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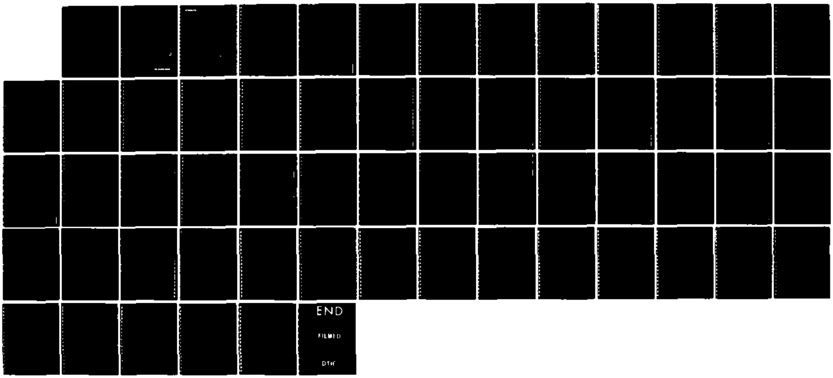

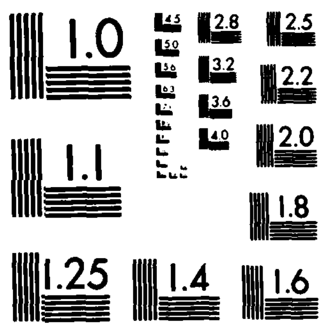

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ESTIMATING SEDIMENT
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FROM ACOUSTIC MEASUREMENTS:
A REVIEW OF AVAILABLE
REGRESSION ANALYSES

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March 198?

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The total system concept for the Buried-Mine Minehunting System (BURMMS) requires the ability to predict the probability that a mine will bury in a given environment. As an expeditious means of providing information upon which to make such a prediction, acoustic techniques hold significant potential. To obtain values for the parameters needed in the mine burial prediction models (density, grain size, and shear strength), quantitative relationships between them and acoustically measurable quantities are required. In search of the best quantitative relationship for general BURMMS application, this study (cont)

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) explores the very large number of regression equations developed in the literature. Several of these equations are singled out for their potential for predicting values for density and grain size from measured values of sound velocity and reflection coefficient. The report addresses several problems that lead to questions regarding the quality of the prediction in some cases. It recommends a field-measurement and data-analysis program to reduce the uncertainty.

PREFACE

The total system concept for the Buried-Mine Minehunting System (BURMMS) requires the ability to predict the probability that a mine will bury in a given environment. As an expeditious means of providing information upon which to make such a prediction, acoustic techniques hold significant potential. To obtain values for the parameters needed in the mine burial prediction models (density, grain size, and shear strength), quantitative relationships between them and acoustically measurable quantitites are required. In search of the best quantitative relationship for general BURMMS application, this study explores the very large number of regression equations developed in the literature. Several of these equations are singled out for their potential to provide values for density and grain size. This study made no attempt to determine the specific regression equations that provided the best fits for specific environments relevant to BURMMS. Available data can not support a full treatment of this broader objective.

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1.0 CONCLUSIONS AND RECOMMENDATIONS

Based on analysis taking into consideration statistical, geological, and acoustical factors, this study found the six regression equations contained in Table 4-1 best suited for general BURMMS applications. These equations provide a means of calculating density and grain size from measured values of compressional-wave velocity and/or reflection coefficient. A plot of the various equations and parametric representations on a density versus grain-size diagram demonstrates the interconsistency of the results. An unexplained small bias was noted, however.

Generally, those regression equations that provide the best chance for satisfying BURMMS requirements were found to apply to a class of sediments established by Hamilton (1970a, 1970b, and 1974) to represent continental-terrace data. The equations selected are recommended as best only when no more detailed information is known *a priori* about the sediments expected in a specific BURMMS application.

The quality of the fit of any of the equations, in terms of its adequacy to predict the needed mechanical properties, could not be established quantitatively from available published work. There are several reasons for this present state of uncertainty. They include:

- Categories of sediment types upon which the published regression equations are based may not match sediment types expected in BURMMS applications with sufficient exactness.
- In the range of parameter values of greatest interest to BURMMS, the curves, in the forms needed, tend to have steep slopes, thus requiring very careful work to insure that small uncertainties in the independent variable are not magnified unreasonably into the dependent variable.

- In no case were all the regression parameters needed to test the goodness of fit given in the literature.

- The precision of fit required for BURMMS applications has not been defined.

- For the regression equations involving reflection coefficient, reflection coefficient was a calculated, rather than measured quantity.

- Full interconsistency among the selected equations could not be established.

This study recommends that a program of field measurement and data analysis be undertaken to reduce the degree of uncertainty in the results. The program should include experimental work in several different coastal environments and concentrate on improving the regression equations describing the relationships in Table 4-1 for those environments. More complete statistical analyses should be applied to the data than typically found in the literature and all the regression parameters needed to judge the goodness of fit should be reported. The precision requirements for sediment properties used in BURMMS should be quantified.

No suitable regression equation has been published relating shear strength, an important sediment property for BURMMS applications, to any acoustical property that can be measured in an operational environment. Prospects for measuring shear strength using acoustical techniques are to be considered in detail in another study in this project and are not within the scope of this phase of work. However, it is recommended that the measurement of this parameter should be included in any field work taken based on the above recommendations.

2.0 GENERAL CONSIDERATIONS

In selecting a quantitative means of predicting density, grain size, and shear strength from acoustical measurements, acoustical, statistical, and geological factors were considered. The details of the acoustical considerations are discussed in an earlier study (Caruthers, 1980). That study considered a multitude of possible relationships between and among sediment acoustical and mechanical properties. It identified those relationships which appeared to be strong enough to warrant detailed study. And it identified those acoustical quantitites that could most readily be measured in a BURMMS operating environment. Those properties are listed in Table (2-1).

This analysis begins with the properties recommended in the previous analysis and attempts to find those which possess the best quantitative statement of their interrelationships for BURMMS applications. To represent the quantitative statements we require, we have examined the published literature on regression analyses interrelating sediment and acoustic properties. There was a notable lack of published regression analyses on shear strength and its related properties (i.e., viscosity, cohesion, plasticity, and the Lame's moduli), permeability, and a number of the acoustical properties (e.g., nonlinearity, particle velocity). Because of this lack of data these properties were removed from further consideration. In future work in this project not specifically oriented to regression analyses, as this work is, those properties will be reconsidered.

For several decades researchers have been using regression analysis to provide quantitative descriptions of the relationships among sediment properties. The work has developed numerous equations that can be used to predict values for a desired property when values of another physically related

Table 2-1

MECHANICAL AND ACOUSTICAL PROPERTIES OF INTEREST

MECHANICAL PROPERTIES	ACOUSTICAL PROPERTIES
Density	Reflection Loss
Porosity	Attenuation of P-waves
Grain Size	Velocity of P-waves
Permeability	Velocity of S-waves
Shear Strength	Pulse Elongation
Viscosity	Nonlinearity
Cohesion	Particle Velocity
Plasticity	Acoustical Impedance
Complex Lame's Moduli	Interface-Wave Speed
	Penetrometer Insertion Noise

property are measured. To determine how good that relationship is and how well the equation describes it, certain parameters from the regression analysis and the quantitative statement of what "good" means must be available for consideration.

We could not obtain all the regression parameters needed for any of the reported regression analyses and no quantitative measure of a good fit has been stated for BURMMS applications as yet. We have, therefore, used a more subjectively interpretated sense of a good fit in this analysis. Since reporting the full details of the regression analyses has not been the rule in the geoacoustic literature, those statistical concepts we feel would be needed in future published work are discussed in Appendix A.

BURMMS mine burial prediction models require values of selected mechanical properties. The objective of this analysis is to determine if these values can be predicted from the measured values of acoustical properties. Most published acoustical/mechanical equations describe the reverse relationship, and therefore, need to be inverted. A regression equation can be inverted in two ways: 1) a regression analysis can be performed on the original data reversing the independent and dependent variables and 2) a straight forward algebraic inversion of the regression equation can be made.

Although problems can arise in obtaining unbiased estimates, the algebraic inversion is chosen because the data was not available to perform the inverted regression analysis directly. Problems can result when inverting an equation with a large slope. Confidence intervals for the predicted value may be indeterminate when inverting such equations. Also, more than one solution within the valid range of independent variable values may exist when second or higher degree polynomials are inverted.

Additional statistics are necessary to determine the new standard error of estimate for the inverted equations. Several such equations appear in this analysis. Care should be exercised in applying these equations in the regions of their large slopes and double values.

Not only must we choose regression equations which adequately fit the data and predict with precision, but also we must choose models which are simple to apply. Multiple regression models in which values of more than one mechanical property predict values of an acoustical property are not included because there is an inability to invert the equation to predict the values of the mechanical properties from the values of the acoustical property. Moreover, there is little evidence that the fit of the regression equations are significantly improved by including multiple independent variables (Anderson, 1974). Also, it is desirable to choose a model which will apply to a large range of values and geological areas rather than to use many separate models, each applying to a small range of values or a single geological area. In the final analysis both the use of multi-parameter regression analysis and the development of distinct regional or sediment-type models may be necessary to provide the "best" equations for BURMMS. However, at this point such additional refinements can not be supported by available data, statistics, or quantitative statements of BURMMS requirements.

The above considerations suggest that the previous data collection efforts and analyses presented in the literature to date are inadequate for a rigorous statistical analysis to determine the best acoustical predictor of sediment properties for BURMMS applications. However, tentative conclusions can be drawn and the resulting regression equations must be tested further to measure the fit to new data, and the precision with which a mechanical property is measured must be compared to the (still-to-be-specified) precision required by BURMMS models.

To facilitate selection among the many regression analyses reported in the literature, criteria were required which established the relevancy of a data set to BURMMS applications. This called for identifying classes of sediment data which are likely to be encountered in BURMMS. In addition to requiring that sediment data pertain to such classes, we would like to find that a wide range of regression analyses have been performed within the classes.

Several classification systems have been devised for subdividing geological provinces into categories serving various purposes. None seemed specially suited for BURMMS which would be best served by data sets involving harbor, coastal zone, and continental shelf sediment data. The closest generally recognized sediment class that best suits BURMMS purposes is a class referred to as continental terrace (shelf, slope, and rise) established by Hamilton (1970a). Other classes established by Hamilton include abyssal-plain and abyssal-hill sediments. In addition to the regional distinction suggested by their names, the sediments are also distinguished by the ranges of values of density, grain size, and porosity they generally cover. Having some overlap, these ranges do not uniquely define the class, however. (For a more complete discussion of Hamilton's classification system and geological considerations in general see Appendix B.)

Hamilton's continental-terrace sediment class was found to be the best for general applications to BURMMS because it not only matched best the types of sediments of interest but also because a very large part of the literature on regression analysis included work in this class. In the detailed analysis that follows, however, it is pointed out several times that for a specific BURMMS application, data relevant to the specific location would probably provide a better regression equation than the one selected for general BURMMS applications.

3.0 DETAILED ANALYSIS

A review of the literature using the criteria established in Section 2.0 provided 59 regression equations describing 13 relationships. These equations were analyzed in detail to determine their potential application to BURMMS. The details of this additional analysis are given in this section.

For convenience in reviewing the results, the details are given in 13 parts of Table 3. This table contains plots of the equations and their regression parameters. Text relevant to each of the relationships is provided on the same page as the appropriate table.

Generally, those regression equations that seem to provide a better chance for satisfying BURMMS requirements were found to apply to Hamilton's (1970a) continental-terrace data. Data from other sources or for other sediment classes were found to have a mixed and somewhat reduced chance for success. Some regression equations present a problem of having a large slope and some uncertainty in the quality of the fit. Coupled together these features suggest a poor prediction ability because of the large errors that could occur.

In a few cases the fit was exceptionally good and seemed to be independent of the sediment class. For use of many of the other relationships it is suggested that one seek some *a priori* knowledge of sediment class in order to choose one of several possible regression equations.

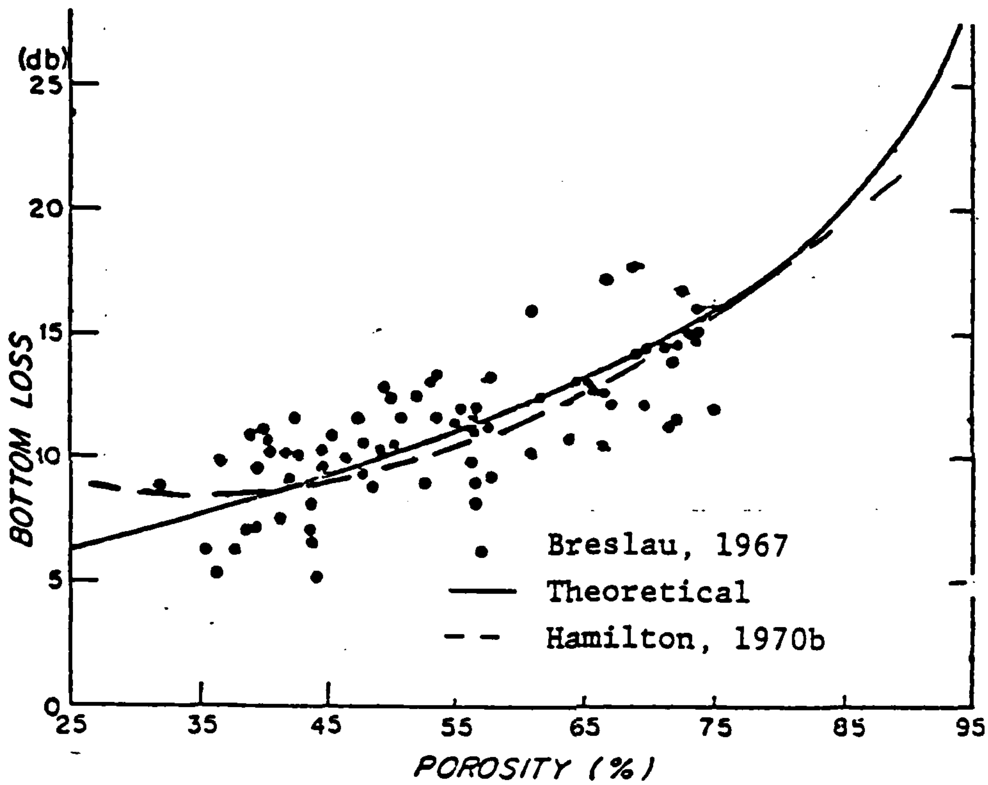
Although the regression equations describing relationships between sediment mechanical properties and reflected-wave properties provide reasonable fits, one is cautioned that researchers have tended to calculate the reflected-wave properties from measured acoustical and mechanical properties, then relate them back to density, porosity, or grain size through regression analysis.

Three reflected-wave properties are dealt with in the literature; these are acoustic impedance, reflection coefficient, and bottom loss. The values used in the literature for each of these are simply mathematical manipulations of density and velocity--acoustic impedance is simply their product. Reflection coefficient at an interface is calculated from the acoustic impedance mismatch. Bottom loss is simply the decibel equivalent of reflection coefficient. In all cases presented in the literature, the mismatch is determined as if the sediment were at the sea-floor/bottom-water interface.

In an actual BURMMS application attempting to use a reflected-wave property, the first quantity measured would be the reflection coefficients at interfaces at the bottom and in the subbottom. Acoustic impedance and bottom loss can be calculated from it. Not until sequential calculation of acoustic impedance from the bottom layer down through subsequent layers are made can the observed reflection properties be reconciled with the regression equation. Another problem that would likely be encountered is that the multiple reflections will cause waveform interference to cause erroneous measures of impedance mismatch. A sophisticated model may be required to sort out the various reflections.

The only published instance of a measured parameter of acoustic reflection is in Breslau (1967). Breslau measures bottom loss and plots it against measured values of porosity (Figure 3-1); but he has not published a complete equation fitting the data. However, Hamilton's (1970b) equation for bottom loss as a function of porosity fits very well Breslau's

(1967) data points (Figure 3-1). This close fit supports the belief that calculated bottom loss may indeed closely approximate measured values of bottom loss, and also, lends credence to Hamilton's (1970b) relationship.



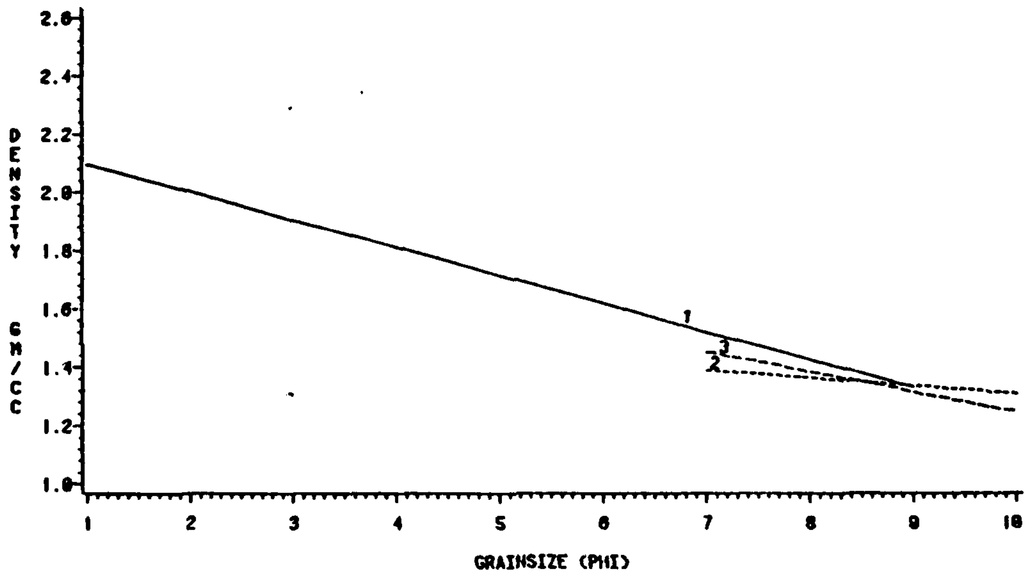
Bottom Loss Measurements (Total Energy Basis) at Sediment Stations Versus Measured Porosity of the Sediment

Figure 3-1

The 13 parts of Table 3 and relevant discussion follow.

Table 3-1

DENSITY VERSUS GRAIN SIZE



No.	Regression Equation	Source of Data
1	$\rho = 2.191 - 0.096\phi$	Continental Terrace
2	$\rho = 1.577 - 0.027\phi$	Abyssal Hill
3	$\rho = 1.933 - 0.069\phi$	Abyssal Plain

3.1 Calculating Density from Measured Grain Size (and the Inverse)

Equations 1, 2, and 3 of Table 3-1 are representative of Hamilton's (1970a) marine environments: continental terrace, abyssal plain, and abyssal hill, respectively. The sediment types most likely to be encountered during the use of BURMMS are best represented by equation 1. However, sediments similar to those represented by equations 2 and 3 (homogeneous clay deposits and interlayered silt-sand and clay deposits, respectively) could be encountered.

Determining the appropriate use of the three equations in a specific application will require *a priori* knowledge of the likely sediment class. Such knowledge can be based on geologic and oceanographic criteria such as bathymetry, number and location of deltaic sources, and current and tidal influences. Since equation 1 covers a broader range of grain sizes, it is recommended for general application in BURMMS for calculating density given some measure of grain size. One should observe caution, however, in applying it to small grain sizes (large ϕ).

In some BURMMS applications a measure of density may be available and a value for grain size might need to be calculated. We found no useful regression analysis for this inverse relation and suggest, with some caution, that the inverse of equation 1 be used in such cases.

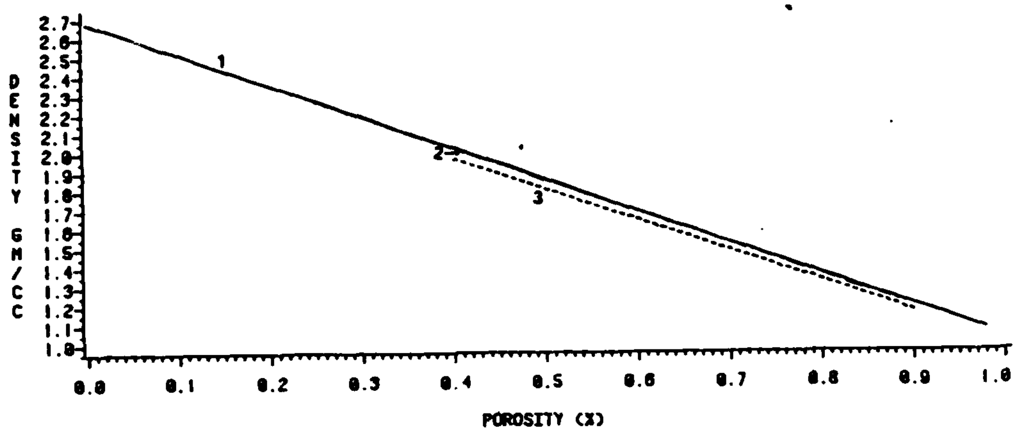
Range of Values: ρ (gm/cc)	Range of Values: ϕ (ϕ)	Sample Size	Standard Error of Estimate	r**	R ***	Reference
1.25–2.10	1–9	160	0.12	-	-	c
1.15–1.50	7–10	144	0.09	-	-	c
1.15–1.70	7–10	68	0.19	-	-	c

References: a) Akal 72; b) Anderson 74; c) Hamilton 74; d) Hamilton 78; e) Milholland 80; f) Morgan 69; g) Nafe and Drake 63; h) Hamilton 70a i) Smith 74; j) Hamilton 70b

** Correlation coefficient
*** Coefficient of determination

Table 3-2

DENSITY VERSUS POROSITY



No.	Regression Equation	Source of Data
1	$\rho = 2.68 - 0.0165P$	Limestones, Dolomites, Sandstones, Shales, Clays, Sands, Gravels, Ocean Sediments
2	$\rho = 2.68 - 0.0166P$	MGS▲ - Combined Data
3	$\rho = 2.604 - 0.01606P$	Pacific Ocean, North Atlantic Ocean Norwegian Sea, Mediterranean Sea, Black Sea

▲MGS - Marine Geological Survey

3.2 Calculating Density from Measured Porosity

The relationship between density and porosity is well established and equation 1 is the most commonly used quantitative statement of that relationship. The only apparent geologic characteristic of the data represented by equations 1, 2, and 3 that provides some distinction among the three equations, is physiographic province. Equations 1 and 2 are based on data characteristic of continental terraces and deeper water environments but are remarkably close. Equation 3, differing only slightly, describes data collected almost entirely in areas other than continental terraces (Anderson, 1974). As BURMMS will be applied in continental terrace settings equations 1 and 2 would be best suited for use during BURMMS' implementation. Although equation 1 extends to lower values of porosity than does equation 2, it is unlikely that sediments of corresponding porosity would be encountered during implementation of BURMMS. Since equation 2 is based on more data it might be considered the best and equation 1 might be considered to confirm equation 2.

Since porosity is not directly applicable in BURMMS, the inverse relationship would not be useful.

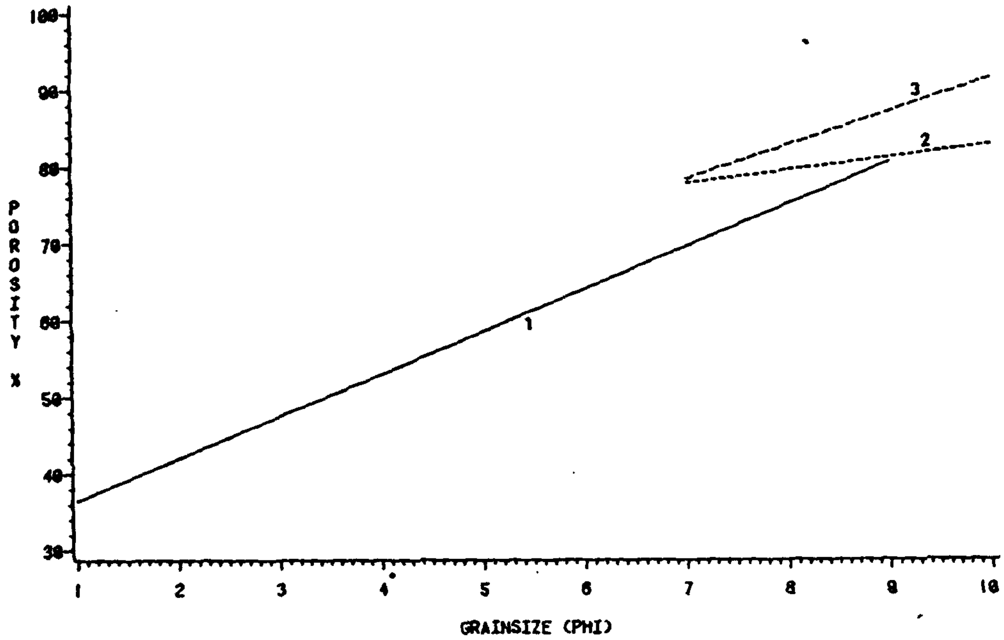
Range of Values		Sample Size	Standard Error of Estimate	r**	R ***	Reference
ρ (gm/cc)	P (%)					
1.2-2.9	0-85	300	-	-	-	g
1.1-2.3	25-90	1,748	-	-	-	b
1.2-1.9	40-90	15,124	0.036	-	-	a

References: a) Akal 72; b) Anderson 74; c) Hamilton 74; d) Hamilton 78; e) Milholland 80; f) Morgan 69; g) Nafe and Drake 63; h) Hamilton 70a i) Smith 74; j) Hamilton 70b

** Correlation coefficient
*** Coefficient of determination

Table 3-3

POROSITY VERSUS GRAIN SIZE



No.	Regression Equation	Source of Data
1	$P=31.05+5.52\phi$	Continental Terrace
2	$P=65.79+1.73\phi$	Abyssal Hill
3	$P=42.47+4.43\phi$	Abyssal Plain

3.3 Calculating Grain Size From Measured Porosity (Inversion Required)

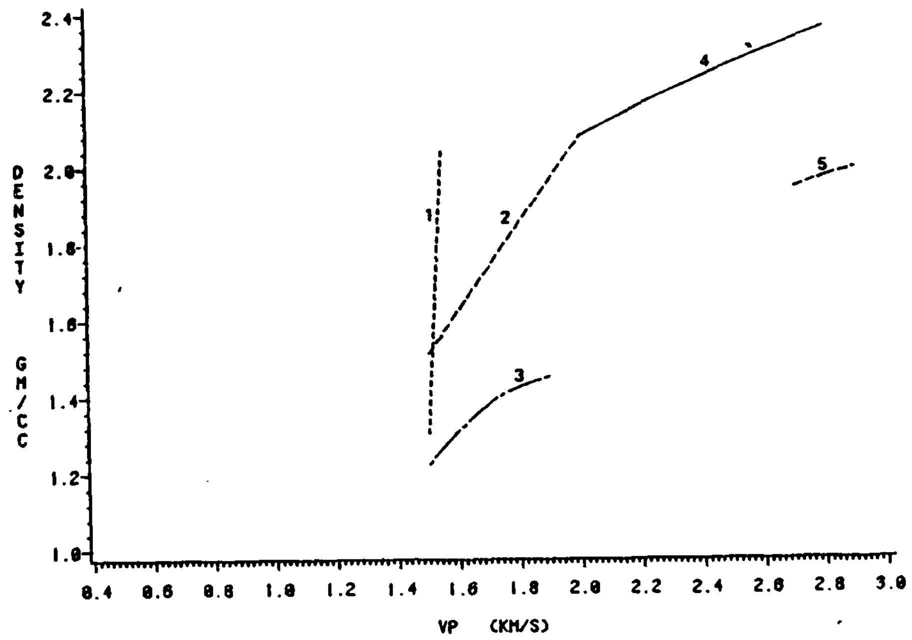
The sediment types most likely to be encountered during the implementation of BURMMS are best represented by equation 1 (Hamilton's continental terrace data). It is possible, however, that the material encountered, within an area of interest, could be more like that represented by equations 2 and 3. *A priori* determination of the appropriate equation could be accomplished through consideration of geologic and oceanographic constraints such as bathymetry, number and location of sediment sources, and current and tidal influences. Without prior knowledge of sediment class, equation 1 (inverted) is recommended for general BURMMS application. Caution should be exercised in calculating grain size from higher measured porosity values.

Range of Values P (%)	Range of Values ϕ (%)	Sample Size	Standard Error of Estimate	r**	R ***	Reference
35-85	1-9	160	7.0	-	-	c
70-90	7-10	144	4.8	-	-	c
70-90	7-10	68	5.8	-	-	c

References: a) Akal 72; b) Anderson 74; c) Hamilton 74; d) Hamilton 78; e) Milholland 80; f) Morgan 69; g) Nafe and Drake 63; h) Hamilton 70a i) Smith 74; j) Hamilton 70b

** Correlation coefficient
*** Coefficient of determination

Table 3-4
DENSITY VERSUS COMPRESSIONAL-WAVE VELOCITY



No.	Regression Equation	Source of Data
1	$\rho = -21.014 + 14.8Vp$	Abyssal Plain, Seafloor
2	$\rho = -0.19 + 1.135Vp$	DSDP△ Site 222, Silt clays, turbidites
3	$\rho = -2.77 + 4.316Vp - 1.102Vp^2$	Diatomaceous Sediments
4	$\rho = 0.917 + 0.744Vp - .08Vp^2$	Shale, Mudstones
5	$\rho = 1.124 + 0.347Vp - 0.0157Vp^2$	Porcelanite, Chert, Quartz

△DSDP - Deep Sea Drilling Project

3.4 Calculating Density from Measured Compressional-Wave Velocity

No single published regression equation describing the density/compressional-wave velocity relationship for which density is the dependent variable is adequate for BURMMS application. Only equations 1, 2, and 3 apply to velocity and density values that are likely to be encountered; however, they vary widely. With this degree of uncertainty and the very steep slope, small variations in measured velocity will lead to large uncertainities in density. No regression equation from this set is recommended for BURMMS application.

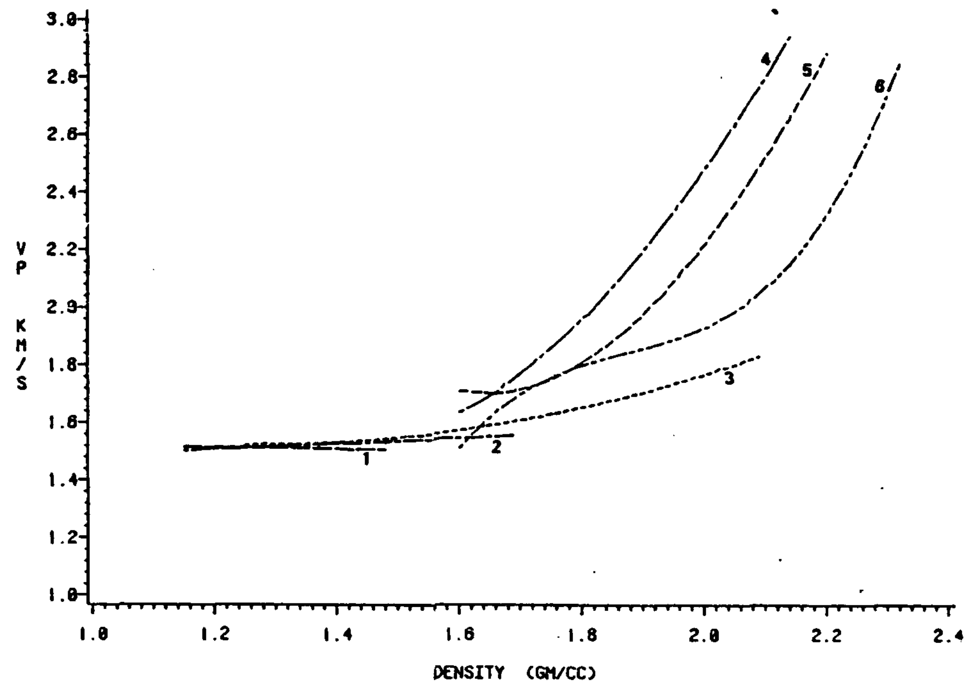
This state of uncertainty leads us to look at published regression equations describing the inverse relationship in the next section.

Range of Values: Vp (km/s)	Range of Values: ρ (gm/cc)	Sample Size	Standard Error of Estimate	r**	R ***	Reference
1.5-1.53	1.3-1.6	74	-	-	-	d
1.5-2	1.5-2.0	-	-	-	-	d
1.5-1.9	1.2-1.5	-	-	-	-	d
2-4.5	2.1-2.7	27	-	-	-	d
2.7-5.3	2.0-2.7	47	-	-	-	d

References: a) Akal 72; b) Anderson 74; c) Hamilton 74; d) Hamilton 78; e) Milholland 80; f) Morgan 69; g) Nafe and Drake 63; h) Hamilton 70a i) Smith 74; j) Hamilton 70b

** Correlation coefficient
*** Coefficient of determination

Table 3-5
COMPRESSIONAL-WAVE VELOCITY VERSUS DENSITY



No.	Regression Equation	Source of Data
1	$V_p=1.5427-0.0253\rho$	Abyssal Hill
2	$V_p=1.387+0.0997\rho$	Abyssal Plain
3	$V_p=2.2344-1.1293\rho+0.4481\rho^2$	Continental Terrace
4	$V_p=10.04-13.32\rho+6.13\rho^2-0.68\rho^3$	DSDP$^{\Delta}$ Site 289 - Calcarious and Siliceous Sediments
5	$V_p=19.06-24.42\rho+10.42\rho^2-1.21\rho^3$	DSDP$^{\Delta}$ Site 288 - Calcarious and Siliceous Sediments
6	$V_p=-56.27+91.88\rho-48.71\rho^2+8.66\rho^3$	DSDP$^{\Delta}$ Site 210 - Clay Enriched Carbonates

$^{\Delta}$DSDP - Deep Sea Drilling Project

3.5 Calculating Density from Measured Compressional-Wave Velocity (Inversion Required)

Despite the fact that calculating density from compressional-wave velocity would be highly desirable for BURMMS application, no single published equation (or its inverse) appears to be fully adequate. First, only equations 1, 2, and 3 (ref. Hamilton, 1974) cover a useful range of values. Second, their inverses have steep slopes and may, therefore, cause serious uncertainty. And finally the existence of data (representing various sediment classes) impinging upon the useful range of values with high variability suggest additional uncertainty.

Nevertheless, with reservation, we recommend that the inverse of equation 3 (representing Hamilton's continental terrace data) be considered for BURMMS application. However, more field work and analysis should be done to confirm its value and possibly seek a better fit.

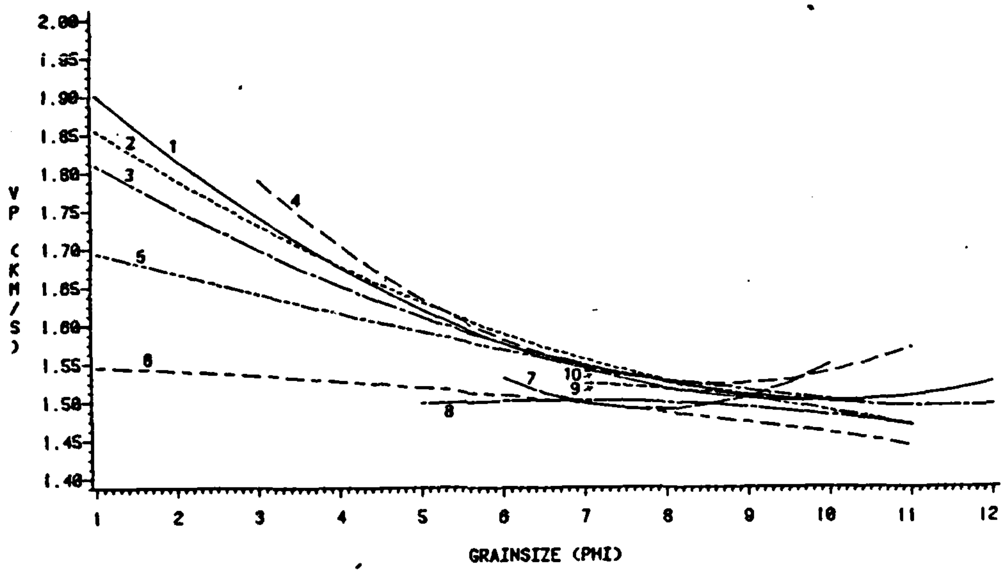
Range of Values						
Vp (km/s)	ρ (gm/cc)	Sample Size	Standard Error of Estimate	r**	R ***	Reference
1.48-1.63	1.15-1.50	144	0.0127	-	-	c
1.48-1.63	1.15-1.70	68	0.0205	-	-	c
1.48-1.88	1.25-2.10	160	0.0356	-	-	c
1.5-6	1.6-3.0	-	0.15	-	-	e
1.5-4	1.6-2.5	-	0.19	-	-	e
1.3-5	1.6-2.5	26	0.17	-	-	e

References: a) Akal 72; b) Anderson 74; c) Hamilton 74; d) Hamilton 78; e) Milholland 80; f) Morgan 69; g) Nafe and Drake 63; h) Hamilton 70a i) Smith 74; j) Hamilton 70b

** Correlation coefficient
*** Coefficient of determination

Table 3-6

COMPRESSIONAL-WAVE VELOCITY VERSUS GRAIN SIZE



No.	Regression Equation	Source of Data
1	$Vp=1.997-0.1015 +0.00518\phi^2$	MGS▲-Continental Slope, Shelf, Plateaus, Abyssal Plains
2	$Vp=1.9272-0.07582\phi+0.00321\phi^2$	Continental Terrace
3	$Vp=1.874-0.0682+\phi.00305\phi^2$	MGS▲-Combined
4	$Vp=2.151-0.1461\phi+0.00848\phi^2$	MGS▲-Oceanic Rises
5	$Vp=1.722-0.0293\phi+0.00057\phi^2$	MGS▲-Continental Rises
6	$Vp=1.594-0.0037\phi-0.00055\phi^2$	MGS▲-Ridges
7	$Vp=2.25-0.1946\phi+0.01244\phi^2$	MGS▲-Seamount Group and Arches
8	$Vp=1.428+0.0225\phi-0.00172\phi^2$	MGS▲-Abyssal Hills
9	$Vp=1.5816-0.0083\phi$	Abyssal Hill
10	$Vp=1.628-0.0127\phi$	Abyssal Plain

▲MGS - Marine Geological Survey

3.6 Calculating Grain Size from Measured Compressional-Wave Velocity (Inversion Required)

There has been considerable work done in providing regression equations for the relationship between grain size and velocity. In this work velocity has been the dependent variable. There are several good datasets providing regression equations useful to BURMMS. In the range of values of interest to BURMMS equations 2 through 5 and 10 show good agreement suggesting that variation in possible sediment classes found in BURMMS applications do not cause serious uncertainty. However, the slope of the curves will be somewhat steep when inverted, which could cause some problems. For general applications we once again recommend Hamilton's continental terrace equation (equation 2), although equation 1 should be good also.

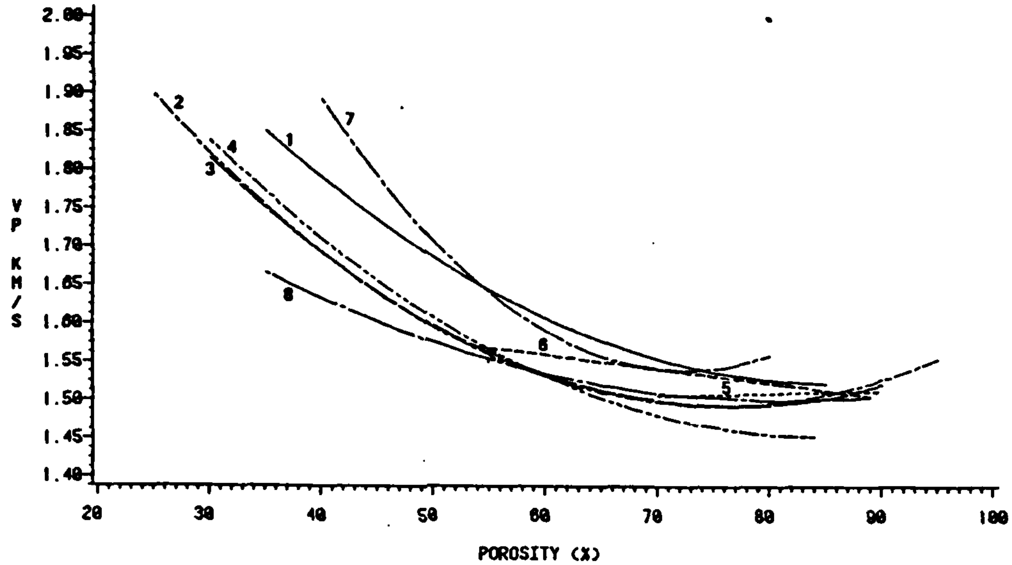
Range of Values: Vp (km/s)	Range of Values: ϕ (%)	Sample Size	Standard Error of Estimate	r**	R ***	Reference
1.48-1.81	2-12	430	0.0455	.86	-	b
1.49-1.81	1-9	160	0.0363	-	-	c
1.48-1.95	1-12	1080	0.0457	.78	-	b
1.48-1.9	3-11	82	0.0472	.86	-	b
1.48-1.8	1-11.5	231	0.0395	.73	-	b
1.48-1.75	1-11	241	0.0359	.41	-	b
1.48-1.60	6-10	38	0.0265	.54	-	b
1.48-1.55	5-11	58	0.0147	.44	-	b
1.49-1.54	7-10	144	0.0109	-	-	c
1.49-1.56	7-10	68	0.0191	-	-	c

References: a) Akal 72; b) Anderson 74; c) Hamilton 74; d) Hamilton 78; e) Milholland 80; f) Morgan 69; g) Nafe and Drake 63; h) Hamilton 70a i) Smith 74; j) Hamilton 70b

** Correlation coefficient
*** Coefficient of determination

Table 3-7

COMPRESSIONAL-WAVE VELOCITY VERSUS POROSITY



No.	Regression Equation	Source of Data
1	$Vp=2.4559-0.021716P+0.000126P^2$	Continental Terrace
2	$Vp=2.399-0.02409P+0.000159P^2$	MGS▲-Continental Rise, Slope, Shelf, Plateau, Abyssal Hills and Plains, Seamount Group
3	$Vp=2.367-0.02291P+0.00015P^2$	MGS▲-Combined
4	$Vp=2.38-0.02197P+.0001333P^2$	Lake Erie
5	$Vp=1.4831+0.00032P$	Abyssal Hill
6	$Vp=1.6691-0.00185P$	Abyssal Plain
7	$Vp=3.312-0.04913P+0.000336P^2$	MGS▲-Oceanic Rises
8	$Vp=2.019-0.01289P+0.0000792P^2$	MGS▲-Ridges

▲MGS - Marine Geological Survey

3.7 Calculating Porosity from Measured Compressional-Wave Velocity (Inversion Required)

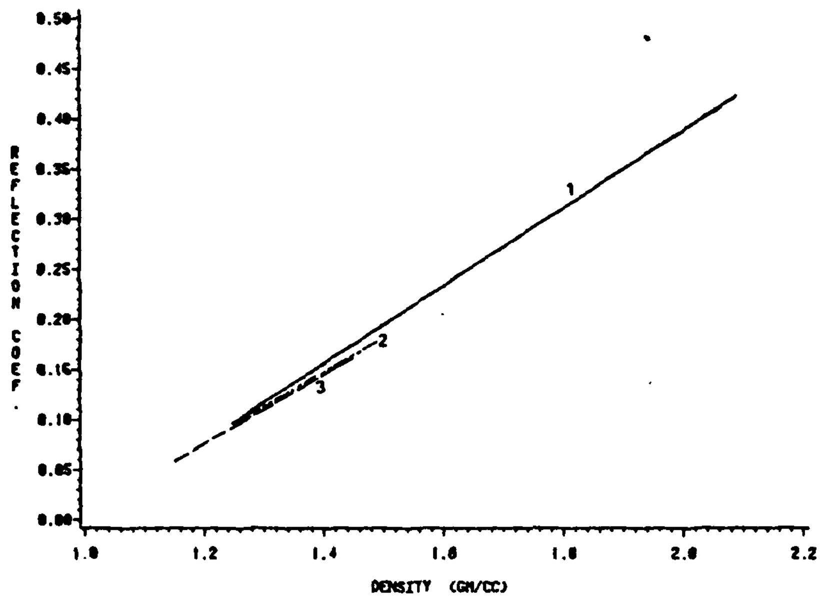
Equations 1 and 2 are the two that describe data from continental terrace environments, which is the principal environment of concern in implementing BURMMS. These two equations represent the same datasets and works associated with the two equations selected as good in the previous section. However, whereas a given measured velocity leads to very nearly the same grain size when put into either of those equations, it leads to considerably more variability in porosity. Because the inverse relation has a steep slope in ranges of interest to BURMMS, serious error could be introduced in calculating porosity from it. Because Hamilton's continental terrace data is likely to be more representative of general BURMMS sediment types, equation 1 has a slight favor over equation 2 for BURMMS application. However, since porosity is needed only indirectly (for possible use in calculating other properties) and this relationship is so poor, none of these equations are recommended for BURMMS application.

Range of Values: Vp (km/s)	Range of Values: P (%)	Sample Size	Standard Error of Estimate	r**	R ***	Reference
1.48-1.85	35-85	160	0.0349	-	-	c
1.48-2.00	25-95	1182	0.0312	0.91	-	b
1.48-2.00	25-95	1748	0.0349	0.86	-	b
1.45-1.84	35-85	68	0.05417	-	0.874	f
1.48-1.54	70-90	144	0.0128	-	-	c
1.49-1.64	70-90	68	0.0192	-	-	c
1.48-1.90	40-80	101	0.0546	0.79	-	b
1.48-1.75	35-90	465	0.0274	0.66	-	b

References: a) Akal 72; b) Anderson 74; c) Hamilton 74; d) Hamilton 78; e) Milholland 80; f) Morgan 69; g) Nafe and Drake 63; h) Hamilton 70a i) Smith 74; j) Hamilton 70b

** Correlation coefficient
***Coefficient of determination

Table 3-8
REFLECTION COEFFICIENT* VERSUS DENSITY



No.	Regression Equation	Data Source
1	$R=-0.3864+0.3870\rho$	Continental Terrace
2	$R=-0.3339+0.3435\rho$	Abyssal Hills
3	$R=-0.3358+0.3428\rho$	Abyssal Plains

*Calculated from measured density and sound velocity

3.8 Calculating Density from Measured Reflection Coefficient* (Inversion Required)

Hamilton's (1970b) equation (Eq. 1) is estimated to best suit BURMMS requirements because it is based on a significant sample of continental terrace data and because it is fitted to density over a broad range. It maintains good agreement with abyssal hill and plain data (Eqs. 2 and 3) over the smaller ranges of densities in which they apply.

*See earlier discussion concerning "measured" reflection properties and the interrelation among the various reflection properties.

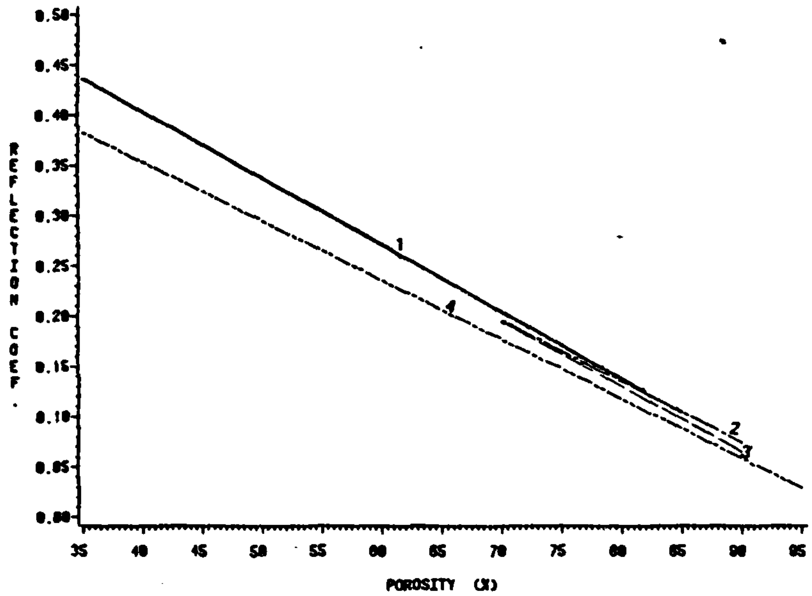
Range of Values R	Range of Values ρ (gm/cc)	Sample Size	Standard Error of Estimate	r**	R ***	Reference
0.09-0.43	1.25-2.10	-	0.0099	-	-	j
0.09-0.18	1.25-1.50	-	0.0045	-	-	j
0.05-0.17	1.15-1.45	-	0.0251	-	-	j

References: a) Akal 72; b) Anderson 74; c) Hamilton 74; d) Hamilton 78; e) Milholland 80; f) Morgan 69; g) Nafe and Drake 63; h) Hamilton 70a i) Smith 74; j) Hamilton 70b

* Calculated from measured density and sound velocity
** Correlation coefficient
***Coefficient of determination

Table 3-9

REFLECTION COEFFICIENT* VERSUS POROSITY



No.	Regression Equation	Source Data
1	R=0.6692-0.00666P	Continental Terrace
2	R=0.6199-0.00607P	Abyssal Hills
3	R=0.6461-0.00646P	Abyssal Plains
4	R=0.589-0.0059P	North Atlantic, Norwegian Sea, Black Sea, Mediterranean Sea

*Calculated from measured density and sound velocity

3.9 Calculating Porosity from Measured Reflection Coefficient* (Inversion Required)

Hamilton's (1970b) equation (Eq. 1) is estimated to best suit BURMMS requirements because it is based on a significant sample of continental terrace data and because it is fitted to porosity over a broad range. It maintains good agreement with abyssal hill and plain data (Eqs. 2 and 3) over the smaller range of porosities in which they apply. Akal's (1972) equation (Eq. 4) is rejected because most of his data (97%) was taken from deep-sea sediments. Also, Akal does not present corresponding reflection coefficient vs density data as does Hamilton.

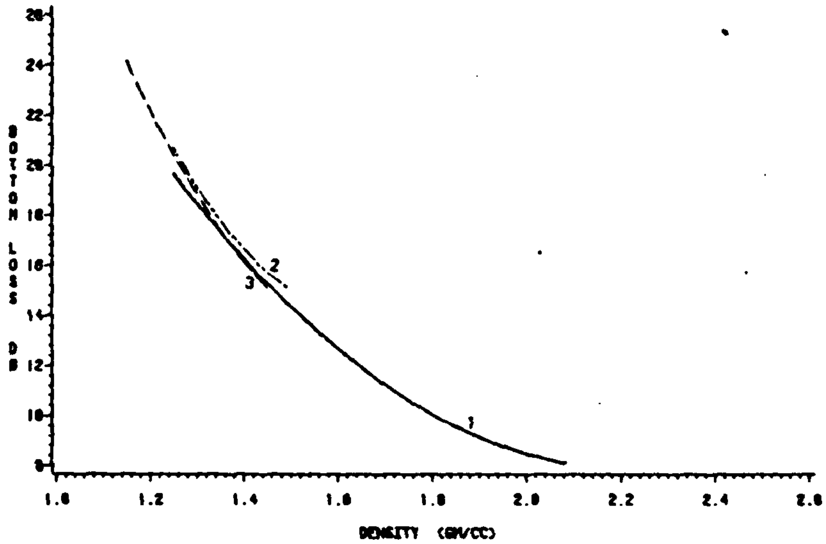
*See earlier discussion concerning "measured" reflection properties and the interrelation among the various reflection properties.

Range of Values R	Range of Values P (%)	Sample Size	Standard Error of Estimate	r**	R ***	Reference
0.10-0.44	35-85	105	0.0131	-	-	j
0.07-0.20	70-90	41	0.0061	-	-	j
0.06-0.20	70-90	54	0.0257	-	-	j
0.03-0.40	35-95	8,287	0.025	-	-	a

References: a) Akal 72; b) Anderson 74; c) Hamilton 74; d) Hamilton 78; e) Milholland 80; f) Morgan 69; g) Nafe and Drake 63; h) Hamilton 70a i) Smith 74; j) Hamilton 70b

* Calculated from measured density and sound velocity
** Correlation coefficient
***Coefficient of determination

Table 3-10
BOTTOM (REFLECTION) LOSS* VERSUS DENSITY



No.	Regression Equation	Source of Data
1	$BL=70.7-57.03\rho+12.95\rho^2$	Continental Terrace
2	$BL=127.4-137.60\rho+41.76\rho^2$	Abyssal Hills
3	$BL=118.6-123.2\rho+35.72\rho^2$	Abyssal Plains

*Calculated from measured density and sound velocity

3.10 Calculating Density from Measured Bottom Loss*
(Inversion Required)

Hamilton's (1970b) equation (Eq. 1) is estimated to best suit BURMMS requirements because it is based on a significant sample of continental terrace data and because it is fitted to density over a broad range. It maintains good agreement with abyssal hill and plain data (Eqs. 2 and 3) over the smaller range of densities in which they apply. Equation 1 does not extend to as low density values as does Eq. 3; however, such low densities are not expected in BURMMS applications.

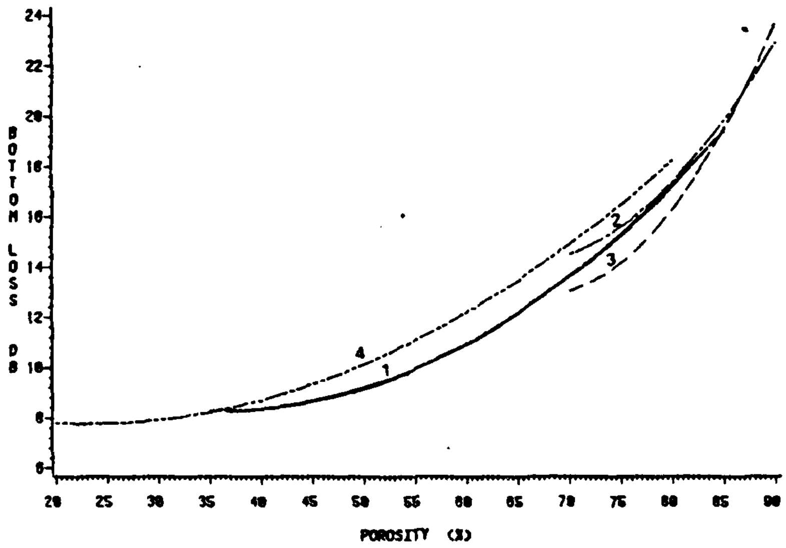
*See earler discussion concerning "measured" reflection properties and the interrelation among the various reflection properties.

Range of Values						
BL (DB)	ρ (gm/cc)	Sample Size	Standard Error of Estimate	r**	R ***	Reference
8-19	1.25-2.10	105	0.4	-	-	j
15-21	1.25-1.50	41	0.3	-	-	j
15-25	1.15-1.45	54	0.4	-	-	j

References: a) Akal 72; b) Anderson 74; c) Hamilton 74; d) Hamilton 78; e) Milholland 80; f) Morgan 69; g) Nafe and Drake 63; h) Hamilton 70a i) Smith 74; j) Hamilton 70b

* Calculated from measured density and sound velocity
** Correlation coefficient
***Coefficient of determination

Table 3-11
BOTTOM (REFLECTION) LOSS* VERSUS POROSITY



No.	Regression Equation	Source of Data
1	$BL=14.2-0.33P+0.0046P^2$	Continental Terrace
2	$BL=68.1-1.69P+0.0132P^2$	Abyssal Hills
3	$BL=106.2-2.78P+0.0207P^2$	Abyssal Plain
4	$BL=9.426-0.1458P+0.0032P^2$	MGS-Combined data

*Calculated from measured density and sound velocity

3.11 Calculating Porosity From Measured Bottom Loss (Inversion Required)

Hamilton's (1970b) equation (Eq. 1) is estimated to best suit BURMMS requirements because it is based on a significant sample of continental terrace data and because it is fitted to porosity over a broad range. It maintains good agreement with abyssal hill and plain data (Eqs. 2 and 3) over the smaller range of porosities in which they apply. Anderson's (1974) equation (Eq. 4) is rejected because it is based on data from sediment types of little interest to BURMMS. The data does extend beyond the range of Hamilton (to porosities between 20 and 35 percent) but these values are of little relevance to BURMMS. Moreover, in its inverted form, the slope tends to be extremely large for porosities less than 40%.

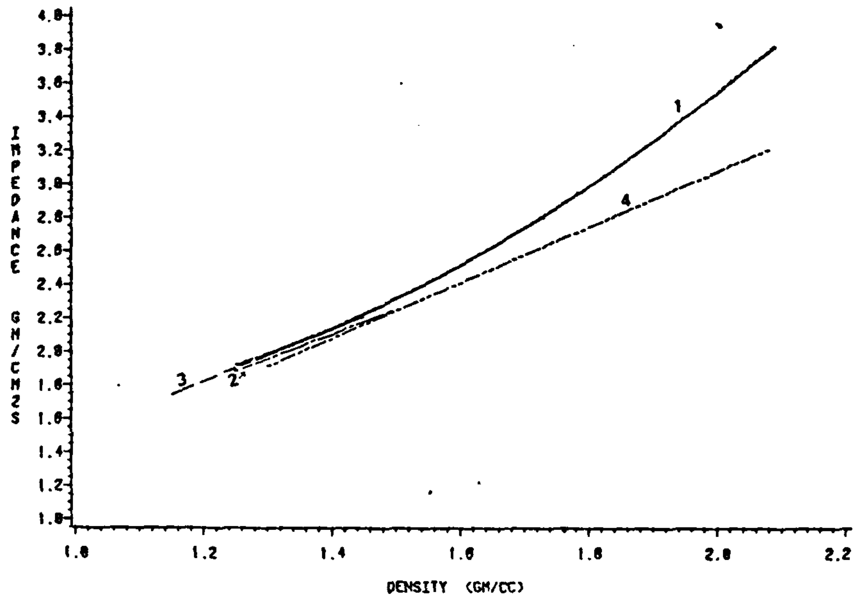
*See earlier discussion concerning "measured" reflection properties and the interrelation among the various reflection properties.

Range of Values BL (DB)	P (%)	Sample Size	Standard Error of Estimate	r**	R ***	Reference
8-20	35-85	105	0.5	-	-	j
14-23	70-90	41	0.4	-	-	j
13-24	70-90	54	3.8	-	-	h
7-19	20-80	1,748	-	-	-	b

References: a) Akal 72; b) Anderson 74; c) Hamilton 74; d) Hamilton 78; e) Milholland 80; f) Morgan 69; g) Nafe and Drake 63; h) Hamilton 70a i) Smith 74; j) Hamilton 70b

* Calculated from measured density and sound velocity
** Correlation coefficient
***Coefficient of determination

Table 3-12
ACOUSTIC IMPEDANCE* VERSUS DENSITY



No.	Regression Equation	Source of Data
1	$Z=2.0960-1.5851\rho+1.1572\rho^2$	Continental Terrace
2	$Z=0.0321+1.4828\rho$	Abyssal Hills
3	$Z=-0.0414+1.5556\rho$	Abyssal Plains
4	$Z=-0.251+1.666\rho$	North Atlantic Cores

*Calculated from measured density and sound velocity

3.12 Calculating Density from Measured Acoustic Impedance* (Inversion Required)

Hamilton's (1970b) equation (Eq. 1) is estimated to best suit BURMMS requirements because it is based on a significant sample of continental terrace data and because it is fitted to density over a broad range. It maintains good agreement with abyssal hill and plain data (Eqs. 2 and 3) over the smaller range of densities in which they apply. Smith's (1974) equation (Eq. 4) is based on measurements made in the deep-sea only and is, therefore, less applicable to BURMMS than Hamilton's (1970b) equation describing continental terrace sediments.

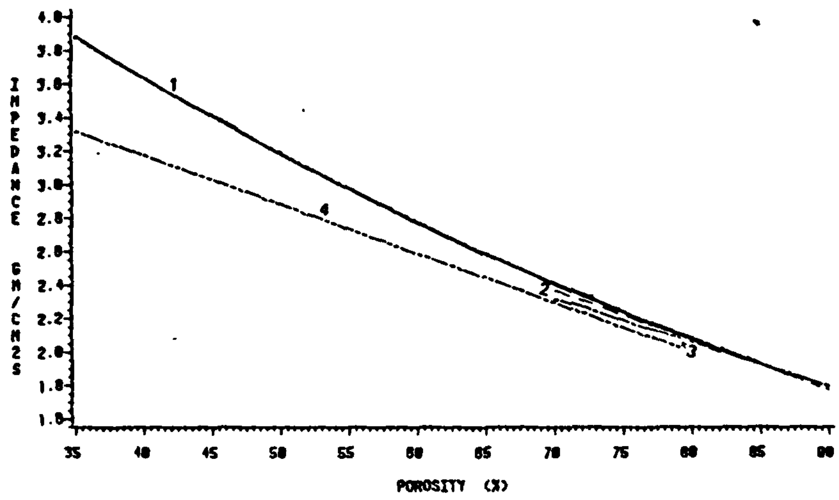
*See earlier discussion concerning "measured" reflection properties and the interrelation among the various reflection properties.

Range of Values						
Z (gm/cm^2s)	ρ (gm/cc)	Sample Size	Standard Error of Estimate	r**	R ***	Reference
1.9-3.9	1.25-2.10	105	0.0621	-	-	j
1.8-2.3	1.25-1.50	41	0.0187	-	-	j
1.7-2.3	1.15-1.45	54	0.0196	-	-	j
1.9-3.3	1.3-2.1	-	-	-	-	i

References: a) Akal 72; b) Anderson 74; c) Hamilton 74; d) Hamilton 78; e) Milholland 80; f) Morgan 69; g) Nafe and Drake 63; h) Hamilton 70a i) Smith 74; j) Hamilton 70b 2

* Calculated from measured density and sound velocity
** Correlation coefficient
***Coefficient of determination

Table 3-13
ACOUSTIC IMPEDANCE* VERSUS POROSITY



No.	Regression Equation	Source of Data
1	$Z=5.8572-0.06408P+0.00021P^2$	Continental Terrace
2	$Z=4.1475-0.0262P$	Abyssal Hills
3	$Z=4.4431-0.0297P$	Abyssal Plains
4	$Z=4.345-0.0294P$	North Atlantic Cores

*Calculated from measured density and sound velocity

3.13 Calculating Porosity from Measured Acoustic Impedance* (Inversion Required)

Hamilton's (1970b) equation (Eq. 1) is estimated to best suit BURMMS requirements because it is based on a significant sample of continental terrace data and because it is fitted to porosity over a broad range. It maintains good agreement with abyssal hill and plain data (Eqs. 2 and 3) over the smaller range of porosities in which they apply. Smith's (1974) equation (Eq. 4) is rejected because it applies to deep-sea sediments primarily and while it matches equivalent data in Hamilton's equation, it departs from the more relevant continental terrace data in a wide range of useful porosity values.

*See earlier discussion concerning "measured" reflection properties and the interrelation among the various reflection properties.

Range of Values						
Z (gm/cm^2s)	P (%)	Sample Size	Standard Error of Estimate	r**	R ***	Reference
1.9-3.9	35-85	105	0.0665	-	-	h
1.7-2.3	70-90	41	0.0261	-	-	h
1.7-2.4	70-90	54	0.0218	-	-	h
2.0-3.3	35-80	-	-	-	-	i

References: a) Akal 72; b) Anderson 74; c) Hamilton 74; d) Hamilton 78; e) Milholland 80; f) Morgan 69; g) Nafe and Drake 63; h) Hamilton 70a i) Smith 74; j) Hamilton 70b

* Calculated from measured density and sound velocity
** Correlation coefficient
***Coefficient of determination

4.0 RESULTS

The previous section discussed each relationship in isolation and selected the "best" regression equation to describe it for BURMMS application. For two of the relationships (see Sections 3.4 and 3.7) no regression equation was found to be adequate. This section will consider the relative merits of the remaining eleven relationships to find the overall best measure of density and grain size. What we will find is that, rather than a single one or several equations, the best measure will be a system of interrelated algorithms based on a minimum set of measurements including both compressional-wave velocity and reflection coefficient.

First, four more equations can quickly be discarded from consideration. As mentioned before, the various reflected-wave properties considered in Sections 3.8 to 3.13 are actually calculated quantities and are, in fact, deterministically interdependent. Therefore, we need only choose one of the three reflected-wave properties--acoustic impedance, reflection coefficient, or bottom loss--to which the sediment properties are to be related. Since reflection coefficient is, in fact, the primary quantity measured and since there is a simple deterministic relation between it and density and velocity, it is chosen over bottom loss and acoustic impedance to represent reflected-wave properties.

Second, porosity is needed only if it facilitates a calculation of density or grain size. It relates extremely well to density (Section 3.2) and to a lesser extent to grain size (Section 3.3). However, density has been related to both velocity (Section 3.5) and reflection coefficient (Section 3.8) while grain size only to velocity. Therefore, the grain size/porosity relationship is needed and the density/porosity relationship, as good as it is, is not.

Through a process of elimination, we have arrived at a set of six equations that have potentially useful applications in BURMMS. These equations and relevant information are given in Table 4-1. These equations should provide the best values of density and grain size for general BURMMS applications when values for compressional-wave velocity and/or reflection coefficient are available with no additional a priori information.

Further analysis provides an opportunity to check for interconsistency among these relationships and a possible basis for additional field work and analysis to verify their value. Note that porosity can be eliminated from relationship F by using relationship B. We then have the pairs of parametric representations of density and grain size

$$\rho = \rho(V_S), \quad \phi = \phi(V_S) \text{ and } \rho = \rho(R), \quad \phi = \phi(R)$$

provided by relationships C and D and relationships E and F, respectively. We also have equation $\rho = \rho(\phi)$ provided by relationship A. Interconsistency can be checked by plotting each on a (ρ, ϕ) diagram. Figure 4-1 is the result. Note that the interconsistency is good; however, there is a bias of about 5%. From the available data we can not determine the reason for the bias. An explanation for this should be sought in the original data. The dip in the value of density at the value of 8.0 for grain size in the parametric representation in velocity is probably due to quadratic equations going bad in the region of the steep slope. Otherwise each of these plots are very nearly parallel straight lines.

Table 4.1

RECOMMENDED EQUATIONS FOR BURMMS APPLICATIONS*

Relation-ship	Regression Equation (Valid range)	Units	Table #	Eq. #	Inverted
A	$\rho = 2.191 - 0.096\,\phi$		3.1	1	No
	$1 \leq \phi \leq 9$	ϕ			
	$2.10 \geq \rho \geq 1.33$	g/cm^3			
B	$P = 31.05 + 5.52\,\phi$		3.3	1	No
	$0.72 \leq \phi \leq 9.77$	ϕ			
	$35 \leq p \leq 85$	%			
C	$\rho = 1.26 + \sqrt{2.23V_p - 3.40}$		3.5	3	Yes
	$1.53 \leq V_p \leq 1.88$	km/sec			
	$1.39 \leq \rho \leq 2.15$	g/cm^3			
D	$\phi = 11.82 - \sqrt{311.5V_p - 460.9}$		3.6	2	Yes
	$1.5 \leq V_p \leq 1.81$	km/sec			
	$9.3 \geq \phi \geq 1.7$	ϕ			
E	$\rho = 0.9984 + 2.584R$		3.8	1	Yes
	$0.09 \leq R \leq 0.43$	-			
	$1.25 \leq \rho \leq 2.10$	gm/cm			
F	$P = 100.5 - 150.2R$		3.9	1	Yes
	$0.10 \leq R \leq 0.44$	-			
	$35 \leq P \leq 85$	%			

*See text concerning reservations about the full validity of these equations.

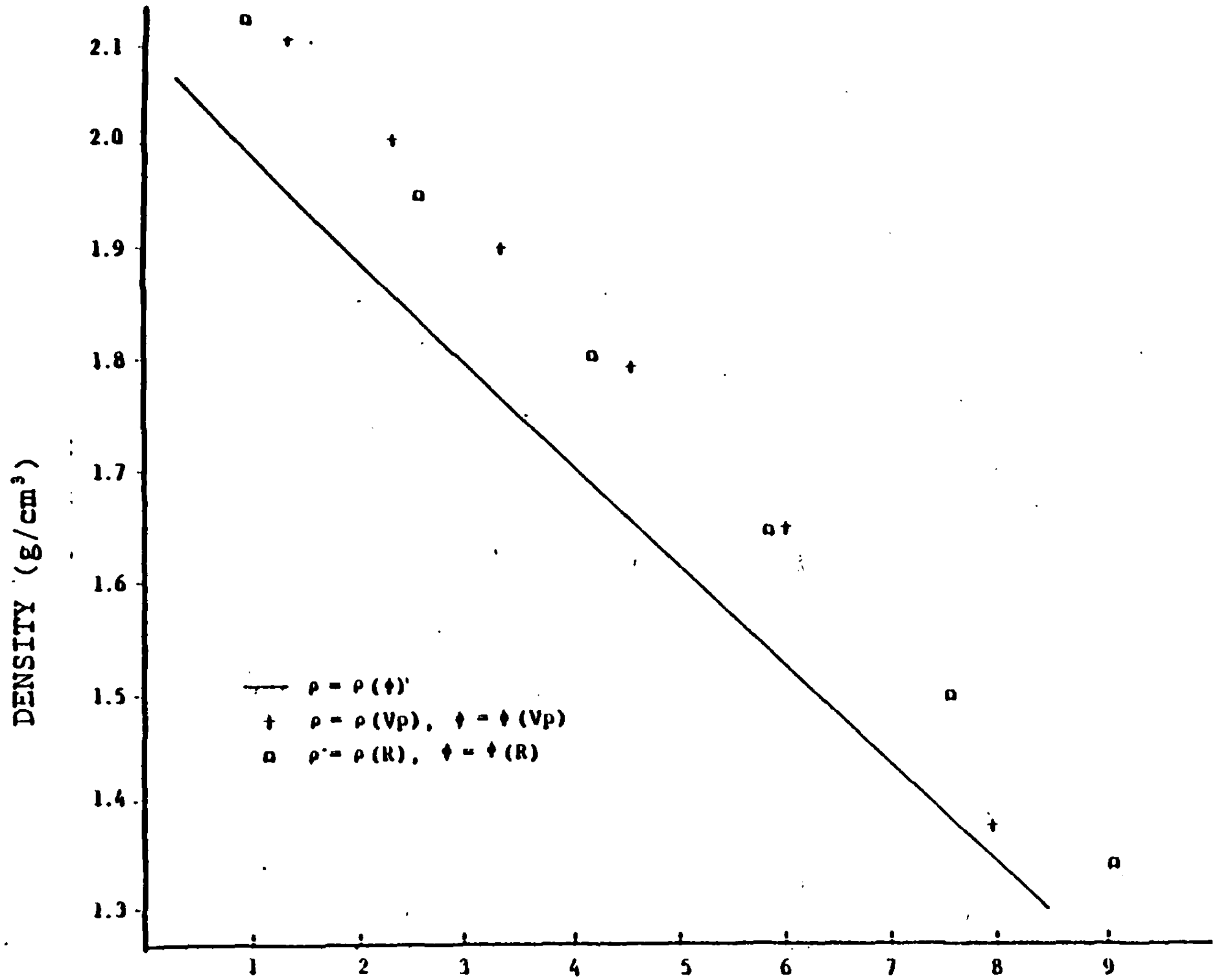


Figure 4-1
DENSITY/GRAIN SIZE DIAGRAM

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APPENDIX A

REVIEW OF PARAMETERS AVAILABLE IN A COMPLETE REGRESSION ANALYSIS

The standard error of estimate, the coefficient of determination, and a test of lack of fit indicate the extent to which a regression curve fits the data.* The standard error of estimate is a measure of the amount of scatter of the data about the fitted regression curve. A large standard error of estimate indicates either an inappropriate equation is fitted to the data or a weak relationship exists between the pair of variables. While most authors report the standard error of estimate, only a few authors (Anderson, 1974; Morgan, 1969) report a statistical test of the fit of a single equation or a statistical test for the best fitting equation among several hypothesized equations. These statistical tests are functions of the standard error of estimate.

The coefficient of determination is the proportion of total variation about the mean value of the dependent variable explained by the regression. For example, if the coefficient of determination of a fitted regression equation is equal to 0.88, then 88% of the total variation about the mean is explained by the regression. Morgan (1969) is the only author to report the coefficient of determination to evaluate the strength of a fitted regression equation. If the fitted regression equation is a straight line, then the square of the correlation coefficient is

*The statistical quantities discussed and used in this report are consistent with those given in Draper and Smith, 1966.

equal to the coefficient of determination. Anderson (1974) reports the correlation coefficient, but his regression equations are curvilinear and squaring the correlation coefficient does not provide the complete measure of the proportion of variance accounted for by the regression.

To evaluate predictive ability for BURMMS application, an equation must be tested with new data sampled from geological areas of interest to BURMMS. A regression equation may effectively predict values if (1) the standard error of estimate derived when an equation is applied to a new data set is similar in value to the experimental error derived from the original curve fit, and (2) if the standard error of estimate is small enough to predict values with sufficient precision. Such tests are not available in the literature reviewed.

A statistical test of lack of fit partitions the mean square error (square of the standard error of estimate) into two portions: (1) the mean square due to experimental error and (2) the mean square due to lack of fit. The ratio of the two mean squares comprises a test of lack of fit. No author reports using this test.

There are several statistical methods which may be used to evaluate the ability of a regression equation to predict values of properties with precision. The confidence interval is the range of values within which the true mean value of the dependent variable for a given independent variable is expected to occur. A regression equation may be used to predict sediment property values with adequate precision if the confidence interval is equal to or smaller than a range that can be tolerated by BURMMS mine burial prediction models. To calculate a confidence interval, additional statistics not reported by any author must be acquired. And to determine if the confidence interval is adequate, the tolerances required by BURMMS models must be established.

Similar equations derived by different researchers on independent data sets indicate that the relationship between some pairs of variables are reproducible. The equations derived by Hamilton (1974), Anderson (1974), and Morgan (1969) relating compressional-wave velocity to porosity are similar, as are the equations derived by Hamilton (1974) and Anderson (1974) relating compressional-wave velocity to grain size. The equations relating density to porosity are clearly in agreement, but this is due, in part, to an overlap in data sets. For example, Akal's (1972) data include those used by Nafe and Drake (1963) and Anderson (1974). The equations relating the other pairs of variables do not show similar agreement.

APPENDIX B

GEOLOGIC CONSIDERATIONS RELEVANT TO BURMMS

Several geologic processes determine the composition and fabric of the material comprising the sea floor. The process of primary importance, in producing the types of materials to be encountered in all conceivable BURMMS applications, is sedimentation. The areas of interest to BURMMS are, generally, coastal regions which are marked by a high degree of variability in the specific sedimentary processes at work. Such process variability results in a variety of sedimentary deposits. The following is a brief discussion of the sedimentary processes and deposits likely to occur in areas of interest to BURMMS. Such consideration is essential in determining the kinds of environments important to BURMMS application, relating those environments to the various categories, and sediment classifications found in the literature, and in establishing quantitative relationships between acoustical and mechanical sediment properties.

Several sediment classification systems have been devised for subdividing the marine environment into rational and useful categories and data relating acoustical to mechanical properties are often presented in such subdivisions. One such system recognizes that physiographic features are of primary importance in determining which mechanism of submarine sedimentation will predominate and therefore results in a classification based on sedimentary mechanism and sediment type. The physiographic features of importance include mid-ocean ridges, terraces, plains, seamounts, and continental terraces, slopes, and rises. The resulting classification is in terms of three general regions: continental terrace (shelf and slope), abyssal plain, and abyssal hill (Hamilton, 1970a). The features which distinguish the three regions are sediment properties, including mean grain size, density, porosity, and sedimentary structure.

Other classification schemes are embellishments on Hamilton's general classification of marine sediments; and usually provide methods for further subdivision of the three groups which are applicable only in local areas. Exemplary of such systems are the works of Winn, et al. (1980); Hanrahan (1980); Milligan, et al. (1978); Houtz (1980); Tucholke (1980); Damuth and Hayes (1977); and Addy et al. (1979).

No classification system exists that clearly sets data of interest to BURMMS apart from the rest. Consequently there is no a priori way in which non-relevant data sets and their resulting regression equations can be eliminated from consideration without analysis. The published classification system found most useful in dealing with the data encountered in this project was that devised by Hamilton (1970a). The three principal categories are discussed below.*

The continental terrace classification, as defined by Hamilton (1970a), includes continental shelf, slope, and rise. The proximity of continental terrace features to subaerial continental masses dictates that the existing, submarine, sedimentary patterns will be strongly influenced by nearby terrestrial geologic processes.

*Although abyssal-hill and abyssal-plain environments are not expected to have direct relevance to BURMMS, data of interest is sometimes presented in these categories. Hence, both are discussed herein along with the more relevant continental-terrace environment.

- Mean grain size between 0.0015 and 0.0035 mm (ϕ 9.4 to 8.2),
- Densities between 1.37 and 1.42 g/cm^3 and
- Porosities ranging from 76.4 and 79.4 percent.

Abyssal-hill sediments are very-fine-grained, clay to clayey-silt, and show little deviation from this average grain size. They exhibit relatively little sedimentary structure (i.e., lamination, ripples, and scour marks). The low density and high porosity are characteristic of deposition via clay flocculation and settling within a marine environment.

Abyssal plains are the extremely flat (slopes of less than 1 in 1,000) portions of ocean basins. Abyssal plains commonly occur at the seaward margin of continental rises; and therefore, are influenced by continental sedimentary processes. The principal mechanism of sedimentation is the turbidity current. Sedimentary piles accumulating on the continental shelf and slope are frequently set in motion (by overloading or earthquakes) and cascade down slopes and rises to be deposited onabyssal plains. In the depositional process coarser (and heavier) material is deposited first with finer-grained material following. After a series of turbidity flows the resulting sedimentary deposit is a rhythmic interlayering of coarse- and fine-grained laminae. Pelagic sedimentation (as in the abyssal-hill setting) occurs simultaneously but provides only a small proportion of the total sedimentary sequence. The physical characteristics of abyssal-plain sediment are (Hamilton, 1970a):

- Grain size ranging from 0.001 to 0.017 mm (ϕ 10 to 5.9),
- Densities between 1.26 and 1.65 g/cm^3, and
- Porosities of 56.6 to 85.8 percent.

Depositional mechanisms at work in continental-terrace environments exhibit considerable variation. Typical of continental-terrace environments are: fluvial deposition, deltaic deposition, tidal reworking and deposition, glacial deposition, longshore current movement and deposition, chemical and biological deposition of carbonate and siliceous material, and pelagic/hemipelagic settling of suspended fine-grained material.

The sedimentary deposits present in continental-terrace environs are as variable as the sedimentary processes at work and the topography/bathymetry of the coastal area. They exhibit many small-scale sedimentary structures such as lamination, cross-bedding, ripples, dunes, scour marks, tool marks, flaser bedding, wavy bedding, and leniticular bedding. Physical properties characteristic of continental-terrace sediments are (Hamilton, 1970a):

- Grain size varying from 0.003 to 0.530 (ϕ 8.4 to 0.9),
- Densities of 1.42 to 2.03 g/cm^3, and
- Porosities within the range of 38.6 to 76.0 percent.

Abyssal hills are the most common topographic feature on the earth's surface. They cover approximately 80 percent of the Pacific Ocean basin floor and 50 percent of the Atlantic. They are generally present in areas with water depths of about 4,000 meters. Abyssal-hill sedimentation is characteristic of moderately deep, open-ocean regions which are sufficiently distant from continental sources so as to preclude "direct" influx of material from them. They are, therefore, environments which primarily experience pelagic sedimentation. They have an average topographic relief of about 200 meters and diameters of approximately six kilometers (Gross, 1972). Hamilton (1970a) characterizes abyssal-hill sediments by the following properties:

The moderate variations in grain size, density, and porosity are directly related to the variety of material deposited by turbidity currents. The presence of sedimentary sructures (i.e., lamination, cross-bedding, sole marks, and prod marks) is the result of high (and varying) energy material transport and deposition.

Sediment deposition on continental terraces contrasts with abyssal-hill and abyssal-plain deposition in both mechanism of deposition and rate of deposition. The depositional mechanisms at work in abyssal hill and plain environments are few in number; whereas there are a multitude of interacting mechanisms in continental terrace environments. In addition, 70 percent of the world's continental terrace environments are covered with relict sediments. Relict sediments are those which were deposited under conditions no longer existing in an area (i.e., due to eustatic sea level change, or local isostatic change). There are no counterparts within the abyssal hill and plain environments. The average rate of deep-ocean sedimentation is about 1 cm/1,000 years; whereas, the rate for continental-terrace environments is more than 10 cm/1,000 years (Gross, 1972).

The implementation of BURMMS requires that all systems be operational at water depths between about 5 and 60 meters (Lockheed, 1980). This implies that submarine environments to be encountered will be within the continental-terrace classification. The diverse processes at work within continental-terrace environments will complicate the implementation of BURMMS especially the accurate use of published acoustic data. For example, layering in the subbottom can cause serious problems with reflection data (Hamilton, 1974).

As a class, the sediment types found in the continental terrace data are more appropriate for BURMMS application. On the other hand, considering only the range of values of density, grain size, and porosity, abyssal hill and plain data are not distinguishable from continental terrace data and form subsets of it. But such a simple scheme of distinction may not take into consideration all the relevant differences. The fundamental differences in sediment types in the three classes may introduce fundamentally different relationships between the acoustical properties and sediment properties. Therefore, given an alternative, we elected to use regression equations developed with continental-terrace data. However, in cases where such data is inadequate or regression equations are not given for continental terrace data per se, we have used other classes. In some cases, the simpler geomorphic structure in abyssal hill and plain environments could lead to better interpretations of available data.

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