypsina septentrionalis* occurs from near the exposed base of the succession at Doberg (Bed Number 10 of Hubach). This horizon is referable to Zone P.19 of Blow, and also was correlated by Hubach and Anderson to be within the interval of the type Kassel Sands. Furthermore, the latest horizon recognized within the Boom Clay of Belgium (type Rupelian) is also within Zone P.19. Thus, in agreement with the work of Batjes (1958), there is a reasonable case for considering the Chattian as part equivalent, at least, of the later parts of the Rupelian. The range of *Miogypsina* ss. must include a part of the Oligocene, and, therefore, cannot be used to decide Neogene or Paleogene affinities.

- (F) The Biarritzian Stage has been shown to be partly upper Lutetian and partly lower Auversian. Curry (1967) has suggested that the term "Auversian" covers a recognizable and useful sequence, although it is not quite as extensive stratigraphically as suggested by its usage by some previous French workers. Since the terms Biarritzian and Auversian are provincial in nature they are not used in this manual.
- (G) Van Hinte (1965) erected a neostatotype for the Campanian which contains planktonic foraminiferal faunas in the lower part and orbitoides in the higher part. The Campanian planktonic foraminiferal faunas are, from analysis of Van Hinte's figured forms (by Pessagno and Blow), an assemblage which is long-ranging in the broad concept of Campanian, but is not likely to be that which occurs in immediately pre-Maestrichtian horizons. There is no justification for accepting Van Hinte's supposition that *G. calcarata* bearing beds (his Unit G), immediately overlies the neostatotype G of Van Hinte. In support of this, Blow (unpublished) has observed a single broken specimen of *G. calcarata* presumably from the same Unit G from which Van Hinte recorded his planktonic faunas. In view of the fact that the

occurrence of *G. calcarata* is sporadic and the fauna from the neostatotype is very much restricted in diversity and in number of species, it appears that Van Hinte's Unit G is in part, at least, representative of the *G. calcarata* zone. However, there is an interval between the top of Unit G and the first horizon of occurrence of undoubted orbitoides (e.g. *Orbitoides media*) which have been accepted by many authors as characteristic of Maestrichtian.

It should be noted that many small "*Orbitoides*" occur in the interval between the first occurrence of *O. media* and the top of the planktonic foraminiferal fauna of Bed G. These forms (e.g. *Schlumbergeria*) have been accepted as Campanian forms by many authors; therefore, at least the lower half of Van Hinte's Unit F must be considered as Campanian, whereas the upper half of Unit F and the younger horizons should be ascribed to Maestrichtian. Because of this, this manual shows *G. calcarata* disappearing just prior to the Campanian-Maestrichtian boundary and *G. ventricosa* disappearing at or very near the Campanian-Maestrichtian boundary.

- (H) Santonian s.s. is that part of the Santonian represented by the stratotype.
- (I) Beneath the exposed beds of the stratotype Santonian is an interval, part of which is undoubtedly Coniacian as represented in its "stratotype", but between the two there are both beds and faunas which have not been unambiguously differentiated.
- (J) The Vraconian of certain Continental authors is here arbitrarily included as low Cenomanian.

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WELL LOGGING

The term "logging" is generally used to cover the acquisition of petrophysical information sensed by proximal devices lowered in the drilled holes. There are several reasons for making in-hole measurements of physical properties. First, such measurements provide data which may permit an inference of the lithology of intervals where no cores are recovered and it may relate these intervals to seismic profiles. Second, measurements of the physical properties on cores and in the hole may make it possible to tie core samples recovered to their proper position within the stratigraphic section; and, third, some physical measurements, such as heat flow, have validity only when made on rocks *in situ*.

The importance of the fact that information about the earth beneath the oceans can be derived not only from the examination and study of core samples obtained by drilling, but also by measuring some of the physical properties of these rocks *in situ* was well understood by those who planned the Deep Sea Drilling Project, although logging in deep water and pelagic sediments had not yet been accomplished and the conditions of the holes were not, at that time, predictable.

Of the logging tools in existence, only the characteristics of those in current use aboard the *Glomar Challenger* will be discussed. These include the gamma-ray, neutron, gamma-density, acoustic and caliper, and electrical survey tools.

The gamma ray tool records the natural radioactivity of the rocks penetrated. This tool consists of an eight inch scintillation counter with an electronic cartridge powered from the surface. The cartridge supplies voltage to the counter to shape and amplify the pulses and transmit them to the surface. At the surface, the pulse rate is converted into voltage and the voltage is recorded continuously as the sonde is pulled up the hole. A time constant for averaging counts is chosen, which is a compromise between the desire to minimize statistical fluctuations and the desire for high stratigraphic resolution.

Tools in current use are calibrated in test pits. One API unit equals 1/200th of the difference between the response of the tool operated under fixed conditions in a pit with known standard radioactivity and in a pit that is not radioactive. Formerly, tools were calibrated in radium equivalents per ton. One microgram of radium equivalent per metric ton equals about 11.7 API units. The following concentrations of radioactive minerals give about the same response as one microgram of radium per ton:

- 2.8 ppm Uranium
- 3.5 ppm Thorium
- 2000. ppm Potassium.

The neutron tool now being used aboard the *Glomar Challenger* consists of an Americum-beryllium source of fast neutrons placed about 15 inches from a detector, sensitive to both high energy captured gamma rays and thermal neutrons. As the emitted neutrons pass through the rock, they collide with other nuclei losing momentum until they reach the thermal velocity of the atomic nuclei of the surrounding material. When so slowed, they may be absorbed by surrounding nuclei and this absorption results in the emission of gamma rays which can be detected by the counter.

The number of gamma rays emitted is related to the number of neutrons absorbed, but only those emitted near the counter are detected and recorded. Hydrogen, having a mass almost equal to the neutrons, is most effective in slowing down the neutrons.

For practical purposes, the neutron tool can be considered to respond to the hydrogen content of the rock. In the presence of relatively large amounts of hydrogen, most of the neutrons will be slowed and captured in the immediate vicinity of the neutron source.

If the rock is relatively free of hydrogen, the neutrons have a greater chance of reaching the rock near the detector where either the captured gamma rays resulting from their absorption or the neutrons themselves can be counted by the detector. Therefore, a high counting rate indicates that relatively few of the

neutrons were impeded in their transmission and, thus, the hydrogen content of the rock is low. Conversely, a low counting rate implies a high hydrogen content.

The response of the neutron tool depends not only on the characteristics of the rock penetrated but on the design of the tool (including its diameter, the nature of the source, and the distance between the source and the detector), on the diameter of the hole and on the nature of the fluid in the hole.

The neutron tools used are calibrated in test pits of known lithology, porosity, and fluid content. Empirically derived departure curves are available for the interpretation of records produced by the tools. In general, it can be considered that the neutron logs obtained here respond as follows, when properly corrected:

- 1680 API units ~ 2 per cent water content
- 1000 API units ~ 19 per cent water content
- 640 API units ~ 40 per cent water content
- 370 API units ~ 100 per cent water content

The gamma-gamma tool: In the case of the gamma-gamma tool, the rock is bombarded by gamma rays emitted from a caesium source in the sonde. The gamma rays suffer Compton scattering and the scattered radiation is measured by a detector in the sonde. The Compton scattering is a function of the electron density. For most sedimentary rocks, the electron density is almost exactly a function of the bulk density of the rock. The tool is normally operated pressed against the borehole wall in order to suppress borehole effects. The tool on the *Glomar Challenger* does not have this capability, hence, there are large and unknown effects on the measurements made with this instrument, making the log impossible to interpret quantitatively without caliper data and calibration.

The acoustic tool measures the time required for the transmission of a compressional wave over a short interval of rock, and this time is measured continuously as the sonde is pulled up the borehole. The tool used aboard the *Glomar Challenger* consists of a sound generator separated from two receivers by low velocity material. Because the travel time is a least time, and the velocity of sound in the rock is higher than that either in the sonde or in the borehole, it is the energy that has traversed the rock that is recorded. The travel path of the sound must traverse the fluid in the borehole to reach the rock from the source and to reach the receiver; but, when two receivers are used, the difference in the travel time can be considered to reflect essentially travel time in the rock between the two receivers only. The travel time is measured in microseconds per foot.

The caliper tool measures the diameter of the borehole. As the tool is pulled up the hole a collapsible set of

arms is expanded to wipe against the walls of the hole. The amount of the expansion is transmitted to the surface where it is recorded in inches.

The electrical survey tool measures both the spontaneous potential and resistivity.

The spontaneous potential log responds to minute currents that flow in the borehole both as a result of dissimilarities between the borehole fluid and the interstitial fluid in the rocks and as a result of differences in the electrical quality of the sediments—these differences being related to lithologic differences. It is recorded in millivolts.

The resistivity tools constitute a conventional resistivity measuring electrode arrangement. A known potential is applied to a source electrode and the potential difference between other electrodes suspended at known fixed distances from it is recorded in ohm-meters. The potential difference is a function of the resistivity of the formation separating the electrodes. The resistivity log in the sedimentary materials expected should respond primarily to the amount and distribution of interstitial fluid in the rocks and its total salinity. Resistivity logs are extremely sensitive to differences in cementation.

The winch used for logging on *Glomar Challenger* is the one designed and built for the Mohole Project. It is powered with a 580 horsepower diesel engine. The winch drum carries 24,500 feet of 5/32 inch diameter, seven-conductor, double armored logging cable. The logging procedures which are followed are in accordance with the operating instructions put out by the companies furnishing the logging equipment.

SCIENTIFIC RECORDS

All information gathered in the course of the Drilling Project is filed at the Drilling Project Headquarters at Scripps Institution of Oceanography and that pertaining to the Atlantic is filed, in addition, at Lamont-Doherty Geological Observatory.

Observations are recorded on a set of appropriate data sheets, which have been designed in the anticipation that ultimately it will be possible to process much of this data by computer. All records are duplicated, and the copies are stored in separate places. The only records which cannot be easily duplicated are the analog records. These are digitized as soon as possible so that there will be a means of reproducing the curves, should the originals be destroyed.

The Initial Reports of the Deep Sea Drilling Project are basically intended to be a compilation of the information gathered on shipboard and in laboratories

on shore which will enable scientists to select samples for further study in their own research projects. It is not intended that the Initial Reports should exhaust the data from the point of view of the research scientist, in fact, scientists involved in their compilation are free to publish whatever interpretive ideas they wish.

In addition to the information appearing in the Initial Reports, at the repositories there are copies of the

color photographs, X-radiographs, the originals of the analog records and well logs, original observations on smear slides and thin sections, site survey information (including topographic magnetic and seismic data), and various other observations and measurements which do not in every case find their way into the initial core reports. These are available, following publication of the Initial Report, for inspection by any qualified person and it is hoped that, ultimately, arrangements can be made to supply copies of these data to interested persons at cost.