EVALUATION OF THE GROUNDWATER RESOURCES OF THE AGAG BASIN, SAIPAN

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Jerry F. Ayers

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Water and Energy Research Institute of the Western Pacific

Technical Report No. 31

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AN EVALUATION OF THE GROUNDWATER RESOURCES OF SAIPAN

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INTRODUCTION

Background

The Agag groundwater basin has long been considered an important resource because of its reliable supply of high-quality water. The basin has been known at least since the American occupation toward the end of World War II. Development began in the early half of 1945 with the drilling of wells 31, 45, and 50 by the military. These wells were cased, with the lower 55 to 60 feet perforated for water entry. The combined initial production of the three wells was approximately a half a million gallons per day (Glander, 1946).

According to Davis (1958), wells 31, 45, and 50 were operated until about 1950 or 1951 and supplied water to the island distribution system at a rate ranging from 200,000 to 450,000 gpd. The production history of the wells during the next few years is not clear. Cox and Evans (1956) indicate that wells 31 and 45 were in operation and that well 50 was in reserve at the time of the writing of their report. Apparently, it was about this time that well 75 was drilled (located about 100 feet from well 31) and fitted with a 100 gpm-rated pump (Cox and Evans, 1956, p. 65).

In November 1969, wells 45 and 50 were redrilled within 50 feet of the old well sites. Well 45 (new) was drilled ten feet deeper than the old well and well 50 (new) was drilled about 100 feet deeper than the old well. In October 1971, well 31 (new) was redrilled a few feet from the old site to a similar depth as old well 31. Later, well 31 (new) was deepened; however, the yield of the well did not increase significantly. The reason for the redrilling of the original wells was probably due to encrustation of the well screens. Rather than purge and clean the old wells, it apparently was easier to drill and construct new ones.

Some time between 1973 and 1979, wells 70, 72, and 73 were drilled, constructed, and put into operation. Uncertainty about these wells is due to the fact that well logs and construction descriptions were not available to this study.

One additional well was drilled within the basin in early summer 1979 as part of an exploratory-drilling program conducted by the Public Works Department and supervised by the U.S. Geological Survey. Test hole 10 (TH-10) is located near the southern boundary of the basin and was drilled to a depth of 356 feet. The well bottomed in the volcanic basement. TH-10 has been fully constructed; however, to date, it does not contain a pump.

Currently, wells 50, 70, 72 and 73 are on line with a combined production of approximately 600,000 gpd. Wells 31, 45, and 75 have been taken out of production over the past few years and are now used as observation wells.

Prior to this study little information was collected concerning the extent of the basin, its hydrogeologic properties, or its sustainable yield. After the original wells (31, 45, and 50) were constructed and put into operation, no follow-up data were collected. Therefore, the effects of pumping on the initial groundwater-flow condition are unknown. Later, with the redrilling of the original three wells and the addition of well 75, a few pumping tests were performed and some data collected on the behavior of the water table through spot measurements and continuous recordings. Although driller's logs were kept on all drilling operations, they are of little help in unravelling the complex geology of the Agag area. Sources of problems relate to a lack of ability on the driller's part to properly identify geologic materials and to poor returns on sample cuttings because of lost circulation (a common problem when drilling in a carbonate terrain).

What had emerged in terms of knowledge of basin hydrogeology amounted to just a few roughly defined parameters. These included an estimate of the depth of the saturated zone of about 60 feet, a calculated value of 25 ft/day for the hydraulic conductivity in the vicinity of the production wells, a measured minimum well yield, and a qualitative view of storage response to recharge events of unknown magnitude. What remained unknown included the type and location of basin boundaries, geologic characteristics of the aquifer, and magnitude and seasonal characteristics of recharge to the flow system. All of these basin characteristics must be known in order to optimize development and provide guidelines for the proper management of the resource.

Purpose and Scope of the Study

Because of the lack of critical information about the hydrogeology of the Agag groundwater basin, the Water and Energy Research Institute (WERI) of the University of Guam was contracted by the Office of Energy and Environment, Commonwealth of the Northern Mariana Islands, to conduct a study of the groundwater resources underlying the Agag area. The study was initiated in August 1980 and field investigations were completed approximately ten months later.

The purpose of the study was to investigate the hydrogeologic characteristics of the basin in order to determine the optimal yield of the groundwater resource. Specific objectives were to determine the size of the basin, to define the type of boundary conditions that are present, to define the geologic properties of the aquifer, and to estimate the sustainable yield of the ground water resource.

In order to achieve the objectives of the study, a number of methods were employed. These methods included acquisition of previous work and data, an exploratory drilling program, a water-level monitoring program, and analyses and interpretation of field data. Of these methods, the exploratory drilling program yielded the most critical information about the subsurface characteristics and extent of the basin and the water-level monitoring program gave information on the present-day water-table configuration.

Location and Description of the Study Area

The Agag groundwater basin is located in the east-central part of Saipan on the northeastern flank of Ogso Tagpochau between San Vicente Village and Capitol Hill (Figure 1). The study area is roughly bounded on the west by a high limestone cliff below the northward-trending central ridge of the island

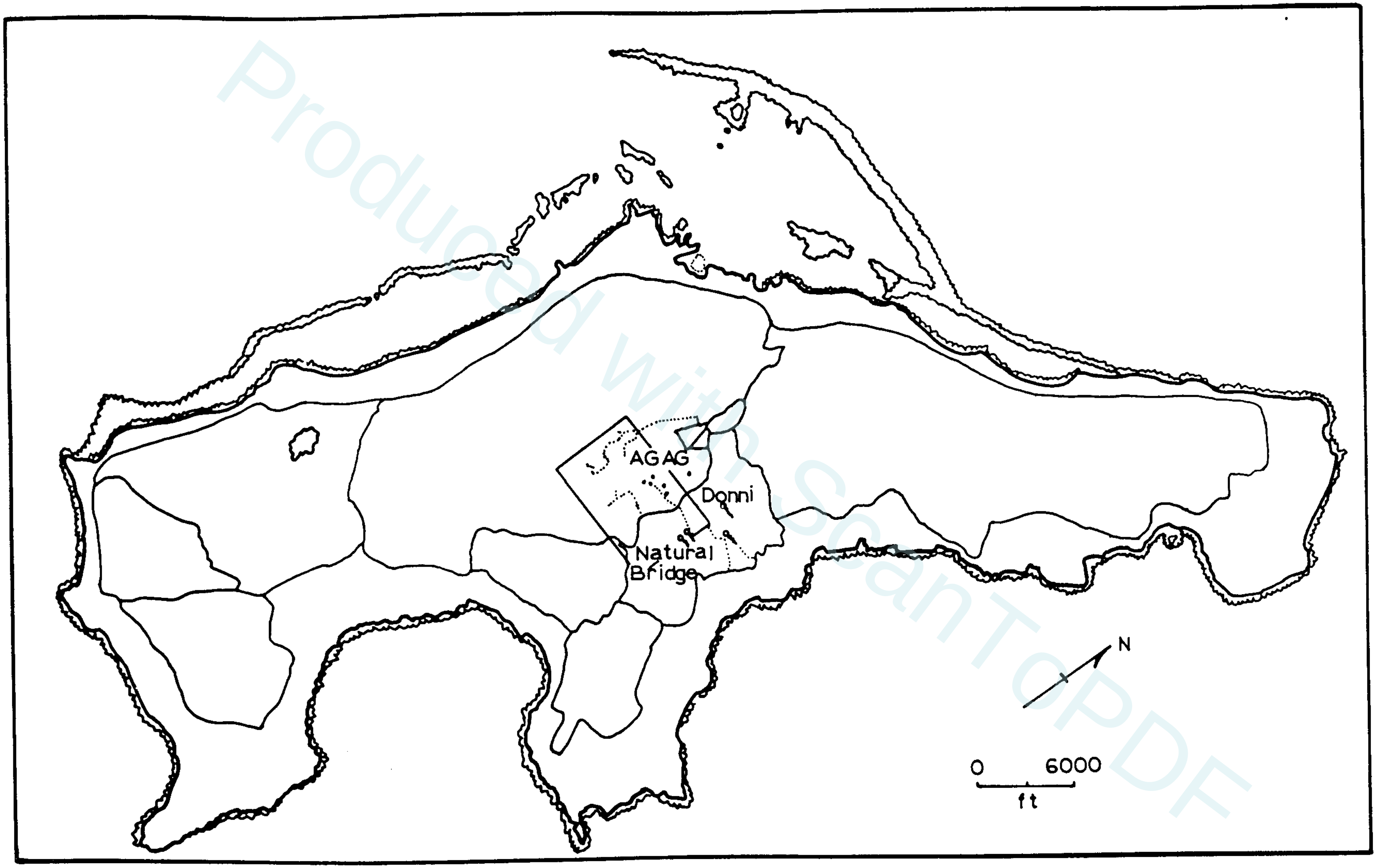

Figure 1. Map of Saipan showing the location of the study area.

and bounded on the east by a line of springs (Natural Bridge Springs) and seepage areas at the foot of a second limestone cliff east of the cross-island highway. North and south boundaries are less distinct and are somewhat arbitrary. The northern boundary is defined by the 15° 12' latitude line and the southern boundary is defined by a line of Ogso Tagpochau due east to the eastern cliff line. The Agag groundwater basin occupies 0.75 mi^2 within the bounded study area.

Ground elevations within the study area range from 400 to about 1000 feet. The terrain is moderately rough and covered, for the most part, by a heavy mantle of vegetation. Some areas are relatively open where cattle have been grazed. The soil cover is thin (except in valley bottoms) with a few patches of stoney ground.

Access to the study area is by tributary roads to the cross-island highway. The highway bisects the area and connects San Vicente with Capitol Hill. Some remote parts of the area are accessed by foot along old Japanese-era roads or by cross-country means.

The surface geology shown in Figure 2, was mapped by H. W. Burke and R. G. Schmidt (Cloud et al., 1956) as part of the post-war mapping effort by the U. S. Army in cooperation with the U. S. Geological Survey. According to Burke and Schmidt, primarily the Tagpochau limestone crops out within the study area. The Tagpochau limestone consists of the inequigranular facies of generally pure detrital limestone (the dominant facies of the formation), the rubbly facies of pure to very argillaceous (high silt or clay content) limestone, and the marly facies of impure limestone. At the eastern boundary (forming the imprevious flow for the Natural Bridge Springs), the Donni sandstone and Machegit conglomerate members crop out at the base of the cliff. Both members are composed of reworked volcanic material. Just south of the Natural Bridge Springs and in the south-eastern part of the study area, the conglomerate and tuffaceous sandstone facies of the Densinyama formation crops out along the cross-island highway and in small valleys. Details of the subsurface geology are given in a later section.

Previously and currently active wells penetrating the aquifer of the Agag groundwater basin are located in the west-central part of the study area (see Figure 3). Currently active wells (50, 70, 72 and 73) are situated along a north-south line and unequally spaced. Well spacings ranges from about 200 to 500 or 600 feet. Wells currently used as observation wells with the exception of TH-10 have been production wells in the past. They have been temporarily abandoned, probably due to well-screen encrustation or pump failure.

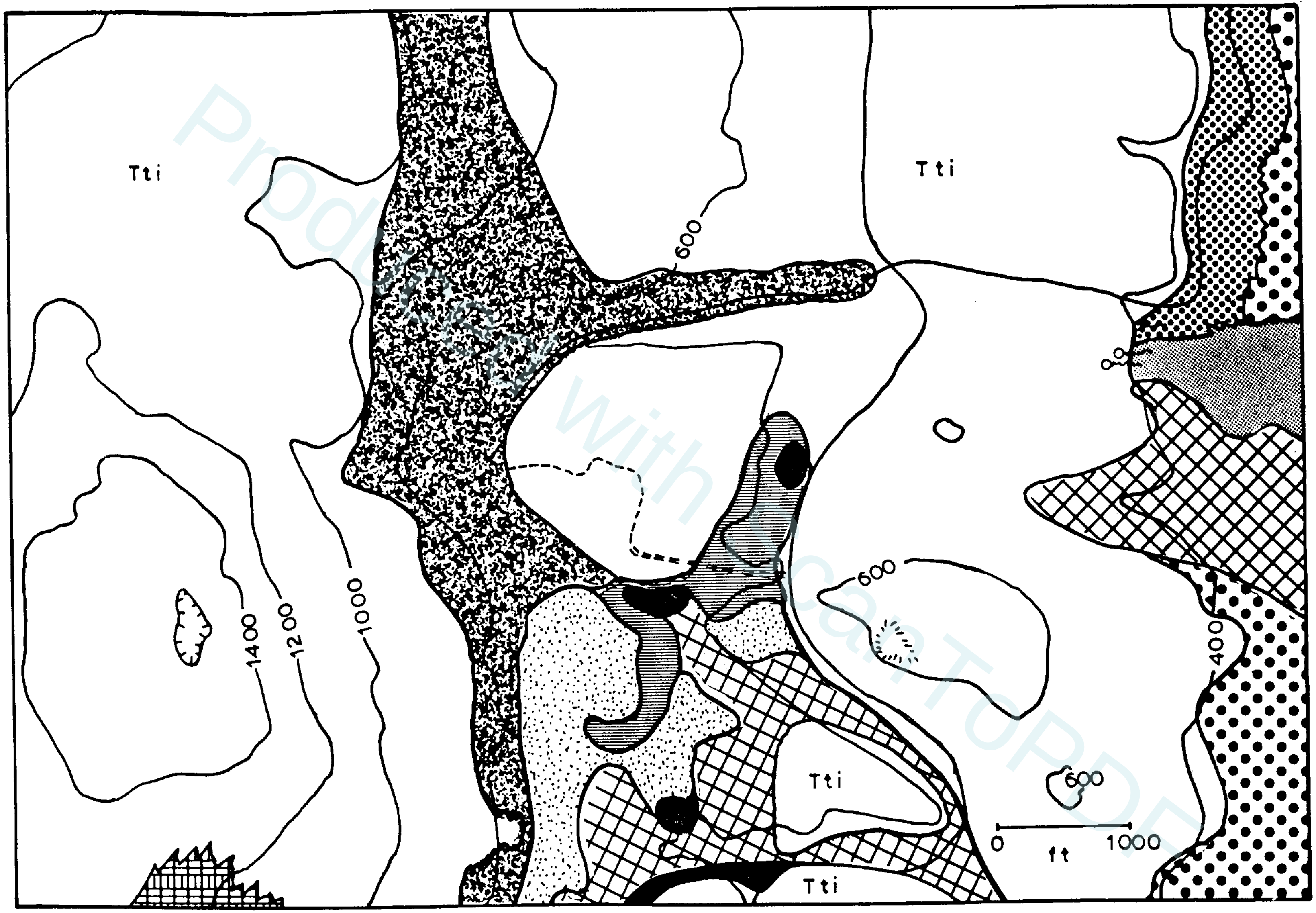

Figure 2. Geologic map of the study area adapted from Cloud et al., 1948. See accompanying key for descriptions of geologic symbols shown above.

Figure 2. Continued: Key to geologic map of groundwater basin. The data was taken from Cloud et al., 1948.

Tagpochau Limestone

A complex formational unit dominated by limestone of 6 major facies types. Includes also a sandstone subunit and a conglomerate subunit designated as members. Most distinctive and extensive limestone is massive, compact, inequigranular and generally pinkish. Maximum inferred thickness of unit is about 900 feet.

Tti, inequigranular facies. Pink, white, and variegated, generally pure, compact, inequigranular, detrital limestone; the dominant facies of the Tagpochau formation.

Ttr, rubbly facies. Mostly white, pure to very argillaceous, rubbly to powdery limestone and brecciated limestone. Locally grades to Ttm.

Ttm, marly facies. Yellowish argillaceous limestone; proportion of argillaceous impurities varies; lenticular or basal facies that grades to Ttv and, locally, to Ttr.

Ttv, tuffaceous facies. Dark brown, yellow-brown and purplish to dull lavender and dirty pink, highly impure limestone containing variable amounts of reworked volcanic material; a marginal (migrating basal) to lenticular or intertonguing facies.

Ttt, transitional facies. Calcareous conglomerate, and tuffaceous limestone, and sandstone; commonly with abundant large Foraminifera. Transitional to Donni member and various limestone facies, of formation.

Ttma, Machegit conglomerate member. Consists of reworked volcanic materials. Resembles conglomerate of Densinyama beds, and in part may be mapped as Densinyama formation.

Ttd, Donni sandstone member. Calcareous and tuffaceous marine sandstone; rich in Globigerina. Occurs in varying stratigraphic relationships with remainder of Tagpochau succession.

Tt, undifferentiated strata. Transitional or mixed limestone not included in any facies.

Ttvc, thick residual clay developed over Ttv and, in part, over Ttm.

Figure 2 continued.

Densinyama Formation

Andesitic breccia and conglomerate, tuffaceous sandstone, tuffaceous limestone, and limestone-volcanic conglomerate. Maximum inferred thickness about 800 feet. Formation transitional between preceding dominantly eruptive and succeeding marine sedimentary formations.

Tdc, conglomerate and tuffaceous sandstone facies; Tdcq where facies contains much quartz.

DESCRIPTION OF THE STUDY

General

The Agag groundwater basin study, initiated August 1980, employed a number of investigative methods. These methods included literature reviews, data and information searches, field work, and laboratory analyses.

Literature reviews were conducted early in the study and consisted of acquiring previous work as it related to water-resource investigations in and around the study area. These investigations provided the background information needed to guide the present study toward achieving its objectives. The data search included additional sources such as the files of the Public Works Department (CNMI) and the U. S. Geological Survey, (Guam Office) and the climatological records of the National Oceanographic and Atmospheric Administration (NOAA), the Nation Weather Service, and the Northern Mariana Agricultural Research Center.

Field work was conducted throughout the study period and consisted of four work efforts. These work efforts were: (1) field checking of previous surface geologic mapping; (2) elevation survey of observation wells; (3) exploratory drilling; and (4) water-level monitoring. Of these efforts, the drilling and monitoring efforts proved to be most useful in unravelling the complexities of the Agag groundwater basin.

Laboratory analyses were conducted toward the end of the study period and consisted of several efforts. These included analyses of pump-test data, description of the geologic properties of core and cutting samples, and interpretation of water-level measurements and other field data.

Each aspect of the study is described in detail below.

Literature Review and Data Acquisition

References listed at the end of this report include all available sources of information on previous investigations of groundwater in the Agag area. Most of these reports repeat the summary presented by Dan Davis (1958). However, nearly all of these reports make essentially the same recommendation, that is, to conduct a formal evaluation in order to determine the optimal or sustained yield of the resource.

Data that has been previously collected consists of water-level measurements, pump-test data, driller's logs, and rainfall data from a nearby recording station (Trust Territory Government Communication Station, Kagman). These data have been reviewed and the most reliable information appears in Appendices A and B. They are probably not complete because some information was not available to this study. For example, it was not possible to acquire well logs or pump-test data on wells 72 and 73, which were drilled some time between 1975 and 1979 or data on an exploratory hole drilled along the pipeline to Capitol Hill on the northwestern boundary of the basin. Other data may be outstanding as well.

Field Work

The various field methods employed by the study provided information on the hydrogeologic characteristics and behavior of the groundwater-flow system within the Agag basin. Previous geologic mapping (Cloud, et. al., 1956) was field checked for two purposes. One purpose was to insure that the area had received adequate attention during the post-war mapping period in terms of accurately describing the surface geology. The second purpose was to gain a familiarity with the geologic properties of the various units that are exposed in the study area. Elevations of observation wells were determined by a level-and-rod survey. All of the newly drilled exploratory holes in addition to wells 31 (new), 45 (old), and 45 (new), and 75 were included in the survey. A large error was found between the reported elevation (Davis, 1958) and the recently determined elevation at well 45 (old). The error amounts to a difference of about 32 feet (reported elevation is 32 feet below measured elevation). Thus water levels converted to water-table elevations by previous workers could not be used to make sensible interpretations in terms of the continuity of the water table across the basin.

Exploratory Drilling

The exploratory drilling program employed by the study warrants special mention because of the valuable information that was gained about the geologic composition of the Agag groundwater basin.

Exploratory drilling (conducted by Geo-Engineering and Testing, Guam) utilized both rotary and core bits. Exploratory holes were drilled from the surface to approximately 10 to 20 feet above the estimated position of the water table. Cuttings were collected at five-foot intervals when return circulation existed. After reaming and cleaning, the hole was extended by core drilling (using a barrel which produced a four-inch core). Core drilling continued for an additional 100 feet or until the volcanic basement was reached. A total of eight exploratory holes was originally planned but because of access and land-owner problems, two wells were eliminated from the drilling program. In general, the returns were very good to excellent considering the type of material that the bit encountered. After completion of the holes, both the cutting samples and cores were boxed and shipped to the WERI for laboratory analyses. For locations and characteristics of the exploratory holes, see Figure 3 and Table 1, respectively.

From the existing geologic map (Cloud et al., 1956) it was known in advance of drilling that the area was composed primarily of the Tagpochau limestone of Miocene age. Thus it was expected that most of the drilling would be within this carbonate unit. Also, it was expected that return cuttings (for sampling purposes) would probably be poor due to lost circulation (which has been the history of well-drilling operations in carbonate rocks of Guam and Saipan). Because of these expectations, it was decided that coring would give the best results in terms of retrieving a representative sample of subsurface units. The greatest advantage of core drilling over the rotary method is that a whole and usually intact sample of the rock comprising the aquifer can be collected, rather than the small-sized chips produced by the rotary bit. Thus the bulk characteristics of the rock (i.e., pore distribution

Contour interval = 40 ft

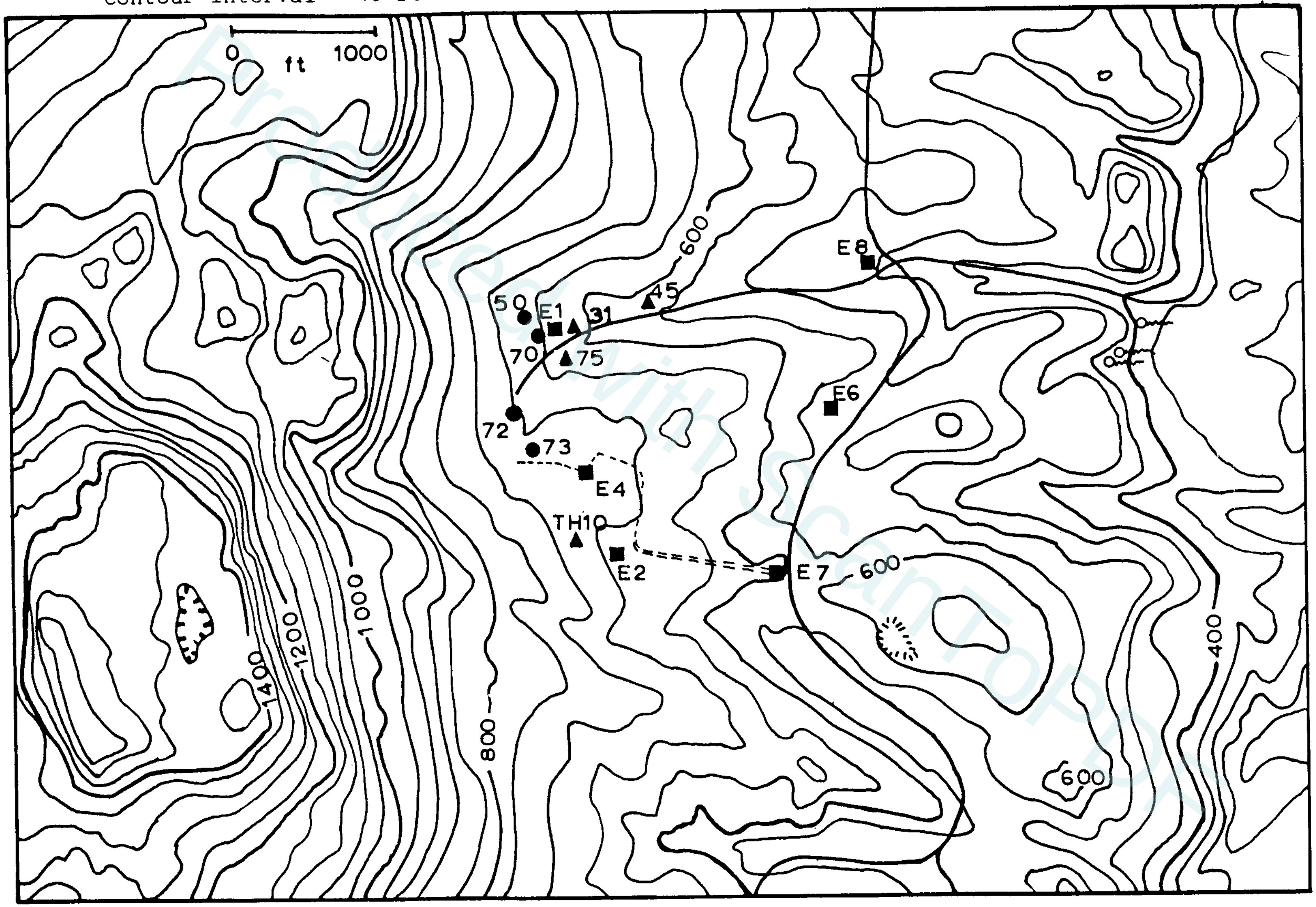

Figure 3. Map of the study area showing locations of current production, observation, and exploratory wells. Closed circles represent production wells, triangles represent observation wells, and squares represent exploratory holes.

Table 1. Characteristics of exploratory holes drilled during the study period.

WELL	ROTARY INTERVAL (ft)	CORED INTERVAL (ft)	TOTAL DEPTH (ft)
EXH-1	0-215	215-315	350
	315-350		
EXH-2	0-200	200-322	322
EXH-4	0-280	280-375	375
EXH-6	0-145	145-156	200
	156-170	170-200	
EXH-7	0-65	65-69	132
	69-115	115-132	
EXH-8	0-60	60-150	192
	150-174	174-192	

and size, composition, and texture) could be readily examined. Because the core is also a continuous sample, the entire rock column could be viewed and, therefore, the gross features (i.e., thickness of units, location of units, position and type of contacts between units, and distribution of fractures and solution features) could be easily observed and described.

Water-Level Monitoring

During the initial visit to the study area, it was found that wells 31, (new) 45 (old and new), and 75 were no longer used as production wells. These, along with TH-10, were converted to observation wells for the purpose of monitoring water levels. The monitoring program was started in September 1980 and the method of measurement was by steel tape and chalk. Later (January 23, 1980) a continuous recorder (Stevens Model A-35) was installed on 45 (old) then moved to 45 (new) on April 23, 1980. The remainder of the wells were measured on a weekly basis.

As exploratory drilling progressed, additional wells were added to the observation well network. These exploratory holes are open except for the upper 10 feet, which has been cased to prevent caving and debris contamination at the surface. As an additional precaution, a small cement pad was poured around the casing at the surface. Some wells have been equipped with a locking cap to prevent vandalism; the remainder of the wells will be equipped with locking caps eventually.

The purpose of monitoring water levels is two-fold. First, water-level measurements across the basin give information about the configuration of the water table. This information, along with knowledge of the size of the basin, provides the means to calculate the volume of groundwater in storage. Since the configuration of the water table is, in part, determined by the activity of wells, it is possible from water-level data to assess the effects of pumping on the groundwater-flow system. Second, water-level measurements collected from each observation site give information on the time response of the flow system to seasonal variations in recharge and fluctuating or intermittent pumping.

Laboratory Work

Laboratory work consisted of data compilation, analysis, and interpretation. Both previously collected data and information by other investigators and data acquired during this study were utilized by this phase of the work effort.

Data Compilation

Data from previous investigations were extracted from various reports (listed in the references) and government agency files (Public Works Department, Water Resources Planning Division, Environmental Quality Division, and others) and compiled into two data reports (in press). Data available to the study includes water-level measurements, rainfall records from a nearby station

(T.T. Government Communication Station), pump-test results from wells 45, 50, and TH-10, well-production figures, and driller's logs. Most of this information pertinent to the Agag basin study is contained in Appendix A.

In addition to the compilation of previously collected information, data acquired during the course of this study were compiled and later analyzed. These data appear in Appendix B.

Pump-Test Data Analyses

Available pump-test results for well 45 (old, new), well 50 (new), and TH-10 were used to calculate the permeability of the aquifer. Standard analytical techniques were applied to the data.

In the case of well 45, time-versus-drawdown measurements from both the pumping well and observation well were available. Therefore it was possible to apply non-equilibrium methods to calculate permeability. Two methods were used: (1) the Theis curve-matching procedure and (2) the Jacob method. As an additional method for purposes of checking the validity of the non-equilibrium procedures, the Thiem equation was applied to drawdown values obtained at the end of the test (assumed to be steady-state drawdown). Details of these methods are readily available in texts by Todd (1959), Davis and De Weist (1966), Walton (1970), Freeze and Cherry (1979), and others. Also, these methods are discussed in various manuals and bulletins on the subject of groundwater (e.g. American Water Works Association, 1973; Kruseman and DeRidder, 1979).

Permeability in the vicinity of wells 50 and TH-10 was determined by the application of the Thiem equation. Well 50 was tested immediately after the completion of drilling and prior to construction and development (i.e., in the open hole) and a second test was conducted after construction. Apparently, TH-10 was tested only after it was cased, screened, and gravel packed.

Data used in the determination of permeability are given in Appendix A; results are discussed in a later section.

RESULTS OF THE STUDY

General

This section presents the results obtained from the analyses and interpretations of data collected during the course of this study. It includes a description of the subsurface geology within the basin, an interpretation of water-level measurements, and the results from pump-test analyses.

Elevations for all the observation wells determined from a rod-and-level survey are listed in Table 2. All elevations are relative to mean sea level.

Geological Description of the Study Area

The following description of the subsurface geology of the Agag groundwater basin is based on the results obtained from the exploratory drilling of six test holes. Of particular interest to the study was the rock type present at and below the water table, that is, that portion of the subsurface which comprises the Agag aquifer. Core drilling provided representative samples of this interval. Detailed descriptions (lithology) of the cuttings and cores collected from the drilling operation are given in the geologic logs contained in Appendix B.

The geology of the Agag groundwater basin is a complex three-dimensional mosaic of interbedded and interfingered facies and members of the Tagpochau limestone of Miocene age. An interpretation of the drilling results is represented by three geologic cross-sections (locations shown in Figure 4). Cross section AA is taken through exploratory holes EXH-7, EXH-6, and EXH-8 in a northerly direction across the central part of the basin. Cross section BB is taken through EXH-1 and parallel to the long axis of the basin and ending at the springs along the eastern boundary. The third cross section (CC) is taken through EXH-1, EXH-4, and EXH-2 along a northwest-southeast line at the western or upper end of the basin. Cross sections AA, BB, and CC are shown in Figures 5, 6, and 7, respectively.

Based on the work of Cloud et al. (1956), the various rock types encountered in the drilling of exploratory holes have been tentatively assigned to four facies of the Tagpochau limestone. The Donni sandstone member (Ttd) was not found during drilling but is believed to interfinger with the marly facies (Ttm) west of the Natural Bridge Springs (as illustrated in cross section BB).

At EXH-1, the rubbly facies (Ttr) occurs from ground surface to a depth of about 40 feet. Chip samples indicate that the rock is a relatively pure, detrital white limestone with abundant fossil debris and chalky zones.

Underlying the rubbly facies and probably interfingering with it is the inequigranular facies (Tti), the dominant facies of the Tagpochau limestone. This unit consists of fine-grained to crystalline, pure, white limestone. A few of the echionoid sismondia were observed at the 45- to 50-foot interval. The lower contact was not identified because circulation was lost and thus, no returns were collected. However, the contact lies between -65 and -215 feet, since the marly facies was identified in the cores at -215 feet.

Table 2. Elevation of observation sites in the study area. All elevations are in feet above mean sea level and were determined by a rod-and-level survey.

Observation Site	Elevation
31 (new)	615.37
45 (old)	582.35
45 (new)	580.63
75	624.97
TH-10	694.40
EXH-2	649.96
EXH-4	683.50
EXH-6	545.21
EXH-7	585.62
EXH-8	493.10

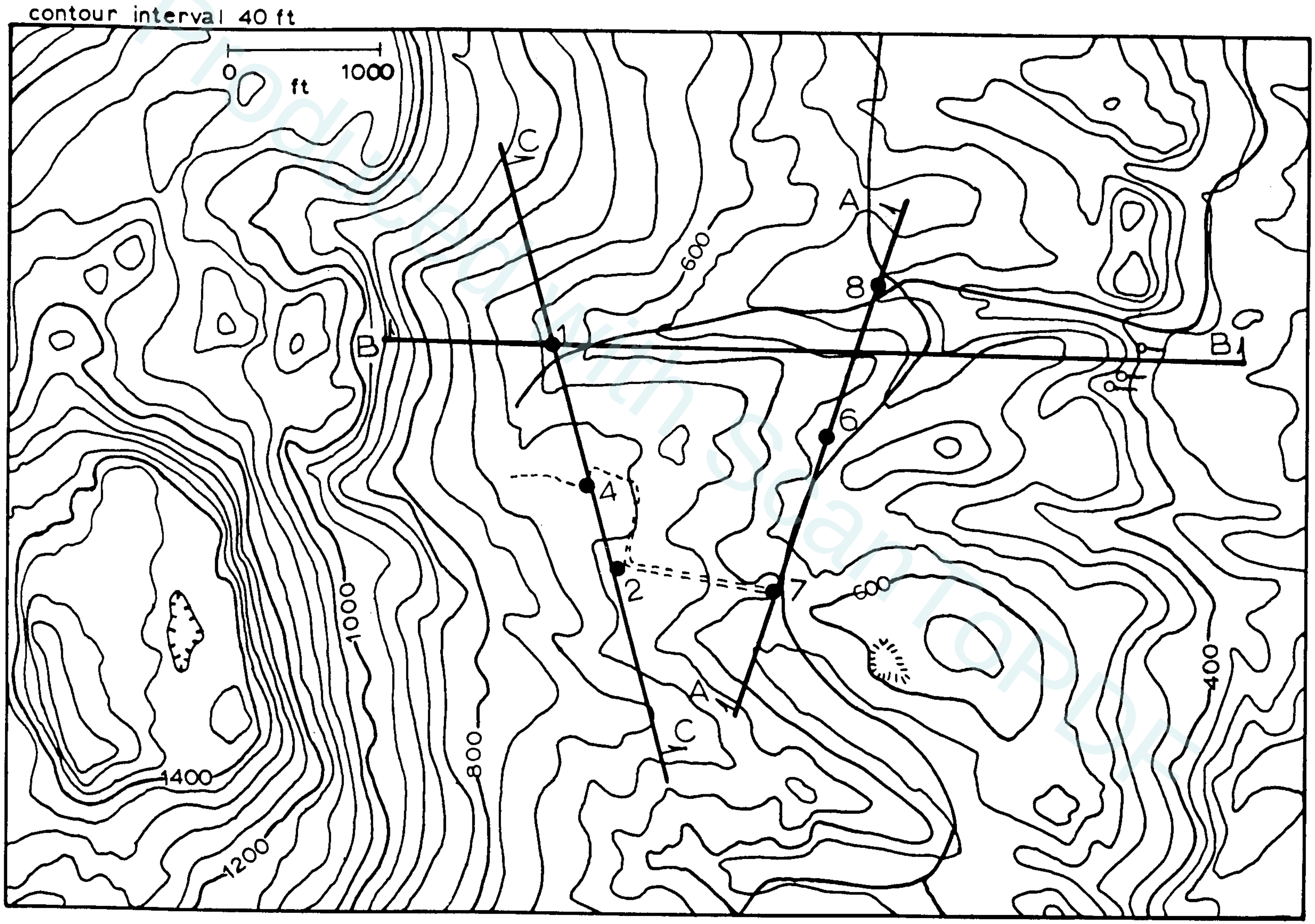

Figure 4. Locations of geologic cross sections through the Agag groundwater basin.

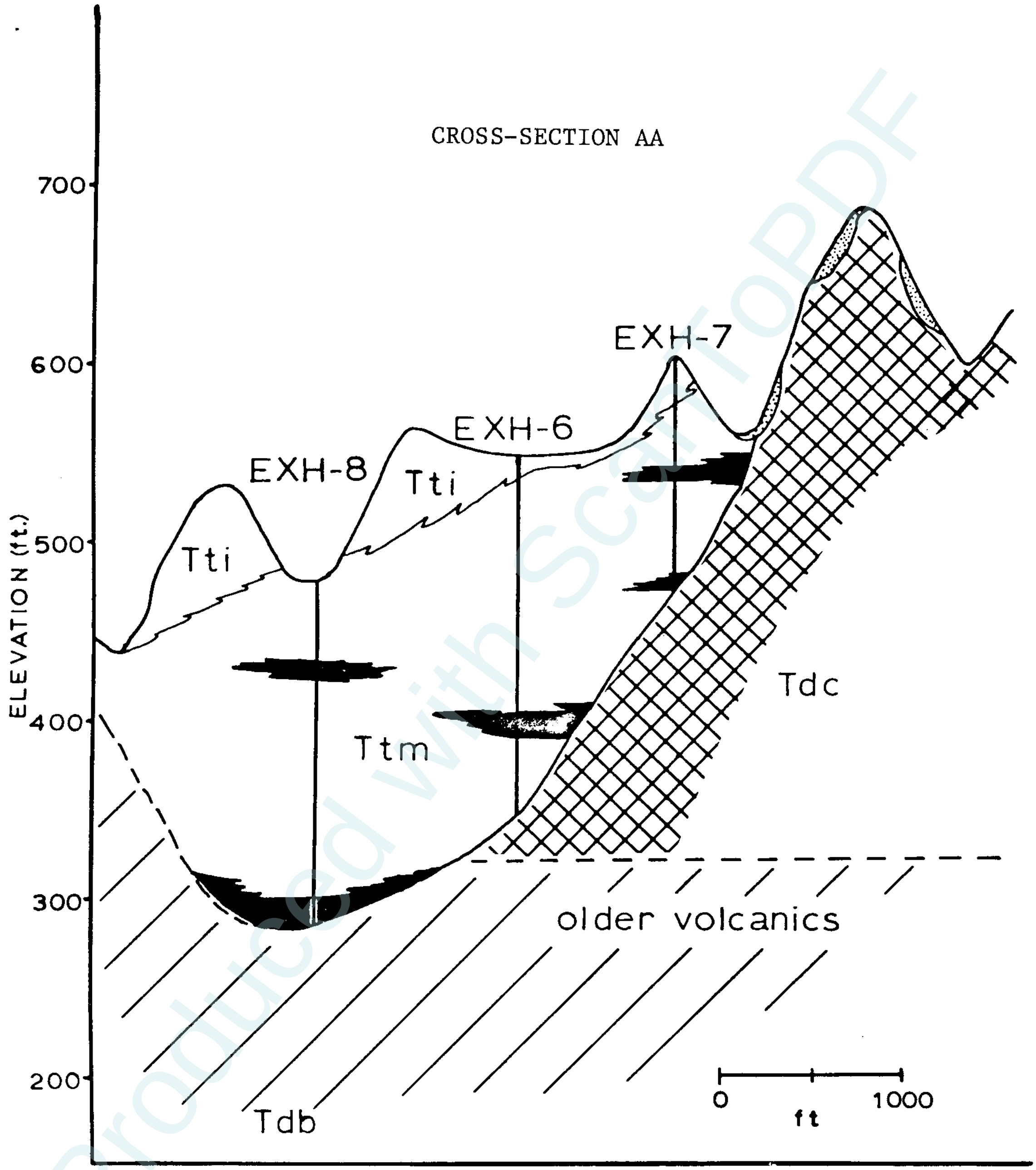

Figure 5. Cross-section AA through the Agag groundwater basin. See figure 4 for location of cross-section and key to geologic map (Figure 2) for description of symbols.

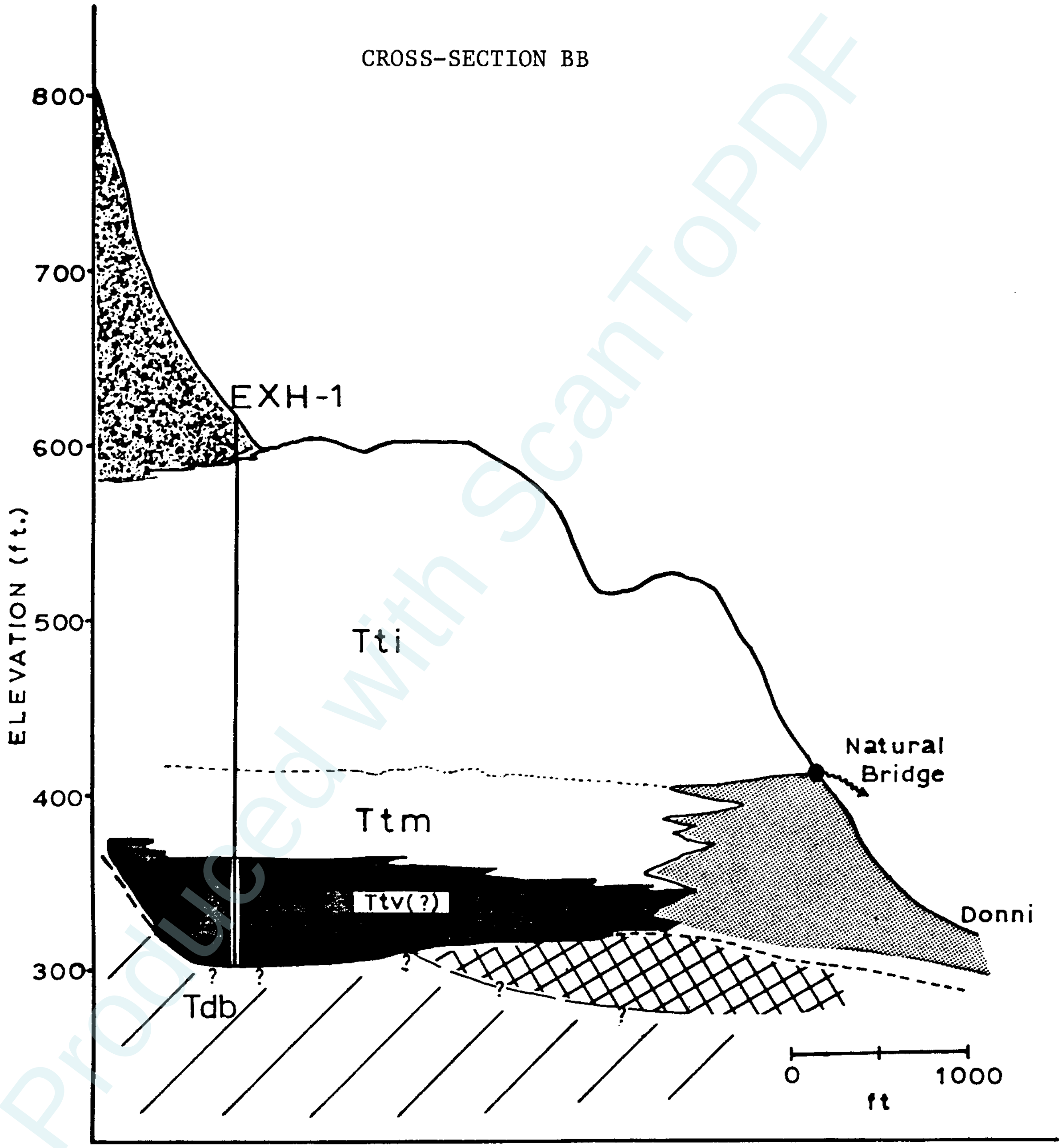

Figure 6. Cross-section BB through the Agag groundwater basin. See figure 4 for location of cross-section and key to geologic map (Figure 2) for description of symbols.

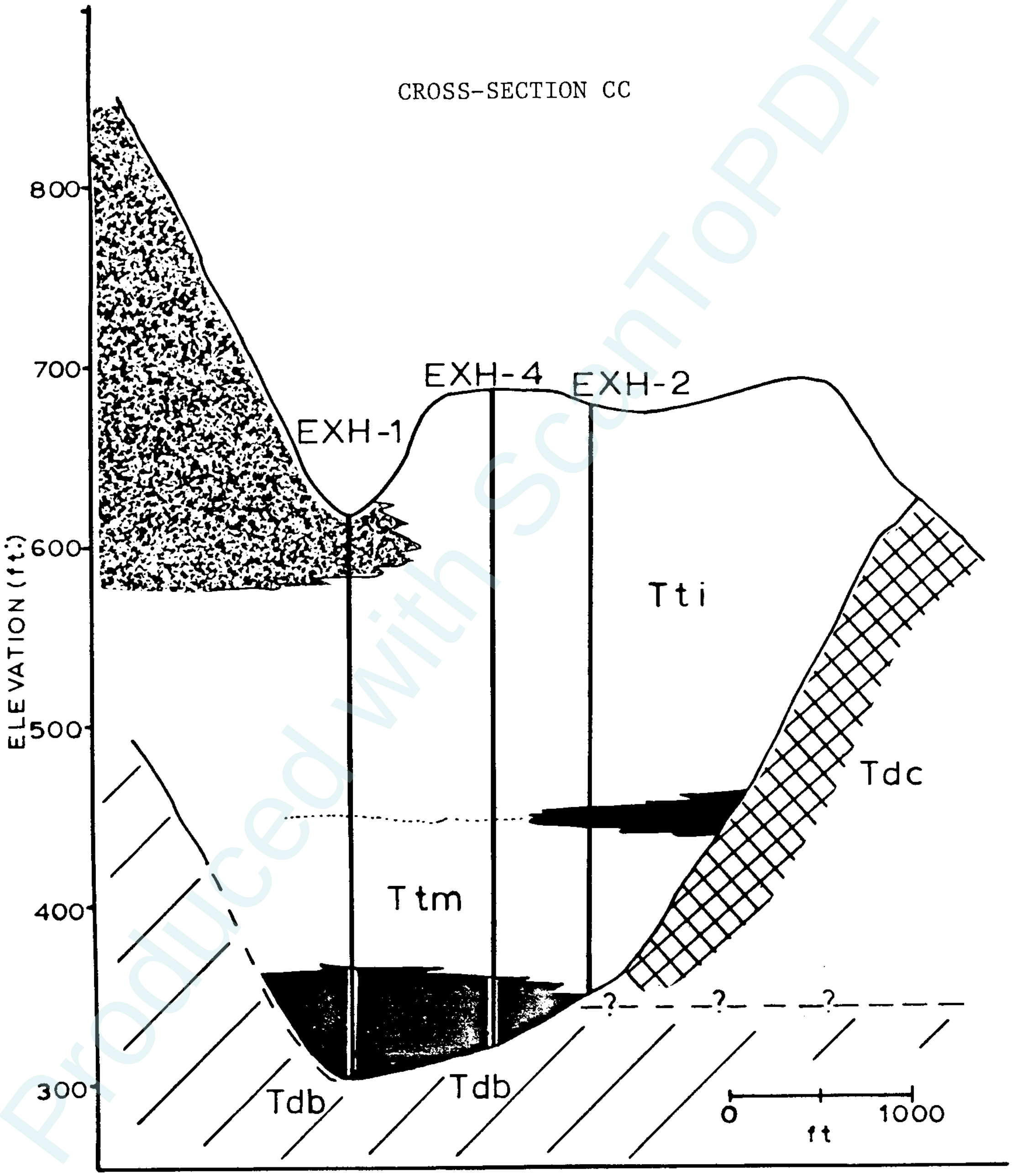

Figure 7. Cross-section CC through the Agag groundwater basin. See figure 4 for locations of cross-section and key to geologic map (Figure 2) for description of symbols.

The marly facies extends to a depth of 252 feet and consists of yellowish-white with minor pinkish-white, fossiliferous limestone with abundant chalky zones (particularly near the water table) and highly fractured and brecciated sections. The limestone contains varying amounts of silt or clay, numerous stylolites (solution fractures), abundant pyrolusite (manganese oxide) and limonite (ferric-oxide) stains, and moldic porosity. An insoluble residue (clay) lines stylolite and pore surfaces.

Underlying the marly facies and extending to the volcanic basement (at 300 feet) is the tuffaceous facies (Ttv). This facies consists of a very impure argillaceous limestone and interbedded calcareous mudstone with abundant volcanic debris. Both the limestone and mudstone are medium to dark gray in color and generally fossiliferous.

In general, the inequigranular facies occupies the unsaturated zone well above the present water-table position and the marly and tuffaceous facies occupy the saturated zone above the volcanic basement. However, it was found that the tuffaceous facies, occurs at several elevations, and interfingers primarily with the marly facies. The tuffaceous facies forms basal and marginal units and its occurrence is probably attributable to the deposition of sediments derived from the volcanic terrain in a near-shore marine environment. This process resulted in lenticular, tabular, and interfingering units of volcanic-debris rich limestones and calcareous mudstones within cleaner carbonate units.

The general configuration and position of the volcanic basement was defined during the course of the exploratory drilling. Volcanic rock or weathered volcanic material was encountered in EXH-4, EXH-6, and EXH-8. Proximity of the volcanic terrain to the bottom of the remaining exploratory holes was inferred from changes in rock type to one mostly or entirely composed of red clay. It was assumed that the red clay was derived directly from an adjacent volcanic shore line or was a product of in situ weathering of volcanic rock. Thus each exploratory hole provided a depth-to-basement measurement and collectively provided the necessary data to construct the basement contour map shown in Figure 8.

In addition to defining the basement topography, the rock type comprising the volcanic terrain was identified at least in general terms. The conglomerate and tuffaceous sandstone facies (Tdc) of the Densinyama formation (Eocene age), which crops out in the southeastern corner of the study area near EXH-7, was encountered at the bottom of EXH-6 and probably lies a few feet below the bottom of EXH-7. It is uncertain if this facies was encountered at the bottom of EXH-8 (returns were very poor and only a small amount of sample was recovered). Cuttings from the bottom of EXH-8 indicate a black, possibly andesitic, flow rock. This facies of the Densinyama apparently underlies the Tagpochau limestone from the south to at least between EXH-6 and EXH-8. The western extent of the conglomerate and tuffaceous sandstone facies is not precisely known but does not reach EXH-1, EXH-2, or EXH-4. The material recovered indicates that this facies is composed of primarily cobble-sized medium-gray andesite clasts set in a fine- to medium-grained tuffaceous matrix. Core samples indicate that the facies, at least at the contact with the Tagpochau limestone, has been subjected to weathering.

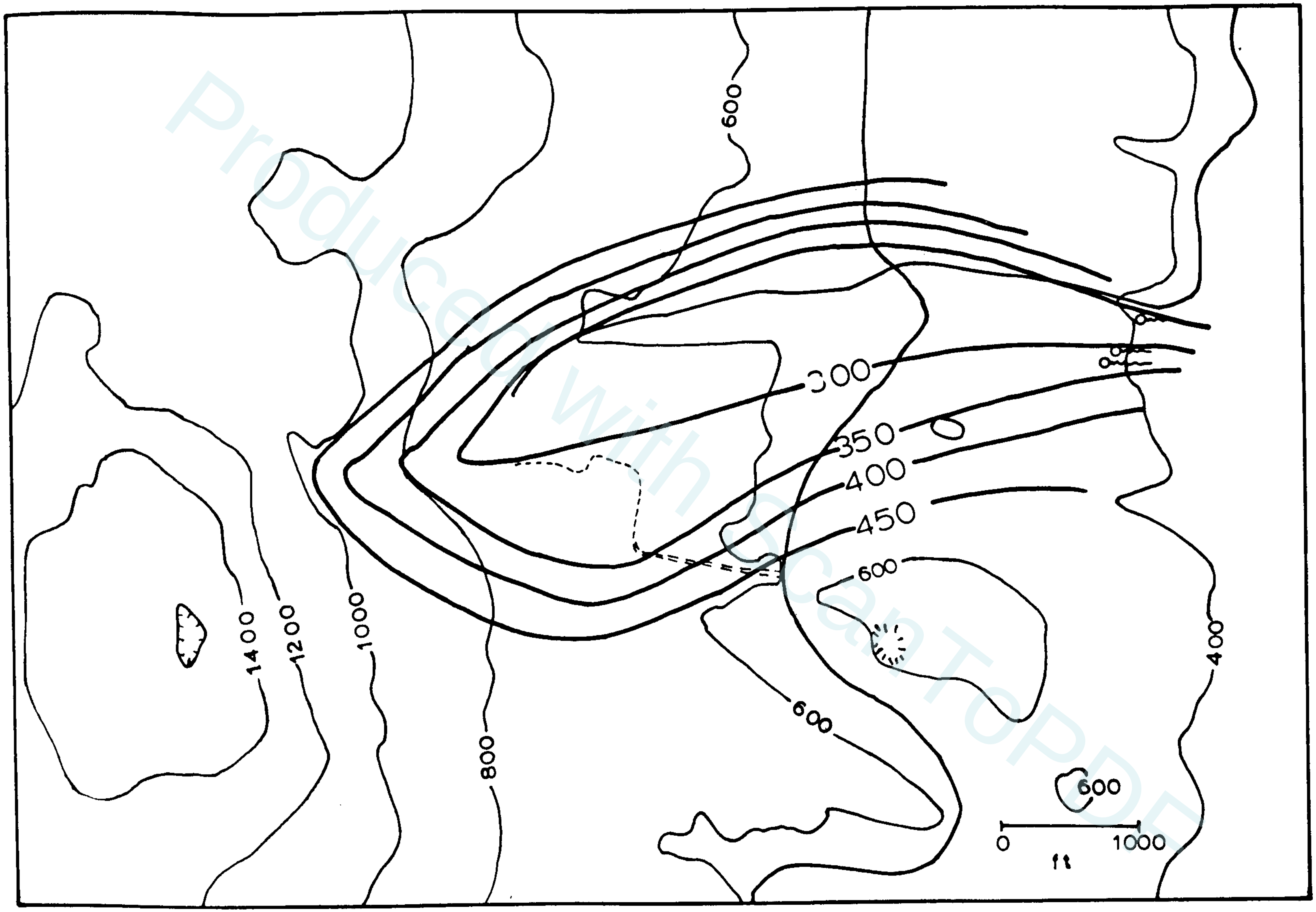

Figure 8. Contour map of the volcanic basement within the study area. Contours are given in feet.

Core samples from exploratory holes in the western part of the basin indicate that the basement, at least in part, is composed of deeply weathered rock. This unit, has tentatively been assigned to the breccia facies (Tdb) of the Densinyama formation. It is possible that this unit is part of the Hagman formation but at this time not enough fresh sample is available to make a proper identification.

In general, it appears that the Tagpochau limestone was deposited over an older volcanic terrain which developed on rocks of the Densinyama formation. The topography of the underlying terrain resembles an eroded valley; however, there is no indication that it was formed by subareal erosion. Regardless of how it formed, the valley opens toward the east and appears to have a steeper north slope compared to the south side. At the western end of the basin, the configuration is not well-defined. However, the general trend may be that of a westward rising valley head as indicated by previous results from drilling (D. Davis, personal communication).

Enterpretation of Water-Level Measurements

Water levels measured prior to and during this study indicate a long-term decline in the elevation of the water table. Water-level data from 1945 to 1981 for wells 31 (old and new) and 45 (old and new) are plotted on Figure 9. Although the data are scanty to non-existent between 1945 and 1973, the gross aspects of water-level behavior can be seen. In the vicinity of the first three wells drilled into the Agag basin, the initial condition (prior to pumping) was a water table at an elevation (above MSL) of approximately 455 feet. Present-day conditions indicate a water-table elevation in the vicinity of well 45 at about 420 feet and in the vicinity of well 31 between 390 and 400 feet (well 31 is probably within the cone of depression of wells 50 and 70 which are currently active). Overall, there has been a substantial decline of about 35 to 40 feet since 1945.

Of particular interest is the time interval between 1973 and the present where data are more complete. The line drawn through the data points of Figure 9 was constructed using the method of linear least squares and has a correlation coefficient of 0.76, which indicates only a fair line fit to the data. This low correlation coefficient is related to the oscillating character of the data about the least-squares approximation. The result of fitting a line to the data indicates that, at least since 1973, there has been a steady decline in water-table elevations at a rate of about 1.25 ft/yr at well 45.

Well 45 is probably a good indicator of the conditions that prevail over the basin. The well is located at a distance from the center of pumping such that interference effects are minimal and measured water levels are therefore representative of the position of the water table in the vicinity of well 45. Thus, variations in the position of the water table with time are related primarily to storage changes due to seasonal recharge and removal of water by pumping rather than the local effects of cone-of-depression interference. (Interference effects are discussed in a later section.) The same decline rate can be inferred from the water-table elevation versus time plot at well 31. However, this is somewhat speculative because of the data gap between 1974 and 1980.

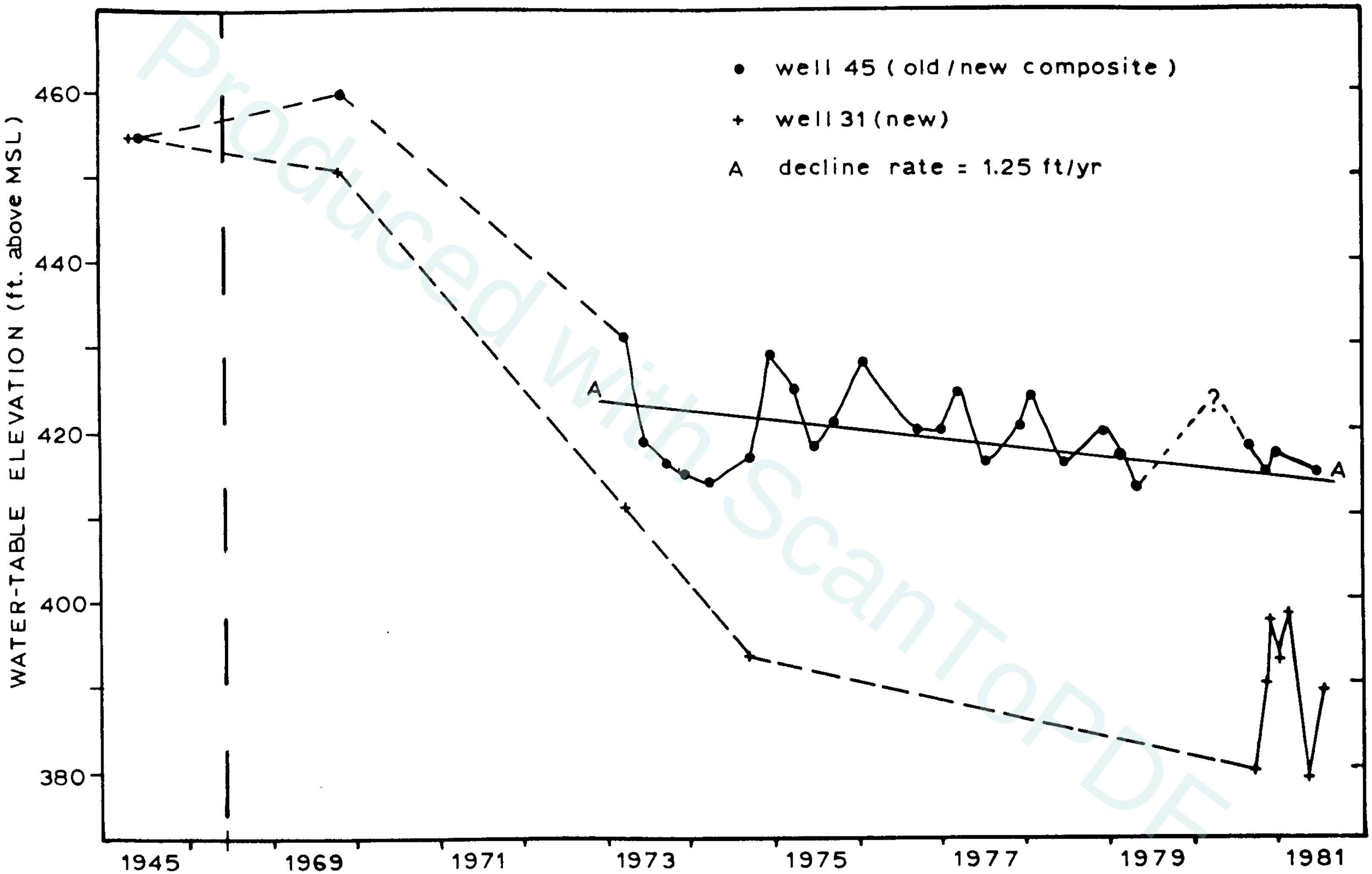

Figure 9. Water-table elevations for wells 31 and 45. Data are from 1945 to 1981.

If it is assumed that rainfall, and therefore recharge, has been relatively constant since 1973 and if wells 31 and 45 are representative of basin water-table behavior, then the decline rate is due strictly to overdraft of the aquifer.

The graph of Figure 9 also indicates a high degree of correlation between fluctuations of the water table and the seasons. Water-table rises appear to correlate with that time of the year when the wet season typically occurs and rapid declines appear to correlate with the typical occurrence of the dry season. The water-table elevation-rainfall graph of Figure 10 clearly shows the correlation between water-table fluctuations and rainfall-related recharge events. Rainfall data are from the Kagman station (Appendix B) and are cummulative values for 15-day intervals. Water-level data are from well 45 (a composite from both old and new wells). By the end of August, the water table at well 45 and presumably across the basin was at the lowest elevation for the year. Saipan was essentially in a drought condition due to the late arrival of the wet-season rains. By this time, the water level in production wells 50 and 70 had reached the pump intakes and air was being introduced into the distribution system reducing the quantity of product water. Heavy rainfall began around September 6 and persisted for the next six days. As shown by the graph, there was a rapid but somewhat delayed rise in water levels. The lag time for recovery appears to be about three weeks, but this is very tentative because water-level measurements were taken on a once-a-week basis. With a decrease in rainfall, there was a corresponding decline in water-table elevations.

The present-day water-table configuration is dramatically different than that of pre-development time. Water-table maps of Figures 11 and 12 were constructed using available data and inferring a relationship between the water levels of the basin and the elevations of Natural Bridge Springs. The map of Figure 11 is the configuration prior to the beginning of development in 1945 and the map of Figure 12 is the present-day configuration (May 1981).

Pre-development contours indicate a relatively smooth and regular surface to the water table. Water levels are higher at the western end of the basin and decline down gradient to the outfall at Natural Bridge Springs. Presumably, the spring elevations forms the base level where all flow within the basin eventually emerges. (The boundary depicted in the maps was established utilizing the results from exploratory drilling). The present-day map shows a much more complicated pattern. At the western end, in the vicinity of the production wells, there is apparently a large area of diversion in which observation wells 31, 45, TH-10, EXH-4 and probably EXH-2 have been included. Water levels within much of this area of diversion are lower than the spring elevation by as much as 20 to possibly 30 feet. Thus, the hydraulic gradient over most of the basin has been reversed (in direction) from that of the initial condition (Figure 11).

In summary, water-level measurements indicate two major features about the history of the groundwater-flow system of the Agag aquifer. First, there has been a relatively large decrease in water-table elevations over the years since pumping began. Although the rate of decline is not known prior to about 1973 due to a lack of reliable data, it probably was substantial. Since 1973, however, the rate of water-table decline appears to be about 1.25 ft/yr, a

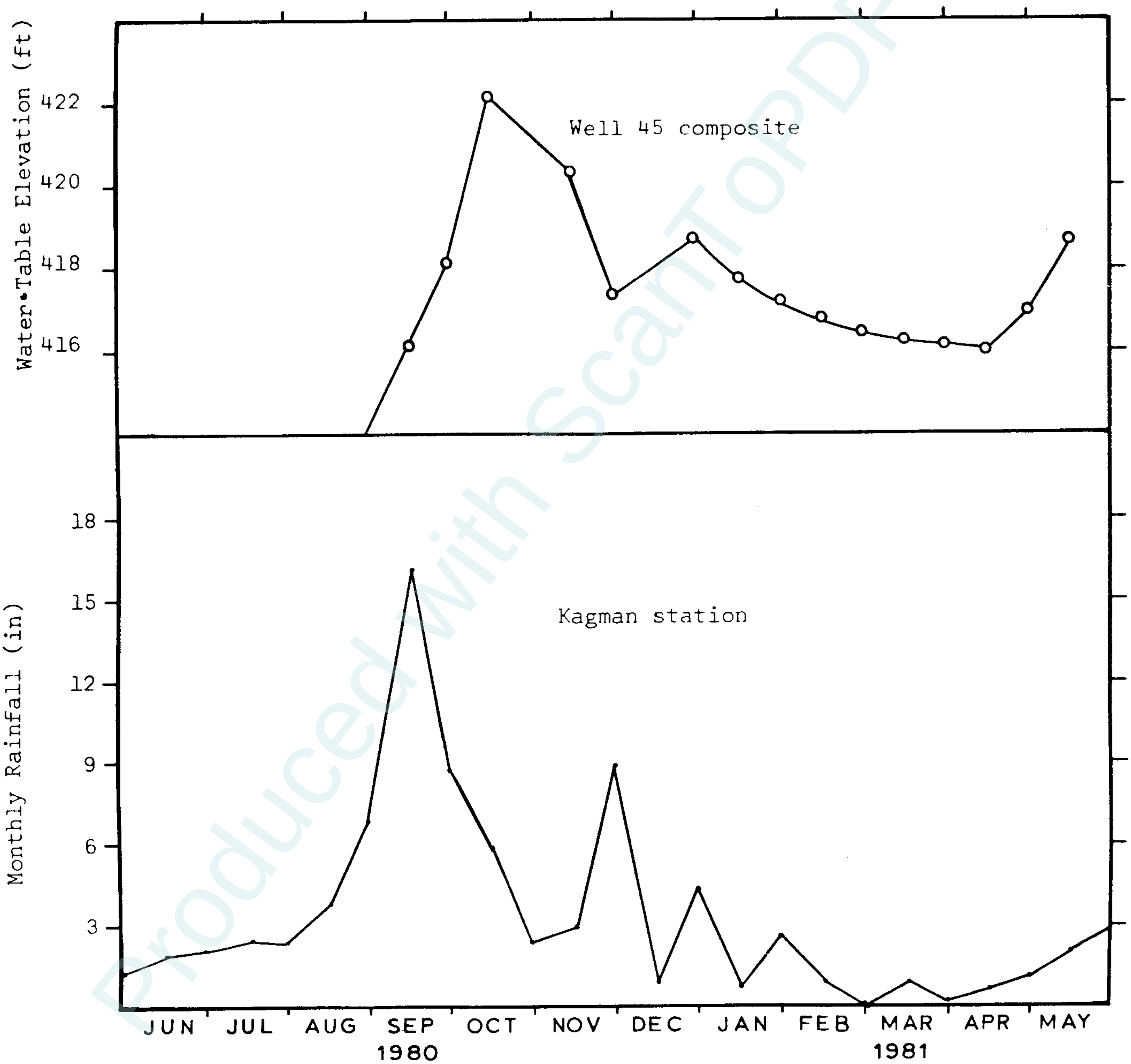

Figure 10. Correlation between water table fluctuations and rainfall events.

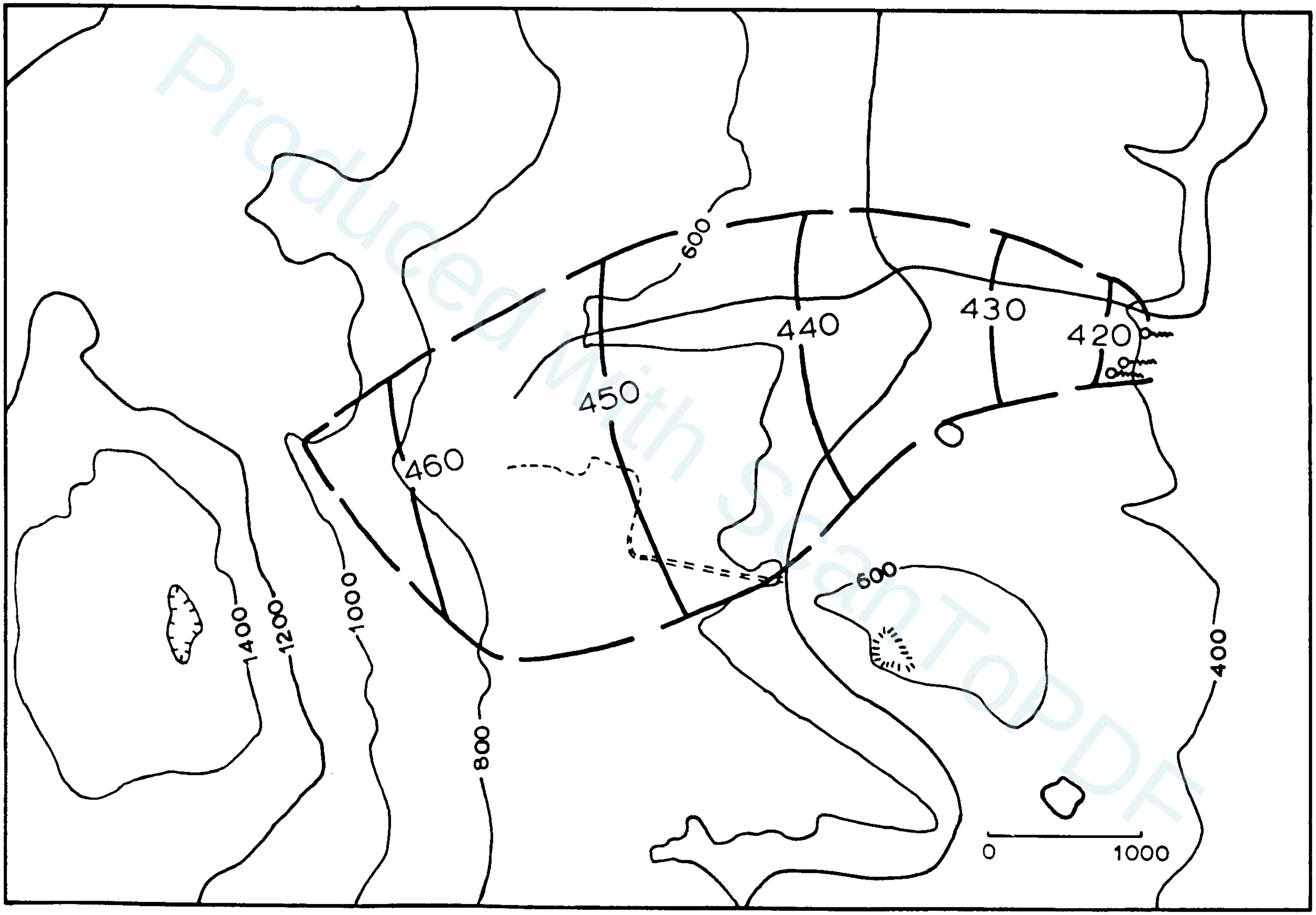

Figure 11. Contour map of the water table prior to development of the Agag groundwater basin. All contours are given in feet above MSL.

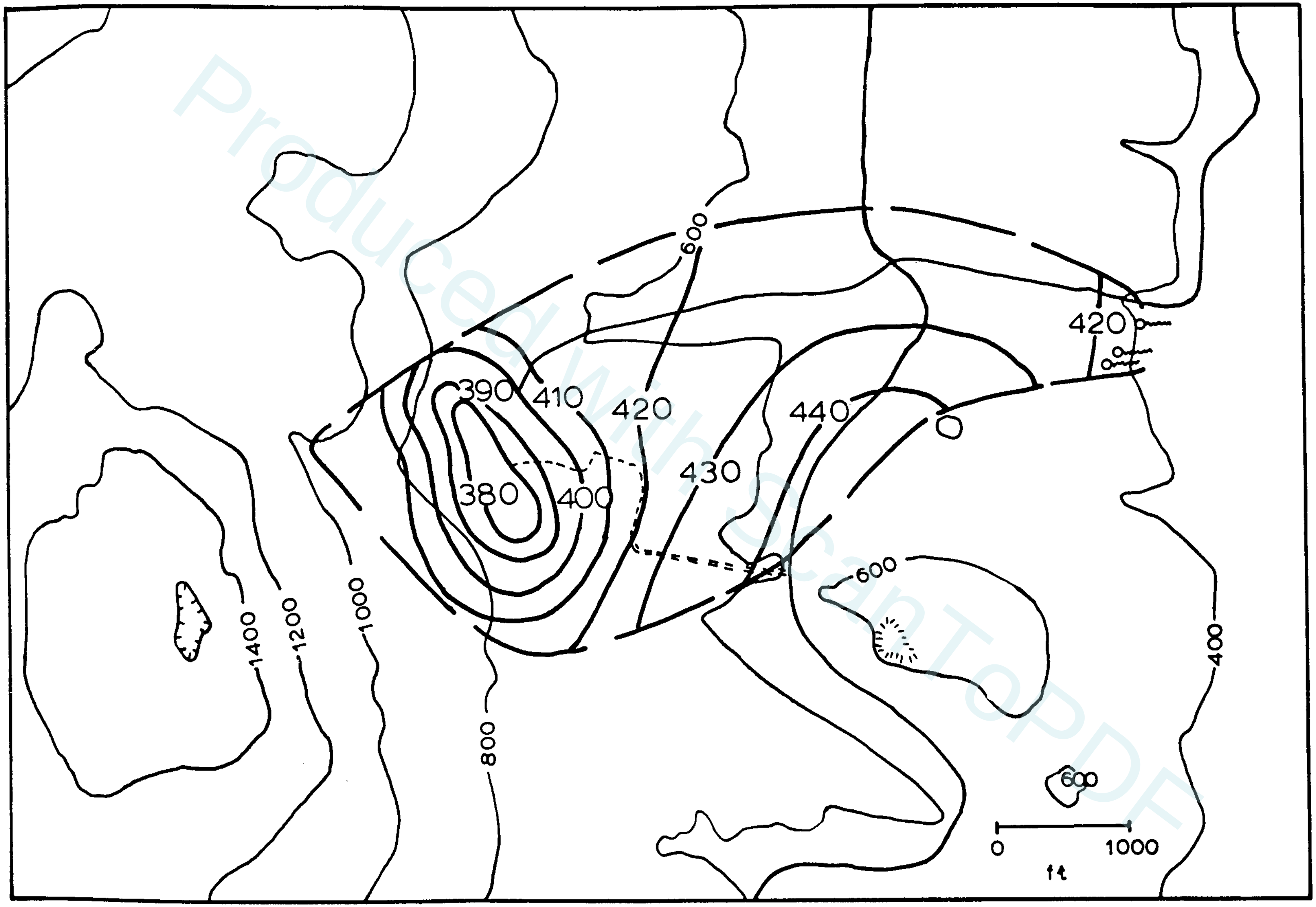

Figure 12. Contour map of the present-day water table of the Agag groundwater basin. All contours are given in feet above MSL.

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very substantial quantity. Second, the configuration of the water table has changed drastically when compared to the initial condition prior to pumping. It appears that the hydraulic gradient has been reversed over much of the basin.

Pumping-Test Results

Results from the application of the Theis and Jacob methods, and the Thiem equation indicate that the permeability ranges between 25 and 70 ft/day. These values apply to the western end of the basin and are assumed to be applicable to other areas of the aquifer until more definite values are available. Results of the analysis are listed in Table 3.

The following assumptions were made in order to apply the analytical methods:

1. Wells penetrated the full saturated thickness of the aquifer.
2. Water is released from storage instantaneously.
3. Boundaries are far enough away not to effect the test results.
4. Recharge over the test period is negligible.
5. Radial flow to the well is horizontal (no vertical flow components present).
6. Aquifer properties are isotropic and homogeneous.

Table 3. Results of pump-test analyses.

Well	METHOD			
	Theis	Jacob	Thiem	Permeability (ft/day)
45 (old)	X			26.0
45 (old)		X		30.7
45 (new)			X	25.4
45 (old)			X	32.0
50 (new-open hole)			X	62.9
50 (new-cased hole)			X	28.0
TH-10			X	70.4

DISCUSSION

General

The following discussion focuses attention upon three areas of prime interest. Specifically, these areas are basin hydrogeology, aquifer yield, and basin management. This discussion represents an overview of what is known or suspected about the flow system within the Agag groundwater basin.

Hydrogeology of the Basin

From results of the exploratory drilling, the limestones that make up the Agag aquifer apparently were deposited in a valley-shaped depression previously formed in older volcaniclastic rocks of the Densinyama formation. Two units, the marly facies and the tuffaceous facies, of the Tagpochau limestone comprise the aquifer. At the western end of the basin, the tuffaceous facies forms a basal unit filling the deeper parts of the valley depression. Elsewhere, the facies forms lenses and tabular bodies that interfinger with the marly facies and probably the Donni sandstone member near Natural Bridge Springs.

The two units that comprise the aquifer probably differ greatly in their hydraulic properties. Contrasts in properties relate to lithologic changes with depth.

Permeability of the marly facies is related to the highly fractured and brecciated zones at various levels and to the presence of stylolites. Near the water table, the unit is very chalky, probably due to mineral metastability and solution activity within the zone of mixing between ground water and recharge water. This zone, extending from the water table to a saturated depth of approximately 20 feet, probably has the highest permeability. Results from pump-test analyses indicate that a range of permeability values from 25 to 70 ft/day is applicable to the marly facies. An accurate description of the distribution of permeability magnitude across the basin cannot be made at this time because only a few wells have been tested and they are located at the western end of the basin.

In general, the permeability of the tuffaceous facies is probably very low. This unit contains abundant clay and silt; calcareous mud stone is interbedded with very impure argillaceous limestone. Although no pump-test data are available for the tuffaceous facies, the performance of well 31 (new) may add validity to the above speculation. At some time in its history, well 31 was deepened an additional 50 feet and reconstructed. Apparently, the water table in the vicinity of well 31 had been lowered such that the pumping level had reached the intake. After completion of the reconstruction, it was found that the well yield was not adequate to warrant continuing production and the well was abandoned. Approximately 25 to 30 feet of the tuffaceous facies was penetrated by the redrilling operation. Because the well yield was low, the tuffaceous facies probably did not contribute a significant volume of water to the well. Therefore, the permeability is assumed to be much less than that of the marly facies.

Rocks of the volcanic basement appear to be weathered to various degrees. Volcanic material retrieved from EXH-4 is very deeply weathered with complete alteration to clay. Other volcanic rocks encountered in the exploratory drilling operation show evidence of at least some alteration to clay by weathering processes. Thus it is assumed, because of the presence of abundant clay, that the volcanic basement is essentially impervious relative to the limestones comprising the aquifer.

Annual recharge to the Agag aquifer has not been determined precisely. However, by making an assumption that evapotranspiration rates are about the same as those for Guam, an estimate of recharge can be made. On a long term basis, the Kagman station receives about 74 inches of rainfall per year (average of a 12-year record). Assuming that evapotranspiration is about 60 percent of the rainfall (Ayers, 1981), the annual recharge rate is about 29.6 in/yr. Taking the area of the basin susceptible to recharge at 0.75 mi^2, the volume rate of recharge to the groundwater-flow system is approximately 1.061 x 10^6 gpd. This figure does not account for seasonal variations in rainfall or evapotranspiration.

Fluctuations in recharge related to seasonal variations in rainfall and evapotranspiration are of greater concern than the annual rate which is calculated from evenly distributed (in time) rainfall events. Again, by making an assumption that evapotranspiration rates are similar to those of Guam, an estimate of monthly recharge can be made. According to Blumenstock (1957), any month with less than four inches of rainfall is a drought month (no water available for recharge). If this value is taken as the critical value below which no recharge occurs, then an estimate of monthly recharge can be calculated by subtracting the critical value from the monthly rainfall totals. Applying this logic to the Kagman station yields the monthly recharge rates listed in Table 4. Monthly rainfall values represent the average for each month over the 12-year record. The annual recharge rate is 34.3 in/yr which is about 46 percent of the annual rainfall and is in good agreement with the annual rate determined previously.

As expected, estimated monthly recharge rates demonstrate a strong seasonal fluctuation. From Table 4, recharge to the basin occurs between July and November inclusive. No recharge can be expected between December and June. Of course, these time periods correspond to the wet and dry seasons, respectively.

During a period of long or extended dry seasons, water-table declines may be substantial. Evidence for this is provided in Figures 9 and 10. The graphs show considerable range from wet season water-table elevations to those of the dry season. It appears that a fluctuation of 10 feet is not uncommon. With water-table responses of this magnitude, if water production continues at unaltered rates from the wet season into the dry season, then water in storage could be removed rapidly (mining). If the wet season does not provide an adequate quantity of recharge to the flow system, water-table elevations will not return to the height of the previous year. The situation will become progressively worse in terms of water production and may lead to a permanent loss of stored groundwater.

It is clear from the graph of Figure 9 that the situation just described currently exists in the Agag basin. Since 1973, there apparently has been a

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Table 4. Estimated monthly recharge rates to the Agag aquifer. Rainfall data from the Kagman station.

Month	Rainfall (in)	Recharge (in)	Volume Rate (gpm x 10^6)
Jan	2.85	0	0
Feb	3.08	0	0
Mar	1.78	0	0
Apr	1.77	0	0
May	3.48	0	0
Jun	2.98	0	0
Jul	10.35	6.35	2.66
Aug	15.54	11.54	4.93
Sep	12.61	8.61	3.69
Oct	7.57	3.57	1.54
Nov	8.35	4.35	1.84
Dec	2.88	0	0
Total	73.24	34.42	14.66

water-table decline of about 1.25 ft/yr. This condition is serious when considering the future of the basin. At present, pumping levels in production wells are only a few feet above the pump intakes. On two occasions during the course of this study, wells 50 and 70 pumped air, once at the end of the drought and again about midway through the dry season of 1981. If this decline persists, wells 50 and 70 will be operational for only a couple of years at best. The life span of wells 72 and 73 is difficult to predict because the pump settings are not known; however, it is probable that they will be functional for a number of years if wells 50 and 70 are removed from the production line.

Taking the recharge rates given above and the current production rate of the Agag wells, approximately one-half of the annual recharge is extracted. The remainder leaves the basin either at Natural Bridge Springs or through seepage areas east of the cliff line (or some other location not identified). Recharge not removed by wells goes to the maintenance of the head distribution across the basin and flow at the outfall. If more than half of the recharge is removed, present head levels will decline at a more rapid rate than the 1.25 ft/yr, the area of diversion will expand greatly, and spring flow will diminish. One additional condition that should be considered is that, with continuing water-table declines, the overall size of the aquifer (and, hence, the volume of storage) will become smaller. The reason for this is related to the valley-shaped depression occupied by the aquifer. As water levels drop, the surface area of the water-table decreases due to the inward sloping boundaries. Because the rate of change in volume is not linear (related to area which is a squared term), as the basin shrinks, water-level decline accelerates. Thus, the situation is self-generating.

There are several factors that contribute to low water levels near production wells other than overdraft. Of these factors, well interference and boundary effects impose the greatest influence on water levels.

Additional drawdown at a well site is produced by the interference of the cone of depression from an adjacent pumping well (see any ground-water textbook for an example). If wells within a field are closely spaced, several wells may interfere producing larger drawdowns at a well site than would be produced if that well were isolated. For example, the cone of depression of well 50 produces an additional drawdown of about 2.5 feet at well 70. Likewise, well 70 produces an interference effect of about 1.4 feet at well 50. In a similar manner, well 72 lowers the drawdown at well 73 by about 2.5 feet and well 73 adds about 1.5 feet of drawdown to well 72. These interference effects were calculated using the equation (Bouwer, 1978, p. 106):

$$\Delta S = \frac{Q \ln(r_2/r_1)}{2K\,b}$$

where:

ΔS = difference in drawdown between pumping well and well at which which interference occurs.
Q = discharge at pumping well.
r_1 = radius of pumping well.
r_2 = distance to interference well.
K = permeability.
b = average saturated thickness between r_1 and r_2.

This equation assumes that steady-state conditions prevail. Values used in the calculation are listed in Table 5.

Additional drawdown at a pumping well is produced when the cone of depression extends to an impervious boundary. Because the production wells in the Agag aquifer are located near the slopes of the valley-shaped depression (impervious volcanic material), additional drawdown can be expected. This additional drawdown can be determined by either the method of images (see Todd, 1960) or utilizing the above equation by making r_2 equal to twice the distance from the pumping well and the boundary. As an example of the boundary effects on drawdown, well 50 is used. In this case r_2 is about 1000 feet. Following through with the calculation yields an additional drawdown at well 50 of about 0.7 feet. Although this boundary effect does not produce a large additional drawdown, it is significant enough to warrant consideration when placing wells close to the outside boundary of the basin.

Aquifer Yield and Basin Management

Aquifer yield is defined by Freeze and Cherry (1979) as the maximum rate of withdrawal that can be sustained by an aquifer without causing an unacceptable decline in the hydraulic head in the aquifer. Under the present scenario of pumping, yield of the aquifer has been exceeded since there currently is a 1.25 ft/yr decline in water-table elevations (i.e., hydraulic head). This decline has placed pumping levels very near pump intakes in at least two of the four production wells. It is obvious that the decline rate is unacceptable.

As discussed above, a part of the problem that exists in the Agag well field is additional drawdown imposed at single wells by the interference of adjacent pumping wells and by the nearby impervious boundary. Production-well spacing is too small and at least one well (well 50) is located very near to the impervious boundary. Considering the permeability of the marly facies and the configuration of the basin boundaries, the Agag wells should have been drilled in a line trending east-west along the long axis of the basin and spaced no less than 500 feet apart (assuming a pumping rate of about 150 gpm). This would have placed wells at locations where drawdown interference is minimized.

Approximately one-half of the estimated annual recharge to the Agag groundwater basin is extracted by the four production wells, leaving the remainder to maintain the present-day water-table configuration and spring flow at the outfall. Because all of the production wells are located in one small part of the basin, the entire flow field is not being utilized. A greater stress, therefore, is imposed on one location rather than distributing the stress evenly across the basin.

To relieve the stress at the upper end, two actions are necessary. First, one of the wells (well 50) must be relocated to an area away from the active well field. One possible site is along the cross-island highway between EXH-6 and EXH-8. The objective of this relocation is three-fold: it removes one source of interference; it reduces the concentration of pumping wells; and it places a well at a site within the basin that receives a greater rate of

Table 5. Parameters used in the calculation of interference effects between wells at Agag field.

Parameter	Well 50	Well 70	Well 72	Well 73
Q	140 gpm	80 gpm	160 gpm	88 gpm
r_1	.33 ft.	.33 ft.	.33 ft.	.33 ft.
r_2	250 ft.	250 ft.	300 ft.	300 ft.
K	70 ft/day	70 ft/day	70 ft/day	70 ft/day
b	50 ft.	50 ft.	60 ft.	60 ft.

groundwater flow. Second, the pumping schedule must be reorganized such that production rates are greatly reduced during the dry seasons. This action will reduce overdraft during the dry season and increase the ability of the wet-season recharge to replace water lost from storage.

Production rates should be regulated according to the seasonal variations in recharge. A recommended pumping schedule is listed in Table 6. As the schedule dictates, dry-season production should be about one-half of that for the wet season. The objective here is to provide insurance that wet-season recharge will be of sufficient volume to replenish groundwater removed from storage during the dry-season production period. An additional point to be made from the schedule of Table 6 is that pumping rates for the various production wells should be adjusted (as well as possible) such that the extraction is more or less the same at each well. This will aid in minimizing the interference effects at any given well.

From the recommended pumping schedule (which assumes the relocation of well 50), two yield values are given for the basin. During the dry season, between January and June inclusive, extractions should not exceed 300,000 gpd (December is considered a transitional month and is allowed the higher rate). During the wet season, production is increased and the aquifer yield is 600,000 gpd for the last half of the year.

Proper management of the Agag groundwater basin will require close coordination between field observations and production regulation. The current water-level monitoring program conducted by the Water Resources Planning Division should be continued. Timely information about the elevation and configuration of the water table is critical to responsible decision-making in terms of protecting the ground-water resource. Data collected from observation wells provides the basis for determining the response of the flow system to pumping and seasonal variations in recharge and provides the means to anticipate the outcome of hydrologic events before a problem arises.

Future Development

Results from this study of the Agag groundwater basin indicate that efforts to increase the yield of basin by the installation of additional wells would be detrimental to the resource. However, once the recommendations of this study are implemented and sufficient data are acquired to define the response of the system to the new conditions, a re-evaluation of the potential of the resource may be warranted. Until that time, efforts must be directed toward relieving the current stresses on the system and stabilizing the annual water-table decline.

Table 6. Recommended pumping schedule for the Agag well field. Rates are in gpd x 10^3.

WELL	MONTH											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
50	75	75	75	75	75	75	150	150	150	150	150	150
70	75	75	75	75	75	75	150	150	150	150	150	150
72	75	75	75	75	75	75	150	150	150	150	150	150
73	75	75	75	75	75	75	150	150	150	150	150	150
TOTAL	300	300	300	300	300	300	600	600	600	600	600	600

SUMMARY AND RECOMMENDATIONS

Summary

The Agag groundwater basin, located in east-central Saipan, is an important resource of high-quality water for the island community. For this reason and because relatively little was known about the basin, a study was conducted by the Water and Energy Research Institute of the University of Guam under contract with the Government of Commonwealth of the Northern Mariana Islands. The purpose of the study was to investigate the hydrogeologic characteristics of the basin in order to determine the optimal or sustained yield of the aquifer.

The geology of the Agag groundwater basin is a complex three-dimensional mosaic of interbedded and interfingered units of the Tagpochau limestone of Miocene age. In general, the Tagpochau limestone was deposited upon an older volcanic terrain which resembles a valley-shaped depression opening toward the east.

Two facies of the Tagpochau limestone comprise the Agag aquifer. These facies have been tentatively identified as the marly and tuffaceous. The latter facies apparently forms a basal unit at the western end of the basin. Elsewhere, it forms lenticular and tabular bodies associated with the marginal boundaries of the basin. The marly facies occupies the greater volume of the aquifer; production wells are drilled into this facies.

Results from pump-test analyses indicate that the marly facies has a permeability in the range of 25 to 70 ft/day. Although no test data are available from the tuffaceous facies, it is assumed that its permeability is much lower than that of the marly facies because of the abundance of very impure argillaceous limestone and calcareous mudstone.

Interpretations of water-level data indicate a strong correlation between water-table fluctuations and seasonal rainfall. Fluctuations over a range of ten feet between the wet and dry seasons are not uncommon. In addition, water-level data plotted against time indicate a water-table decline of 1.25 ft/yr. This decline is apparently related to overdraft during the dry season and inadequate recharge during the wet season.

Groundwater recharge is seasonal. Calculations indicate that the annual recharge is about 40 to 46 percent of the yearly rainfall and is distributed unevenly through the year. It appears that recharge occurs during the wet-season months and no recharge occurs during the dry-season months.

Because recharge to the aquifer varies with the seasons, two values of sustained yield have been determined for the basin. The dry-season yield is about 300,000 gpd between the months of January to June inclusive. A yield of 600,000 gpd has been determined for the wet-season period between July and December inclusive.

Proper management of the Agag groundwater basin is dependent on maintaining a stable water-table configuration such that wet-season recharge will replenish the groundwater removed from storage during the dry-season production period.

Recommendations

The following recommendations are based on the results of this study and are viewed as essential in order to maintain the productivity of the Agag groundwater basin.

1. Well 50 should be relocated to a site between EXH-6 and EXH-8. The new well should be drilled to a depth of at least 60 feet below the water table, cased, screened, and gravel packed. Screen length is equal to the depth of penetration, that is equal to 60 feet.

2. The present Well 50 should be converted to an observation well.

3. The current water-level monitoring program, conducted by Water Resources Planning, should be continued with routine weekly water levels measured in all of the available observation wells.

4. Piezometers should be installed in all production wells in order to monitor hydraulic head under pumping conditions.

5. A two-season pumping schedule should be implemented immediately and pumping rates equalized between wells as much as possible.

6. TH-10 can be put on line providing that Well 50 has been relocated and that the pumping rate of TH-10 does not exceed 30 gpm (43,200 gpd).

ACKNOWLEDGEMENTS

The Water and Energy Research Institute extends its appreciation to those individuals and agencies that cooperated in the study effort. Specifically, we thank the Water Resources Planning Division of the Commonwealth Government for logistic support and field personnel, Technical Services Division of the Public Works Department of the Commonwealth Government for contributing valuable information from their files, and the Water Resources Division of the U. S. Geological Survey, Guam Subdistrict Office, for providing rainfall and preliminary water-level data. Additional rainfall data were provided by the Northern Mariana Agricultural Research Center, Saipan, and the Trust Territory Government Communication Station at Kagman, Saipan.

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APPENDIX A

DATA FROM PREVIOUS STUDIES

LIST OF TABLES

Table A-1. Water-level observations 1945-79.

WATER LEVELS IN OBSERVATION WELL

WELL NUMBER : 31 old and 31-n (1945-77)
LOCATION : Agag
ELEVATION : 613.8 (old) and 615.37 (new)
REMARK : 31-n Leveled 1-8-81 from BM-1

DATE	*DTW (FT)	**ELEV	DATE	DTW (FT)	ELEV
31-OLD			**31-N**		
1-22-45	165 (?)		3-21-73	202.96	412.41
10-22-69	163 (?)		8- 1-74	221.60	393.77
3-21.73	189.14				
3-29-73	192.78				
4- 5-73	192.04				
4-19-73	196.59				
5- 4-73	199.42				
2-11-77	188.85				

* Depth to water (below MP)
** Elevation of water level relative to MSL

Table A-1. Con't.

WATER LEVELS IN OBSERVATION WELL

WELL NUMBER : 45 (Old)
LOCATION : Agag
ELEVATION : 580.63
REMARK : Leveled 1-8-81 from BM-1

DATE	*DTW (FT)	**ELEV	DATE	DTW (FT)	ELEV
3-45	125	***456	11-8-73	164.78	415.85
3-22-69	120.2	***460.4	11-26-73	164.88	415.75
3-28-73	149.58	431.05	12-6-73	165.00	415.63
4-4-73	150.88	429.75	12-20-73	165.26	415.37
4-19-73	153.32	427.31	1-3-74	166.00	414.63
5-4-73	154.17	426.46	1-14-74	165.62	415.01
5-11-73	156.88	423.75	1-18-74	165.62	415.01
5-24-73	159.16	421.47	1-31-74	165.72	414.91
6-4-73	160.56	420.07	2-14-74	165.60	415.03
6-7-73	161.52	410.11	2-28-74	165.76	414.87
6-14-73	161.47	419.16	4-2-74	166.00	414.63
6-21-73	161.84	418.79	4-26-74	166.02	414.61
6-28-73	164.35	416.28	5-10-74	165.47	415.16
7-5-73	162.73	417.90	5-24-74	166.05	414.58
7-31-73	163.64	416.99	6-20-74	166.10	414.53
8-9-73	164.02	416.61	7-5-74	163.40	417.23
8-30-73	164.30	416.33	7-22-74	165.23	415.40
9-13-73	164.58	416.05	7-31-74	165.63	415.00
9-27-73	163.51	417.12	8-1-74	165.28	415.35
10-11-73	164.70	415.93	8-20-74	163.50	417.13
10-25-73	164.87	415.76	10-9-74	151.19	429.44

* Depth to water (below MP)
** Elevation of water level relative to MSL
*** Approximate Elevation

Table A-1. Con't.

WATER LEVELS IN OBSERVATION WELL

WELL NUMBER : 45 (Old) Continued
LOCATION : Agag
ELEVATION : 580.63
REMARK :

DATE	*DTW (FT)	**ELEV	DATE	DTW (FT)	ELEV
10-30-74	153.74	426.89	11-7-75	158.43	422.20
1-15-75	152.43	428.20	12-19-75	151.10	429.53
1-30-75	153.90	426.73	1-15-76	160.53	420.10
2-7-75	154.60	426.03	1-30-76	149.10	431.53
2-21-75	155.63	425.00	2-12-76	152.40	428.23
2-28-75	155.72	424.91	11-19-76	160.57	420.06
3-14-75	155.51	425.12	12-2-76	150.08	430.55
3-31-75	159.00	421.63	12-16-76	160.60	420.03
4-11-75	154.79	425.84	1-3-77	160.52	420.11
4-25-75	161.24	419.39	1-14-77	160.52	420.11
5-9-75	162.19	418.44	1-27-77	153.59	427.04
5-23-75	162.57	418.06	2-11-77	155.27	425.36
6-6-75	162.37	418.26	2-26-77	156.58	424.05
6-19-75	163.11	417.52	3-11-77	157.13	423.50
7-3-75	163.52	417.11	5-6-77	161.67	418.96
7-17-75	163.80	416.83	6-2-77	161.47	419.16
8-29-75	159.31	421.32	6-20-77	164.55	416.08
9-11-75	157.46	423.17	7-1-77	165.43	415.20
9-25-75	160.18	420.45	7-28-77	162.62	418.01
10-9-75	158.23	422.40	8-25-77	164.26	416.37
10-28-75	158.60	422.03	12-16-77	160.54	420.09

* Depth to water (below MP)
** Elevation of water level relative to MSL

Table A-1. Con't.

WATER LEVELS IN OBSERVATION WELL

WELL NUMBER : 45 (Old) Continued
LOCATION : Agag
ELEVATION : 580.63
REMARK : Leveled 1-8-81 from BM-1

DATE	*DTW (FT)	**ELEV	DATE	DTW (FT)	ELEV
2-13-78	163.57	417.06			
4-10-78	167.29	413.34			

* Depth to water (below MP)

** Elevation of water level relative to MSL

Table A-1. Con't.

WATER LEVELS IN OBSERVATION WELL

WELL NUMBER : 45-n
LOCATION : Agag
ELEVATION : 582.35
REMARK : Leveled 1-8-81 from BM-1.

DATE	*DTW (FT)	**ELEV	DATE	DTW (FT)	ELEV
10-22-69	121.75	406.60	11-8-73	166.88	415.47
10-31-72	144.30	438.05	10-9-74	152.99	429.36
3-20-73	151.77	430.58	1-15-75	154.18	428.17
3-28	151.31	431.04	1-30	155.63	426.72
4-4	154.58	427.77	2-7	156.38	425.97
4-19	155.35	427.00	2-21	157.33	425.02
5-4	157.58	424.77	2-28	157.45	424.90
5-11	158.61	423.74	3-14	158.85	423.50
5-24	160.85	421.50	3-31	160.75	421.60
6-4	162.25	420.10	4-11	161.77	420.58
6-7	162.00	420.35	4-25	162.27	420.08
6-14	163.18	419.17	5-8	164.59	417.76
6-21	163.62	418.73	5-23	164.36	417.99
6-28	164.15	418.20	6-6	164.72	417.63
7-5	164.58	417.77	6-19	165.05	417.30
7-31	165.52	416.83	7-3	165.48	416.87
8-9	165.44	416.91	7-17	165.70	416.65
8-30	160.73	421.62	8-29	167.36	414.99
9-27	165.67	416.68	9-11-75	159.09	423.26
10-11	166.85	415.50	4-10-78	167.29	415.06
10-25	167.00	415.35			

* Depth to water (below MP)

** Elevation of water level relative to MSL

Table A-2. Pump-test data for wells 45, 50, and TH-10.

PUMP-TEST DATA

WELL: 45 (Old) DIAMETER (FT): 0.50
DATE: 10/22/69 DEPTH (FT) : 185
TYPE: Observation PUMP SETTING : N/A
HOLE: Cased, screened lower 50 ft. *SWL (FT) : 120.2
REMARK: Old 45 used as abreviation, used for pump testing new 45

TIME (MIN)	Q (GPM)	DRAWDOWN (FT)	TIME (MIN)	Q (GPM)	DRAWDOWN (FT)
0	0	0	1200	240	17.25
2		2.75	1230	236	17.50
3	250	2.85	1240		17.50
5		3.25	1300		17.50
6		3.45	1330		17.25
7		3.65	1400		17.25
8		3.85	1430		17.25
9		4.00	1500		17.25
10		4.25	1530		17.25
11		4.50	1600	240	17.25
12		4.75	1630		17.75
13		4.95	1700	236	18.25
18		5.75	1730		18.25
23		7.75	1806		18.25
28		9.25	1830		18.25
33	243	9.75	1900		18.25
47		10.75	1930		18.25
52	250	11.25	2000	240	18.25
100	245	11.75	2030		18.25
105		11.75	2100	225	18.25
110		11.75	2130	231	18.25
120	230	12.25	2145	234	18.75
134	231	12.55	2200		18.75
200	245	12.95	2230		18.75
215		13.75	2300		18.75
300	240	14.25	2330		18.75
400	240	14.25	2400		18.75
430	236	14.75	2430		18.75
500	231	14.75	2500		18.75
530		14.75	2530		18.75
600		15.25	2600		18.75
630		15.25	2630		18.75
700		15.75	2700	240	18.75
730		15.75	2730	222	18.75
800		15.75	2800	245	18.75
830		15.75	2830	245	18.75
900		15.75	2900		18.25
930		15.75	2930		18.25
1000		16.25	3000		18.75
1030		16.25	3030		18.75
1100		16.25	3100		18.75
1130		16.75	3200		18.75

*SWL - STATIC WATER LEVEL

Table A-2. Con't.

PUMP-TEST DATA

WELL: 45 (Old) Continued

TIME (MIN)	Q (GPM)	DRAWDOWN (FT)	TIME (MIN)	Q (GPM)	DRAWDOWN (FT)
3300		18.75			
3400		18.75			
3500		18.75			
3600	236	18.75			

Table A-2. Con't.

PUMP-TEST DATA

WELL: 45-n
DATE: 10/22/69
TYPE: Pumping Well
HOLE: Open (no casing)
REMARK:

DIAMETER (FT): 0.92
DEPTH (FT) : 195
PUMP SETTING : 185
*SWL (FT) : 121.75

TIME (MIN)	Q (GPM)	DRAWDOWN (FT)	TIME (MIN)	Q (GPM)	DRAWDOWN (FT)
0	0	0			
1		17.0	1500		37.5
2		22.0	1530		37.5
3	250	24.0	1600	240	37.8
4		24.5	1630		37.9
5		25.0	1700	236	38.2
30	243	31.0	1730	236	38.2
50	250	32.2	1810		38.2
100	245	22.9	1830		38.2
110		33.0	1900		38.2
120		33.8	1930		38.2
125	230	33.9	2000	240	38.2
134	231	33.0	2030		38.2
200	245	32.0	2100	225	38.2
215		34.5	2130	231	38.5
230	231	34.5	2145	234	39.0
300	240	35.5	2200		39.0
330	240	35.0	2230		39.0
400	240	35.5	2300		39.0
430	236	36.0	2330		39.0
500	231	36.0	2400		39.5
530		36.0	2430		39.5
600		36.5	2500		39.5
630		36.5	2530		39.5
700		36.5	2600		39.5
730		36.5	2630		39.5
800		37.0	2700	240	39.5
830		37.0	2730	222	39.7
900		37.0	2800	245	39.7
930		37.0	2830	245	39.7
1000		37.0	2900		39.5
1030		37.0	2930		39.5
1100		37.0	3000		39.5
1130		37.5	3030		39.5
1200	240	37.8	3100		39.5
1215	238	37.2	3130		39.5
1230	236		3200		39.5
1250		37.5	3230		39.5
1300	236	37.8	3300		38.5
1330		37.5	3330		39.0
1400		37.5	3400		39.0
1430		37.5	3430		39.0

*SWL - STATIC WATER LEVEL

Table A-2. Con't.

PUMP-TEST DATA

WELL: 45-n Continued

TIME (MIN)	Q (GPM)	DRAWDOWN (FT)	TIME (MIN)	Q (GPM)	DRAWDOWN (FT)
3500		39.0			
3530		39.0			
3600	236	39.0			
3610		39.0			
3630		39.0			

Table A-2. Con't.

PUMP-TEST DATA

WELL: 45-n
DATE: 5/6/70
TYPE: Pumping Well
HOLE: Cased lower 50 ft. screened
REMARK: Test after completion of well 45-n

DIAMETER (FT): 0.67
DEPTH (FT) : 195
PUMP SETTING : 185
*SWL (FT) : Unknown

TIME (MIN)	Q (GPM)	DRAWDOWN (FT)	TIME (MIN)	Q (GPM)	DRAWDOWN (FT)
0	0	0			
0.5	150	21.0			
1.0	160	25.0			
1.5		28.0			
2.0	200	30.0			
2.5		31.0			
3.0		31.5			
3.5	198	32.0			
4.0		32.2			
4.5		32.8			
5.0		33.1			
5.5		33.5			
6.0		33.9			
6.5		34.0			
7.0		34.1			
7.5		34.2			
8.0		34.8			
8.5		34.9			
9.0	195	35.0			
9.5		35.2			
15	180	36.2			
18		35.0			
21	180	35.2			
25	180	35.9			
30	180	36.0			
45	180	37.0			
60	180	37.8			
120	180	38.9			
180	181	39.5			
240	180	40.0			

*SWL - STATIC WATER LEVEL

Table A-2. Con't.

PUMP-TEST DATA

WELL: 50-n
DATE: 12/11/69
TYPE: Pumping Well
HOLE: Open hole
DIAMETER (FT): 1.0
DEPTH (FT) : 350
PUMP SETTING : 332
*SWL (FT) : 192.5
REMARK: Test conducted immediately after drilling and before completion of well.

TIME (MIN)	Q (GPM)	DRAWDOWN (FT)	TIME (MIN)	Q (GPM)	DRAWDOWN (FT)
0	0	0			
30	226	15.0			
60	297	29.8			
90	240	15.0			
120	240	15.0			
150	240	15.0			
180	240	15.0			
210	240	15.0			
240	240	15.0			
270	240	15.0			
300	240	15.0			
330	240	14.0			
360	222	12.8			
390	207	12.8			
410	226	14.0			
440	240	14.5			
470	231	14.2			
500	235	14.5			
530	235	14.5			

*SWL - STATIC WATER LEVEL

Table A-2. Con't.

PUMP-TEST DATA

WELL: 50-n
DATE: 5/5/70
TYPE: Pumped Well
HOLE: Cased screened lower 50 ft.
REMARK: Well pump tested after completion of casing, screening and gravel packing.

DIAMETER (FT): 0.67 (8 in)
DEPTH (FT) : 350
PUMP SETTING : 323
*SWL (FT) : 192

TIME (MIN)	Q (GPM)	DRAWDOWN (FT)	TIME (MIN)	Q (GPM)	DRAWDOWN (FT)
0	0	0			
0.5		18.0			
1.5		24.0			
2.0		24.5			
2.5	170	24.8			
3.0		24.8			
3.5		24.8			
4.0		24.8			
4.5		24.8			
5.0		24.8			
10	170	24.8			
15	172	24.8			
20	170	24.8			
25	172	24.8			
30	170	24.6			
35	171	24.5			
45	170	24.4			
60	170	24.1			
90	170	24.1			
120	170	24.1			
180	171	24.0			
210	170	23.9			
240	168	23.9			

*SWL - STATIC WATER LEVEL

Table A-2. Con't.

PUMP-TEST DATA

WELL: TH-10
DATE: 8/23/79
TYPE: Pumped Well
HOLE: Cased, screened lower 128 ft.
REMARK: Well completed with steel casing, screen and gravel pack.

DIAMETER (FT): 0.83
DEPTH (FT) : 348
PUMP SETTING : 290
*SWL (FT) : 261.20

TIME (MIN)	Q (GPM)	DRAWDOWN (FT)	TIME (MIN)	Q (GPM)	DRAWDOWN (FT)
0	0	0			
1	86.1	3.60			
2		3.80			
3		3.92			
4		3.97			
5	86.1	4.02			
10	86.1	4.01			
15	86.1	4.06			
20	84.2	4.08			
25	84.2	4.11			
30	82.5	4.13			
45	82.6	4.19			
60	84.2	4.24			
75	86.1	4.27			
90	86.1	4.23			
120	84.2	4.40			
150	82.5	4.45			
180	86.1	4.47			
210	86.1	4.49			
240	82.5	4.47			
270	82.5	4.45			
300	82.5	4.50			
330	86.1	4.50			
360	82.5	4.55			
390	82.5	4.55			
420	86.1	4.60			
450	82.50	4.66			

*SWL - STATIC WATER LEVEL

Table A-3. Drillers logs of Agag groundwater basin wells.

WELL	Location	Depth (ft)	Interval (ft)	Substratum Log
31	Agag	0-15	15	hard limestone
		15-25	10	chalky limestone
		25-53	28	hard limestone
		53-55	2	white beachsand
		55-90	35	hard limestone
		90-125	35	hard and chalky limestone
		125-135	10	hard limestone
		135-167	32	hard and chalky limestone
		167-170	3	white and gray sand
		170-190	20	hard and chalky limestone
		190-192	2	sand and chalky limestone
		192-197	5	hard and chalky limestone
		197-201	4	beachsand
		201-212	11	sand and chalky limestone
		212-220	8	beachsand
				water @ 165 ft
31n	Agag			same log as well 31
45	Agag	0-7	7	top soil and broken coral
		7-17	10	medium coral
		17-19	2	hard coral
		19-30	11	medium coral
		30-62	32	white medium coral, crevice @ 60 ft,
		62-67	5	soft coral
		67-85	18	hard lime
		85-105	20	hard chalky lime
		105-128	23	hard lime
		128-150	22	hard lime and sharps
		150-153	3	clay and sand
		153-155	2	coarse water sand
		155-160	5	fine water sand
		160-171	8	soft clay formation; coral
		171-179	8	clay and sand
		179-185	6	red clay
				water @ 125 ft.
45n	Agag			same log as well 45, except 10 ft deeper
50	Agag	0-7	7	top soil and broken soil
		7-20	13	yellow sandy coral
		20-45	25	hard and pink lime mix
		45-58	13	hard lime
		58-65	7	chalky lime
		65-78	13	hard lime
		78-84	6	pink lime
		84-98	14	hard coral
		98-102	4	beachsand

Table A-3. Con't.

50	Agag	102-111	9	chalky lime
		111-118	7	hard lime
		118-129	11	sandy coral
		129-152	28	hard lime
		152-160	8	soft chalky lime
		160-184	24	medium chalky lime
		184-190	6	hard lime
		190-204	14	medium chalky lime
		204-220	16	soft lime
		220-232	12	hard lime
		232-237	5	sand and hard lime
		237-241	4	beachsand
		241-249	8	hard lime
				water @ 202 ft.
50n	Agag			same log as well 50, except hard lime layer @ 241' extends to 350' instead of to 249'; blue clay on bit @ 350'.
TH-10	Agag	0-3	3	fill
		3-37	34	white medium hard coral
		37-39	2	brown medium soft clay
		39-49	10	white medium hard coral
		49-51	2	brown medium soft clay
		51-88	37	white clay and coral rubble
		88-90	2	medium hard coral and coral rubble
		90-96	6	extra hard coral
		96-122	26	very hard coral, chatter
		122-135	13	very hard coral, smooth drill
		135-175	40	hard coral very hard layers
		175-182	7	hard clay and coral rubble
		182-198	16	hard coral w/medium hard layers and trace clay
		198-208	10	hard coral w/medium hard coral
		208-262	54	medium hard coral w/hard coral
		262-266	4	hard rough drilling
		266-298	32	medium hard coral w/hard layers
		298-305	7	hard coral
		305-319	15	medium hard coral
		319-328	9	hard coral
		328-343	15	hard coral w/medium hard layers
		343-346	3	hard bouncy drill
		346-352	6	medium soft coral w/medium hard layers
		352-356	4	hard rough w/volcanic on bit
				water @ 261 ft.

APPENDIX B

DATA FROM PRESENT STUDY

LIST OF TABLES

Table B-1. Water-level observations 1980-81.

WATER LEVELS IN OBSERVATION WELL

WELL NUMBER : 31-n
LOCATION : Agag
ELEVATION : 615.37
REMARK : Leveled 1-8-81 from BM-1

DATE	*DTW (FT)	** ELEV	DATE	DTW (FT)	ELEV
8-3-80	235.54	379.83			
9-5-80	235.33	380.04			
11-18-80	224,47	390.90			
11-21-80	224.75	390.62			
11-26-80	217.89	397.48			
12-3-80	222.14	393.23			
12-10-80	217.14	398.23			
1-7-81	217.87	397.50			
1-16-81	217.26	398.11			
1-26-81	217.31	398.06			
1-29-81	217.96	397.41			
2-5-81	217.26	398.11			
2-10-81	217.04	398.33			
2-16-81	216.79	398.58			
2-24-81	218.04	397.33			
3-5-81	222.47	392.90			
4-14-81	226.05	389.32			
4-24-81	224.58	390.79			
5-13-81	215.79	399.58			

* Depth to water (below MP)

** Elevation of water level relative to MSL

Table B-1. Con't.

WATER LEVELS IN OBSERVATION WELL

WELL NUMBER : 45 (Old)
LOCATION : Agag
ELEVATION : 580.63
REMARK : 1-23-81 to 4-23-81 USGS Continuous Recorder

DATE	*DTW (FT)	**ELEV	DATE	DTW (FT)	ELEV
			4-81		417.05
			2-5-81		416.99
10-27-80	162.50	418.13	2-6-81		416.95
11-18-80	164.73	415.90	2-7-81		416.93
11-20-80	164.00	416.63	2-8-81		416.90
11-20-80	164.22	416.41	2-9-81		416.89
12-12-80	163.32	417.31	2-10-81		416.85
1-7-81	161.79	418.84	2-11-81		416.83
1-16-81	162.61	418.02	2-12-81		416.81
1-23-81	****	417.38	2-13-81		416.79
1-24-81		417.34	2-14-81		416.76
1-25-81		417.30	2-15-81		416.76
1-26-81		417.28	2-16-81		416.73
1-27-81		417.27	2-17-81		416.71
1-28-81		417.25	2-18-81		416.70
1-29-81		417.24	2-19-81		416.70
1-30-81		417.22	2-20-81		416.68
1-31-81		417.20	2-21-81		416.67
2-1-81		417.17	2-22-81		416.64
2-2-81		417.14	2-23-81		416.63
2-3-81		417.09	2-24-81		416.61

* Depth to water (below MP)
** Elevation of water level relative to MSL
**** USGS Continuous recorder (gage height)

Table B-1. Con't.

WATER LEVELS IN OBSERVATION WELL

WELL NUMBER : 45 (Old) Continued
LOCATION : Agag
ELEVATION : 580.63
REMARK : USGS Recorder

DATE	*DTW (FT)	**ELEV	DATE	DTW (FT)	ELEV
2-25-81		416.59	3-18-81		416.32
2-26-81		416.56	3-19-81		416.32
2-27-81		416.54	3-20-81		416.31
2-28-81		416.52	3-21-81		416.31
3-1-81		416.49	3-22-81		416.31
3-2-81		416.48	3-23-81		416.30
3-3-81		416.48	3-24-81		416.29
3-4-81		416.47	3-25-81		416.29
3-5-81		416.47	3-26-81		416.28
3-6-81		416.47	3-27-81		416.28
3-7-81		416.47	3-28-81		416.28
3-8-81		416.43	3-29-81		416.27
3-9-81		416.38	3-30-81		416.26
3-10-81		416.34	3-31-81		416.25
3-11-81		416.33	4-1-81		416.24
3-12-81		416.33	4-2-81		416.22
3-13-81		416.33	4-3-81		416.22
3-14-81		416.33	4-4-81		416.21
3-15-81		416.32	4-5-81		416.20
3-16-81		416.32	4-6-81		416.20
3-17-81		416.32	4-7-81		416.18

* Depth to water (below MP)
** Elevation of water level relative to MSL
**** USGS Continuous recorder (gage height)

Table B-1. Con't.

WATER LEVELS IN OBSERVATION WELL

WELL NUMBER : 45 (Old) Continued
LOCATION : Agag
ELEVATION : 580.63
REMARK : USGS Recorder

DATE	*DTW (FT)	**ELEV	DATE	DTW (FT)	ELEV
4-8-81		416.17			
4-9-81		416.15			
4-10-81		416.13			
4-11-81		416.12			
4-12-81		416.11			
4-13-81		416.11			
4-14-81		416.11			
4-15-81		416.10			
4-16-81		416.09			
4-17-81		416.08			
4-18-81		416.07			
4-19-81		416.06			
4-20-81		416.06			
4-21-81		416.01			
4-22-81		416.00			
4-23-81		416.00			
5-13-81	163.63				

* Depth to water (below MP)
** Elevation of water level relative to MSL
**** USGS Continuous recorder (gage height)

Table B-1. Con't.

WATER LEVELS IN OBSERVATION WELL

WELL NUMBER : 45-n Continued
LOCATION : Agag
ELEVATION : 582.35
REMARK : USGS Continuous recorder 4-24 to 6-16-81

DATE	*DTW (FT)	**ELEV	DATE	DTW (FT)	ELEV
8-30-80	168.33	414.02			
9-5-80	169.31	413.04	2-5	164.06	418.29
9-19	165.85	416.50	2-10	163.92	418.43
9-29	164.46	417.89	2-16	163.92	418.43
10-3	163.50	418.85	2-16	163.94	418.41
10-10	159.63	422.72	2-18	164.75	417.60
11-10	161.99	420.36	2-24	163.88	418.47
11-14	161.73	420.62	3-5	159.85	422.50
11-18	166.45	415.90	3-9	163.94	418.41
11-18	166.20	416.15	4-14	161.02	421.33
11-20	166.42	415.93	4-24-81	***	415.92
11-21	166.20	416.09	4-25		415.90
11-26	160.79	421.56	4-26		415.89
11-28	163.98	418.37	4-27		415.89
12-3	159.18	423.17	4-28		415.88
12-12	163.32	419.03	4-29		415.87
12-12	164.61	417.74	4-30		415.86
1-7-81	163.56	418.79	5-1		415.84
1-7	163.56	418.79	5-2		415.83
1-16	163.63	418.72	5-3		415.82
1-26	164.08	418.27	5-4		415.81
1-29	164.22	418.13	5-5		415.80

* Depth to water (below MP)
** Elevation of water level relative to MSL
*** USGS Continuous recorder

Table B-1. Con't.

WATER LEVELS IN OBSERVATION WELL

WELL NUMBER : 45-n Continued
LOCATION : Agag
ELEVATION : 582.35
REMARK : USGS Continuous recorder 4-24 to 6-16-81

DATE	*DTW (FT)	**ELEV	DATE	DTW (FT)	ELEV
5-6-81		415.78	5-27		415.59
5-7		415.77	5-28		415.59
5-8		415.76	5-29		415.59
5-9		415.75	5-30		415.58
5-10		415.74	5-31		415.56
5-11		415.73	6-1		415.55
5-12		415.72	6-2		415.55
5-13		415.71	6-3		415.55
5-14		415.70	6-4		415.54
5-15		415.67	6-5		415.52
5-16		415.66	6-6		415.51
5-17		415.65	6-7		415.51
5-18		415.64	6-8		415.50
5-19		415.63	6-9		415.49
5-20		415.62	6-10		415.48
5-21		415.61	6-11		415.47
5-22		415.61	6-12		415.46
5-23		415.61	6-13		415.44
5-24		415.60	6-14		415.43
5-25		415.60	6-15		415.41
5-26		415.60	6-16		415.40

* Depth to water (below MP)
** Elevation of water level relative to MSL

Table B-1. Con't.

WATER LEVELS IN OBSERVATION WELL

WELL NUMBER : TH-10
LOCATION : Agag
ELEVATION : 694.40
REMARK : Leveled 1-8-81 from BM-1

DATE	*DTW (FT)	**ELEV	DATE	DTW (FT)	ELEV
11-18-80	290.47	403.93			
11-19	dry	---			
11-21	297.22	397.18			
12-10	297.62	396.78			
1-16-81	290.74	403.66			
1-26	290.97	403.43			
1-29	291.24	403.16			
2-5	290.84	403.56			
2-10	292.75	401.65			
2-16	293.13	401.27			
2-28	290.69	403.71			
3-5	296.20	398.20			
3-9	292.26	402.14			
4-14	299.95	394.45			
5-13	298.09	396.31			

* Depth to water (below MP)
** Elevation of water level relative to MSL

Table B-1. Con't.

WATER LEVELS IN OBSERVATION WELL

WELL NUMBER : EXH-1
LOCATION : Agag
ELEVATION : 615 (estimate)
REMARK :

DATE	*DTW (FT)	**ELEV	DATE	DTW (FT)	ELEV
5-5-81	226.07	389			
5-13-81	224.42	391			

* Depth to water (below MP)
** Elevation of water level relative to MSL

Table B-1. Con't.

WATER LEVELS IN OBSERVATION WELL

WELL NUMBER : EXH-2
LOCATION : Agag
ELEVATION : 646.67
REMARK :

DATE	*DTW (FT)	**ELEV	DATE	DTW (FT)	ELEV
2-25-81	231.85	414.82			
2-28-81	231.69	414.98			
3-25-81	220.36	426.31			
4-25-81	220.80	425.87			
5-5-81	220.29	426.38			
5-13-81	220.12	426.55			

* Depth to water (below MP)
** Elevation of water level relative to MSL

Table B-1. Con't.

WATER LEVELS IN OBSERVATION WELL

WELL NUMBER : EXH-4
LOCATION : Agag
ELEVATION : 681.58
REMARK : Leveled 1-8-81

DATE	*DTW (FT)	**ELEV	DATE	DTW (FT)	ELEV
1-7-81	270.61	410.97			
1-16-81	270.31	411.27			
1-26-81	276.32	405.26			
1-29-81	276.52	405.06			
2-5-81	274.87	406.71			
2-16-81	274.72	406.86			
2-24-81	274.58	407.00			
3-5-81	278.81	402.77			
3-9-81	274.31	407.27			
4-14-81	283.36	398,22			
4-25-81	284.80	396.78			
5-5-81	284.65	396.93			
5-13-81	283.99	397.59			

* Depth to water (below MP)
** Elevation of water level relative to MSL

Table B-1. Con't.

WATER LEVELS IN OBSERVATION WELL

WELL NUMBER : EXH-6
LOCATION : Agag
ELEVATION : 493.10
REMARK : Leveled 1-8-81

DATE	*DTW (FT)	**ELEV	DATE	DTW (FT)	ELEV
3-5-81	95.23	449.98			
5-5-81	95.88	449.33			
5-13-81	96.04	449.17			

* Depth to water (below MP)
** Elevation of water level relative to MSL

Table B-1. Con't.

WATER LEVELS IN OBSERVATION WELL

WELL NUMBER : EXH-8
LOCATION : Agag
ELEVATION : 545.21
REMARK : Leveled 1-8-81

DATE	*DTW (FT)	**ELEV	DATE	DTW (FT)	ELEV
5-5-81	68.80	424.30			
5-13-81	69.04	424.06			

* Depth to water (below MP)
** Elevation of water level relative to MSL

Table B-2. Monthly rainfall record for Kagman Communication Station.

Record year	J	F	M	A	M	J	J	A	S	O	N	D	Yearly total
1968												1.63	
1969	0.54	1.48	2.41	1.50	1.69	3.79	1.31	11.90	8.55	4.92	16.32	4.04	58.45
1970	11.23	3.38	0.60	0.18	0.19								
1971	1.18	8.67	3.75	4.04	5.33	1.50	17.31	4.82	4.76	7.29	1.06	0.59	60.30
1972	1.06	0.54	0.90	0.73	0.45	1.58	9.80	3.79	0.93	1.45	1.15		
1975							18.36	22.34	9.86	5.44	6.63	3.18	
1976			1.48	2.12	13.24	3.61	11.71	18.13	16.77	2.48		1.65	
1977	2.69	1.40	3.22	1.22	0.65	2.01	7.36	3.73	20.15	16.09	13.73	1.11	73.36
1978	1.12	1.19	1.31	3.34	3.35	4.50	14.06	13.25	14.74	10.58	13.49	4.14	85.07
1979	3.66	2.04	1.71	1.53	3.24	3.13	8.69	10.90	12.28	11.86	2.75	3.87	65.66
1980	0.88	5.90	0.66	1.28	3.20	3.71	4.57	10.99	25.49	8.04	11.70	5.69	82.11
1981	3.33												
$\bar{x}$	2.85	3.08	1.78	1.77	3.48	2.98	10.35	15.54	12.61	7.57	8.35	2.88	70.83
±	3.34	2.82	1.12	1.23	4.03	1.13	5.65	22.25	7.64	4.68	6.20	1.71	11.20

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Table B-3. Geologic logs of chip and core samples from Agag Field exploratory boreholes drilled in 1980-1981. See Figure 3 for the locations of drilled boreholes.

EXH-1

Depth (ft)	Description
0-1	Soil: brown clay (?).
1-20	Limestone: dense; aphanitic to medium crystalline limestone; white; scattered molds and vugs; minor amounts of fossil debris; dessiminated manganese-oxide and ferric-oxide staining.
20-45	Limestone: dense to chalky; fine grained bioclastic limestone; mottled white and light brown with abundant manganese-oxide and ferric-oxide staining (the latter may be weathered volcanic debris); abundant and vugs associated with fossil debris; abundant foraminifera present at 20' level but decrease with depth; cuttings have a speckled appearance.
45-65	Limestone: very chalky; sismondia zone; fine grained bioclastic limestone; white; very little contamination by volcanic debris or staining; abundant foraminiferal and fossiliferous debris.
65-215	Poor to no recovery of cuttings: coring started at 215' (10' above water table; poor recovery (10%) between 215 and 252' (primarily broken and rolled cored pieces.
215-233	Limestone: chalky to dense; aphanitic to very fine crystalline limestone with fossiliferous bioclastic limestone; mottled light pink and white limestone; moldic porosity with some large vugs; scattered large gastropod and coral fragments.
233-237	Limestone: chalky to dense; aphanitic to very fine crystalline limestone with fossiliferous bioclastic limestone; mottled light pink and white limestone; highly fractured and brecciated with heavy coating of pyrolusite (manganese-oxide) on fractured surfaces; scattered large gastropod and coral fragments.
237-252	Limestone: very chalky; finely crystalline fossiliferous limestone; mottled yellowish-brown and white; minor moldic porosity and crystalline calcite-lined vugs; brown clay (?) lining pores and stylolite surfaces (stylolites in horizontal attitude); clay (?) content appears to increase down section.
252-315	Argillaceous Limestone: very argillaceous fossiliferous limestone with abundant irregularly bedded calcareous mud seams and lenses; limestone is light to medium gray and the mud-medium to dark gray; bedding is parallel to sub-parallel to the normal to the borehole; scattered large rugosa coral

Table B-3. Con't.

EXH-1

Depth (ft)	Description
	rubble; unit has a gritty texture at several intervals; recrystallized (?) zones associated with some large fossil debris; some sections are comprised of fossil debris in a dark gray mud grading into a red-brown clay (?) matrix at a depth of 313'; unit is extremely argillaceous toward bottom with the fossil type grading into a brown clay (?).

EXH-2

Depth (ft)	Description
0-2	Soil: brown clay (?)
2-80	Limestone: dense; aphanitic to very finely crystalline limestone with some chalky zones; white with finely disseminated red, yellowish-red, brown and black ferric stains; minor amounts of fossil debris (primarily tabular rugosa coral).
80-185	Limestone: dense; aphanitic to very finely crystalline limestone with some chalky zones; white to very light brown with traces of disseminated red, yellowish-red, brown and black ferric stains; few zones of bioclastic limestone with clasts set in a very finely crystalline calcite matrix; minor amounts of fossil debris (primarily tabular rugosa coral).
185-200	No Sample Recovery: start core at 200'
200-202	Argillaceous Limestone: dense; very argillaceous, medium to fine grained, bioclastic limestone; numerous irregularly bedded dark gray fossiliferous calcareous mud seams; limestone is medium to dark gray; fossil debris in clay has same size fraction as that of the limestone; thickness of this unit is not known but does not exceed 15'
202-208	Argillaceous Limestone: very argillaceous crystalline, fossiliferous limestone; yellowish-white with abundant limonitic stains (ferric-oxide); moldic porosity; pockets of medium brown clayey mud; scattered large fragments of coral debris; change from gray unit to yellowish-white unit is abrupt at an irregular surface contact.
208-210	Argillaceous Limestone: dense; very argillaceous, medium to fine grained, bioclastic limestone; numerous regularly bedded dark gray fossiliferous calcareous mud seams; limestone is medium to dark gray; fossil debris in clay has same size fraction as that of the limestone.

Table B-3. Con't.

EXH-2

Depth (ft)	Description
210-224	Limestone: dense to slightly fractured; coarse grained fossiliferous limestone; pink to white with yellow limonitic staining; fossil debris are primarily coral fragments.
224-227	Mudstone: very argillaceous limestone and calcareous mudstone; dark gray; *Acropora* coral zone.
227-240	Mudstone: no core recovery; sample from inside of core barrel is a plastic dark reddish-brown clayey mud, probably clay.
240-298	Argillaceous Limestone: dense; argillaceous, fossiliferous limestone; light brown with yellow limonitic staining; highly fractured in upper section, becoming chalky toward the bottom of the section; solution enlarged fractures present between 268 and 298'; fossil fragments and few whole coiled gastropods with increased coralline algae debris toward the bottom of section.
298	Mudstone: plastic; medium non-calcareous clayey mud, probably clay; brown.

EXH-4

Depth (ft)	Description
0-1	Soil: brown clay (?)
1-50	Limestone: dense to chalky with some intervals showing primary porosity and vugs; medium to fine grained bioclastic limestone; white and tan with disseminated yellowish-brown to pink ferric-oxide stains (possible volcanic debris origin); bioclasts set in matrix of very finely crystalline calcite; manganese-oxide associated with some fractures and pores; rare to abundant fossil debris.
50-75	Limestone: dense; aphanitic limestone with chalky zones; white with widely disseminated iron and manganese-oxide stains; scattered coral fragments and larger benthic foraminiferans with associated moldic porosity.
75-280	No recovery of cuttings.
280-319	Argillaceous Limestone: Chalkly, stylolitic and fractured; slightly argillaceous, fossiliferous bioclastic limestone; white to light-yellowish brown with limonitic stains on fractured surfaces; highly fractured between 294 and 296'; solution tubes and enlarged fractures present at 300 to 303'; reddish-brown insoluble residue on stylolite surfaces; chalky zones and blebs

Table B-3. Con't.

EXH-4

Depth (ft)	Description
	associated with fossil debris (primarily coral, gastropod and pelecypod origin).
319-329	Argillaceous Limestone: very argillaceous limestone with a gritty texture to calcareous mud; medium gray; the unit between 327 and 328' appears as a recrystallized fossiliferous limestone in a matrix of gray mud; numerous soft clay zones; few large rugosa coral fragments; upper contact grades abruptly into overlying limestone unit.
329-344	Mudstone and Argillaceous Limestone: very argillaceous limestone with a gritty texture and a calcareous mudstone; brown color to both limestone and mudstone; numerous soft clay zones; scattered large rugosa coral fragments; very fossiliferous and highly fractured at 330', some fractures are solutionally enlarged; lower half of section appears to be regularly bedded and cyclic with alternating limestone and mudstone (about ½ to 1 inch thick).
344-361	Argillaceous Limestone: very argillaceous limestone to calcareous mud, fossiliferous; medium to dark gray; Acropora coral zone at 344 to 345'; upper contact an abrupt gradation and lower contact unconformal on weathered volcanic rock with a 1 to 2 inch bed of manganese-oxide at contact; lower mudstone section has well developed bedding and is very fossiliferous with manganese oxide replaced wood fragments; whole high-spired gastropods (cerithids) and large coralline algae fragments scattered throughout the limestone.
361	Volcanics: weathered volcanic rock; lower unconformal contact.

EXH-6

Depth (ft)	Description
0-5	Soil: brown clay (?)
5-35	Limestone: dense to moderately porous; medium to fine grained bioclastic limestone with very chalky fossil debris; white; few larger benthic foraminiferans; some yellow limonitic staining.
35-130	No sample recovery.
130-145	Mudstone: dark gray clayey mud, probably clay; poor recovery and thickness estimated.
145-150	No sample recovery.

Table B-3. Con't.

EXH-6

Depth (ft)	Description
150-156	Calcareous Mudstone: calcareous clayey mud; dark gray; unit contains a very thin bed of coarse grained white limestone sand about ¼ inch thick; abundant fossil debris; unit of unknown thickness and contacts not preserved.
156-174	No sample recovery
174-180	Mudstone: cohesive and fractured; clayey mudstone with interbedded greenish-gray waxy non-calcareous clay (?); yellowish-brown mudstone; scattered pyrolusite dendrites; unit may be a highly leeched or weathered (*in situ*) zone.
180-193	Limestone: highly fractured with vugs; coarse grained bioclastic limestone; mottled yellowish-brown and white with manganese-oxide stains; abundant coral debris; some irregular zones may be recrystallized; the unit is highly fractured and fossiliferous between 186 and 193; lower contact is non-conformal on volcanic-clastic unit.

EXH-7

Depth (ft)	Description
0-1	Soil: brown clay (?)
1-20	Limestone: dense; very fine grained limestone; white with minor yellow limonitic stains; some chalky zones and vugs lined with calcite crystals; scattered shell fragments and tabular coral debris.
20-55	Limestone: well cemented with apparent primary porosity preserved; medium to fine grained foraminiferal limestone; light tan to white; fossil debris is very chalky; there is better cementing in middle of section; scattered angular coarse sized quartz sand grains and disseminated volcanic debris (?) apparent at about 40' and increases in abundance toward the base of section.
55-60	Mudstone: light yellowish-brown clayey mud (clay) mixed with a light gray-green, non-calcareous, waxy clay (?).
60-65	Shale and Mudstone: calcareous friable black shale and non-calcareous dark-brown mudstone; thickness of unit only an estimate.
65-69	Argillaceous Limestone: high secondary and moldic porosity; very argillaceous irregularly bedded limestone; white to tan with yellow limonitic stains and pyrolusite dendrites; hard possibly recrystallized limestone in a matrix of irregularly bedded soft clay or mudstone; this is a cored unit.

Table B-3. Con't.

EXH-7

Depth (ft)	Description
69-80	Limestone: moderately dense; aphanitic to very fine crytalline limestone with some chalky zones; white to tan; some void filling by crystalline calcite deposits.
80-85	Siltstone: calcareous siltstone; medium grayish-brown; abundant foraminifera; rare coarse dark lithic or mineral grains; thickness of unit is only an estimate.
85-90	Argillaceous Limestone: very fine grained argillaceous limestone; light gray; disseminated weathered (to limonite) volcanic debris (?); scattered larger foraminifera.
90-126	Limestone: medium to fine grained bioclastic limestone; white and tan; primarily a foraminiferal sand with abundant planktonic and benthic foraminiferans, coral and shell fragments; limonitic stains associated with fossil debris; abundant coarse to medium-sized clear quartz grains.
126-131	Argillaceous Limestone: very argillaceous, irregularly bedded, medium to fine grained bioclastic limestone; light yellowish-brown with heavy ferric-and manganese-oxide staining; small quantity of soft yellowish-brown calcareous laminated clay (?) seams; scattered larger fossil fragments.
131-133	Argillaceous Limestone: very argillaceous, fine grained limestone; light to medium gray with extensive yellow limonitic stains and manganese-oxide coating on many grains; unit has finely speckled appearance; abundant foraminifera with fossiliferous (Acropora zone); many coarse-sized quartz sand grains; clay content increased at 132'; gray unit grades upward into the overlying yellowish-brown limestone; thickness of unit unknown (bottom of hole).

EXH-8

Depth (ft)	Description
0-2	Soil: brown clay (?)
2-35	Limestone: moderately well cemented and exhibits primary porosity; aphanitic to medium grained bioclastic limestone with scattered chalky zones; white with yellow limonitic staining; few larger foraminifera and scattered coralline algae fragments.

Table B-3. Con't.

EXH-8

Depth (ft)	Description
37-60	No sample recovery (lost circulation)
60-63	Limestone: chalky; fossiliferous bioclastic limestone; very light tan with yellow limonitic staining associated with coral and shell detritus; scattered larger foraminifera.
63-72	Calcareous Mudstone: friable; calcareous mud with minor quantities of very argillaceous limestone; grayish-brown; few large coral fragments and scattered broken gastropod shells; crude bedding shown by fossil debris; grades abruptly in to both the overlying and underlying units.
72-118	Limestone: chalky and fractured; medium to fine grained bioclastic limestone; white to light yellowish-brown with abundant yellow limonitic staining; abundant stylolities; some argillaceous intervals exhibit good to slightly irregular bedding; unit became very argillaceous (primarily a friable, calcareous, well bedded, mudstone) in lower portion of the section; few large coral and gastropod shell fragments; medium yellowish-brown clay residue on stylolite surfaces; interval between 78 and 80' is highly fractured.
118-123	Mud: sticky; cohesive clayey mud, probably clay, very dark brown; neither the upper or lower contacts preserved in core.
123-164	Limestone: chalky and fractured; medium to fine grained bioclastic limestone; white to light yellowish-brown with abundant limonitic staining and manganese-oxide stains on fossil debris and fractured surfaces; abundant stylolites with prominent moldic porosity and crystalline calcite lined vugs; unit becomes coarse grained and argillaceous toward base; lower contact appears to be gradational.
164-178	Calcareous mudstone: friable; moderately well bedded, fossiliferous, calcareous mudstone; dark gray; gravel to fine-grained sized fossil debris composed of high spired gastropods (cerethids), brown gastropod and bivalue shells and coral fragments; some zones are composed of very dense, possibly recrystallized, gray limestone associated with concentrations of fossil debris; a zone of vuggy porosity between 168 and 170'.
178-180	Calcareous Mudstone: friable, moderately well bedded, fossiliferous, calcareous mudstone with possible inclusions of volcanic rock debris, occasional quartz sand grains, mafic mineral grains and pyritic mineralization; dark gray with light gray lenses; gravel to fine-grained sized fossil debris; scattered coral and gastropod shell fragments; common planktonic foraminiferans.

Table B-3. Con't.

EXH-8

Depth (ft)	Description
	(Globigeunidae) and larger and smaller benthic foraminiferans (including *Sorites*, *Hauerina*, *Triloculina*, *Quinqueloculina*, *Spriloculina*); lower contact was not preserved in the drill core but is presumed to be unconformal with underlying volcanic rock terraine.