INTRODUCTION

Tinian, which lies in the western Pacific Ocean at latitude 15°N and longitude 145°W (fig. 1), is the second largest island (39.2 mi^2) in the Commonwealth of the Northern Mariana Islands (CNMI). Fresh ground water is obtained from shallow wells that tap the surface of a freshwater lens found in an aquifer composed mainly of coralline limestone. The main water-supply well withdraws water with a chloride concentration ranging from 160 to 220 mg/L. Current (1999) pumping rates adequately supply the island residents but future demands are expected to be higher. To better understand the ground-water resources of the island and to learn more about the hydrology of oceanic islands, the U.S. Geological Survey (USGS) entered into a cooperative study with the Municipality of Tinian. The objective of the study, conducted between 1990 and 1997, was to assess the ground-water resources of the island.

This report presents some of the results of the study including a description of the island's geology and geography, the current land use, the water-production system, the thickness and areal extent of the freshwater lens, the water-table configuration and directions of ground-water flow. The report also discusses the relation of the changes in water-table elevation to daily and seasonal changes in ocean level.

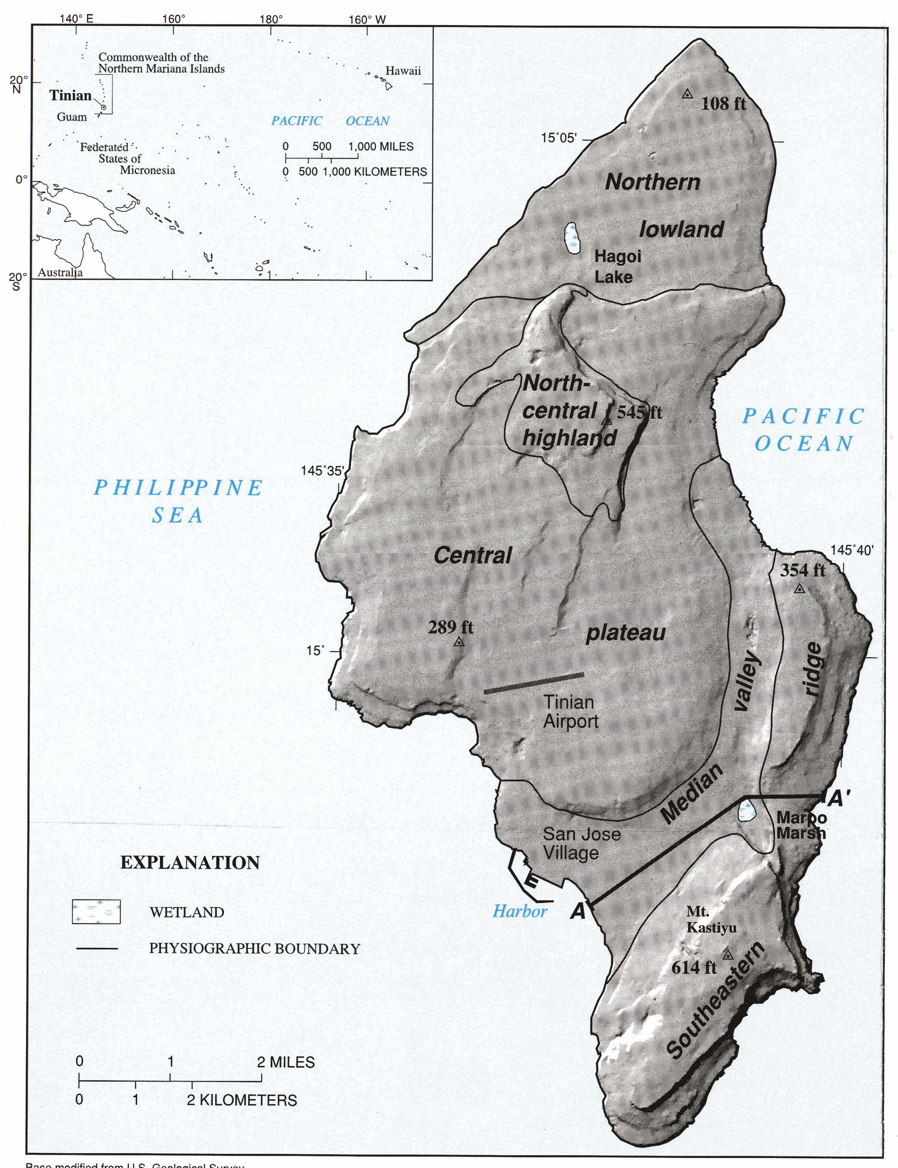

Figure 1. Location map and physiographic areas of Tinian (modified from Doan and others, 1960).

GROUND-WATER RESOURCE: THE FRESHWATER LENS

A portion of rainfall infiltrates and maintains a freshwater lens within the island. Some fraction of the infiltration can be withdrawn by wells, but high salinity can result from overpumping or dry weather.

A density difference between freshwater and saltwater creates a lens-shaped body of freshwater that floats on saltwater within the island (fig. 2), much the way an iceberg floats in the ocean. The primary aquifer on Tinian is composed mostly of well-indurated limestone consisting of coral, calcareous algae, and shells and skeletons of calcareous organisms (Doan and others, 1960). Water occupies small, intergranular pores and spaces between the accumulated material as well as larger voids, which originated as openings in the growth structure of the coral reef or developed later by dissolution of the calcium carbonate.

Theoretical freshwater lens and actual conditions on Tinian.--The Ghyben-Herzberg relation commonly is used to relate the thickness of a freshwater lens in an ocean-island aquifer to the density difference between freshwater and saltwater under hydrostatic conditions. Assuming a density difference of 0.025, a theoretical interface between freshwater and saltwater will be located at a depth below sea level that is 40 times the height of the water table above sea level (Todd, 1980). Instead of a sharp freshwater-saltwater interface, however, freshwater is separated from saltwater by a transition zone in which salinity grades from freshwater to saltwater (fig. 2*A*). In many field studies, the theoretical Ghyben-Herzberg interface depth has been found to correspond to the depth of about a 50-percent mix of freshwater and saltwater. Under equilibrium flow conditions in permeable aquifer systems, the Ghyben-Herzberg relation may provide a reasonable estimate of freshwater depth if the transition zone is comparatively thin.

Definition of potable freshwater.--Salinity in a freshwater lens is gradational, from an upper freshwater core through the underlying transition zone to saltwater. A chloride concentration of 250 mg/L is the maximum contaminant level (MCL) for drinking water recommended as a secondary standard by the USEPA (U.S. Environmental Protection Agency, 1989). Secondary standards are not mandatory requirements, but instead establish limits for constituents that may affect the aesthetic qualities of drinking water (taste and odor, for example). In this report, freshwater is defined as water having a chloride concentration less than or equal to 250 mg/L (fig. 2*A*). Seawater has a chloride concentration around 19,200 mg/L (Thurman, 1990).

Ground-water flow, recharge, and temporal variations in lens size.--Water flows continuously in a freshwater lens. Rainfall infiltrates and recharges the aquifer, where frictional resistance to flow within the aquifer matrix causes the water to accumulate and a lens to form. Freshwater flows by gravity to the shore, where it discharges as diffuse seepage and as springflow at shoreline and submarine springs. On small islands, mixing in the transition zone results mainly from tidal fluctuations superimposed on the gravity-driven flow of freshwater toward the shore. Under conditions of steady recharge and no pumping the lens would have a fixed size. In reality, rainfall is episodic and seasonal, and lens volume fluctuates naturally with time. The lens discharges continuously throughout the year, but shrinks during dry periods when recharge diminishes or ceases. The lens expands during high recharge episodes, which commonly are clustered within a definable wet season.

Ground-water withdrawal from wells, saltwater upconing, and regional lens depletion.--Some fraction of the recharge can be withdrawn continuously by wells, in effect capturing a fraction of the natural discharge. The most efficient means of developing a thin lens is to locate widely spaced shallow wells where the lens is thickest and to maintain low uniform pumping rates at each well. This spreads withdrawal over a wide area and skims freshwater from the lens. The more widespread the withdrawal, the greater the fraction of recharge that can be withdrawn with acceptable salinity for drinking. Saltwater upconing can contaminate wells if the lens is too thin, if wells are too deep, or if too much water is withdrawn from a small area. Even if wells are designed and placed to minimize local upconing, the lens will gradually shrink to a size that is in balance with the withdrawal. This regional shrinkage raises the transition zone closer to the wells, potentially close enough to raise the salinity of pumped water. Shrinkage of the freshwater lens due to dry weather can also contribute to high salinity in wells.

Small island freshwater lens at true scale.--Typically, sectional diagrams of a freshwater lens are drawn with the vertical scale greatly exaggerated (fig. 2*A*). If the section is drawn with no vertical exaggeration (fig. 2*B*), the extreme thinness of the freshwater lens on a small island is more evident, as is the difficulty of withdrawing freshwater without causing saltwater upconing.

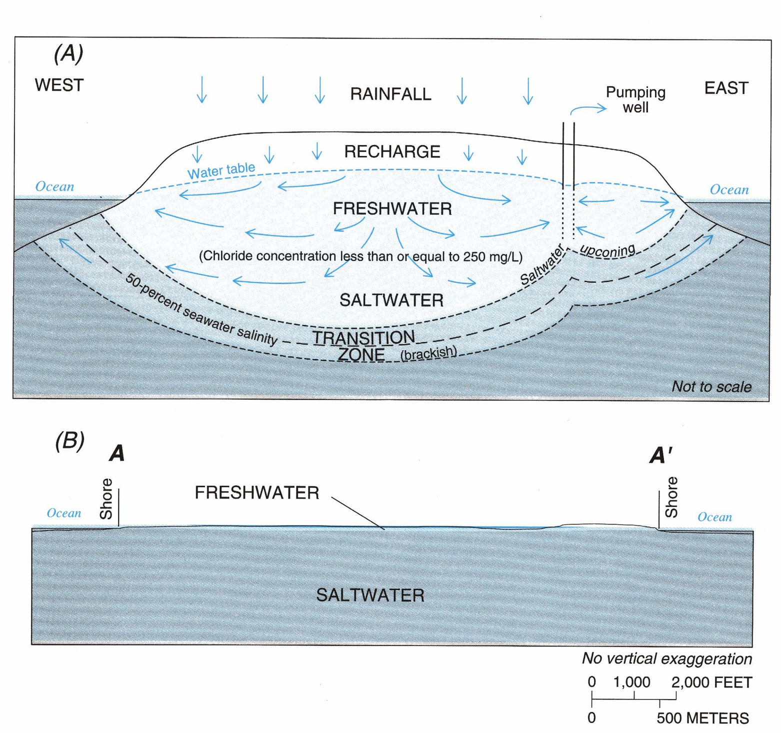

Figure 2. Diagrams of the Tinian freshwater lens. (*A*), Salinity structure and ground-water flow pattern, vertical dimension greatly exaggerated, (*B*), freshwater lens, no vertical exaggeration. Line of section shown in figure 1.

GEOGRAPHY

Flat terraces and plateaus dominate the surface terrain of Tinian and are separated by steep scarps. The greatest relief is formed by two relatively prominent blocks in the north-central and southeastern areas of the island. Land-surface elevation is near sea level at wetland depressions in southeastern and northwestern Tinian. The coast of the island largely consists of steep cliffs, most ranging from 20 to 100 ft high, separated by several small beaches and coves.

The island of Tinian is about 12 mi long and as much as 6 mi wide. The surface landforms can be divided into five major physiographic areas (fig. 1).

The southeastern ridge is the southernmost and highest part of the island and consists of a north and south ridge, separated by a gap near its midpoint. Steep slopes and cliffs that are as much as 500 ft high form the southeast boundary of the ridge. The highest point on Tinian is Mt. Kastiyu on the south ridge, at 614 ft altitude. To the northwest, the median or Marpo valley, a low, broad depression that separates the southeastern ridge from the central plateau, reaches an altitude of about 150 ft. The land surface intersects ground water at a depression in the valley, forming the Marpo marsh. The north and west flanks of the median valley steeply slope to the central plateau.

The central plateau extends northward and comprises all of central and some of the northern part of Tinian. The central plateau is broad and gently sloping with principal relief along its boundaries with the median valley and northern lowland. The north-central highland rises within the northern part of the central plateau, midway between the east and west coasts. The highest point of the north-central highland, 545 ft altitude, is exceeded in height only on the southeastern ridge. The northern lowland generally is flat and about 100 ft in altitude except at Hagoi Lake where the altitude is near sea level.

Two wetland areas near sea level are supplied perennially by ground water. Hagoi Lake in the northern lowland is a fresh to brackish water body surrounded by a marsh. The area of open water may extend to one-half mile in length during the wet season, and decrease to a marsh with little open water during the dry season. Marpo marsh in the median valley is a wetland with a small area of shallow open water.

LAND USE

The population of Tinian resides within and adjacent to the median valley. The rest of the island is unused grassland and secondary forest, except for areas of scattered grazing and occasional military training exercises. Land uses include one resort, small businesses, agriculture, and residential activities. Several quarries, a solid waste dump, and sewage-waste systems may affect the potential for ground-water contamination.

The population of Tinian, 2,631 people in 1995 (Bureau of Census, 1996), resides in a rural setting located in the median valley and parts of the adjacent central plateau and southeastern ridge, occupying about 25 percent of the island (Baldwin, 1995) (fig. 3). Most public and residential land-use activities take place in this area. Public land accounts for about 60 percent of the rural area and land use includes the airport, harbor, schools, cemetery, agricultural cooperatives, Marpo marsh, parks and beaches, and unused grassland and secondary forest. Residential and commercial land covers about 40 percent of the rural area and land use includes a casino resort, small businesses, farming, grazing, and housing. Ground-water contamination from these types of rural land use can be from many sources, including: nutrients from human and animal wastes emanating from septic systems and animal feedlots, fertilizers used on agricultural land, and detergents; pesticides and herbicides applied to homes and gardens; and petroleum compounds and solvents from spills, leaking underground storage tanks, and improper disposal.

About 75 percent of the island is grassland and secondary forest supporting minor land-use activities. About 40 percent of the grassland is reserved exclusively for military use in the northern part of the island, except for a U.S. Information Agency radio station operating in the southwestern part of this area. Military activities usually consist of occasional military exercises. About 60 percent of the remaining grassland and secondary forest, mostly on the central plateau and southeastern ridge, is used for scattered grazing of cattle and horses.

Other land uses that may affect the potential for ground-water contamination include several quarries used for extracting limestone building materials, and a solid-waste dump site near the west coast and south of the airport. All solid waste, including toxic materials and sewer waste from holding tanks, is dumped at the landfill. Tinian presently has no sewer facility and all residences and businesses use septic and seepage tanks, leaching fields, or holding tanks to dispose of sewage. The shallow depth to water and the abundance of pathways for infiltrating rainwater to travel in the limestone aquifer increase the potential for contaminants to reach and move through the aquifer rapidly.

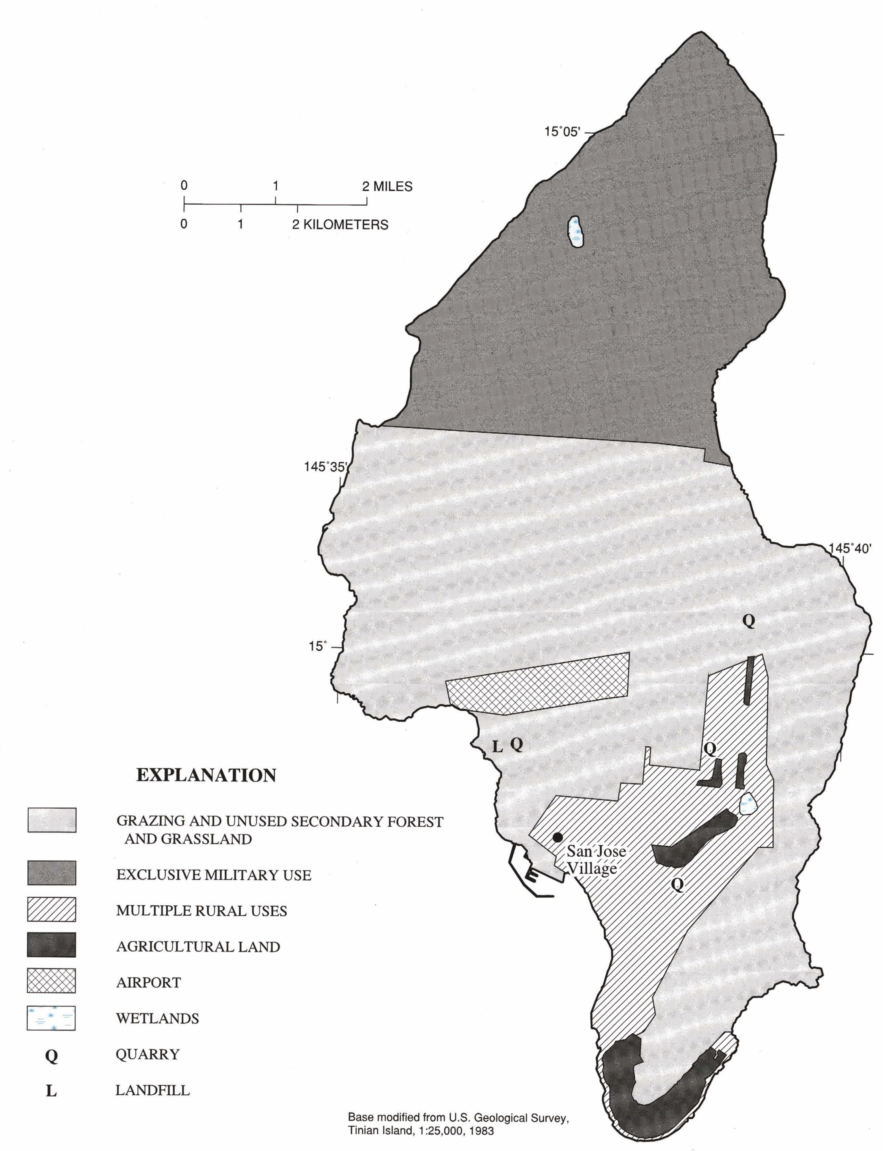

Figure 3. Generalized land use, Tinian (modified from U.S. Geological Survey, 1983; Young, 1989; and U.S. Department of Agriculture, 1994).

GEOLOGY

Volcanic rock forms the foundation of the island, predominantly below sea level, and coralline limestone dominates the lithology above sea level, comprising 98 percent of the surface exposures. The composition and natural porosity of coralline limestone usually cause high permeability, whereas the texture and poor sorting of the volcanic material usually cause low permeability. Faults transect the island throughout, complicating the structure and permeability of the rock units.

Four major geologic units make up the island (fig. 4). The Tinian Pyroclastic Rocks are the oldest exposed rocks, of late Eocene age, and underlie all other exposed rock units (Doan and others, 1960). This unit is exposed in the north-central highland and southeastern ridge and forms about 2 percent of the surface of the island. The thickness of the unit is unknown because the position of the base is undetermined. The Tinian Pyroclastic Rocks consist of fine to coarse-grained consolidated ash and angular fragments of volcanic origin. Outcrops usually are highly weathered and altered to clay.

The Tagpochau Limestone is of early Miocene age (Doan and others, 1960). It is exposed on about 15 percent of the surface on Tinian, principally in the north-central highland and the south part of the southeastern ridge. The unit thickens from zero to at least 600 ft in all directions away from the surface exposures of the Tinian Pyroclastic Rocks in the north-central highland and southeastern ridge. The Tagpochau Limestone is composed of fine to coarse-grained, partially recrystallized broken limestone fragments, and about 5 percent reworked volcanic fragments and clays. Surface exposures are highly weathered.

The Mariana Limestone is of Pliocene to Pleistocene age and is the most extensive unit areally and volumetrically above sea level. It comprises about 80 percent of the surface area, forming nearly all of the northern lowlands, the central plateau, and the median valley. The Mariana Limestone thickens from zero to at least 450 ft in all directions away from the surface exposures of the Tinian Pyroclastic Rocks and the Tagpochau Limestone. It is composed of fine to coarse-grained fragmented limestone, commonly coralliferous, with some fossil and algal remains, and lesser amounts of clay particles (Doan and others, 1960). Small voids and caverns are common in surface exposures. The Mariana Limestone differs from the Tagpochau Limestone in its higher coral content and lesser incidence of recrystallization.

The beach deposits, alluvium, and colluvium are of Pleistocene to Holocene age. These deposits cover less than 1 percent of the surface of Tinian, and may be as much as 15 ft thick. The deposits are composed of poorly consolidated sediments, mostly calcareous sand and gravel thrown onto beaches by waves, but also clays and silt deposited inland beside Hagoi Lake and Marpo marsh, and loose soil and rock material deposited at the base of slopes, especially in the north-central highlands.

The porous and well-washed character of coral reefs, and the high susceptibility of limestone to solution weathering favor high permeabilities in the limestone units. In contrast, permeabilities of the pyroclastic rocks tend to be low due to poor sorting and the high susceptibility of some volcanic minerals to chemical weathering and alteration to clays.

Normal faults transect the island throughout, displacing rock units relative to one another by generally less than 100 ft. The regional strike of the faults is north-south, approximately parallel to the trend axis of the Mariana Arc. Faults in limestone rock exposed at the surface commonly show weathered gaps along the fault, ranging from inches to feet in width; thus faults in limestone may represent narrow zones of relatively higher permeability than surrounding rock. The Tinian Pyroclastic Rocks and Tagpochau Limestone are dissected by faults concealed by the Mariana Limestone.

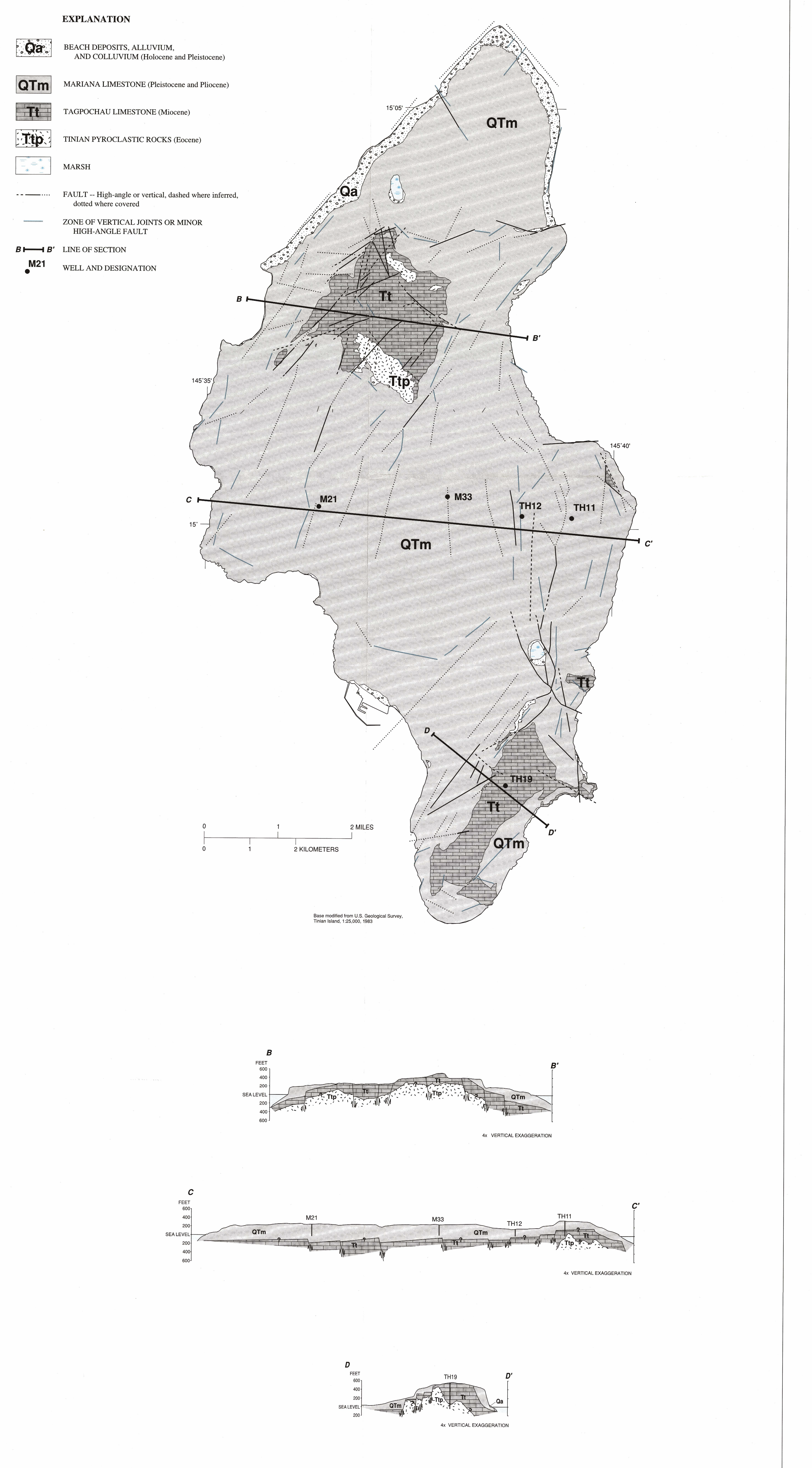

Figure 4. Generalized surficial geology and geologic sections, Tinian (modified from Doan and others, 1960).

GROUND-WATER RESOURCES OF TINIAN, COMMONWEALTH OF THE NORTHERN MARIANA ISLANDS

by

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