3. GAMMA-RAY DENSIOMETRY

3.1. Principles

PHYSICAL BACKGROUND

Bulk density of sediments and rocks is estimated from the measurement of gamma-ray attenuation (GRA) (Tittman and Wahl, 1965; Evans, 1965). The familiar acronym GRAPE (Evans, 1965) stands for GRA porosity evaluator, referring to the computer that Evans attached to the density measurement device to compute porosity using an assumed grain density. The measurement device does not estimate porosity, and is therefore referred to as GRA densiometer.

The principle is based on the facts that medium-energy gamma rays (0.1–1 MeV) interact with the formation material mainly by Compton scattering, that the elements of most rock-forming minerals have similar Compton mass attenuation coefficients, and that the electron density measured can easily be related to the material bulk density. The ^{137}Ce source used transmits gamma rays at 660 KeV. A scintillation detector measures the gamma-ray beam transmitted through the core material. If the predominant interaction is Compton scattering, transmission of gamma rays through matter can be related to the electron density by:

$$Y_t = Y_i\, e^{-nsd}, \qquad (1)$$

where Y_i is the flux incident on the scatterer of thickness d, Y_t is the flux transmitted through the scatterer, n is the number of scatterers per unit volume or the electron density, and s is the Compton cross section for scattering per scatterer in square centimeters per electron. Bulk density ρ of the material is related to the electron density by

$$n = \rho\, N_{Av}\, (Z/A), \qquad (2)$$

where Z is the atomic number or the number of electrons, A is the atomic mass of the material, and N_{Av} is the Avogadro number. Bulk density estimates are therefore accurate for a wide range of lithologies if the Z/A of the constituent elements is approximately constant. Variations of Z/A are indeed negligible for the most common rock-forming elements. The GRA coefficient is defined as

$$\mu = (Z/A)\, N_{Av} \times s\ (\mathrm{cm}^2/\mathrm{g}). \qquad (3)$$

For the medium energy range of gamma rays and for materials with Z/A of about 1/2, such as the most common minerals, the “Compton µ” is approximately 0.10 cm^2/g, increasing with decreasing energy. For water, µ is about 11% higher than for common minerals at a particular energy (e.g., Harms and Choquette, 1965). Sediments can therefore be regarded as two-phase systems in regard to GRA (mineral-water mixtures).

Equation on page 1 can now be written in the more frequently referenced form

$$Y_t = Y_i \times e^{-\rho\mu d} \tag{4}$$

and the expression for the bulk density becomes

$$\rho = \ln (Y_t / Y_i) / \mu d. \tag{5}$$

If the coefficient μ could be determined with sufficient accuracy, it could be used directly to compute bulk density. However, μ is a function of detected gamma-ray energy and is therefore dependent on the particular device, including source, detector, spectral component used, and the material itself (degree of scattering). A more practical and accurate method is to calibrate the gamma radiation with bulk density standards as described later in this chapter.

ENVIRONMENTAL EFFECTS

Attenuation Coefficient of Minerals

An important assumption of this densiometry method is that for a given measurement system the average attenuation coefficient μ is constant for the measured materials. For a more accurate density estimate, variations in the average composition of the material must be taken into consideration. If mineralogical analysis determines that the average μ_1 deviates significantly from the standard μ, the following correction can be applied:

$$\rho_1 = \rho \times \mu/\mu_1 , \tag{6}$$

where the ratio of average coefficients can be calculated from reference tables.

Core Thickness

The GRA routine calculations assume a constant core diameter of 66 mm. If voids or otherwise incompletely filled core liner segments occur because of gas pressure, gas escape, or other coring disturbances, the density estimate will be too low. (The highest values are therefore the most reliable ones in disturbed cores.) Using a thickness log obtained from core photographs or by other means, density can easily be corrected for varying core thickness using

$$\rho_1 = \rho \times d/d_1 . \tag{7}$$

USE OF GRA DATA

GRA data provide a precise and densely sampled record of bulk density, an indicator of lithology and porosity changes. The records are frequently used for core-to-core correlation. Another important application is the calculation of acoustic impedance and construction of synthetic seismograms.

3.2. MST (Whole-Core) GRA System

EQUIPMENT

Gamma-ray Source

The ^{137}Ce source used transmits gamma rays at 660 KeV.

Scintillation Counter

A standard NaI scintillation detector is used in conjunction with a universal counter.

CALIBRATION

New Procedure

GRA calibration assumes a two-phase system model for sediments and rocks, where the two phases are the minerals and the interstitial water. Aluminum has an attenuation coefficient similar to common minerals and is used as the mineral phase standard. Pure water is used as the interstitial-water phase standard. The actual standard consists of a telescoping aluminum rod (five elements of varying thickness) mounted in a piece of core liner and filled with distilled water (Figure 3—1). The standard element i has an average bulk density ρ_i of

$$\rho_i = d_i / D \times \rho_{Al} + (D - d_i)/D \times \rho_{water} \quad (8)$$

where D is the maximum aluminum rod thickness (inner diameter of core liner, 6.6 cm), d_i is the diameter of the aluminum rod in element i, and ρ_{Al} and ρ_{water} are the densities of aluminum and water, respectively. The first element (porosity of 0%) has a bulk density of aluminum (2.70 g/cm^3) and the last element (porosity of 100%) has a bulk density of water at laboratory temperature (1.00 g/cm^3). Intermediate elements are used to verify the linearity of the ln(Y) to density relationship, as well as the precise alignement of core and sensor. A linear least squares fit through three to five calibration points (ln($counts/t_{cal}$), ρ) yields the calibration coefficients m_0 (intercept) and m_1 (slope, negative). Total measured counts are automatically divided by the counting time, t_{cal}, to normalize the coefficients to counts per second. Sample density is then determined:

$$\rho_{core} = m_0 + \ln(counts/t_{sample}) \times m_1 , \quad (9)$$

where the measured counts are again normalized to counts per second using the sampling period, t_{sample} , before the calibration coefficients are applied.

Old Procedure

The present calibration procedure has been implemented only since Leg 169 (August 1996). Before that time, calibration was performed with two aluminum cylinders of different thickness, but without water. The thinner aluminum rod was cut to a diameter of 25 mm to give an “aluminum density of 1.00.” The counts returned from measuring the thin aluminum rod were not compatible with the Compton attenuation coefficient for water, however, and when measuring water the density was about 11% too high. A fluid-correction had to be applied to the initial density estimate. This procedure is obsolete now, and no fluid correction is required because water is used in the calibration procedure.

MEASUREMENT

The GRA is logged downcore automatically..

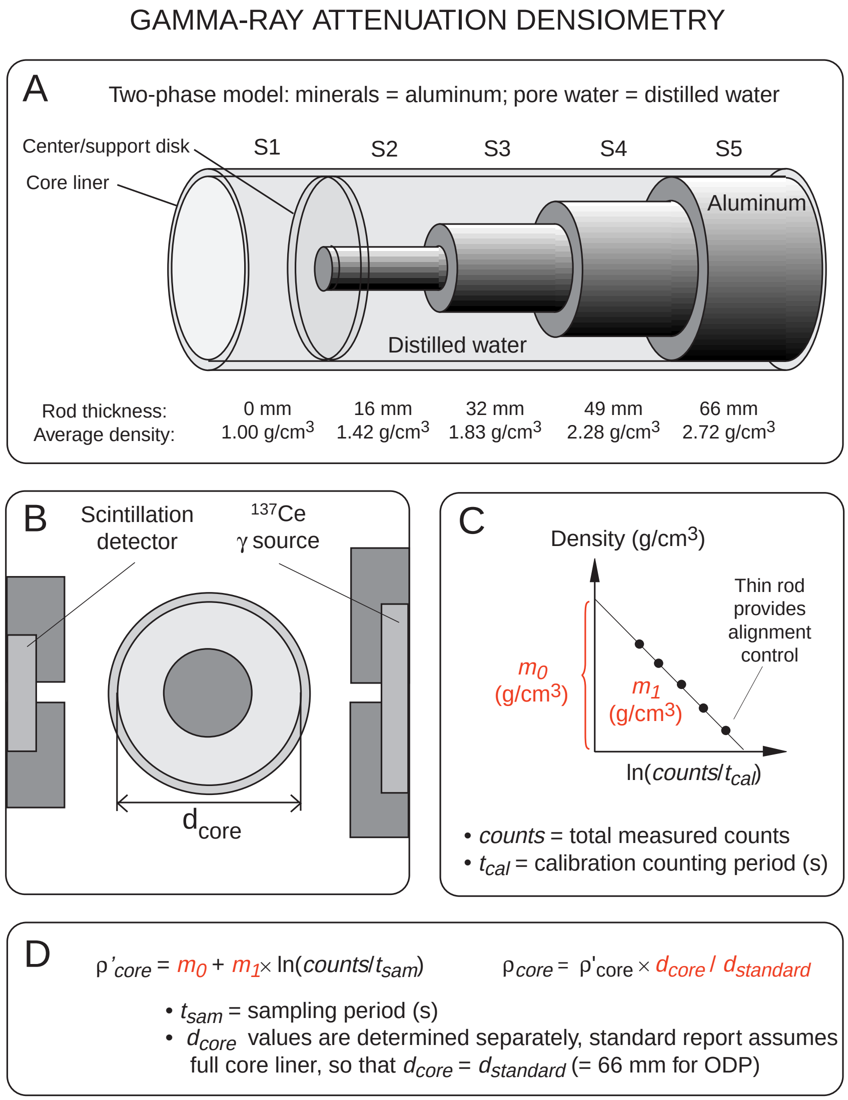

Figure 3—1 Schematic of GRA calibration. A. Physical standard used. B. Measurement geometry. C. Calibration principle. D. Application of calibration to core measurement

PERFORMANCE

Precision

Precision is proportional to the square root of the counts measured because gamma-ray emission is subject to Poisson statistics (see “Natural Gamma Radiation” chapter for additional explanation). The statistical uncertainty is

$$t\,N \pm z\,(t\,N)^{1/2}, \qquad (10)$$

where N is the count rate (counts per second, cps), t is the sampling period (s), and z is the number of standard deviations for the normal distribution (0.68 probability, or confidence, for $z = 1$; 0.95 for $z = 1.96$, etc.). Measurements with the present system have typically count rates of 10,000 (dense rock) to 20,000 cps (soft mud). If measured for 4 s, the statistical error is therefore less than 40,000 ± 200, or

0.5%. This shows that the high flux of the ^{137}Ce source does not require excessive counting times.

Accuracy

Accuracy is limited by the assumption that the measured material has the same attenuation coefficent as the calibration standards used. For general sediment-water mixtures, this should be the case and errors should be less than 5%.

Spatial Resolution

The GRA system allows high spatial resolution of about 0.5 cm.

DATA SPECIFICATIONS

Database Model

Table 3—1 GRA database model.

GRA section
gra_id [PK1]
section_id
run_number
run_date_time
core_status
liner_status
requested_daq_interval
requested_daq_period
density_calibration_id
mst_gra_ctrl_2_id
mst_gra_ctrl_3_id

GRA control 1
gra_ctrl_1_id [PK1] [FK]
run_number
run_date_time
core_status
liner_status
requested_daq_interval
requested_daq_period
density_calibration_id
standard_id

GRA control 3
gra_ctrl_3_id [PK1]
run_number
run_date_time
requested_daq_period
actual_daq_period
density_calibration_id
standard_id
meas_counts

GRA calibration
density_calibration_id [PK1]
calibration_date_time
run_number
system_id
liner_status
requested_daq_period
density_m0
density_m1
density_mse
comments

GRA control 2
gra_ctrl_2_id [PK1]
run_number
run_date_time
requested_daq_period
actual_daq_period
density_calibration_id
meas_counts

GRA section data
gra_id [PK1] [FK]
mst_top_interval [PK2]
mst_bottom_interval
actual_daq_period
meas_counts
core_diameter

GRA control 1 Data
gra_ctrl_1_id [PK1] [FK]
mst_top_interval [PK2]
mst_bottom_interval
actual_daq_period
meas_counts
core_diameter

GRA calibration data
density_calibration_id [PK1] [FK]
mst_top_interval [PK2]
standard_id [PK3][FK]
mst_bottom_interval
standard_density
actual_daq_period
meas_counts

Notes: GRA control 1 are control measurements run the same way as a core section. GRA control 2 are measurement taken before run. GRA control 3 are control measurements from a standard mounted on the core boat.

Standard Queries

Table 3—2 GRA report.

Short description	Description	Database
A: Results		
Sample ID	ODP standard sample designation	Link through [GRA Section]section_id
Depth	User-selected depth type	Link through [GRA Section]section_id
Bulk density		= [GRA Calibration] density_m0 + ln ([GRA Section data] meas_counts) / [GRA Section data] actual_daq_period) * [GRA Calibration] density_m1
B (optional): Parameters and measurements		
Run	Run number	[GRA Section] run_number
Date/Time	Run date/time	[GRA Section] run_date_time
Core Status	HALF or FULL	[GRA Section] core_status

Table 3—2 GRA report.

Liner Status	NONE, HALF or FULL	[GRA Section] liner_status
Req. Interval	User-defined sampling interval (cm)	[GRA Section] requested_daq_interval
Req. Period	User-defined sampling period (s)	[GRA Section] requested_daq_period
Period	Measured sampling period (s)	[GRA Section Data] actual_daq_period
Counts	Measured counts (not normalized)	[GRA Section Data] meas_counts
Core Dia.	Core diameter, default = 6.6 cm	[GRA Section Data] core_diameter
Cal. Date/Time	Calibration date/time	[GRA Calibration] Calibration_date_time
Cal. m0	Calibration intercept (g/cm^3)	[GRA Calibration] density_m0
Cal. m1	Calibration slope ([g/cm^3)]/cps)	[GRA Calibration] density_m1

Table 3—3 GRA control 1 measurements (to be implemented).

Short description	Description	Database
Bulk density		=[GRA Calibration] density_m0 + ln ([GRA Ctrl 1 Data] meas_counts / [GRA Ctrl 1 Data] actual_daq_period) * [GRA Calibration] density_m1
Run	Run number	[GRA Ctrl 1] run_number
Date/Time	Run date/time	[GRA Ctrl 1] run_date_time
Core Status	HALF or FULL	[GRA Ctrl 1] core_status
Liner Status	NONE, HALF or FULL	[GRA Ctrl 1] liner_status
Standard	Standard name	[Phys. Properties Std.] standard_name
Std. Set	Standard set name	[Phys. Properties Std.] standard_set_name
Std. Expected	Expected value (range) (g/cm^3)	[Phys. Prop. Std. Data] property_value
Interval	Interval top	[GRA Ctrl 1 Data] mst_top_interval
Req. Interval	User-defined sampling interval (cm)	[GRA Ctrl 1] requested_daq_interval
Req. Period	User-defined sampling period (s)	[GRA Ctrl 1] requested_daq_period
Period	Measured sampling period (s)	[GRA Ctrl 1 Data] actual_daq_period
Counts	Measured counts (not normalized)	[GRA Ctrl 1 Data] meas_counts
Core Dia.	Core diameter, default = 6.6 cm	[GRA Ctrl 1 Data] core_diameter
Cal. Date/Time	Calibration date/time	[GRA Calibration] Calibration_date_time
Cal. m0	Calibration intercept (g/cm^3)	[GRA Calibration] density_m0
Cal. m1	Calibration slope ([g/cm^3)]/cps)	[GRA Calibration] density_m1

Table 3—4 GRA control 2 measurements (to be implemented).

Short description	Description	Database
Bulk density		=[GRA Calibration] density_m0 + ln ([GRA Ctrl 2 Data] meas_counts / [GRA Ctrl 2 Data] actual_daq_period) * [GRA Calibration] density_m1
Run	Run number	[GRA Ctrl 2] run_number
Date/Time	Run date/time	[GRA Ctrl 2] run_date_time
Req. Period	User-defined sampling period (s)	[GRA Ctrl 2] requested_daq_period
Period	Measured sampling period (s)	[GRA Ctrl 2 Data] actual_daq_period
Counts	Measured counts (not normalized)	[GRA Ctrl 2 Data] meas_counts
Cal. Date/Time	Calibration date/time	[GRA Calibration] Calibration_date_time
Cal. m0	Calibration intercept (g/cm^3)	[GRA Calibration] density_m0
Cal. m1	Calibration slope ([g/cm^3)]/cps)	[GRA Calibration] density_m1

Table 3—5 GRA control 3 measurements (to be implemented).

Short description	Description	Database
Bulk density		=[GRA Calibration] density_m0 + ln ([GRA Ctrl 3 Data] meas_counts / [GRA Ctrl 3 Data] actual_daq_period)

Table 3—5 GRA control 3 measurements (to be implemented).

		* [GRA Calibration] density_m1
Run	Run number	[GRA Ctrl 3] run_number
Date/Time	Run date/time	[GRA Ctrl 3] run_date_time
Standard	Standard name	[Phys. Properties Std.] standard_name
Std. Set	Standard set name	[Phys. Properties Std.] standard_set_name
Std. Expected	Expected value (range) (g/cm^3)	[Phys. Prop. Std. Data] property_value
Req. Period	User-defined sampling period (s)	[GRA Ctrl 3] requested_daq_period
Period	Measured sampling period (s)	[GRA Ctrl 3 Data] actual_daq_period
Counts	Measured counts (not normalized)	[GRA Ctrl 3 Data] meas_counts
Cal. Date/Time	Calibration date/time	[GRA Calibration] Calibration_date_time
Cal. m0	Calibration intercept (g/cm^3)	[GRA Calibration] density_m0
Cal. m1	Calibration slope ([g/cm^3)]/cps)	[GRA Calibration] density_m1

Table 3—6 GRA calibration data (to be implemented).

Short description	Description	Database
Date/Time	Calibration date/time	[GRA Calibration] calibration_date_time
Cal. m0	Calibration intercept (g/cm^3)	[GRA Calibration] density_m0
Cal. m1	Calibration slope ([g/cm^3)]/cps)	[GRA Calibration] density_m1
Cal. mse	Calibration mean squared error	[GRA Calibration] mse
Run	Run number	[GRA Calibration] run_number
Liner Status	NONE, HALF or FULL	[GRA Calibration] liner_status
Req. Period	User-defined sampling period (s)	[GRA Calibration] requested_daq_period
Comments	Comments	[GRA Calibration] comments
Standard	Standard name	[Phys. Properties Std.] standard_name
Std. Set	Standard set name	[Phys. Properties Std.] standard_set_name
Std. Expected	Expected value (range) (g/cm^3)	[Phys. Prop. Std. Data] property_value
Density	Density value from MST control	[GRA Calibration Data] standard_density
Interval	Interval top	[GRA Calibration Data] mst_top_interval
Period	Measured sampling period (s)	[GRA Calibration Data] actual_daq_period
Counts	Measured counts (not normalized)	[GRA Calibration Data] meas_counts

3.3. Split-core GRA System

ODP has purchased a split-core GRA system that will be implemented as soon as resources become available. This system must be implemented together with the latest model GEOTEK *P*-wave logger which provides the caliper measurement required to correct split-core GRA measurements for uneven split-core thickness.