X-RAY TOMOGRAPHIC IMAGING OF GASSY MARINE SEDIMENTS

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ABSTRACT

Of all the possible constituents of marine sediments, few have attracted more interdisciplinary study or are of greater practical importance than gas bubbles. The key missing element in the study of gassy marine sediments, however, has been information about the characteristics of gas present in the sea floor: neither the amounts of gas nor details of its distribution within the sea floor are known. The primary obstacle has been an inability to obtain sea-floor samples that are representative of *in situ* conditions. Release of hydrostatic pressure during core retrieval permits expansion and effervescence of bubbles that alter original structures significantly. Clearly, quantitative study of gassy marine sediments requires a technique to examine their internal structure either *in situ* or nondestructively in the laboratory under *in situ* conditions. Formidable technical difficulties, however, make *in situ* investigations impractical at this time. Therefore, a major emphasis of this study will be to evaluate the usefulness of x-ray computed tomography, a powerful nondestructive diagnostic technique used extensively by the medical field, to address the latter case.

X-ray computed tomography (CT) is a medical modality, developed during the early 1970's, which has found considerable utility in petroleum engineering and soil science for quantitative study of geologic media (Vinegar and Wellington, 1987; Warner et al., 1989). In short, CT is a method of reconstructing detailed cross-sectional images of a sample from a series of projections taken at angular increments about the object (Figure 1). The fundamental measured property is the linear attenuation coefficient (μ) of x-ray energy. Assuming sample homogeneity, a monochromatic x-ray source, and a narrowly collimated x-ray beam, the attenuation coefficient and the intensities of entering and existing radiation are related by Beer's Law:

$$\frac{I}{I_o} = \exp\left[-(\mu/\varrho)\varrho x\right] = \exp(-\mu x)$$

where I_o is the incident radiation intensity; I is the transmitted radiation intensity; μ/ϱ is the mass attenuation coefficient; and ϱ is the density of the test material of thickness x. Although there is a slight dependence on the atomic number of the subject and energy spectrum of the x-ray beam, the predominant factor determining x-ray attenuation at the energies used for most medical scanners is the density of the material (McCullough, 1975). Attenuation occurs through Compton scattering, which is essentially a billiard-ball collision between a photon and an electron. The collision results in ejection of the electron and deflection of the photon with the preservation of momentum and energy. The volumetric electron density of the substance, a function of mass density, controls the magnitude of scattering (McCullough, 1975).

The standard unit displayed and output by CT scanners is the Hounsfield unit (HU), which is related to x-ray attenuation by the expression:

$$HU_{(x,y)} = \frac{\mu_{(x,y)} - \mu W}{\mu_w}$$

where $HU_{(x,y)}$ is the computed Hounsfield unit as a function of position; $\mu_{(x,y)}$ is the x-ray attenuation coefficient of the material, also as a function of position; and μ_w is the x-ray attenuation coefficient of water. By convention, HU_{water} is assigned a value of zero and HU_{air} a value of -1000 HU; thus each HU represents a 0.1% change in μ. Values in this study will be expressed as:

$$CT = \frac{HU + 1000}{1000} = \frac{HU}{1000} + 1$$

The transformation is useful in that comparisons with conventional HU can easily be made by inspection; but what is more important, the transformed CT values correspond more nearly with actual densities (in g/cm^3), e.g., $CT_{air} \simeq 0$ and $CT_{water} \simeq 1$.

Feasibility tests designed to evaluate CT for the quantitative study of gassy marine sediments suggest strongly that CT is a powerful technique uniquely suited for the study of fabric and the physical properties of gassy sediments. To quantify the scanner's ability to differentiate various types (densities), sizes, and shapes of materials, tests were conducted using laboratory standards and constructed mixtures designed to simulate ''typical'' marine sediments using those of the Gulf of Mexico as a guide. Results of preliminary tests demonstrate: (1) the strong correlation between CT number and sediment bulk density (Figure 2); and (2) the CT scanner's ability to differentiate among several possible constituents of marine sediments (Figure 3). Determination of the statistical variability of these relationships will require additional tests using other standards, as well as inhomogeneous material, e.g., actual Gulf of Mexico sediments. Other issues, such as spatial resolution, are also presently under investigation.

Adaptation of x-ray computed tomography to the quantitative study of marine sediments will create exciting new avenues in which to examine the geotechnical characteristics of sediment structure. Due to the nondestructive nature of CT, investigations of the structure of gassy marine sediments will be possible, a feat that previously has been unattainable. Further, CT can guide sample selection for traditional analytical methods, such as geotechnical testing and electron microscopy. The strong geological foundation established for the structural characteristics of gassy marine sediments can guide development of numerical models commonly used in offshore engineering, underwater acoustics, and marine geochemistry.

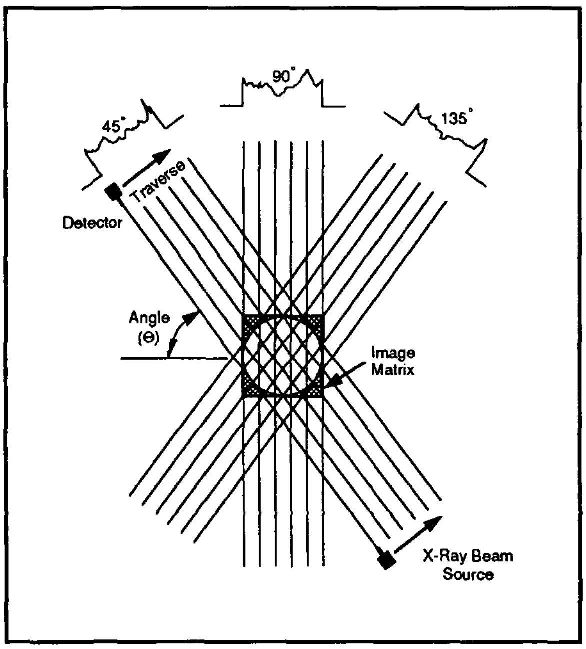

Figure 1. Scan geometry of a translate-rotate CT scanner.

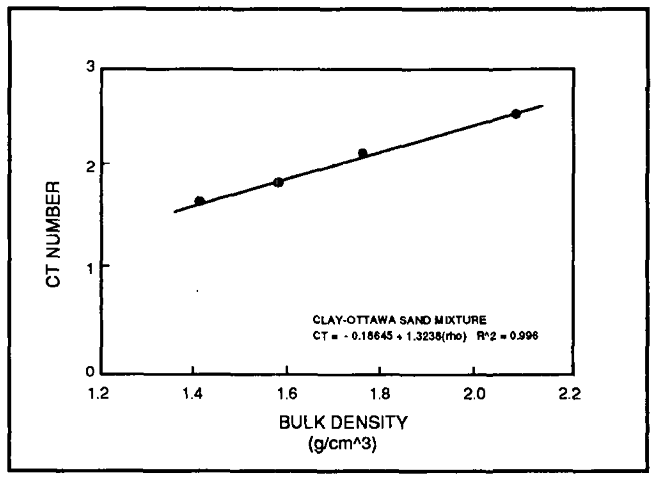

Figure 2. Correlation between CT number and sediment bulk density. Various mixtures of Ca-montmorillonite and Ottawa sand were prepared to create the stepwise density variation.

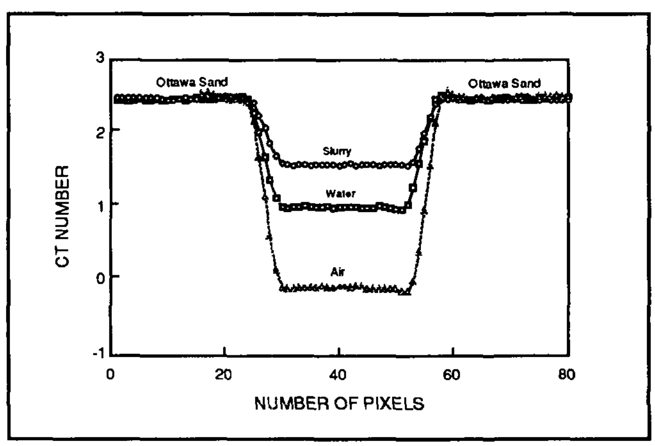

Figure 3. Differentiation of materials using CT. Profiles are CT numbers taken across test tubes filled with different substances embedded in saturated Ottawa sand.

ACKNOWLEDGMENTS

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