A PRELIMINARY STUDY OF THE HYDROGEOLOGY OF NORTHERN GUAM

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INTRODUCTION

General Statement

The Water and Energy Research Institute (WERI) of the University of Guam was responsible for two study sectors of the Northern Guam Lens Study (NGLS): Mathematical Modeling and Hydrogeology. This report is a summary of work completed within the Hydrogeology Sector.

Hydrogeology can be defined as the relationship between geological features of a sequence of rock units and the occurrence and movement of groundwater. Hydrogeologic investigations normally include a wide variety of exploratory techniques and analytical methods to determine magnitude and distribution of aquifer properties, type and location of aquifer boundaries, composition and physical characteristics of the porous media, structural fabric of rock units, and any other hydraulic aspects of the system that may affect groundwater movement. Field exploration techniques often employed in hydrogeologic investigations include surface geophysical methods (primarily seismic-refraction surveys and earth-resistivity soundings), bore-hole geophysical applications, geological mapping and detailed subsurface rock sampling (from exploratory drilling operations), pump and tracer tests, and periodic or continuous flow-system monitoring (both hydraulic and chemical aspects). Field data, once collected, are subject to a variety of analytical approaches which include megascopic and microscopic examination of rock samples, and statistical and mathematical data manipulations. Interpretations based on both field and analytical results lead to an understanding of the sometimes complex interaction between the solid rock environment and the enclosed hydrologic regime.

Many of the above-mentioned features of a hydrogeologic investigation were, at least in part, employed in the NGLS. Because of budgetary constraints and other factors, a complete investigation of this type could not be performed.

Objectives

Geological investigations were conducted for the island of Guam twenty five years ago by the U.S. Geological Survey (Tracey, et al., 1964). The products of those efforts in the form of geological maps and descriptions have adequately served as basis for subsequent work in hydrology and geotechnical engineering. The original investigations were made in the classical tradition of identifying formations, describing their properties, mapping their surface distributions, and unveiling histories. The focus, however, was not on hydrogeological relationships that are required for properly assessing the extent, exploitability and reliability of the groundwater resources.

The objective of the Hydrogeology Sector of the NGLS, therefore, was to interpret the geology of northern Guam with respect to groundwater hydrology. In particular, hydrogeological conditions and boundaries needed for mathematical and other types of model studies were to be defined. Where existing geological information was inaccurate or was insufficient for hydrogeological interpretations, additional field studies would be necessary.

These hydrogeological investigations were to be part of a set of studies aimed at fully describing the aquifers of northern Guam in three dimensions. Separate geophysical surveys and an exploratory drilling program were undertaken to assist in establishing the boundaries and features of the aquifers. None of these efforts were considered to be independent of the others. The goal of the program was to achieve full understanding of the limestone aquifers and how they can best be exploited.

In order to accomplish these objectives, certain tasks were suggested in the scope of work for the Hydrogeology Sector of the NGLS. These were:

(Task 1) Definition of the physical boundaries of the aquifers,

1. Critique of the literature
2. Field confirmation or rebuttal of previous work
3. Additional field studies
    a. Special attention to be given to the Agana Swamp Drainage Basin and to Agana Swamp proper
4. Quantitative description of the boundaries

(Task 2) Division into regional aquifers,

1. Regionalization based on published data supplemented with field studies,
2. Quantitative definition and description of regional aquifers

(Task 3) Determination of aquifer features,

1. Critique of literature
2. Evaluation of exposed aquifer formations and of drill core and cuttings
3. Participation in pump testing and evaluation of results

(Task 4) Mapping of lateral and vertical aquifer variations,

1. Formation discontinuities
    a. Continuous
    b. Abrupt (structural)
2. Relationship between local and regional aquifer features

(Task 5) Drilling Program,

1. Participation in testing and in evaluation of data

(Task 6) Establish need for new information; propose methods of obtaining it,

1. Hierarchy of needs
   a. Formation characteristics
   b. Geographical distributions
2. Review and discussion of methods of obtaining new information
   a. Location of exploratory drill holes
   b. Application of geophysics
   c. Others

To some extent all of these tasks were undertaken. However, as the study progressed, it became necessary to emphasize certain tasks more than others in order to accomplish the study objectives. Some reasons that led to these changes in approach were:

1. Difficulty in accessing areas for surface field studies (and the greater importance of devoting time to subsurface studies);
2. Delays in receiving historical hydrological data and new geological data generated during the course of the study; and
3. No pump tests were conducted.

Under these conditions, certain activities were undertaken to approach the various tasks. These activities included:

1. Analysis of well hydrographs;
2. Analysis of salinity profiles;
3. Examination of geophysical logs;
4. Preparation and examination of cuttings and core samples;
5. Classification of rock properties;
6. Stratigraphic correlation of subsurface units;
7. Description and classification of porosity types; and
8. Estimation of hydraulic conductivity.

These activities are described in the Methods section.

Review of Available Data

This section reviews the kind of data available as of early June 1982 for hydrogeologic investigation and discusses the usefulness of that data. The data can be classified into a number of categories; each category is discussed below.

Formation Sample Description

Lithological and paleontological descriptions are based on drill cuttings and cores retrieved from drilling of twelve exploratory holes during the course of the NGLS. In general, a reasonable quantity of sample was acquired from the rotary-drilling operations and good to excellent core recovery was experienced from EX-5 (only totally cored hole). A small number of short cores were taken from a few exploratory holes at pre-determined depths (primarily at the water table and within the transition zone).

Sample descriptions for holes EX-1, EX-4, EX-7, EX-9, and EX-11 are presented in Appendix A. These descriptions, prepared by the U.S. Geological Survey, are preliminary and thus subject to change upon further, more detailed study.

Detailed logs for EX-5, prepared by the WERI, are presented in Plate 1 (Appendix C with summary of lithological descriptions in Appendix A). Both geophysical logs and lithologic descriptions are given in addition to other pertinent information obtained from core samples. A large blue-print version of Plate 1 can be obtained from WERI upon request.

A number of thin sections from EX-1 (13 slides) and EX-5 (10 slides) were made available to the WERI for petrographic examination. Relevant features observed in these thin sections are discussed in later sections.

Paleontological descriptions, prepared by WERI, have been completed for EX-5 and EX-7 and are presented in Appendix B.

Geophysical Data

Geophysical data are of two types surface surveys and borehole geophysics. As separate parts of the NGLS gravity and seismic-refraction surveys were conducted over the northern plateau (gravity surveys were extended to the southern half of the island). Results from these surveys in conjunction with drilling logs were used to produce a volcanic basement map. This map forms the basis for locating the impervious lower boundary to the groundwater-flow system of northern Guam and is one of the most significant contributions to the NGLS. There are, however, a number of locations for which information is scarce or lacking, particularly in the vicinity of Agana Swamp and north of Dededo.

Borehole geophysical logging was conducted by the U.S. Geological Survey on most of the exploratory wells. The types of logs obtained were natural gamma radiation, spontaneous potential (SP), single-point resistivity, fluid conductance and a caliper log. A general description of the logs and the results of the logging effort are presented in Appendix C.

Of the logs obtained from boreholes, the most useful are the caliper and fluid conductance. The electric logs (i.e., SP and single-point resistivity) have limited usefulness. The natural gamma log appears to be unusable due to its sensitivity to changes in borehole diameter. All logs represent raw measurements taken directly from the strip-chart readouts.

Water-level Measurements

Water-level records fall into two categories: sea-level measurements and groundwater-level measurements.

The National Oceanographic and Atmospheric Administration (NOAA) maintains and operates a tidal recording station at the entrance to Sumay Cove in Apra Harbor. Water levels are recorded on a paper tape by the recording instrument and are relative to staff zero, a datum used by the NOAA at tidal stations. WERI and USGS personnel leveled the reference staff to a nearby U.S. government bench mark. Therefore, NOAA data can be interpreted relative to the local datum used to establish elevations at pertinent observation points of the NGLS. The Apra Harbor station is the only operating tidal-recording facility of Guam since the destruction of the USGS Pago Bay station formerly located at the Marine Laboratory, a research unit of the University of Guam.

The USGS maintains and operates a number of water-level recording observation wells. These wells penetrate the fresh-water lens of northern Guam and provide a continuous record of water-table elevation changes. Hourly values for wells BPM, A-16, M-10A, M-11, and Harmon 107 were processed for 1978 and 1979. However, a number of problems were encountered. These problems included missing data, erroneous values in the data record, and record breaks that required special treatment. An additional problem that appeared in the original data is one of recorder sensitivity. Every observation well hydrograph contains a significant tidal signature. Often the float sensitivity (drag on borehole or casing wall) was such that that most of the detail of the water-level fluctuations due to tidal effects was lost, that is, peaks and troughs of the attenuated signal tended to be truncated. Well A-16 is particularly plagued with this problem.

Climatological Data

Daily rainfall data are provided by monthly climatological reports issued by the NOAA. Rainfall values are recorded at a number of stations including the National Weather Service station located at Finegayan. Other rainfall data are provided by the U.S. Geological Survey.

METHODS OF INVESTIGATION

General

A variety of methods were used during the course of the investigation in an attempt at describing and classifying rock types and hydrogeologic features. In this section the various investigative approaches are discussed.

Formation Sample Examination

Two approaches were utilized in order to describe cutting and core samples in terms of lithology, type and amount of porosity, and paleontology. The two methods were hand specimen examination aided by a binocular microscope and petrographic observations, which were are restricted to EX-1 (13 slides) and EX-5 (10 slides).

Two rock classification systems were used to categorize the examined samples. The system of Dunham (1962), given in Table 1, was used to classify samples examined megascopically (aided by hand lens or binocular microscope). Dunham's classification system for limestone is based on recognizable depositional textures and is one of the simplest to use for "first cut" examinations. The second classification system is that presented by Folk (1959; 1962) and is reserved for describing thin sections. Folk's scheme, summarized in Table 2, is based on the petrographic relationship between allochem types ("clasts") and the surrounding matrix.

The nomenclature and classification of porosity used by this investigation are based on the work of Choquette and Pray (1970). Their system, outlined in Table 3, is designed to aid in geologic description and interpretation of pore systems and their carbonate host rocks. It is a descriptive and genetic classification system in which 15 basic porosity types are recognized: seven abundant types (interparticle, intraparticle, intercrystal, moldic, fenestral, fracture, and vug), and eight more specialized types. Modifying terms are used to characterize genesis, size and shape, and abundance of porosity. This classification system has been applied in detail to cores of EX-5.

Paleontological Examination

Preliminary identification of fossil material was prepared by WERI for EX-5 and EX-7. (Additional samples were not available at the time of report preparation). Slabbed core sections and cutting samples were examined, aided by the binocular microscope, for larger foraminifera, marine microfossils, and reef-associated organisms.

Paleontological evidence provides the basis for stratigraphic correlation and subsurface mapping of the various limestone units comprising the aquifer of northern Guam.

Geophysical-Log Examination

Geophysical logs obtained by the USGS were examined on a qualitative basis only (except for fluid conductance). Because the logs, for the most part, represent raw data and have not been corrected for borehole and fluid effects, no quantitative evaluation is possible.

Fluid-conductance logs, unlike natural gamma and electric logs, are not subject to borehole effects since the sonde only measures the electrical conductivity of the fluid within the borehole. Therefore a quantitative estimate can be made of the thickness of the transition zone between the fresh-water region and the underlying salty groundwater. From fluid- conductance logs, it is also possible to get an indication of changes with depth in water quality within the fresh-water column.

Well-Hydrograph Analysis

Several approaches, both qualitative and quantitative, were utilized to analyze water-level data from observation-well records. Short-term records were used to determine the response of the aquifer to tidal changes

Table 1. Classification of carbonate rocks according to depositional texture (adapted from Pettijohn, 1975).

RECOGNIZABLE DEPOSITIONAL TEXTURE	
Mudstone	original components are not bound together during deposition; mud-supported with less than 10% grains.
Wackestone	original components are not bound together during deposition; mud-supported with more than 10% grains.
Packstone	original components are not bound together during deposition; grain-supported; contains mud (fine silt and clay size particles).
Grainstone	original components are not bound together during deposition; grain-supported; lacks mud.
Boundstone	original components are bound together during deposition; coarse biogenic framework.
NON-RECOGNIZABLE DEPOSITIONAL TEXTURE	
Crystalline carbonates	

Table 2. Classification system of carbonate rocks (adapted from Folk, 1962 and Pettijohn, 1975).

LIMEMUD MATRIX GREATER THAN 2/3

Allochems			
0 - 1%	1 - 10%	10 - 50%	over 50%
Micrite and Dismicrite	Fossiliferous Micrite	sparse Biomicrite	packed Biomicrite
(micro-crystal-line rocks)	(micro-crystal-line rocks)	(<25% intra-clasts and oolites)	(>25% intra-clasts and oolites)

LIMEMUD MATRIX AND SPAR CEMENT SUBEQUAL

Allochems over 50% poorly washed Biosparite

SPAR CEMENT GREATER THAN 2/3

Allochems over 50%		
Sorting Poor	Sorting Good	Rounded & Abraded
unsorted Biosparite	sorted Biosparite	rounded Biosparite

NON-CLASTIC LIMESTONE

Biohermite

REPLACEMENT DOLOMITES

Allochems Ghosts		
>25% Intraclasts	>25% Oolites	<25% Interclasts & Oolites
intraclastic dolomite	oolitic dolomite	Biogenic and Pellet dolomite

No Allochems Ghosts

coarse, medium, fine crystalline dolomite

Table 3. Geologic classification of carbonate rock pores and pore systems (adapted from Choquette and Pray, 1970).

BASIC POROSITY TYPES

Fabric Selective	Not Fabric Selective	Fabric Selective or Not
1 interparticle	1 fracture	1 breccia
2 intraparticle	2 channel	2 boring
3 intercrystal	3 vug	3 burrow
4 moldic	4 cavern	4 shrinkage
5 fenestral		
6 shelter		
7 growth-framework		

MODIFYING TERMS

Genetic Modifiers		Size Modifiers	
Process	Direction	Classes	Size, mm
1 solution	enlarged	1 megapore	large, 256
2 cementation	reduced		small, 32
3 internal sediment	filled	2 mesopore	large, 4
			small, 0.5
		3 micropore	less than, 0.625

and to rainfall events while long-term records were used to determine the magnitude of seasonal variations in the position of the water table with respect to actual sea level.

Only data from 1978, 1979, and part of 1980 (30-month period) were processed because the numerical model was originally calibrated and verified utilizing data from these years, and tidal data were available for this period only. Both tidal and ground-water levels were available on an hourly basis. All data were processed on the computer because of the volume of measurements involved.

Short-Term Records

Ferris (1951) presented equations, based on heat flow analogy, that describe the behavior of ocean tides propogated inland through a confined aquifer system in terms of the hydraulic properties of the porous media. The relevant equations are

$$- \ln (R_x/R_o) = X \sqrt{S/Tt_o} \qquad (1)$$

and

$$t_\ell = X \sqrt{t_o S/4\pi T} \qquad (2)$$

where R_x is the tidal range in the observation well, R_o is the tidal range in the ocean, X is the inland distance of the well, S is the storage coefficient of the aquifer, T is the transmissivity of the aquifer, t_o is the tidal period, and t_ℓ is the lag time between the occurrence of the tidal signal in the ocean and the occurrence of the tidal signal in the well. According to Todd (1959) the equations of Ferris are applicable as a good approximation to water-table fluctuations of an unconfined aquifer if the range of fluctuation is small in comparison to the saturated thickness. For unconfined aquifer conditions, the storage coefficient must be replaced by the effective porosity (specific yield) of the system.

Both tidal and water-level records for six observation wells were scanned to determine a period that offered the most complete set of range values. A 34-day period beginning in the latter part of January 1979 appeared to be the best suited. Range values for diurnal and semidiurnal components of the tidal record and of the well hydrograph were recorded and equation 1 applied to the data. A short FORTRAN program was written to solve for the hydraulic conductivity and run on the computer with the appropriate input parameters. A sensitivity test was also run to determine the variability in the results by changing the parameters of specific yield and saturated thickness. Results of the application of the Ferris model are discussed in a later section of this report.

Long-Term Records

Well hydrographs for longer periods were used to determine the magnitude of seasonal changes in the position of the water table. In this analysis, mean monthly values of sea level were removed from observed mean monthly values of ground-water levels. The underlying assumption, though unqualified, is that sea-level oscillations of a period greater than a few days does not significantly affect the general trend of water-table fluctuations due to seasonal variations in recharge. This assumption appears to be sound, at least in general terms, based on the results obtained. Prior to the removal of sea level, groundwater-level fluctuations closely resemble those of sea level; however, after subtracting sea-level from the observations, groundwater trends appear to be related to seasonal variations in rainfall events and hence to recharge (as would be expected).

RESULTS

General

Results of the hydrogeologic investigation presented here include a number of new findings. Of special interest are the estimates of porosity abundance and type obtained from visual inspection of cuttings and from thin-section examination. This is probably the first attempt at quantifying and describing the pore systems found in the limestones of northern Guam. Other results of interest include lithologic descriptions of cuttings and cores, paleontological information from EX-5 and EX-7, calculations of hydraulic conductivity from tidal-response data, and qualitative description of water-table response to seasonal rainfall.

The following discussion presents the relevant findings of the hydrogeologic investigation. Emphasis is placed on describing both qualitatively and quantitatively characteristics observed in samples retrieved from drilling operations and in water-level records obtained from the few observation wells that penetrate the northern lens. The discussion is subdivided into three sections which focus attention on the geology of the limestones that make up the aquifer, on the response of the aquifer to external factors, and on the hydrogeologic properties of porosity and hydraulic conductivity.

Geology

In general, rocks of the Mariana and older Barrigada formations were encountered during the drilling of exploration boreholes. These formations are composed of permeable limestone and comprise the bulk of the aquifer that underlies northern Guam. Volcanic material, tentatively assigned to the Alutom formation, was encountered in three boreholes at varying depths beneath a limestone overburden. Geologic features and relationships observed in drill cuttings and cores are described below, in general terms. Special attention is given to the only fully cored exploration borehole (EX-5).

Lithology of Borehole Samples

Lithologic descriptions, prepared by the USGS, are presented in Appendix A. These descriptions represent "first cut" trials and are subject to revision with further study. However, they serve the purpose of this investigation by providing information on the most obvious characteristics of the subsurface rocks encountered during drilling operations.

According to the classification system of Dunham (1962), the samples examined can be placed in one of four categories of limestone types. Specifically, these categories are (1) mudstone, (2) wackestone, (3) packstone, and (4) boundstone. The majority of samples fall into the categories of types and 1 and 2. Under the Classification system of Folk (1959, 1962), types 1 and 2 are equivalent to micrite and biomicrite, respectively. Allochem constituents include mainly foraminifera, shell fragments of pelecypods and gastropods, algal fragments, and coral debris. With respect to the Agana argillaceous member of the Mariana limestone, clay or clay-sized detritus is an additional component of the rock fabric.

In thin section, the matrix is composed of micrite (microcrystalline calcite less than 4 microns in size). Some slides show evidence of recrystallization of micrite to microspar. Although staining (to differentiate calcite from argonite) was not done, it is certain that a portion of the original aragonitic (and probably high mg-calcite) skeletal material has been removed and replaced with calcite. A large portion of the fossil debris, including Halimeda segments, has been removed by solution and many fragments have been replaced by sparry calcite. A number of slides particularly those from EX-1, exhibit vug replacement by sparry calcite. Thin sections for EX-1 also show clay or clay-sized grains disseminated throughout the micritic matrix.

Bedding characteristics for the the most part are lacking; only crude discontinuous features that may have been bedding planes are observed. In slabbed cores from EX-5, much soft-sediment deformation is observed; a feature that formed contemporaneously with deposition of the original carbonate mud.

Paleontology

Twenty-four species of larger benthic foraminiferans have been identified from EX-5 samples (Table 4). The foraminiferal assemblage is generally characteristic of species associated with Bonya and Alifan limestones (Cole, 1963) rather than the Barrigada. Positive identification could be made on 2 diagnostic foraminiferans, Rotalia atjehensis and Clycloclypeus (Clycloclypeus) indopacificus. Rotalia atjehensis is diagnostic of Tertiary f (Miocene) and is abundant in both the Bonya and Alifan limestones, but does not occur in younger limestone (e.g. Barrigada limestone) according to Cole (1963). Clycloclypeus (c.) indopacificus is associated with limestone units of the western Pacific region which are paleontologically similar to the Bonya limestone.

The molluscan assemblage observed in EX-5 samples indicates upper reef slope or deeper shoal depositional environments. The bivalves are generally articulate, which suggests short transport distances. Major molluscan zones occur at 322-338, 399-405, 425-431, and 481-490 feet. The first 3 molluscan zones are characterized by a Nemocardium bivalve which has recent representatives found living in offshore beds at depths of 200

Table 4. Preliminary checklist of benthic foraminifera in core sections from the Northern Guam Lens Study exploratory hole 5, Dededo. The surface limestone unit is mapped as Barrigada Limestone. Uncommon specimens of planktonic formainifera were found belonging to the genera Globigerina and Orbulina.

Acervulina sp.
Amphistegina radiata d'Orbigny
Calcarina sp.
Carpenteria monticularis (Carter)
Cycloclypeus (cycloclypeus) indopacificus Tan
Eorupertia semiornata (Howchin)
Gyspina cf. vesicularis (Parker and Jones)
G. cf. marianensis Hanzawa
Heterostegina sp.
Lepidocyclina (Nephrolepidina) sp.
Miogypsinoides cf. dehaartii (Vander Vlerk)
Nummulites cf. fichteli (Michelotti)
Operculina cf. ammonoides (Gronovius)
O. cf. bartschi Cushman
O. cf. rectilata Cole
O. cf. venosa (Fichtel and Moll)
Operculina sp.
Planorbulinella larvata (Parker and Jones)
Rotalia cf. atjehensis (Vander Vlerk)*
Rotalia sp.
Sorites martini (Verbeek)
Sphaerogypsina globulus (Reuss)
Spirocylpeus cf. orbitoideus H. Douville
Sporadotrema cyclindricum (Carter)

*Diagnostic of Teritiary f - middle Miocene to 300 feet. The last molluscan zone is characterized by a sedentary boring bivalve, Lithophaga, which is found living today in coral to depths of 300 feet.

Seventeen species of larger foraminifera and 7 species of small foraminifera have been identified in samples from EX-7 (Table 5). Foraminiferal assemblages generally characteristics of the Mariana limestone have been identified within the upper portion of the borehole (10 to 225 feet) and those characteristic of the Barrigada limestone have been identified in the section below 225 feet. Two diagnostic species have been found in good condition, Clycloclypeus (Clycloclypeus) postindopacificus and Operculina rectilata. O. rectilata has been assigned to Tertiary g (Miocene) by Cole (1963). Smaller foraminifera (Table 5) occur in yellow, tan, and white mudstone below 335 feet. These small foraminifera are usually associated with lagoonal mud deposits.

Foraminiferal assemblages between 10 and 225 feet, characterized by A. radiata, are indicative of shallow-water environments. The assemblages below 225 feet contains A. bicirculata, Operculina spp., and Clycloclypeus spp. and are usually associated with deeper water environments on seaward slopes.

Geophysical Logs

Of the geophysical logs obtained by the USGS (Appendix C), those from EX-4, EX-8, EX-9, EX-10, and EX-11 are of interest. Relevant observations are summarized below.

EX-4

1. The caliper log indicates a change in rock competency in the vicinity of the water table. Borehole roughness significantly increases below about 150 feet.

2. Electric logs and one fluid-conductance log show a major excursion at about 380 feet. These deflections may be related to lithologic changes, however, they also correlate with a significant increase in borehole diameter. The more recent conductance log does not resemble the earlier one, therefore, drilling fluid may also be an influence on the logs.

3. Fluid conductance logs indicate a fresh-water column of approximately 160 feet.

EX-8

1. The more recent fluid conductance log (2-10-82) shows a slight decrease in conductivity then remains constant to the top of the transition zone.
2. Fluid-conductance logs indicate a fresh-water column of about 130 feet.

Table 5. Foraminiferal checklist from chip samples of the Northern Guam Lens Study exploratory hole 7, Dededo. The surface limestone unit is mapped as Mariana Limestone.

Depth interval 10-225 feet

Amphistegina radiata d'Orbigny [common small specimens]
Amphistegina sp.
Gypsina vesicularis (Parker and Jones [common specimens]
Elphidium sp.
Marginopora vertebralis Blainville
Sphaerogypsina globulus (Reuss)

Depth interval 225-698 feet

Larger Formainifera

Amphistegina radiata d'Orbigny
A. bicirculata [common below 335 feet]
A. lessonii d'Orbigny
Amphistegina
Clycloclypeus (clycloclypeus) postindopacificus Tan [common below 475 feet]
Clycloclypeus sp.
Heterostegina cf. depressa d'Orbigny
Heterostegina sp.
Marginopora cf. vertebralis (Parker and Jones) [rare specimens]
O. bartschi Cushman
O. rectilata Cole
Operculina sp.
Sporadotrema sp.

Smaller Forminifera*

Archaias sp.
Discorbis sp.
Eponides sp.
Osangularia sp.
Osangularia sp.
Planorbulina sp.
S. globulus (Reuss)
Triloculina spp.

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*common in allochems of yellow and white mudstone below 335 feet

EX-9

1. Both the electric and fluid-conductance logs deflect around 320 feet; these deflections do not correlate with excursions in the caliper log.

2. Fluid-conductance logs indicate a fresh-water column of about 100 feet.

EX-10

1. Both the electric and fluid-conductance logs are similar in behavior to those of EX-9.

2. The fluid-conductance log indicates a fresh-water column of approximately 110 feet.

EX-11

1. The electric logs deflect significantly at about 440 feet or near the limestone-volcanic contact.

Water-Table Fluctuations

Water-table fluctuations observed in wells that penetrate the northern lens are due to oscillations of sea level and variations in recharge. These external factors influence the position of the water table (and, hence, the lens) on a long-term as well as a short-term basis. Sea-level effects are the dominant features observed in well hydrographs. To illustrate this point, the graph of Figure 1 shows the relationship between mean monthly values of sea level and mean monthly values of water levels for a 30-month period beginning in January, 1978. Water levels are from records for well 107 (Harmon). The correspondence between the two hydrographs is obvious; the general trend of fluctuation in sea level is reflected in the well hydrograph. An additional point of interest is that sea-level changes range over a significant interval (approximately 0.8 feet) for the 30-month period. This annual fluctuation in sea level has been attributed to steric effects (Shaw and Donn, 1964), that is, to temperature-related density variations in the upper few hundred feet of the ocean. The magnitude of the annual fluctuation indicated in the sea-level graph of Figure 1 is in agreement with that recorded by Wyrtki and Leslie (1980) for longer period sea-level records.

Sea-level effects mask water-table fluctuations due to variations in recharge. A totally different well hydrograph is obtained when sea level is removed from the monthly values derived from observation-well records. The graph of Figure 2 illustrates this point. Water-table fluctuations reflect the seasonal variability of rainfall and, hence, recharge. During the dry season water levels are low and during the wet season water levels are high as expected. However, there may be a lag time of a couple of months between peak events in the rainfall graph and peak events in the well hydrograph, at least for the first half of the 30-month period.

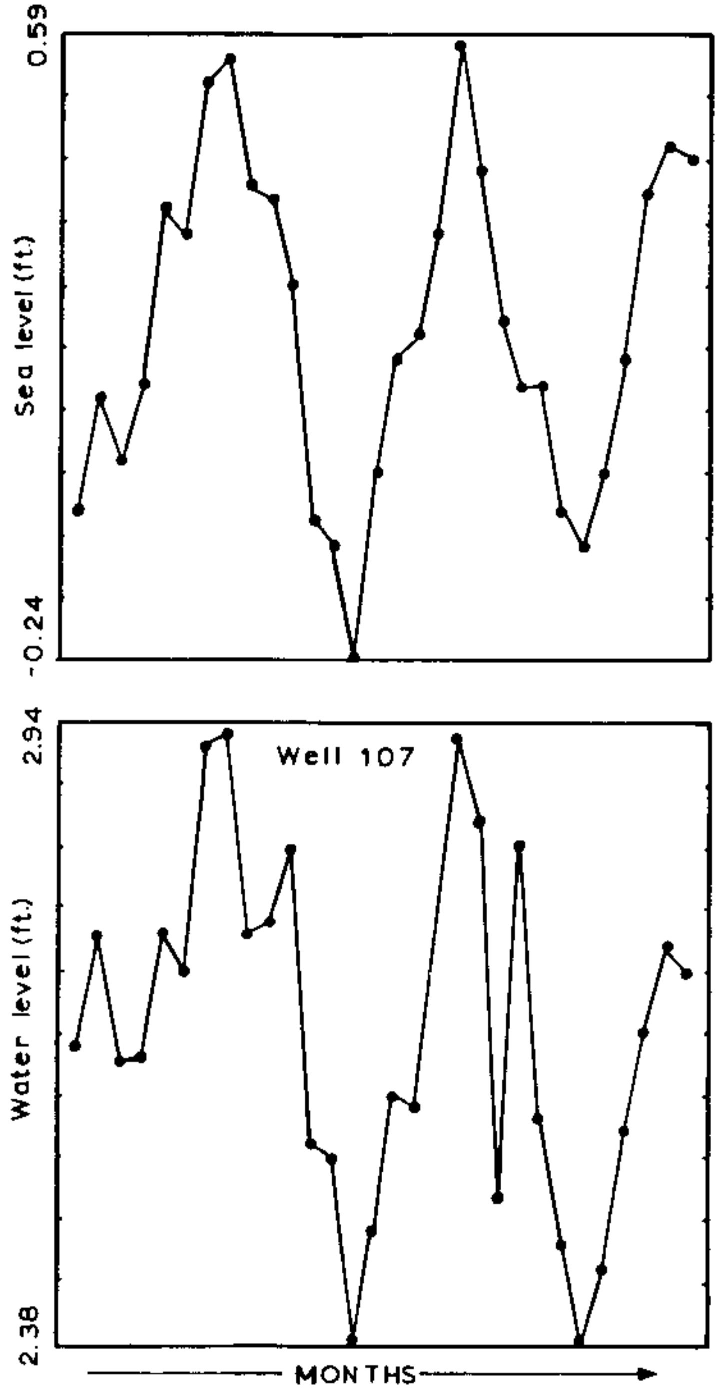

Figure 1. Raw water-level data at well 107 and sea-level values for 30-month period.

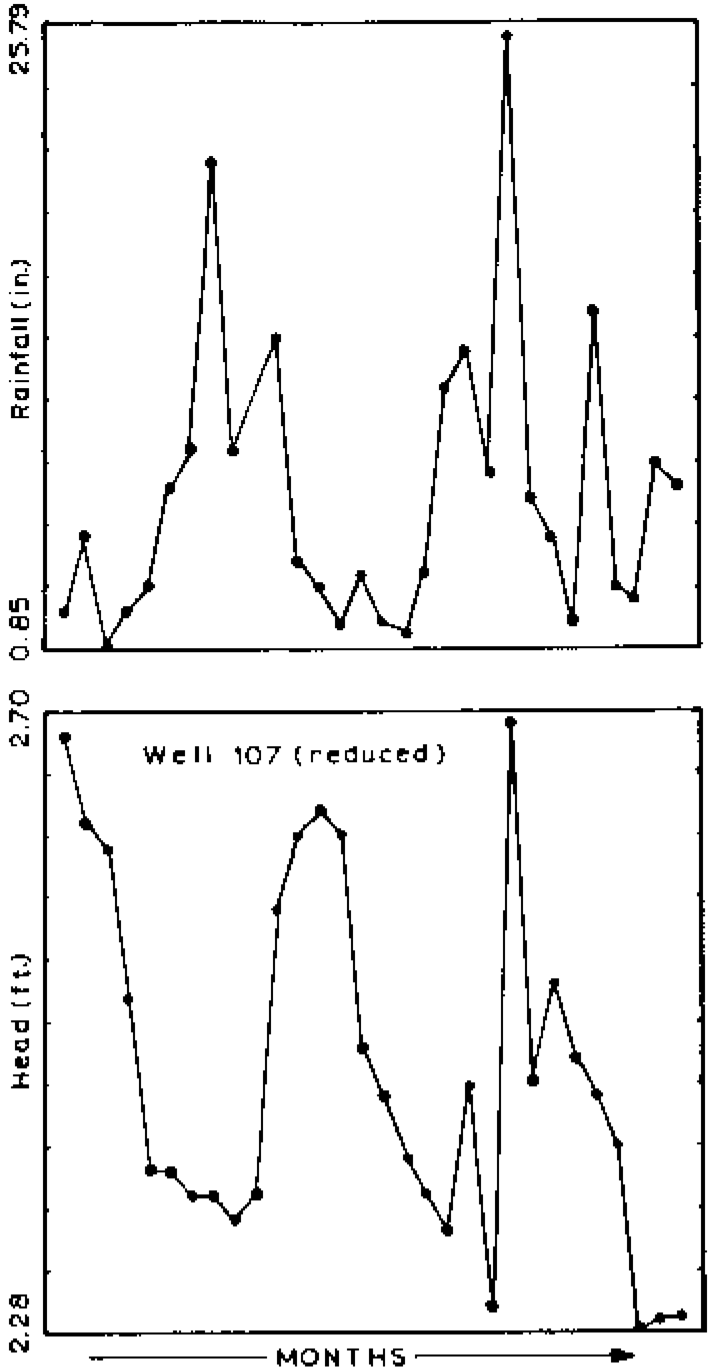

Figure 2. Reduced water-level data at well 107 and rainfall values for 30-month period.

Monthly water-table fluctuations across the lens of northern Guam appear to be relatively uniform. Several well hydrographs are presented in Figure 3. It is apparent that there is a general correspondence of water-table fluctuations between observation wells. Although small differences in magnitude are present, as evidenced by the deviations between hydrographs, the implication of this correlation is that the distribution of recharge from month to month is more or less uniform across the portion of the lens represented by the areal distribution of observation wells.

Short-term hydrographs for all observation wells contain a significant, although attenuated, tidal signal. Both diurnal and semi-diurnal components of the tides are represented in the hydrographs. The attenuation rate of the tidal signal as it moves through the aquifer is shown in the graph of Figure 4. This approximation is based on data from three observation wells, 107 (Harmon), M-10A, M-11, located progressively farther inland from the western shoreline of northern Guam. As would be expected, the curve indicates that the rate of attenuation is an exponential-decay function (see Todd, 1959). Tidal-signal attenuation is a function of the hydraulic properties of the aquifer (Ferris, 1951); therefore, data related to the phenomenon can be useful in the determination of specific yield (effective porosity) and hydraulic conductivity.

Hydraulic Properties of the Aquifer

The hydraulic properties of interest are porosity and hydraulic conductivity. In this section the results of attempts at quantifying these parameters are presented.

Porosity

In very general terms, the type of porosity observed in rock samples is formed from secondary solution of either the micrite matrix or fossil skeletal detritus. By far the most abundant porosity type can be classified as vug porosity or moldic porosity. Locally, however, channel porosity may be the dominant type, particularly near the water table. In the description of EX-5 given in Plate 1 (See Appendix A) the porosity observed in slabbed cores has been classified and abundance estimated for the length of the borehole (including EX-5A). The classification system used is based on the work of Choquette and Pray (1970).

Estimations of porosity abundance in thin sections were made from the slides for EX-1 and EX-5 (Table 6). Porosity percentages in EX-1 slides were relatively low, generally less than 4%. A great amount of void space has been filled with sparry calcite, thus greatly reducing the abundance of void spaces. Thin-section counts for EX-5 indicate a greater abundance of voids relative to EX-1. Average values of 13% above the water table and 21% below the water table were computed. It should be noted that considerable variability in porosity abundance existed across most of the slides that were examined.

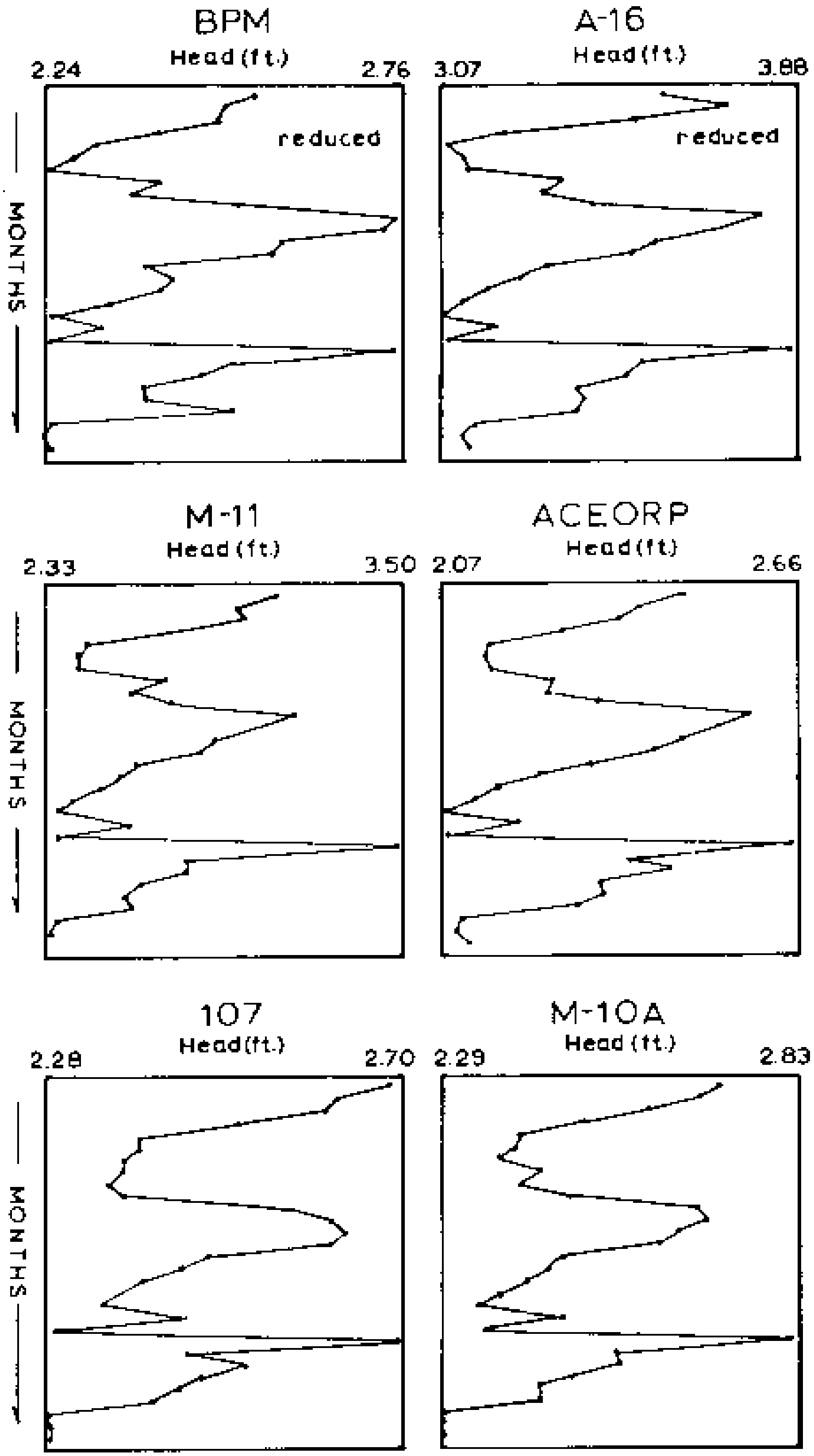

Figure 3. Hydrographs showing correspondence of water-level fluctuations between wells.

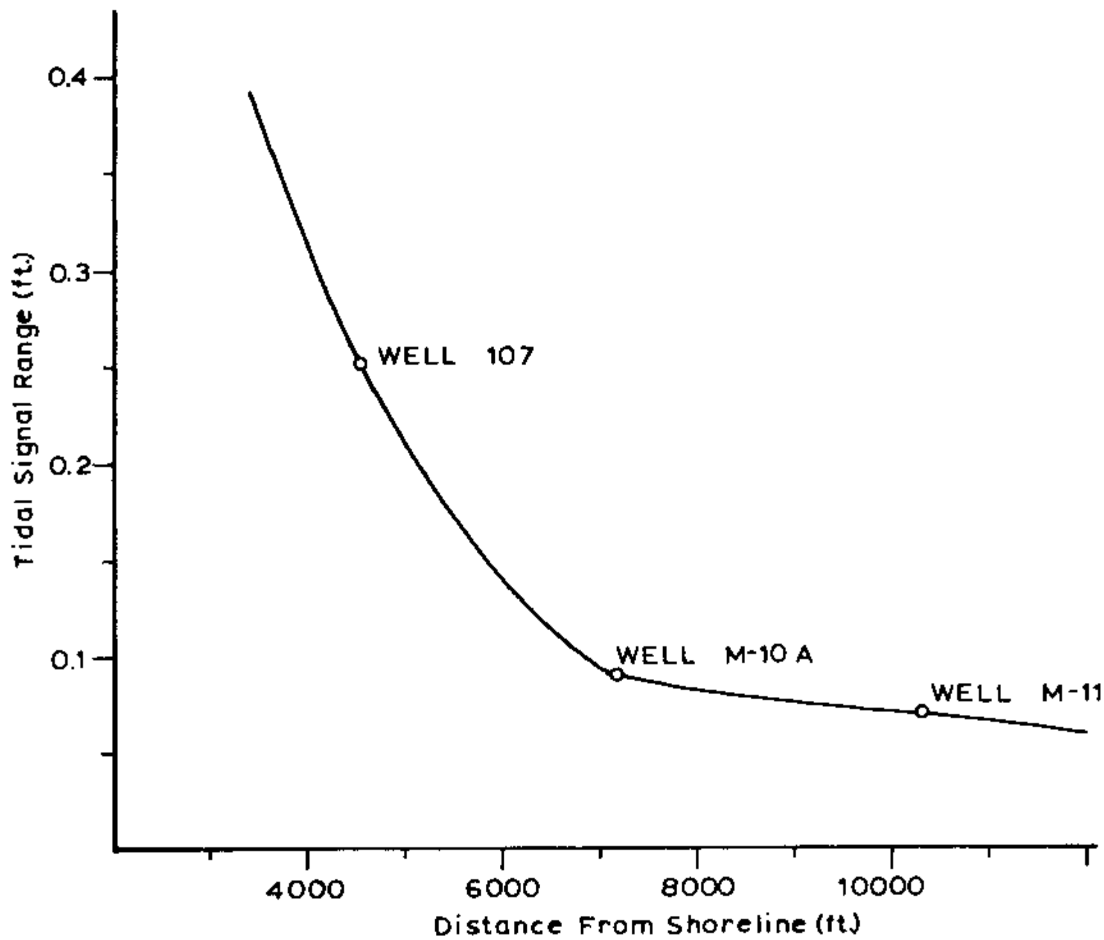

Figure 4. Tidal-signal attenuation rate for inland wells.

Table 6. Estimates of porosity abundance in thin-sections.

EX-1 Depth (ft)	EX-1 % Porosity	EX-5 Depth (ft)	EX-5 % Porsity
80	1.5	25	12.5
100	1.5	62	11
120	16	105	3
125	4	172	9
150	3	205	19
217	4	313	22
222	4	382	18
		420	25
		490	14
		530	26

Table 7. Estimates of hydraulic conductivity based on calculations using tidal-signal data.

WELL	Distance from Shoreline (ft)	Depth of Basement* (ft)	Hydraulic Conductivity (ft/d)
BPM	4550	600	3950
107	4550	500	9350
M-10A	7200	550	11330
A-16	8900	600	13590
M-11	10300	550	20670

*Average depth of sloping basement.

Hydraulic Conductivity

Estimates of hydraulic conductivity based on tidal-signal attenuation data are listed in Table 7. Four of the five wells are located on the western side of the island and thus receive a tidal signal which originates in the Philippine Sea. One well (BPM), located in the eastern portion of the island, receives its tidal signal from the Pacific Ocean. Average depths to the volcanic terrane were obtained from the basement map derived from geophysical and drilling information and distances to the shoreline were measured on USGS topographic maps.

The estimates of Table 7 range from about 4000 ft/day in the vicinity of BPM to about 20,000 ft/day around M-11. There appears to be a large contrast in hydraulic conductivity for opposite sides of the northern plateau. Also, there is an apparent increase in hydraulic conductivity inland from the eastern shoreline. These aspects of the results of applying the work of Ferris (1951) to the attenuation data are discussed in the next section.

DISCUSSION

General

A number of interpretations based on the field data and analytical results given above are presented here in an effort to describe pertinent geological features, aquifer response, and hydraulic characteristics of the limestone units that underlie the northern plateau. These interpretations are preliminary and therefore subject to re-evaluation as additional information is acquired through the administration of future geologic and hydrologic studies.

Subsurface Geology

Except where volcanic material was found, all exploratory boreholes were drilled into rocks that have been tentatively assigned to either the Mariana or Barrigada limestones (Table 8). In general, these rocks can be classified as biomicrites (classification system of Folk) or the equivalent wackestones (classification system of Dunham). However, the depositional environment of Barrigada limestones is very much different from that of Mariana rocks. Paleontological evidence from EX-5 and EX-7 indicates that the Barrigada formation is related to the Bonya and Alifan limestones (Cole, 1963) and may be a deeper water facies of the reef-associated units of the Alifan. From lithologic descriptions, it appears that rocks of the Mariana limestone, encountered during drilling, resemble those related to shallow-water lagoonal environments.

Diagnostic foraminifera identified in samples from EX-5 and EX-7 indicate a slight age difference in biota. That is, foraminifera from EX-5 are lower to middle Miocene while foraminifera of EX-7 (below 225 feet) are upper Miocene. The implication is that during Miocene time the Barrigada prograded seaward. Fossil assemblages and the generally broken condition

Table 8. Top and bottom stratigraphy of NGLS exploration boreholes.

Borehole	Total Depth (ft)	Formation Top	Formation Bottom
EX-1	513	Mariana*	Mariana*
EX-2	300	Barrigada	Alutom (?)
EX-3	535	Mariana	Alutom (?)
EX-4	400	Mariana*	Mariana*
EX-5(5a)	600	Barrigada	Barrigada
EX-6	462 (not drilled)	Barrigada	Barrigada (?)
EX-7	698	Mariana	Barrigada
EX-8	657	Mariana	Unknown
EX-9	513	Mariana*	Mariana (?)
EX-10	704	Mariana	Unknown
EX-11	513	Mariana	Alutom (?)

*Agana Argillaceous member of the Mariana Limestone.

of skeletal material from the Barrigada indicate a depositional environment similar to that of a near reef shoal at a depth of between 300 and 1000 feet. Carbonate sediment, originating on the reef flat or back-reef lagoon was probably transported to the site by debris avalanche or turbidity currents.

Stratigraphic correlation of subsurface units on a plateau-wide basis is not possible at this time. Fossil identification has been completed on only two of the twelve exploration holes drilled for the NGLS. However, a probable contact between the Mariana and underlying Barrigada has been placed at about 225 feet below ground surface in EX-7. Since EX-5 is presumably located entirely in Barrigada, the land surface expression of the contact appears to be well-approximated by the mapping efforts of Tracy et al. (1964). How much of the remainder of the northern plateau is underlain by the Barrigada limestone and to what depth are not known from the results of this study.

Aquifer Response

Response of the aquifer system to ocean tides is readily observable in well hydrographs. Water-level records for each of the recording observation wells exhibit diurnal and semi-diurnal components of the tidal cycle. Since the attenuation of inland propogating tidal signals is a function of aquifer properties, it can be inferred from well records that the hydraulic conductivity of the northern aquifer is relatively high.

From analysis of well hydrographs, it was found that the amplitude of the attenuated tidal signal is significantly less at BPM than that at 107. Both wells are located at about the same distance from the shore and presumably in the same rock type (according to the geologic map). This apparent anomally may be related to a difference in shoreline geology. According to the geologic map (Tracy et al., 1964), the reef facies of the Mariana limestone crop out along the eastern shore in the vicinity of BPM, however, along the western shore, opposite 107, only the headland is mapped as reef facies. Since Mariana limestone is presumed to be in the subsurface in these areas, it is possible that either the reef facies or fore-reef facies (over which the reef facies prograded) is present along the shoreline. The point to be made is that shoreline rocks may be lower in hydraulic conductivity and thus increase the tidal-signal attenuation rate. In other words, the subsurface rocks of the reef or fore-reef facies act as a dam to the inland propogating tidal signal.

Aquifer Properties

Estimates of porosity and hydraulic conductivity, based on available information, represent an attempt at quantifying the hydraulic properties of the aquifer.

Estimates of porosity abundance based on megascopic examination of rock samples indicate a range of porosity between 15 and 25 percent. In no samples was porosity estimated to be higher than 30 to 35 percent. These estimates were made only on samples retrieved during drilling and do not necessarily reflect the true "in situ" abundance of porosity. Small pencil-sized solution tubes, for example, would be destroyed by the rotary bit returning only gravel-sized cuttings to the surface for examination. Thus, estimates based on cuttings alone provide only limited information on porosity abundance, distribution, and type. More reliable data are obtained from cored holes such as EX-5 which provide not only "in situ" approximations of abundance but also information on porosity types and their distribution within the rock column. It is readily apparent, for example, that, near the present water table, channel porosity is the dominant type while elsewhere vug porosity or moldic porosity types are dominant (see logs in Appendix C). Thus zones of higher permeability associated with interconnected porosity types (e. g. channel or fracture) can be identified.

Examination of thin sections provided an estimate of the abundance of porosity (and type) on a microscopic level. However, a large number of slides are required to make statistically valid approximations. Only a few slides were available and thus provided only a glimpse of the micropore development in Guam's limestones. From the thin-section examination an estimate of 21% porosity was made for rocks below the water table in EX-5 and less than 4% for rocks below the water table in EX-1. Two limitations come to mind immediately for data of this type. First, a thin section is only a very small portion of the rock volume and may not be a representative sample. Material to be sectioned must be selected such that it represents a relatively large volume of rock, a task that is not easily accomplished in a complex carbonate lithology. Second, on the scale of the thin section, little information can be obtained concerning the degree to which pores are interconnected. The degree of interconnection is an integral part of the concept of permeability.

In the previous section, estimates of hydraulic conductivity based on the work of Ferris (1951) were presented. A wide range of values was obtained from the exercise of applying equation 1 to the well hydrograph data. This range in hydraulic conductivity, in part, may be related to the sensitivity of equation 1 to the input parameters of effective porosity (specific yield) and saturated thickness. Results of a sensitivity test where these parameters were varied is listed in Table 9. Input values of effective porosity were varied from 0.15 to 0.40 while other parameters were unchanged. A set of computer runs was then made for each of the five observation wells. A similar test was made to check the sensitivity of the method to variations in saturated thickness. Observation well 107 (Harmon) was selected and the saturated thickness was varied from 300 feet to 650 feet. Test results indicate that the Ferris model is relatively sensitive to variations in input parameters, particularly effective porosity. A difference of 0.1 in porosity input values between runs brings about a significant difference in output values of hydraulic conductivity.

The progressive increase of hydraulic conductivity inland indicated by the values given in Table 7 may be related to the physics of wave movement along a sloping base. From the basement map, the volcanic terrane slopes upward from the shoreline inland. The Ferris model assumes a horizontal lower boundary and hence a constant saturated thickness. Changes in

Table 9. Results of sensitivity test of the Ferris model.

Well	Calculated Hydraulic Conductivity (ft/d) *N_e = 0.15	N_e = 0.25	N_e = 0.40
BPM	2380	3950	6330
107	5610	9350	14960
M-10A	6790	11330	18130
A-16	8155	13590	21750
M-11	12400	20670	33070

Well	Depth (ft)	Hydraulic Conductivity (ft/d)
107	300	15500
	450	10350
	500	9350
	550	8470
	650	7170

*N_e is effective porosity (specific yield)

elevation of the impervious boundary may cause an increase in wave amplitude similar to the "tsunami" effect along shorelines of sloping ocean bottom topography.

The significant difference between the hydraulic conductivity calculated at BPM and that calculated at 107 (both are located approximately the same distance from the shore) may be related to actual differences in hydraulic properties of the aquifer, differences in the character of sea-level oscillations on the windward (eastern) side of the island, or the daming effect previously discussed. The solution to this problem will require further study.

Electric and fluid-conductance logs obtained shortly after drilling, in some cases, show excursions in the lower portion of the freshwater column. These excursions or deflections of the recordings indicate either a change in properties of the borehole fluid (probably drilling foam) or a zone of higher permeability. Groundwater would probably be lower in total dissolved constituents in the low-permeability zone because of a shorter residence time and, therefore, conductance logs would indicate relatively fresher water as is the case. In wells where these deflections have been observed, the relative depths are the same; that is, the deflections appear to occur consistently within the lower portion of the fresh-water column and above the transition zone.

CONCLUSIONS

Each of the tasks outlined in the scope of work for the Hydrogeology Sector of the NGLS has, to some extent, been addressed by the hydrogeologic investigation. Following is a brief summary of the major findings for each of these tasks.

Task 1: Definition of the physical boundaries of the aquifers.

Based on the results of the geophysical survey and the drilling program addition to previous work, a volcanic basement map was prepared (by other participants in the NGLS). Volcanic rocks are presumed impermeable and thus act as a lower no-flow boundary to the groundwater-flow system of northern Guam. Limited field-checking of previous geologic mapping has been undertaken as part of the hydrogeologic investigation. All observations thus far confirm previous results. Activities related to this task are still ongoing.

Task 2: Division into regional aquifers.

At this stage in the hydrogeologic study of the northern aquifer, it seems reasonable to consider the Agana argillaceous member of the Mariana limestone as a separate unit with different hydraulic conductivity and effective porosity as compared to the remainder of the more permeable limestone units of the northern plateau. Additional study is needed before differences between the clean limestone units of the Mariana and the Barrigada formations can be quantified.

Task 3: Determination of aquifer features.

Physical characteristics of limestone units comprising the northern aquifer were determined, at least in part, from surface and subsurface rock samples. Well hydrographs were examined in an effort to describe and quantify the properties of hydraulic conductivity and porosity. From the study results, it seems reasonable that the majority of the aquifer is composed of rocks with an average porosity that probably does not exceed 0.25. Hydraulic conductivity values may range over a considerable interval. It is unlikely that the high values obtained by this investigation are realistic. Intuitively, it is doubtful that the hydraulic conductivity for clean permeable limestone exceeds 10,000 ft/day. However, much work has yet to be done in order to obtain quantitative values for the hydraulic conductivity.

Task 4: Mapping of aquifer variations.

Some indications of homogeneity and anisotropy of the aquifer were obtained from a few geophysical logs and the core from EX-5. Zones of higher permeability and porosity abundance appear to be associated with the water table and the lower portion of the freshwater column which implicate positional and directional variations in permeability. However, not enough data was available to map these features.

Task 5: Drilling program.

Evaluation of rock samples obtained from the drilling operations was an activity included in Tasks 3 and 4.

Task 6: Establish need for new information.

A brief discussion on future hydrogeologic studies is presented in the following section.

RECOMMENDATIONS FOR FURTHER STUDY

The various study activities associated with the hydrogeologic investigation of the northern Guam aquifer conducted by the WERI have provided only limited information about the characteristics of the complex relationship between the groundwater body and the limestone terrane within which it moves. This includes knowledge of the physical properties of the aquifer, their distribution in space, and their effect on the movement of water. Thus, other study sectors of the NGLS that depend on this information (such as modeling of groundwater movement and estimates of sustainable yield) should be cautious in formulating final conclusions. Finally, management policies formulated as a result of the NGLS should be conservative as, in general, a great deal of information is still required before one will be able to predict with confidence how the aquifer will respond to present, proposed, or predicted development. The most important result of the Hydrogeology Sector of the NCLS is that it has provided the means to define those subjects that will require detailed study in the near future.

In order to further the understanding of the hydrogeologic environment of the northern aquifer, it is recommended that future studies involve the following tasks:

1. Stratigraphic correlation of subsurface units.

2. Determination of porosity types, their development and distribution.

3. Determination of hydraulic conductivity in terms of homogeneity and anisotropy.

4. Evaluation of aquifer response to independent external factors (e.g. rainfall, tides, and pumping).

5. Development of analytical approaches appropriate to island groundwater-flow systems.

These tasks would necessarily involve a number of activities such as detailed geologic studies, nuclear geophysical logging, long-term monitoring of the flow system, and development of methods to analyze new data. In addition to the collection and interpretation of new information, it will be necessary to re-evaluate the results of the NCLS and to "fill in" the data gap. This task would probably require additional drilling, surface geophysical surveys, and flow-system monitoring.

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APPENDIX A

LITHOLOGIC DESCRIPTIONS

Appendix A contains the lithologic descriptions of the rock chip samples obtained from the drilling operations. These descriptions were prepared by the U. S. Geological Survey and are based on preliminary examination of rock samples.

Lithologic descriptions of EX-5, prepared by the WERI, appear on Plate 1. The EX-5 lithological descriptions and porosity classification of core smaples, which are presented in plate 1, are summarized in this appendix. Rock names are based on the classification system of Dunham (1962).

Depth Interval (feet) From	To	EX-1: Sample Description
0	15	Clay, organic, medium to high plasticity, moderate yellowish brown, very low porosity. Made up of some organic silts.
15	20	Clay with coarse carbonate sand medium-grained dark yellowish orange, low porosity. Made up of foraminiferal detritus, broken spicules.
20	25	Limestone with clay, well-cemented, fine to medium grained, yellowish orange, low porosity. Variable texture. Made up of chips of white calcite.
25	30	Limestone, crystalline, medium to coarse grained, pale yellowish orange, low to moderate porosity. Argillaceous. Well indurated. Made up of white calcite rhombs and detritus.
30	35	Limestone, crystalline, medium to coarse grained, pale yellowish orange, moderate porosity. Argillaceous. Made up of yellow calcite-replaced mollusc shell fragments, and white calcium carbonate rhombs.
35	40	Limestone, crystalline, medium to coarse grained, pale yellowish orange, moderate porosity. Argillaceous. Made up of platy fragments with euhedral calcite replacing shell material.
40	43	Limestone, crystalline, coarse grained, pale yellowish orange, moderate to high porosity. Argillaceous. Made up of abundant euhedral calcite rhombs, fossil molds of bivalves, replaced shell fragments (casts), clear vein calcite, and circular foraminifera.
43	47	Limestone, crystalline, coarse grained, pale yellowish orange, moderate porosity. Argillaceous. Made up of recrystallized shell fragments and pure white to clear euhedral calcite in fossil relics.
47	50	Limestone, crystalline, medium to coarse grained, pale yellowish orange, moderate porosity. Argillaceous. Most fossils not recognizable. Recrystallized.
50	55	Limestone, crystalline, medium to coarse grained, pale yellowish orange, moderate porosity. Argillaceous. Made up of light brown calcite replacing shell fragments.
55	60	Limestone, crystalline, medium to coarse grained, pale yellowish orange, moderate porosity. Argillaceous. Made up of light brown calcite-replaced fossil fragments.

Depth Interval (feet) From	To	EX-1: continued
60	65	Limestone, crystalline, coarse grained, pale to dark yellowish orange, moderate porosity. Argillaceous. Made up of platy detrital fragments, replaced by calcite with small (<1mm) dark inclusions.
65	70	Limestone, crystalline, medium to coarse grained, pale yellowish orange, moderate porosity. Argillaceous. Made up of platy fragments with dark inclusions, and euhedral calcite rhombs in voids.
70	75	Limestone, crystalline, medium to coarse grained, pale yellowish orange, moderate porosity. Argillaceous. Made up of platy detrital fragments, calcite-replaced foraminifera, and branching coralline algae.
75	80	Limestone, crystalline, medium to coarse grained, very pale orange, moderate porosity. Argillaceous. Made up of detritus, with dark inclusions; shell fragments and foraminifera replaced by clear white calcite with surrounding recrystallized cement pale orange in color.
80	85	Limestone, crystalline, medium to coarse grained, very pale orange, moderate porosity. Argillaceous. made up of recrystallized detritus, white to clear calcite with euhedral crystals and replaced foraminiferal tests.
90	95	Limestone, crystalline, medium grained, pale yellowish orange, moderate porosity. Argillaceous. Made up of abundant shell fragments, Madrepora corals, and discoid foraminifera all replace by calcite, forming euhedral crystals, and nearly obliterating primary structure.
95	98	No Sample.
98	100	Limestone, crystalline, coarse grained, pale yellowish orange, moderate porosity. Arigillaceous. Made up of replaced fossils: echinoid spines, two types of foraminifera (football-shaped and discoid-shaped), branching coral molds, worm tubes and coralline algae Halimeda.
100	105	Limestone, crystalline, coarse grained, very pale orange, moderate to high porosity. Argillaceous. Made up of replaced fossils: foraminifera (discoid), echinoid spines, fecal pellets(?), coral fragments, and a coiled test (spirula?), all replaced by clear to yellow calcite as euhedral rhombs.
105	110	Limestone, crystalline, coarse grained, very pale orange, moderate to high porosity. Argillaceous. Made up of coral and algal fragments, mollusc shell fragments, and foraminifera all calcite-replaced.

Depth Interval (feet) From	To	EX-1: continued
110	115	Limestone, crystalline, coarse grained, pale yellowish orange, high porosity. Argillaceous. Made up of coral and algal fragments, mollusc shell fragments molds.
115	120	Limestone, crystalline, coarse grained, very pale orange, high porosity. Argillaceous. Made up of fossil molds and casts replaced by calcite: coiled gastropod shell, thin shelled bivalve, and foraminifera. "Phreatic zone fabric": leached voids in framework, zones of dissolution with overall density low.
120	125	Limestone, crystalline, medium grained, pale to dark yellowish orange, low to moderate porosity. Argillaceous. Dark red-brown clay present (probably in pockets). Made up of broken mollusc shell fragments.
125	130	Limestone, crystalline, coarse grained, pale yellowish orange, moderate porosity. Argilleceous. Red brown clay present. Made up of broken gastropod and bivalve fragments.
135	140	Limestone, crystalline, pale to dark yellowish orange, coarse grained, moderate porosity. Argillaceous. Red pronoxide stains. Dark red brown clay fragments in cuttings (12%), also filling pore spaces. Made up of coral fragments, coralline algae. Some disseminated fossils in clay.
140	145	Limestone, crystalline, coarse grained, pale yellowish orange, moderate porosity. Argillaceous. Dark red brown clay fragments in cuttings (15%). Made up of coral fragments, whole clams, coralline algae fragments, and organic leaf material.
145	150	Limestone, crystalline, medium to coarse grained, dark yellowish orange, low porosity. Argillaceous. Dark red brown clay fragments in cuttings (20-25%) filling pore voids. Made up of coral fragments, discoid foraminifera, and coralline algae detritus.
155	197	No Sample.
197	201	Limestone, crystalline, coarse grained grayish orange to very pale orange, low to moderate porosity. Argillaceous, but very little free clay (<1%) in cuttings. Made up of rhombs of white calcite, mollusc shell fragments, coralline algae detritus and abundant discoid foraminifera.
201	203	Limestone, crystalline, medium to coarse grained, pale yellowish orange to grayish orange, low porosity.

Depth Interval (feet) From	To	EX-1: continued
		Argillaceous; also brown silt in cuttings. Made up of brown to light orange calcite replacing shell fragments; some pure white calcite rhombs also.
203	207	No Sample.
207	212	Limestone, crystalline, medium to coarse grained, pale yellowish orange, low porosity. Argillaceous; also silt. Made up of platy fragments of mollusc shells. coralline debris, echinoid spines and small foraminifera (not many large discoid type). Yellowish-orange calcite replacement.
212	217	Limestone, crystalline, medium to coarse grained, pale yellowish orange to grayish orange, low porosity. Argillaceous; some red-brown clay in pore voids. Made up of pure white calcite, coral casts, platy shell fragments, coralline algae, worm tubes, some foraminiferal tests.
217	222	Limestone, crystalline, coarse grained, pale yellowish-orange,moderate porosity. Argillaceous. Made up of platy fragments of coral debris, coralline algae, shell fragments, pure white calcite, some discoid foraminifera.
	@222	Limestone, crystalline, coarse grained, pale yellowish-orange, moderate porosity. Argillaceous. Made up of fragmentary coral molds, shell molds, discoid foraminifera, white and brown calcite present as fossil replacement.
222	298	No Sample.
298	299	Limestone, crystalline, medium to coarse grained, very pale orange, low porosity. Argillaceous. Made up of coralline debris, broken mollusk shells, discoid foraminifera, some pure white calcite.
299	300	Clay (50%) and limestone (50%), dark yellowish orange to light brown. Limestone, highly crystalline, medium to coarse grained, very pale orange, low porosity. Made up of abundant calcite, coralline algal fragments, coralline debris, broken mollusk shell molds, some orange calcite.
300	303	No Sample.
303	306	Limestone, (75%) and clay (25%), dark yellowish orange to light brown. Limestone, crystalline, coarse grained, pale yellowish orange, low porosity. Made up of white and orange calcite rhombs replacing fossil material: echinoid spines, broken mollusk shells, coralline algae detritus.
306	515	No Sample.

Depth Interval (feet) From	To	EX-1: continued
@555.5		Limestone, crystalline, fine to medium grained, very pale orange, low porosity. Argillaceous. Few recognizable fossils, clear to white calcite.
524	525(?)	Limestone, chalky to crystalline, fine grained, white, low porosity. Large thick mollusk shell with brown to gray halo, preserved growth striations.
526	527	No Sample.
527	532	Limestone, crystalline, fine grained, white to very pale orange, very low porosity. Few recognizable fossils.
532	537	Limestone, crystalline, fine grained, white to very pale orange, low to very low porosity. Few recognizable fossils. Yellow calcite rimming white calcite centers, yellow calcite.
537	542	Limestone, crystalline, fine grained, white to very pale orange, very low porosity. Few recognizable fossils, yellow to grayish orange calcite.
542	547	No Sample.
547	552	Limestone, crystalline, fine grained, white to very pale orange, low porosity. Made up of pale yellowish orange calcite, mollusc shell fragment.
552	557	Limestone, crystalline, fine grained, white to very pale orange, very low porosity. Few recognizable fossils, pale yellowish orange calcite.
557	562	Limestone, crystalline, fine grained, white to very pale orange, low porosity. Few recognizable fossils, white calcite.
562	567	Limestone, crystalline, fine grained, white to very pale orange, low porosity. Few recognizable fossils.
567	572	Limestone, crystalline, fine grained, white to very pale orange, very low porosity. Few recognizable fossils, broken shell cast, white calcite.
572	582	Limestone, crystalline, fine grained, white to very pale orange, very low porosity. Few recognizable fossils, white to yellowish white calcite.
582	587	No Sample.

Depth Interval (feet) From	To	EX-1: continued
587	592	Limestone, crystalline, fine grained, white to very pale orange, very low porosity. Made up of several broken mollusc shell fragments (coiled), highly crystallized spine.
592	597	Limestone, crystalline, fine grained, white to very pale orange, very low porosity. Few recognizable fossils, white to yellow calcite.

Depth Interval (feet) From	To	EX-4: Sample Description
0	9	Clay, moderate reddish brown, low porosity. Dense. Organic discoloration.
9	19	Clay, moderate yellowish brown to dark yellowish brown. Dense. Organic.
19	26	Mudstone with limestone sand-size fragments, moderate yellowish brown.
26	30	Limestone, boundstone, fairly cemented medium-grained, dark yellowish orange to light brown, low porosity. Argillaceous. Made up of shell fragments, echinoid spines.
30	35	Limestone, boundstone, fairly cemented, medium to coarse grained, orange, low porosity. Argillaceous. Few recognizable macro-fossils. Abundant discoid foraminiferal tests.
35	40	Limestone, boundstone, fairly cemented, medium to coarse grained, orange, low porosity. Argillaceous. Few recognizable macro-fossils.
40	44	Limestone, boundstone, well cemented to crystalline, medium to coarse grained, white to very pale orange, low porosity. Argillaceous. Some foraminiferal tests.
44	49	Limestone, boundstone, well cemented to crystalline, coarse grained, pale yellowish orange, low interparticle porosity. Argillaceous. Few recognizable macro-fossils.
49	55	Limestone, crystalline, coarse grained, gray-orange, low porosity. Argillaceous. Brown-gray calcite mottling. Few recognizable fossils.
55	59	Limestone, grainstone, coarse grained grayish orange, low intergranular porosity. Argillaceous. Few recognizable fossils.
59	62	No Sample.
62	65	Limestone, grainstone, coarse grained, grayish orange, low to moderate intergranular porosity. Argillaceous. Few recognizable fossils.
65	70	Limestone, crystalline, coarse grained, pale yellowish orange, low porosity. Argillaceous. Stylolites? Few recognizable fossils.

Depth Interval (feet) From	To	EX-4: continued
70	75	Limestone, packstone, well cemented to crystalline, coarse grained, grayish orange to medium gray, moderate intergranular porosity. Argillaceous. Medium gray mudstone in pockets. Few recognizable macro-fossils.
70	75	Limestone, boundstone, well cemented to crystalline, coarse grained, pale yellowish orange, moderate intergranular and moldic porosity. Argillaceous. Olive gray siltstone in pockets with hinged white clams (Bivalvia), broken echinoid spines. Black inclusions possibly organic.
75	78	Limestone, packstone, well cemented to crystalline, coarse grained, grayish orange to medium gray, moderate intergranular porosity. Argillaceous. Medium gray mudstone in pockets. Few recognizable macro-fossils.
78	80	Limestone, packstone, well cemented to crystalline, coarse grained orange to medium gray, low to moderate intergranular porosity. Argillaceous. Medium gray mudstone in pockets. Some discoid foraminifera, broken shell fragments.
80	85	Limestone, wackestone, >30% particles, coarse grained, yellowish gray, very low porosity. Few recognizable fossils.
85	90	No Sample.
90	93	Limestone, packstone, coarse grained, yellowish gray, very low porosity. Few recognizable fossils.
93	95	Limestone, grainstone, coarse grained, yellowish gray, low porosity. Argillaceous. Few recognizable fossils.
95	100	Limestone, boundstone, coarse grained, very pale orange, low porosity. Argillaceous. Broken bivalve fragments recrystallized to calcite. Light gray siltstone in pockets.
100	105	Limestone, boundstone, partially crystalline, coarse grained, very pale orange. Moderate moldic porosity. Argillaceous. Broken coral molds. Spheroid foraminifera. Shell molds abundant.
105	110	Limestone, crystalline, coarse grained, very pale orange, moderate to high moldic porosity. Argillaceous. Coralline and foraminiferal molds abundant as secondary porosity. Broken gastropod shells. Some light gray clay pockets.
110	115	Limestone, crystalline, coarse grained, very pale orange, moderate to high moldic porosity. Argillaceous. Foraminiferal molds abundant as secondary porosity. Broken bivalve and gastropod shell. No clay.

Depth Interval (feet) From	To	EX-4: continued
115	120	Limestone, grainstone, coarse grained, very pale orange, low porosity. Highly argillaceous. Grayish orange clay as matrix (<10%). Broken bivalve and gastropod shell. No clay.
120	125	Limestone, boundstone, medium to coarse grained, pale yellowish orange, low porosity. Argillaceous. Gray clay present (<2%). Few recognizable macro-fossils.
125	130	Limestone, crystalline, medium to coarse grained, pale yellowish orange, low porosity. Argillaceous. Black opaque inclusions (magnetite?). Few foraminifera present. Few recognizable marco-fossils.
130	135	Limestone, crystalline, medium to coarse grained, very pale orange, low porosity. Argillaceous. Abundant biconvex discoid foraminifera; Amphistegina. Adequate gravel size sample.
	(core)	Limestone, crystalline, medium to coarse grained, very pale orange, low porosity. Argillaceous. Abundant biconvex discoid foraminifera; Amphistegina. Echinoid spines. Broken molluscan shell molds.
135	138	Bit sample. Limestone, packstone, fine to coarse gained, moderate yellowish brown to light brown, low porosity. Abundant shell fragments. Opaque silt size fragments in clay matrix.
138	145 (core)	Limestone, packstone, fine to coarse grained, white to very pale orange, moderate to high moldic porosity. Crystalline near and along fractures (recrystallization) with Fe-stain. Argillaceous. Some chalky fraction in interstices. The upper half of core fairly cohesive with continuous cylinders. The lower half tends to be broken up. Abundant macro-fossils: coiling gastropod shells, biconvex foraminifera, small bivalves also broken Halimeda algal plates.
144	151	A 0.5' section of a coral head in growth position with calcite replaced septal walls, fine chalk-filled septal cavities. Pure recrystallized calcite replacing original coral.
	(core)	Limestone, packstone, fine to coarse grained, white to very pale orange, moderate to high moldic porosity.
138	145	Limestone, boundstone, fine to coarse grained, very pale orange, moderate to high moldic porosity. Argillaceous. Abundant recrystallized gastropod fragments, foraminifera, broken coral, and worm tube segments. Adequate gravel size sample.

Depth Interval (feet) From	To	EX-4: continued
150	152	Limestone, boundstone to crystalline, fine to coarse grained, very pale orange, moderate moldic porosity. Argillaceous. Some pure calcite rhombs, abundant recrystallized macro-fossil molds and casts of gastropod, bivalvia, foraminifera. Adequate gravel size sample.
152	155	Limestone, boundstone to crystalline, medium to coarse grained, very pale orange, moderate to high moldic porosity. Argillaceous. Recrystallized calcite and spar present. Some bivalve molds, foraminifera.
155	160	Limestone, crystalline, interlocking crystals, medium to coarse grained, very pale orange to yellowish gray, moderate intergranular porosity. Argillaceous. Few recognizable fossils. Abundant recrystallization.
160	165	Limestone, crystalline, interlocking crystals, medium to coarse grained, very pale orange to yellowish gray, low to moderate intergranular porosity. Argillaceous. Some clay as matrix locally. Abundant white sparry calcite. Few recognizable fossils.
165	170	Limestone, crystalline, interlocking crystals, medium to coarse grained, very pale orange to yellowish gray, low porosity (intergranular?). Argillaceous. White sparry calcite present. Few recognizable fossils or particles.
170	175	Limestone, crystalline, interlocking with some recognizable particles, medium to coarse grained, very pale orange to grayish orange, low porosity (intergranular to vuggy). Argillaceous. White spar present. Few recognizable fossils or particles. Obliterated by recrystallization.
175	180	Limestone, crystalline, interlocking with few recognizable particles, medium to coarse grained, very pale orange to grayish orange, low vuggy porosity. Argillaceous. Some gray clay. White sparry calcite in platy chips. Few macro-fossils. Adequate gravel size sample.
180	185	Limestone, crystalline with recognizable particles, medium to coarse grained, very pale orange to dark yellowish orange, low to moderate vuggy porosity. Argillaceous. Light brown clay fragments and medium gray clay. Abundant white spar calcite. Broken bivalve fragments, replaced by recrystallization, discoid foraminiferal tests; Amphistegina. Adequate gravel size sample.

Depth Interval (feet) From	To	EX-4: continued
185	207	Limestone, crystalline with recognizable fossils and particles, medium to coarse grained, very pale orange to pale yellowish orange, low to moderate vuggy undifferentiated porosity. Argillaceous. Abundant white spar calcite. Broken ribbed bivalve fragments as molds and casts in recrystallized limestone. Foraminiferal tests; Amphistegina. Coiled gastropod fragments. Adequate gravel size sample.
207	220	Limestone, boundstone with crystalline particles, possibly mud-supported, medium to coarse grained, grayish orange to pale yellowish orange, vuggy porosity but filled with mud. Highly argillaceous. Abundant clay. Few recognizable fossils.
	220 (core)	Limestone, crystalline with recognizable fossils and particles, medium to coarse grained, very pale orange, moderate to high vuggy undifferentiated porosity, some relict moldic porosity. Argillaceous. Abundant macro-fossils: large coiled gastropod (segment), bivalve fragments, separated clam valve, coralline framework with clay-filled septal cavities.
220	235	Limestone, crystalline, medium to coarse grained, very pale orange to pale yellowish orange, moderate vuggy undifferentiated porosity. Argillaceous. Light brown clay in pockets. Few recognizable macro-fossils. Foraminiferal tests. Dark diffuse inclusions, possibly mafic minerals.
235	295	Limestone, micro-crystalline, fine to medium grained, pale yellowish orange to grayish orange, moderate vuggy undifferentiated porosity. Highly argillaceous. Light brown clay in pockets. Few recognizable macro-fossils. Recrystallized texture.
295	300	Clay with crystalline limestone fragments from surrounding rock, moderate yellowish brown, low porosity. Probably mud pocket in limestone.
300	310	Limestone, crystalline with interlocking crystals, medium grained, grayish orange, moderate vuggy porosity. Argillaceous. Light brown clay in pockets. Few recognizable macro-fossils (obliterated by recrystallization).
310	350	Limestone cryptocrystalline with interlocking crystals, fine to medium grained, dark yellowish orange, moderate to poor vuggy porosity. Highly argillaceous. Light brown clay voids and in pockets. Few recognizable macro-fossils; abundant calcite rhombs as vein calc-spar.

Depth Interval (feet) From	To	EX-4: continued
	350 (core)	Limestone, crystalline to cryptocrystalline with interlocking crystals, moderate to coarse grained, white to very pale orange, moderate vuggy porosity. Argillaceous. Coralline debris with filled septal cavities. No continuous cylinders, just broken fragments. Abundant recrystallization. No bedding features.
	350	Clay, with cryptocrystalline limestone fragments, light to moderate brown, low porosity. No recognizable macro-fossils. Mud pocket in formation. Some silt size clasts of possibly volcanic origin in clay: gray green siltstone from Alutom volcanics(?).
350	365	Limestone, cryptocrystalline limestone with interlocking crystals, fine to medium grained, pale yellowish orange, low to moderate vuggy porosity. Argillaceous. Light brown clay in voids and in pockets. Recrystallized calc-spar abundant. Some platy shell chips.
365	389	Limestone, crystalline wit interlocking crystals, fine to medium grained, very pale orange, moderate vuggy porosity. Argillaceous. Light brown clay in pockets. Recrystallized fragments of echinoid spine and replace cast of coiled gastropod(?) shell in cryptocrystalline calcite. Possible bryozoan clusters. Discoid foraminifera. Large oyster shell with calcite crystals in between growth layers and within fractures.
389	400	Limestone, cryptocrystalline with interlocking cystals, fine grained, pale yellowish orange to grayish orange, moderate vuggy porosity. Argillaceous. Abundant light brown clay in pockets and voids. Recrystallized calc-spar. Few recognizable macro-fossils.

Depth Interval (feet) From	To	EX-7: Sample Description
0	10	No Sample.
10	100	Limestone, grainstone, fairly well-cemented to finely recrystallized, medium- to coarse-grained, white to very pale yellow, 10% moldic microporosity (concavo-convex voids). Abundant foraminifera: Amphistegina radiata. Recrystallized shell casts. Abundant reef detritus, coral fragments, broken gastropod shell, coralline algae, worm tubes. Slight infilling with calcite.
100	135	Limestone, packstone, well-cemented to finely crystalline, medium-grained white to very pale yellow, 15-20% microporosity. Reef detritus sparse. Foraminifera sparse. Limonite stains.
135	145	Limestone, packstone, well-cemented to finely crystalline, medium-grained, very pale yellow 15% microporosity. Recrystallized reef detritus, hinged bivalve, shell fragments, coral debris, foraminifera: Amphistegina.
145	170	Reef detritus; hinged bivalve, shell fragments, coral debris, larger discoid foraminifera; Amphistegina.
170	175	No gradation - unconformable?
175	185	Limestone, packstone, very well-cemented to crystalline, medium-grained, white to very pale yellowish tan, microporosity 15% moldic. Slightly argillaceous. Recrystallized detritus: coral fragments, filled septal cavities with fine-grained mud, burrows also infilled with tan fine-grained material.
185	195	Foraminifera; Amphistegina.
200	220	Some dark opaque inclusions, slightly disseminated, possibly mafic minerals in limestone.
220	275	Limestone, mudstone, well-cemented, slightly chalky to fine-grained, extremely white, micro-porosity 10%. Few recognizable fossils. Some coral debris, foraminifera.
275	285 core	Limestone, mudstone, poorly to moderately cemented, medium- to coarse-grained, white to very pale tan, mottled, moldic microporosity 10%, but voids possibly further enhanced by secondary dissolution; total porosity about 20%. Sandy with chalky zones. Locally argillaceous. Very pale orange clay infilling large voids. Large coral molds and fragments. Abundant foraminiferal molds.

Depth Interval (feet) From	To	EX-7: continued
285	335	Limestone, mudstone, well-cemented, fine- to medium-grained, white, microporosity 15% moldic. Rounded fragments of coral detritus; rounded shell fragments. Foraminifera casts poor.
335	350	Limestone, wackestone, medium-grained, fairly well-cemented, white to very pale yellowish tan, mottled, moldic microporosity 15%. Slightly argillaceous. Platy fragments. Few recognizable fossils; echinoid spine; less argillaceous.
350	395	Limestone, mudstone, fine-grained, white well-cemented to finely crystalline, moldic microporosity slight solution 15%. Few recognizable fossils: broken recrystallized coral fragments. Some calcite rhombs as spar.
395	435	Limestone, mudstone to crystalline carbonate, fine- to medium-grained, white to very pale tan, moldic microporosity 10%, solution voids about 5-10% indicated by limonite-lined voids. Some very fine-grained opaque minerals in matrix elongate boring clam; Lithophaga Coral fragments replaced as slightly argillaceous fine-grained limestone. Abundant spar.
435	445	Limestone, mudstone, poorly cemented, fine-grained, chalky in places, white, moldic microporosity 10%, fractures occasionally. Poorly indurated. Few recognizable fossils. Limonite-lines fractures.
445	460	Abundant recrystallized coral fragments, argillaceous infilling matrix. Boring clams; articulate; Lithophaga.
460	525	Limestone, mudstone, very well-cemented to finely crystalline, fine-grained, white, moldic microporosity 15%. Few fossils.
525	550	Limestone, mudstone, very well-cemented to crystalline, medium-grained, white, moldic and secondary solution microporosity 20%. Argillaceous coral fragments at 535', foraminifera (biconvex).
550	575	Limestone, crystalline, medium-grained, white, solution pores >20%. Slightly argillaceous. Recrystallized coral, bryozan, echinoid spines. Jagged platy fragments. Spar present.
575	585	Sand and clay, limy, well-rounded, moderately sorted, tan, uncemented. Black grains. Sample taken from drill pipe.
585	598	Limestone, mudstone, very well-cemented to finely crystalline, fine-grained, white, moldic microporosity 15%.

Depth Interval (feet) From	To	EX-7: continued
598	613	Limestone, mudstone, very well-cemented to crystalline, coarse-grained, white to pale orange, moldic porosity 15%. Solution voids 10-15%. Slightly argillaceous. Abundant larger discoid foraminifera. Large oyster shell, worm tube.
613	649	Abundant foraminifera, white. Echinoid spines.
649	653	Abundant Amphistegina, recrystallized coral fragments (white $CaCo_3$) Spar.
653	678	Abundant fossils: coiled gastropods, bryozoan, hinged clam, coral fragments. Moldic porosity with some calcite infilling and limonite stains. Abundant Amphistegina.
678	693	Amphistegina - less fossiliferous.
693	698	Limestone, mudstone, fine-grained, white, well-cemented, microporosity 8-10%.

Depth Interval (feet) From	To	EX-9: Sample Description
0	20	Limestone, white to very pale yellow, crystalline, porosity 7% dissolution. Abundant calcite spar. Few recognizable fossils.
20	40	Limestone, white, crystalline, porosity 10% dissolution openings.
40	60	Limestone, white to very pale yellow, finely crystalline, porosity 8% moldic and dissolution pores. Fossils: bryozoan, foraminiferal molds, coiled gastropod. Some of the calcite spar in fine-grained white matrix, but still well-indurated. Platy fragments.
60	100	Limestone, white to very pale yellow, finely crystalline, porosity 5% moldic. Few recognizable fossils. Abundant sparry calcite.
100	120	Limestone, white to very pale yellow, fine-grained, very well-cemented to crystalline. Solution porosity about 9%. Spar very pale yellow to white in places. Boring tubes, broken coiled shell fragments. Lithophaga, echinoid spine replaced to clear calcite. Locally white spar coating leaving a rounded texture.
120	130	Limestone, very pale yellow to light yellow-orange, crystalline, solution pores 5% porosity. Dominantly yellow calcite spar. Minute amount of fragments of lacy Madrepora coral, coral fragments, undifferentiated replaced to pure calcite. White limestone surrounded by yellower limestone.
130	160	Limestone, white to very pale yellow, crystalline, solution pores 7-9% porosity. Minor moldic pores (?) foram casts. Dominant white calcite spar. Few recognizable fossils. Fragments with sugary texture coating.
160	170	Limestone, white to very pale tan, crystalline, solution porosity 10-12%.
170	180	Limestone, white to very pale tan to slightly pinkish, crystalline, solution porosity about 15%. Tan and pink fragments show higher porosity and more argillaceous matrix. (micritic?) Trimodal sampling. Coiled gastropod fragments in crystalline matrix, sugary spar coating. Black inclusions show fresh surfaces but slightly disseminated into surrounding calcite. Some do not attract to magnet when separated, Others do. Also small siliceous (?) starlike skeletons of biological origin after dissolution of $CaCo_3$.

Depth Interval (feet) From	To	EX-9: continued
180	190	Limestone, white to very pale orange to tan, very well cemented to dominantly crystalline, solution voids, porosity 12-15%. Slightly <10% argillaceous matrix with brown calcite veins. Recrystallized foraminifera tests; planktonic. Abundant orange sparry calcite.
190	200	Limestone, white (70%) to very pale tan (30%), crystalline dominantly, solution voids ≤5%. Finely crystalline calcite. Few recognizable fossils: coral mold. Mudstone.
210	330	Limestone, white, (mudstone) very well cemented to crystalline. Solution void 7%. Fine calcite. Very fine-grained limy mud. Few recognizable fossils. @240-250: Lessening amounts of crystalline, calcite. aphanitic limestone. @260-270: 15% porosity, solution voids.
330	340	Limestone, white, crystalline, solution voids, porosity 12%. Few recognizable fossils. Fragmental mold of bivalve.
340	350	Limestone, white (mudstone) crystalline, solution porosity 10-12%, possibly secondary porosity. Slightly argillaceous in pockets. Limonite stains near voids. Some minor amounts of clay infilling voids. Relict molds of bivalves(?). Few recognizable fossils otherwise. White sparry calcite.
350	360	Limestone, white, crystalline, solution porosity 15%. Limonite stains rare. Few recognizable fossils.
360	380	Limestone, white to very pale tan to light yellow, crystalline, solution porosity 18%, some lenticular moldic voids. Clay in interstices, some pale orange clay disseminated into limestone via microporosity. Occasional branching coral molds.
380	390	Limestone, white to very pale yellow, coarse-grained constituents, crystalline, moldic porosity expanded by secondary dissolution 20%. Relict coral septa still visible. Large voids show limonite stains. Fine-grained limy mud pockets. Non-homogeneous sample. 3% black (opaque) inclusions of equant shaped grains of magnetite(?).
400	430	Limestone, white to very pale orange, crystalline, solution porosity 10%. Few recognizable fossils. Abundant white to clear sparry calcite. 3% black inclusions of magnetite. Limy mud pockets locally.

Depth Interval (feet) From	To	EX-9: continued
430	440	Limestone, white to very pale grayish tan, finely crystalline, moldic solution porosity 15%. Abundant reef detrital components: coralline debris, bryozoan colonies, boring hinged mollusc valves. Larger foraminifera: spheriodal. Local infilling of voids with gray limy mud.
440	460	Limestone, white to very pale yellow, crystalline, moldic and solution porosity 8%. Minor amount of reef detritus: coralline debris, boring tubes, mollusc shell fragments. Locally limonite stains near voids. Abundant pale tan and white calcite spar.
460	510	Limestone, white to very pale yellow, crystalline, solution porosity 5-7%. Few recognizable fossils. Abundant sparry calcite, minor amounts of vein yellow calcite infilling fractures.

Depth Interval (feet) From	To	EX-11: Sample Description
0	5	Limestone, white to very pale orange, finely crystalline, solution porosity 8%. Few recognizable constituents: broken bivalve fragment? Clear calcite infilling voids. Light brown adobe clay (cascajo) from topsoil layer.
5	20	Limestone, white, finely crystalline, solution porosity 5%. Slightly mottled. Few recognizable constituents. Abundant sparry calcite infilling irregularly shaped voids within whiter more finely crystalline limestone.
20	60	Limestone, white, very well-cemented to dominantly finely crystalline, solution porosity 10-15%. Calcite replaced fossil fragments. Small gastropod shells: Olivella?. Broken bivalve, coral fragments (lacy Madrepore), echinoid spines, boring tubes. Generally coarse-grained particles with clear crystalline calcite.
60	100	Limestone, grayish white to very pale yellow, finely crystalline, solution porosity 8-10%. Abundant yellow calcite spar. Few fossils: infilled borings, bryozoan colonies. Rounded inequigranular clasts of white limestone in crystalline calcite. Oolites? locally floating in white matrix.
100	110	Limestone, grayish white to very pale yellow, finely crystalline, solution porosity 15%. Yellow calcite infilling moldic voids (original porosity?).
110	140	Limestone, white, finely crystalline, solution porosity 5-7%. No recognizable fossils. Abundant platy fragments. Well-indurated. Localized calcite spar.
140	160	Limestone, white to very pale yellow, crystalline, solution porosity 10%. No recognizable fossils.
440	(?)	Sandstone, lithic, moderately cemented, poorly sorted, black to dark greenish gray, interparticle porosity <3%. Volcanogenic sediment. Detrital phases: 30% Limestone, bioclastic, white, to pale tan, well-rounded argillaceous. Fossils: gastropods, coral debris, echinoid spines, bryozoa. 55% Siltstone, fine-grained, tuffaceous, greenish gray, deeply weathered. 10% Volcanic fragments, black, ultra mafic minerals: orthopyroxene? olivine-serpentine? Authigenic: 3% Clay minerals: smectite? <1% Calcite <1% Quartz

EX-5: SUMMARY SAMPLE DESCRITION

Depth Interval from (feet)	to	Lithological Description
0	11	Surface soil; no sample.
11	21	Wackestone; friable chalky zone, white, moderately fossiliferous.
21	28	Wackestone with zones of mudstone, compact, white, moderately fossiliferous.
28	44	Wackestone; moderately-compact, chalky, white and mottled, few fossils.
44	61	Wackestone with zones of mudstone; compact, chalky, white, moderately fossiliferous.
61	87	Wackestone; very friable, white, moderately fossiliferous.
87	100	Wackestone; chalky mud matrix, few fossils.
100	120	Wackestone; limonite stained fractures, white and mottled, fossiliferous (large foraminifera).
120	129	Mudstone; white to tan, finely crystalline lined pores, rare fossils.
129	136	Mudstone; compact, few large clasts of calcareous algae, white, rare fossils.
136	167	Wackestone; friable, chalky, fossils primarily coral debris.
167	187	Wackestone with zones of mudstone, slightly chalky, white, rare fossil debris.
187	193	Wackestone; moderately-compact, few foraminiferal tests replaced by calcite, white.
193	215	Wackestone; dense, few chalky zones, fossiliferous (large foraminifera).
215	274	Mudstone with zone of wackestone, friable, white to pale yellow, moderately fossiliferous.
274	304	Mudstone; moderately-compact, white to pale yellow and mottled.
304	344	Wackestone with zones of mudstone; slightly chalky zones, white to mottled, mollusk debris.

Depth Interval from (feet)	to	Lithological Description
344	361	Wackestone; medium- to coarse-grained fossil debris, white.
361	391	Wackestone with zones of mudstone and packstone; chalky, crumbly, white, fossiliferous.
391	411	Wackestone; chalky zones with clasts of reef debris, white to pale yellow-orange, mollusk debris.
411	448	Wackestone; fine-grained reef debris, mollusk debris, white to tan, mottled.
448	457	Mudstone; limonite staining in fractures, white to yellow, rare fossils.
457	463	Poor sample, grout.
463	490	Wackestone; limonite staining in fractures, mollusk debris (Lithophaga), white to tan.
490	500	Mudstone; limonite staining in fractures, white, rare fossils, foraminiferal tests replaced.
500	531	Wackestone; fairly compact, few chalky zones, fine grained tan matrix, mottled, uncommon fossils.
531	541	Wackestone; compact, limonite lined solution pores, moderately fossilierous, tan matrix with white mud.
541	584	Wackestone; moderately compact to compact, large clasts of coral debris, tan matrix, foraminiferal tests replaced by yellow calcite.
584	600	Wackestone; moderately well-cemented, chalky in pores, tan matrix, traces of black opaque glass.

EX5: POROSITY CLASSIFICATION SUMMARY

Depth Interval (feet) from	to	Dominant Type	Subordinate type
11	113	Meso to small megamold	Fracture
113	125	Solution-enlarged fracture	Small megachannel
125	182	Mesomold mesochannel	Fracture; small mesovug;
182	195	Meso to small megachannel	Solution-enlarged fracture
195	200	Meso to small megamold	Fracture; solution-enlarged fracture
200	280	Meso to small megachannel	Small megamold; meso to small megavug
280	286	Solution-enlarged fracture	Mesovug to small megavug; small mesomold to small megamold
286	312	Small megachannel enlarged fracture	Mesomold; mesovug; solution-
312	357	Solution-enlarged fracture	Mesomold to small megamold
357	369	Small megachannel	Solution-enlarged fracture; mesovug; reduced to filled mesomold
369	384	Small mesovug	Mesochannel (rare)
384	400	Solution-enlarged fracture	Mesomold
400	410	Small megachannel	Mesomold; mesovug to small Megavug; solution-enlarged fracture
410	418	Solution-enlarged fracture	Mesomold; small mesovug
418	446	Fracture	Meso to small megamold; mesovug; solution-enlarge fracture; small megachannel
446	453	Fracture	Solution-enlarge fracture; small mesovug; mesomold

Depth Interval (feet) from	to	Dominant Type	Subordinate type
453	492	Meso to small megamold	Meso to small megavug; fracture; solution-enlarged frature
492	505	Small megachannel	Meso to small megavug; mesomold; solution-enlarged
505	534	Mesomold	Mesovug; fracture, small megachannel (channel increases between 520 and 526 feet)
534	542	Meso to small megavug	Mesomold; small and megachannel
542	600	Meso to small megavug	Mesomold; fractures; solution-enlarged fracture

APPENDIX B

PALEONTOLOGICAL DESCRIPTIONS OF EX-5 AND EX-7

Appendix B presents Paleonotological Descriptions of EX-5 and EX-7 made at WERI. Descriptions for EX-5 were based on micro- and macroscopic examinations of split core samples and thin sections of selected fossils. Descriptions for EX-7 were based on microscopic examination of chip samples.

Paleontological log of EX-5 core samples.

INTERVAL (ft.)	DESCRIPTION OF LIMESTONE	LARGER FORAMINIFERA	OTHER FOSSILS	CORAL and CACLCAREOUS ALGAE	NOTES
11-110	Wackestone w/layers of mudstone; zones of abundant fossils; fossils white w/few chalky and some replaced with yellow calcite; limestone ranges from friable to compact.	N. fichteli (?) S. orbitoides A. inhearns (?) G. vesicularis G. marianensis O. Ammonoides O. bartschi O. venosus O. rectilata (?) R. atjehensis M. dehaarti S. martini P. Larvata S. globulus E. semiornata Spiroclypeus sp. Lepidocyclina sp.	planktonic foraminifera: Globigerina, Orbulina. Serpulidae worm tubes: Spirobis; pelcypods (bivalves). Gastropods.	thin branching coral coral includes Porities and Acropora massive coral. clasts of calcareous algae (encrusting and massive). calcareous algae encrusting coral fragments.	Zone of most abundant foram between 100 to 110 feet below ground surface.
110-197	Wackstone and mudstone (120-137); zones of common fossils; fossils white w/few chalky and some replace with yellow calcite; from fractured to compact	E. Semiornata O. Ammonoides G. marianensis S. Orbitoideus R. atjehensis	Serpulidae worm tubes:	Possible Halimeda thin layers of calcareous algae, branching coral massive coral (Favities ?)	

INTERVAL (ft.)	DESCRIPTION OF LIMESTONE	LARGER FORAMINIFERA	OTHER FOSSILS	CORAL and CACLCAREOUS ALGAE	NOTES
197-280	Wackestone and mudstone (220-280); zones of abundant fossils; tan matrix; friable to compact; traces of yellow limonite staining.	E. semiornata D. Ammonoides D. bartschi G. marianensis A. radiata S. globulus R. atjehensis S. cylindricum A. inhearns (?) S. orbitoideus Lepidocyclina Sorities sp.	Planktonic foraminifera: Globigerina Serpulidae worm tubes: Spirobis, pelecypods (bivalves). Gastropods (fragments).	Clasts of calcareous algae. massive coral. Halimeda (?) encrusting calcareous algae.	rare occurrence of dark volcanic grains in pockets, Globigerina ssp. found with grains.
280-310	Mudstone w/zones of wackestone; low amount of fossil debris; moderately compact; white to pale yellow.	No Forams	Broyzoan. pelecypod valves. cerithid gastropod.	massive and branching coral. encrusting calcareous algae	
310-353	Wackestone w/zones of mudstone; slightly chalky; zones of abundant fossils; white.	E. semiornata G. marianensis Calcarina sp.	Serpulidae worm tubes: Spirobis; Polychaetia. Bivalvia: Nemocardium Tridacna Cardiidae Mytilacea Fragum Pecten.	massive and branching coral (Porites and Fungidae). Clasts of calcareous algae.	Mollusk fossil zone between 322-338 feet; Nemocardium sp. very abundant

INTERVAL (ft.)	DESCRIPTION OF LIMESTONE	LARGER FORAMINIFERA	OTHER FOSSILS	CORAL and CACLCAREOUS ALGAE	NOTES
			Gastropoda: *Conus* *Terebra* *Saginafusus* *Turbo* *nerites*.		
353-399	Wackestone w/zones of mudstone and packstone; medium to coarse grained fossil debris; white to pale yellow-orange.	*Carpenteria* *Heterostegina*	Serpulidae worm tubes: *Spirobis*. pelecypod and gastropod shell debris.	massive and branching coral. Fungidae.	
399-439	Wackestone; chalky zones; zones of abundant fossil debris; white to pale yellow-orange; friable to compact.	*C*.(*c*.) *indopacifius*	Serpulidae worm tubes: *Spirobis*, *Serpula*; Polychaetia. Pelecypoda: *Nemocardium* *Fragum*, *Pecten*, Cardiidae. Gastropoda: *conus* cf. *affinis*, *Saginafusus*. Echinode Spines.	clasts of calcareous algae. Encrusting calcareous algae. *Halimeda*. Branching and massive coral.	Mollusk fossil zones between 399-405, and 423-431; *Nemocardium* sp. very abundant. *C*. (*c*.) *indopacifius* is diagnostic of Tertiary f.

INTERVAL (ft.)	DESCRIPTION OF LIMESTONE	LARGER FORAMINIFERA	OTHER FOSSILS	CORAL and CACLCAREOUS ALGAE	NOTES
440-480	Wackestone and mud-stone; zones of common fossil debris, Limonite stained fractures; white tan and pale yellow	<u>Sorities</u> (?)	Serpulidae worm tubes. planktonic foraminifera: <u>Globigerina</u> pelecypod: fragments of <u>Lithophaga</u>. Gastropod fragments.	branching coral (<u>Porities</u>, <u>Acropora</u>). clasts of calcarenus algae.	reef debris generally fine grains. @ 450-451 small lens of dark volcanic grains.
480-490	Wackestone; limonite stained fractures; abundant fossil debris; white to tan	No Forams	pelecypods: <u>Lithophaga</u>.	Branching coral (<u>Proities</u>)	Mollusk fossil zone between 481-490; <u>Lithophaga</u> sp. very abundant.
490-531	Mudstone and wacke-stone; rare fossils Limonite staining in fractures; fairly compact; white to tan	No Forams	Serpulidae worm tubes. pelecypods: <u>Lithophaga</u>. Planktonic foraminifera.	<u>Halimeda</u> calcareous algae: <u>Porolithon</u> Branching coral: (<u>Seriatopora</u> ?).	foraminiferal tests replaced by yellow calcite.
EX-5a 520-600	Wackestone w/zones of mudstone; moderately fossiliferous; chalky in pores; moderately compact to compact; limonite lines solu-tion pores; tan matrix w/white mud.	<u>E. semifornata</u> <u>O. ammonoides</u> <u>Sorities</u> sp. <u>Operculina</u> sp. <u>S. globulus</u> <u>C. marianesis</u>	Serpulidae worm tubes: <u>Spirobis</u>. Echinode spines, pelecypods: <u>Lithophaga</u>, fragments.	Large clasts of coral debris. <u>Halimeda</u>. Calcareous Algae. Branching and massive	foraminiferal tests replaced by yellow calcite. Traces of black opaque grains

INTERVAL (ft.)	DESCRIPTION OF LIMESTONE	LARGER FORAMINIFERA	OTHER FOSSILS	CORAL and CACLCAREOUS ALGAE	NOTES
			Crab caripace. Gastropod fragments. Siliceous spicule.	coral: Porcillipora Porities ? Seriatopora ?	from 585-600.

Paleontological log of EX-7 chip samples.

INTERVAL (ft.)	DESCRIPTION OF LIMESTONE	LARGER FORAMINIFERA	OTHER FOSSILS	CORAL and CACLCAREOUS ALGAE	NOTES
10-145	Wackestone; moderately compact; white w/yellow cavity fill; common pelecypod and gastrupod debirs; few chalky clasts; rare compact, fine-grained fragments between 100-145 feet few fragments of white fossiliferous mudstone.	G. vesicularis M. vertebralis S. globulus A. cf. radiata Amphistegina sp.	Pelecypods: Chama Pectens cardidae Tridacna Lithophaga. Serpulidae: worm tubes Spirobis, Sedertaria. Plychaetia. cellana exarata (keyhole limpet). Castropods: olivia Cyprea Turbo fragments. Echinode spines and plates. Bryozoan (Lacy type). Smaller forams: Elphidium.	Halimeda? clasts of calcareous algae replaced coral fragments Favities coral, thin branching coral, Alveopora? Millepora Goniastrea Acropora	Lithophaga occurs only @135-145: A. radiata common in zones.
145-210	Packstone w/wackestone and mudstone; moderately compact to compact;	A. radiata	Pelecypods: Pectens fragments.	clasts of calcareous algae.	A. radiata Abundant in zones

INTERVAL (ft.)	DESCRIPTION OF LIMESTONE	LARGER FORAMINIFERA	OTHER FOSSILS	CORAL and CACLCAREOUS ALGAE	NOTES
	white w/yellow, tan, pink cavity fill; common fossil debris; few clasts of chalky mudstone; few tan fine-grained fragments.		Gastropods: Drupa fragments. Serpulidae worm tubes: Spirobis Sedentaria Polychaetia Echinode spines and plates.	thin branching coral (Porities). Acopora, caryophyllidae coral (Ahermetipic), Alveopora? Pavona Favities	
220-235	Packstone; compact; white w/small quanity of yellow cavity fill; rare chalky clasts; rare fossils.	Heterostegina?	planktonic foraminifera (rare). echinode spine.	No structures.	
235-325	Packstone, wackestone and mudstone mix; moderately compact; white w/yellow, tan, pink cavity fill; slightly chalky; moderately fossiliferous w/zones of abundant fossils; mudstone w/smaller forams; white mudstone very fossiliferous; rare limonite clasts.	Heterostegina Sporadotrema Cycloclypeus M. vertebralis O. ammonoides A. radiata Operculina sp. O. bartschi S. globulus	Pelecypods: fragments, clasts and molds. Pectens. Gastropods: fragments. Serpulidae worm tubes: Spirobis. Polychaetia. Echinode spines.	clasts of calcareous algae and encrustations. coral fragments Acorpora.	many fossils are chalky and replaced. cavity fill w/bright orange calcite crystals. white mudstone fragments contain smaller forams usually found in lagoon environments,

INTERVAL (ft.)	DESCRIPTION OF LIMESTONE	LARGER FORAMINIFERA	OTHER FOSSILS	CORAL and CACLCAREOUS ALGAE	NOTES
220-235 (cont)			Smaller forams: *Archaias*.		probably transported.
335-425	Packstone, wackestone and mudstone mix; white and tan compact fragments; white chalky fragments; yellow and orange calcite cavity fill; tan and white mudstone fossiliferous; traces of limonite.	*A. bicirculata* *O. rectilata* *Cyclyoclypeus* *Calcarina*? *Marginopora* *H. depressa*	Smaller forams: *Triloculina* spp. *Discorbis* *Espondies* *Spirillina* *Osangularia*. Serpulidae worm tubes: *Spirobis* *Sedentaria*. Polychaetia. Echinode spines. Pelecypods: fragments, cockle, pectens. planktonic foraminifera. Gastropods: fragments, *Conus*	thin branching coral. replaced coral fragments *Pavona* (?). *Seriatopora*, *Favities*	yellow mudstone w/lagoonal sp. of smaller foraminifera. *A. bicirculata* is a deeper water (>50m) species, common. many foraminiferal fossils chalky and altered (replaced).
425-485	Mudstone w/wackestone and packstone moderately compact; tan and white w/yellow, tan, pink cavity fill; slightly chalky;	*C. (c.) postindopacificus* *A. bicirulata* *A. lessonii*?	Pelecypods: *Osterea* fragments, casts, molds, Pectens, *Lithophaga*,	coral replaced and altered: *Acropora*, *Alveopora*, *Pavona*.	fossils in white mudstone very chalky.

INTERVAL (ft.)	DESCRIPTION OF LIMESTONE	LARGER FORAMINIFERA	OTHER FOSSILS	CORAL and CACLCAREOUS ALGAE	NOTES
425-485 (cont)	moderately fossiliferous; traces of limonite.		*Fragum* Gastropods: fragments, Limpet. Smaller forams: *Triloculina* spp., *Gaudryina*. Bryozoan (lacy type).		
485-525	Mudstone; yellow and white; moderately compact to friable; fossiliferous; fossils slightly chalky; traces of white compact packstone.	*Clycloclypeus* *C.* (*c.*) *postindopacificus* *Operculina*	Small forams: *Triloculina* spp. Pelecypods: fragments, casts, molds. Serpulidae worm tubes: *Spirobus*. Polychaetia, worm tubes. Echinode spines.	coral replace and altered: *Pavona*, *Porities*, *Acropora*	small forams in yellow mudstone are replaced and chalky.
525-580	Packstone and mudstone; compact to moderately compact; white packstone; yellow and white mudstone; traces yellow limonite; mudstone w/ common fossils; traces	*Clycloclypeus* *A.* *bicirculata* *O.* *rectilata*	Small forams: *Triloculina* *Planorbulina*. Gastropod fragment. Pelecypods: *Ctena*,	coral fragments: *Acopora* *Heliopora*	yellow mudstone w/small forams, mostly replaced or chalky.

INTERVAL (ft.)	DESCRIPTION OF LIMESTONE	LARGER FORAMINIFERA	OTHER FOSSILS	CORAL and CACLCAREOUS ALGAE	NOTES
525-580 (cont)	of cavity fill; traces of orange chalk.		Pectens, fragments, casts, molds, Lighophaga, Echinode spines. Serpulidae and Polychaetia worm tubes.		
580-585	Sand(?); medium to fine grains; white and tan; traces of orange chalk; grains are angular to subrounded.	None	None	None	
590-698	Mudstone w/wackestone and small amount of packstone; white and yellow mudstone; compact friable; few chalky clasts; yellow mudstone fossiliferous; traces of yellow limonite.	A. bicirculata M. vertebralis ? Clycloclypeus Operculina sp. A. radiata O. rectilata O. ammonoidis P. Larvata Sorities C. monticularis	Pelecypod: fragments, casts, molds, Tridacna, Pectens, Lithophaga, cardidae. Small forams: Triloculina Quenquelocu-lina. Gastropods: Terebra, cerithids, conus, fragments, Trochus.	thin branching coral Seriatopora Millepora Pocillapora Pavona.	many forams in yellow mudstone are replaced.

590-698 (cont)	Olivia Rhinoclavis Strombus. Pyramidellidae. Lacy Bryozoan. Serpulidae worm tubes: Spriobus. Polychaetia.

APPENDIX C

GEOPHYSICAL LOGS

Introduction

Appendix C contains a brief description of geophysical logs obtained by the USGS in addition to the actual logs (Plates 1-7). Tracings of the logs were made from strip-charts readouts and represent raw data (ie., no correction for borehole effects has been applied). Some logs are missing from the figures due to either the logs were not run for that borehole or the logs were not available at the time of report preparation. Large scale blue ot prints of the request. Enclosed plates, showing geophysical logs, are obtainablc from WERI upon.

Description of Geophysical Logs

Caliper Log

The caliper log provides a continuous record of the average borehole diameter. The sonde physically measures the hole diameter by three extended, spring-loaded arms. As the sonde is trolled up the hole, the signal produced by the arms in integrated and sent to the control electronics where it is recorded on a strip chart.

The caliper log is used to evaluate the physical condition of the borehole in order to correct other logs for effects of varying hole diameter. In addition, the log may provide information on lithology by detecting breakouts or weaker rock strata. Some information concerning well construction may be provided by the log.

Natural Gamma Log

The sonde provides a continuous measurement of the natural gamma photon emission of the surrounding rock through which it is trolled. The gamma radiation received by the detector is primarily related to the decay of Potassium-40 and to a lesser extent, the daughter products of the uranium- and thorium-decay series. Since clays contain relatively large amounts of potassium, the natural gamma log is used primarily in stratigraphic correlation work.

The natural gamma sonde can be used in case, uncased, fluid-filled a=or air-filled boreholes.

Spontaneous-Potential Log

The spontaneous-potential log provides a continuous record of the natural potentials developed between borehole fluid, formation water, and the surrounding rock. The potential has been attributed to two sources. The first and of least effect on the SP magnitude, is the streaming potential caused by the development of an electromotive force (emf) as an electrolyte flows through the porous media. The second source and probably most important in the development of potential differences is the electrochemical emf produced at the boundary between materials of different properties. Such boundaries are mud-mud filtrate (drilling and infiltration into the surrounding rock), mud filtrate-formation water, formation water-shale, and shale-mud. These potential differences across junctions cause current to flow near the aquifer boundaries of the surrounding rock.

The continuous SP record is obtained by trolling a lead electrode connected to an insulated conductor. The moving electrode senses the potential drops caused by the flowing current at lithologic boundaries and references the measurement to the constant potential of a second ground electrode, usually located at the surface.

The spontaneous-potential log is used with success to distinguish lithologies within shale-sandstone or shale-carbonate sequences. In conjunction wich resistivity logs, contacts between fine-grained sediments and carbonates may be distinguished and bed thickness determined. The SP measurements can only be successful in fluid-filled, uncased boreholes.

Single-Point Resistivity Log

The device used is a short normal tool which provides a continuous record of the apparent resistivity of the surrounding rock. Measurements are taken between a close-coupled lead electrode and the housing of the measuring sonde. The same tool is used for both single-point resistivity and spontaneous potential measurements.

The log provides information concerning the porosity and permeability of an aquifer and is used in determination of bed thicknesses and lithologies. The log is also useful in establishing contacts between strata of differing resistivity.

As with the SP measurements, the single-point resistivity sonde is usually used in fluid-filled, uncased boreholes, although some applications in cased holes have proved to be successful in locating corroded liners.

Fluid-Conductance Log

The fluid-conductance log provides a continuous record of the electrical conductivity of the borehole fluid. Groundwater can be considered as an electrolyte solution because nearly all its dissolved constituents are present in ionic form. A general indication of the total dissolved ionic constituents can be obtained by determining the capability of the water to conduct an applied electrical current. The property is normally reported as electrical conductance and is expressed in units of micromhos.

Plate 1a

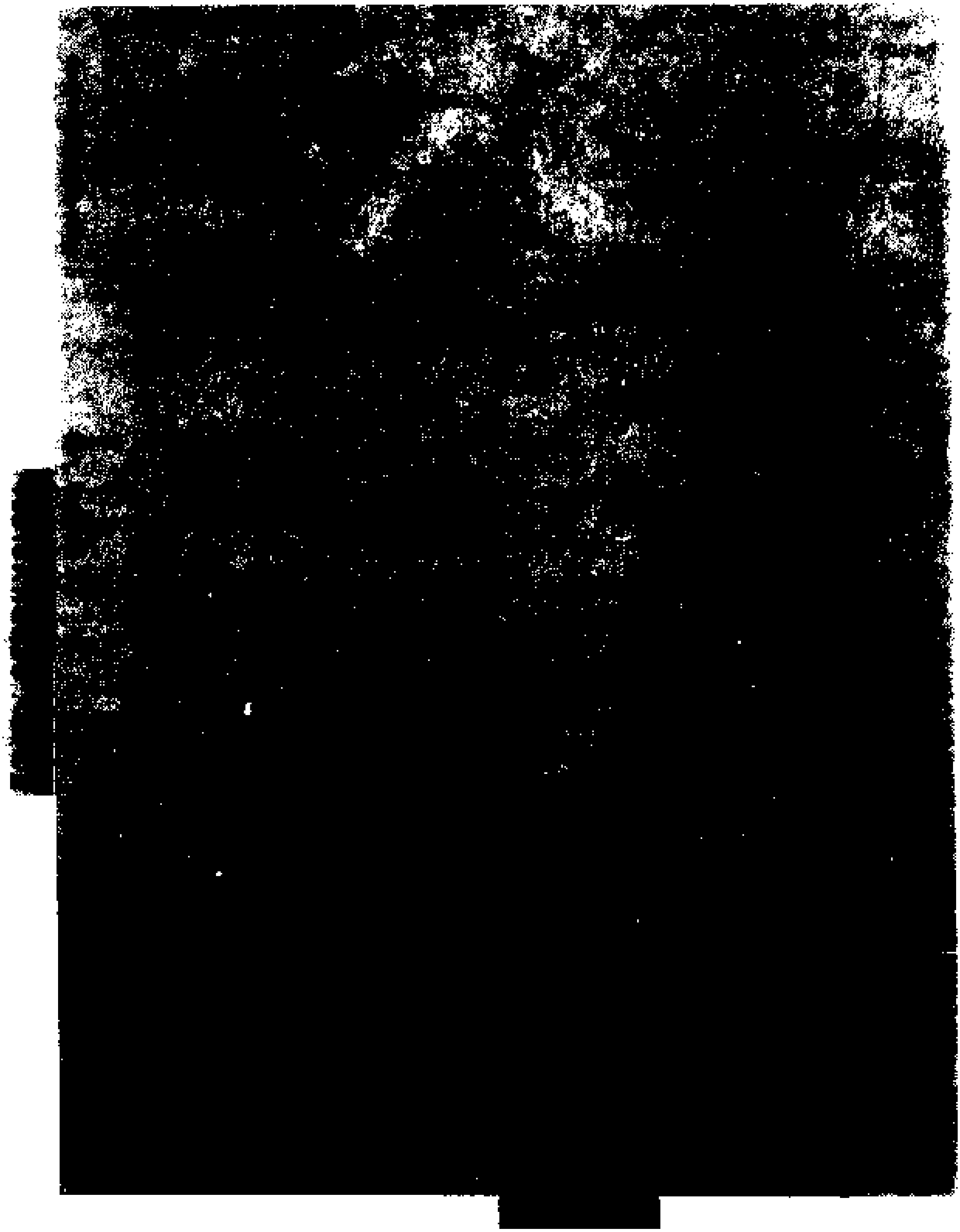


Plate 1b

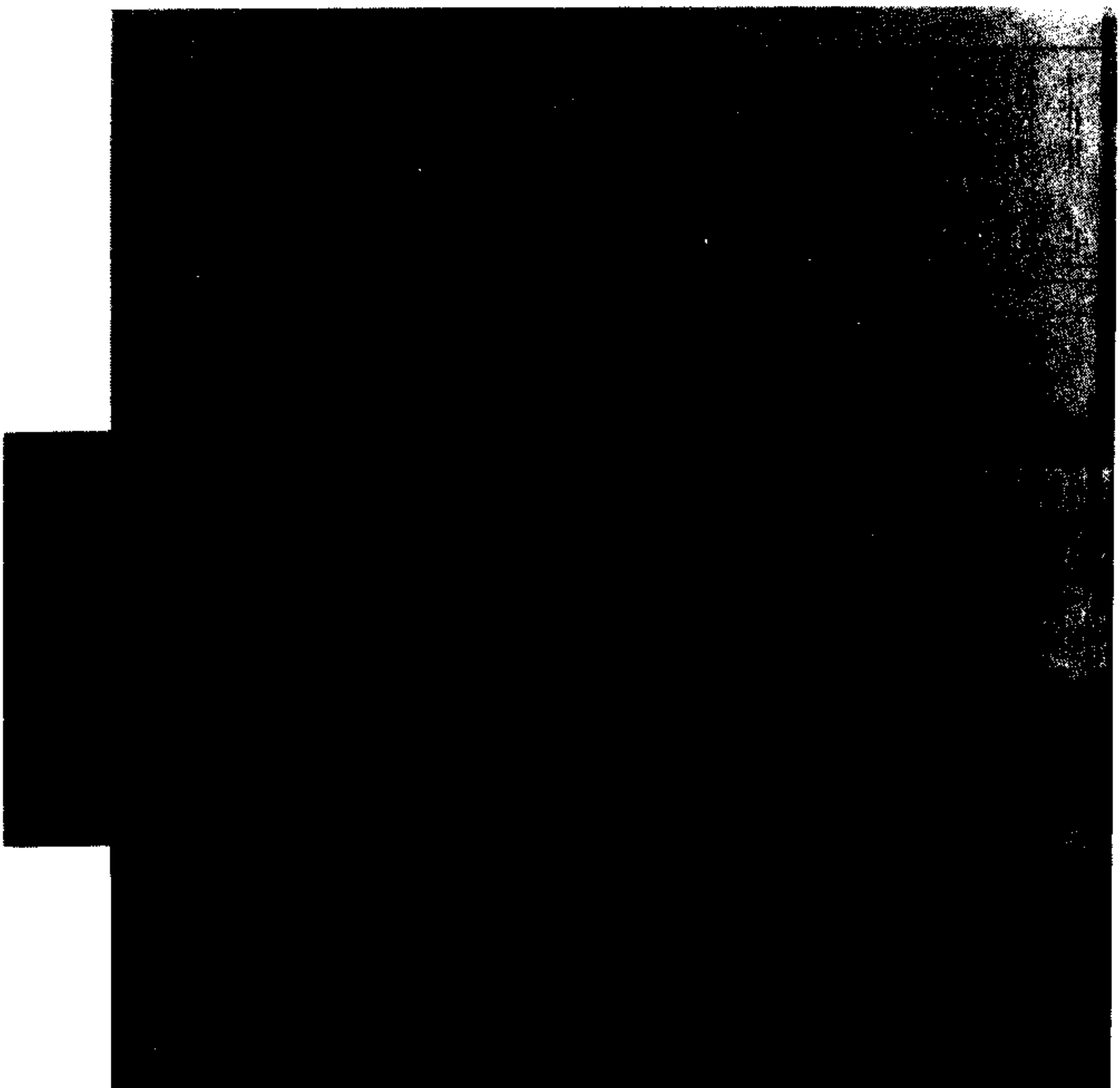


Plate 2

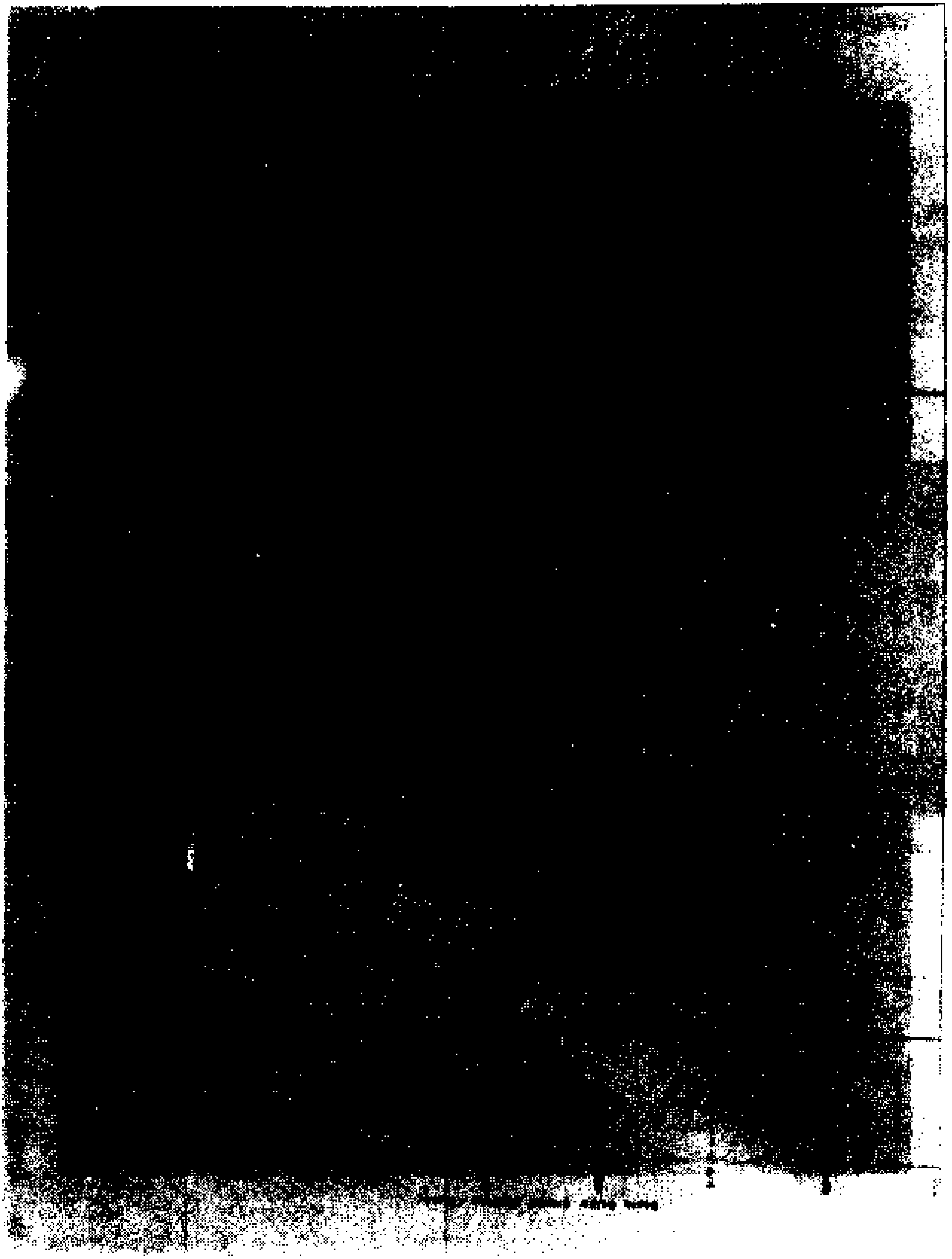


Plate 3

Plate 4

Plate 5

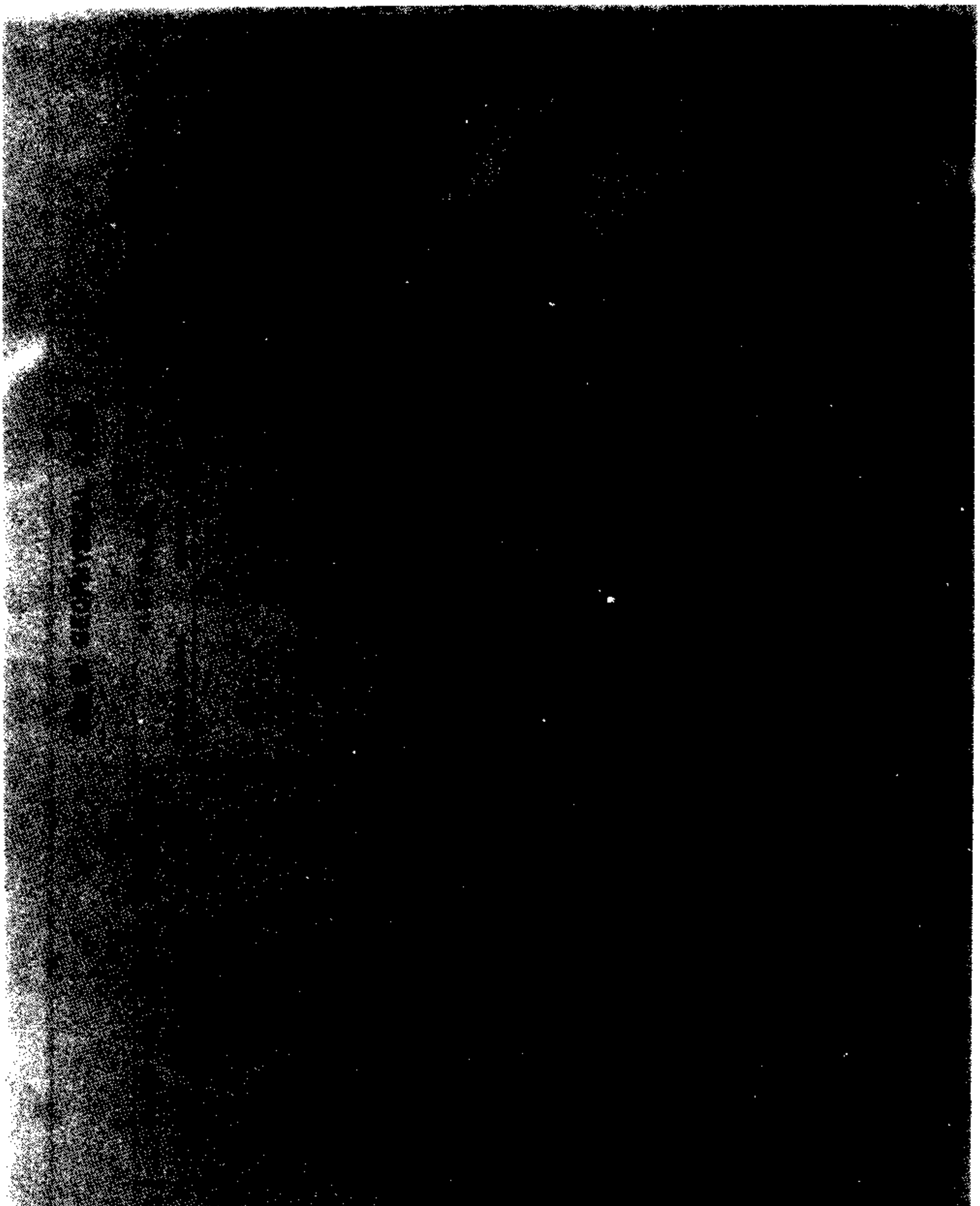


Plate 6

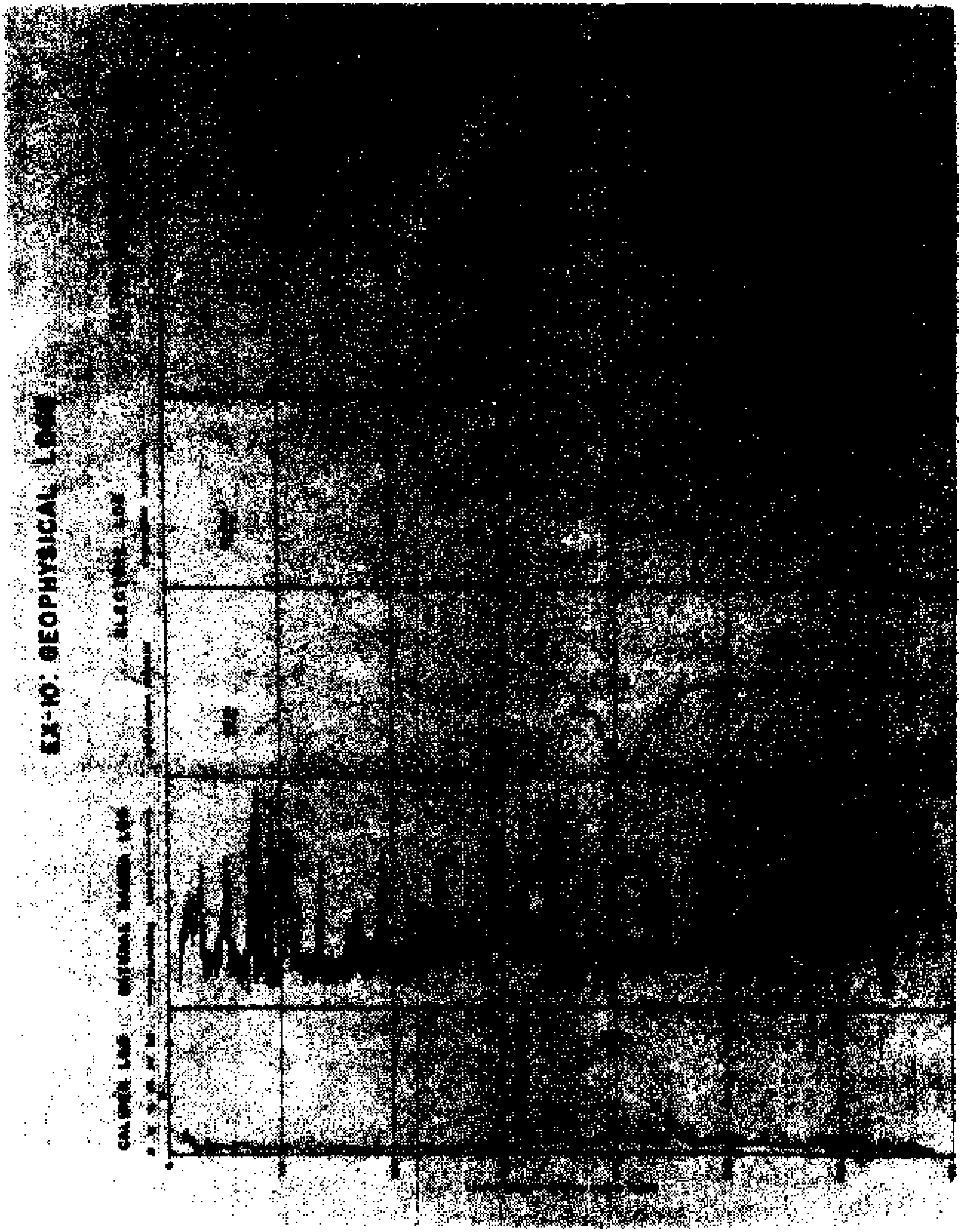
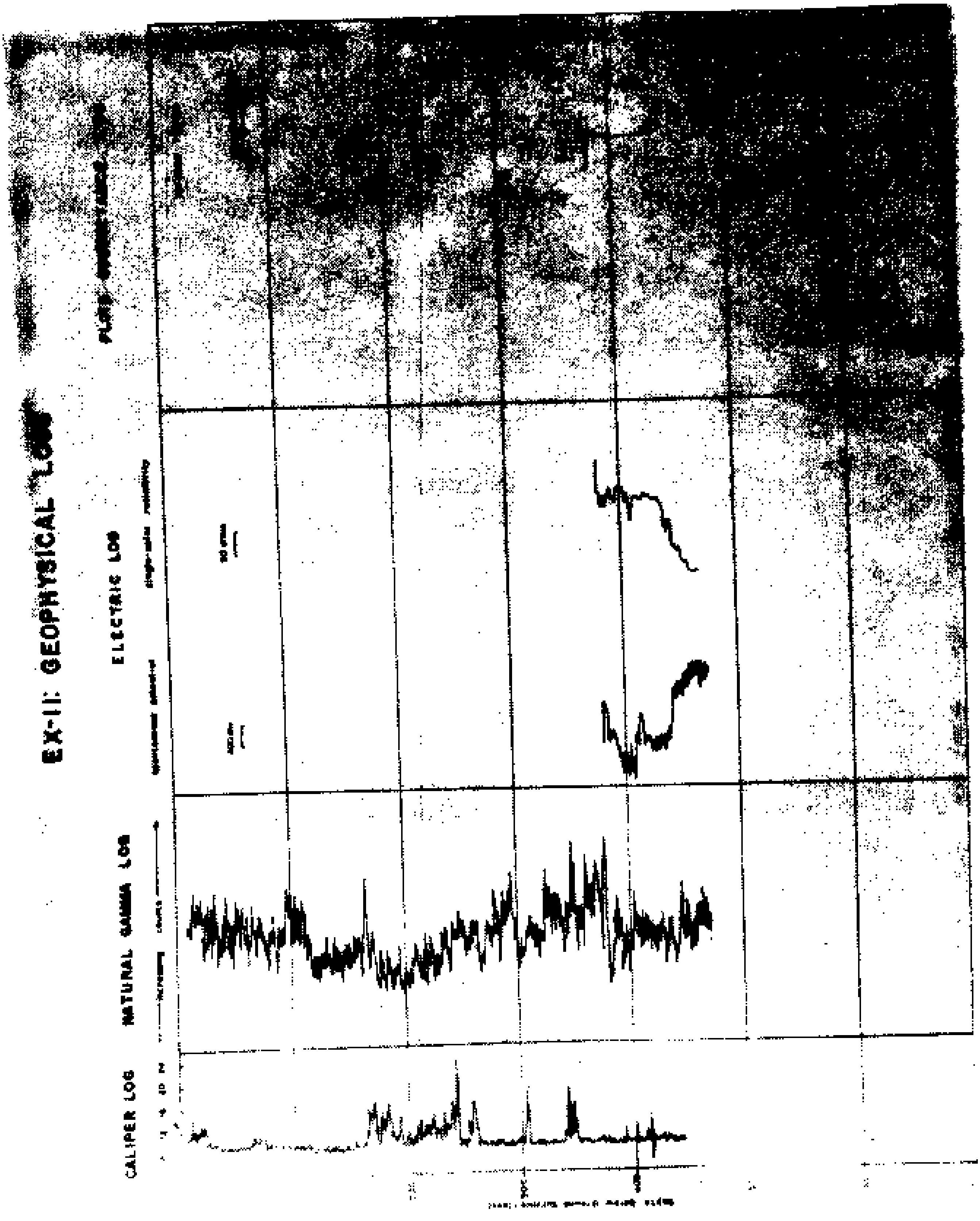


Plate 7


EX-11: GEOPHYSICAL LOGS
ELECTRIC LOG
NATURAL GAMMA LOG
CALIPER LOG