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Back Cover: Dr. John Milliman, The College of William and Mary. Keynote Speaker for the 13th Symposium. Photograph by Sandy Voegeli.

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GIS OF THE CAVES AND KARST OF THE MARIANA ISLANDS

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ABSTRACT

The Mariana Islands are a volcanic island chain in the western Pacific Ocean composed of Eocene volcanic cores with a carbonate mantle. The five islands in this study are Guam, Rota, Aguijan, Tinian, and Saipan. Other workers previously have classified the cave and karst features of these islands into the cave types described in the Carbonate Island Karst Model or CIKM, but no comprehensive GIS has been developed. For this project, a comprehensive GIS of the cave and karst features was produced. The cave and karst features were divided by cave type, physiographic province, and island. The data were then entered into a relational geodatabase for ease of maintenance and analysis. A total of 740 karst features were entered. Layer files were created to retrieve information and to display the feature locations in GIS maps. A total of 82 layers were created for each combination of island, physiographic province, and cave type for a total of 82 distinct layers. A total of 7 GIS maps were produced: one for each island, one with the five islands in the study in a spatially correct orientation, and one with each of the five islands in an individual panel, with each island having its own scale. The karst features in the GIS maps were hyperlinked to a number of HTML pages--one for each feature with additional information, and a set of HTML navigation pages mirroring the organization of the GIS layers. The HTML pages contain textual descriptions, and links to final and working feature maps, and line plot data, and other data not amenable to storage in a relational database. In addition to the karst data, various raster layers were added to the GIS including: LANDSAT images, DRG, DEM, and other layers calculated from the DEM.

INTRODUCTION

Geographic Setting

The Mariana Islands are a volcanic island chain in the western Pacific Ocean located south of Japan (Figure 1), where the Pacific Plate is being subducted beneath the Philippine Plate to the west of the Mariana Trench and the Mariana Islands. The Mariana Islands are composed of fourteen islands divided into two parallel island chains that are the subaerially exposed portion of the Mariana Ridge (Figure 2) (Karig, 1971). The western-most, volcanically active chain is composed entirely of volcanics and is not included in this study. The six islands in the eastern chain are composed of an Eocene volcanic basement with a cover of Cenozoic carbonates. The five islands in this study are Guam, Rota, Aguijan, Tinian, and Saipan. Farallon de Medinilla (located approximately 84 km north of Saipan) was not included in this study because of its remote location and use as a military munitions training area (Jenson et al., 2006). There have been several attempts to characterize cave and karst features in the past, most notably the Carbonate Island Karst Model, or CIKM, but no comprehensive GIS has been developed.

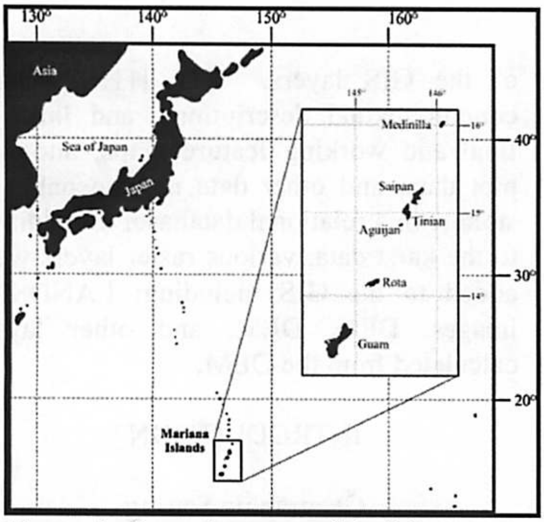

Figure 1. Location map of the Mariana Islands (Jenson et al., 2006).

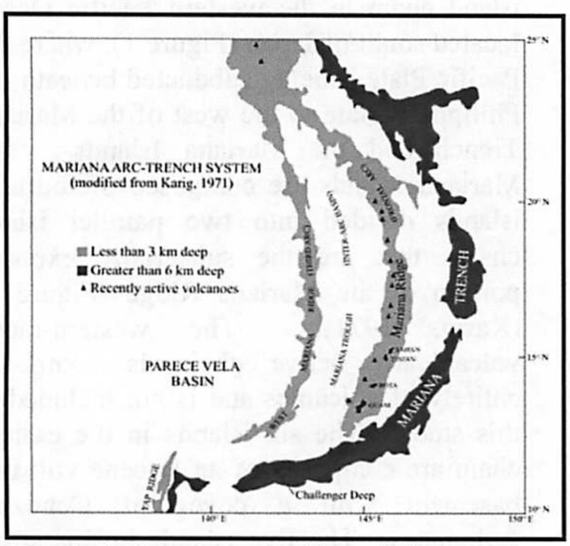

Figure 2. Mariana Arc-Trench System (Keel, 2005).

To construct a comprehensive GIS of the cave and karst features the features first were divided by cave type, physiographic province, and island. The data then were entered into a relational geodatabase for ease of maintenance and analysis. A total of 740 karst features were entered into this database and a total of 5 GIS maps were produced—one for each island. The karst features in the GIS maps were hyperlinked to a number of HTML pages, one for each feature with additional information, and a set of HTML navigation pages mirroring the organization of the GIS layers was also created. The HTML pages contain textual descriptions and links to the final and working feature maps, line plot data, as well as other data not amenable to storage in a relational database. In addition to the karst data various raster layers were added, including: LANDSAT images, DRG, DEM, and other layers calculated from the DEM, such as hillshade, contour lines, and island outline.

Geology

Guam, the southern-most island in the western chain, is located about 2800 km southeast of Tokyo, Japan and 2400 km east-southeast of Manila, Philippines. Guam is the largest of the Mariana Islands with a land surface of about 550 km^2. Guam is divided into two equally-sized physiographic provinces separated by the Pago-Adelup Fault. The Northern Province is an uplifted carbonate plateau with near-vertical cliffs at the coast. The southern province is mostly volcanics and volcanoclastics with isolated limestone bands. The only sizable surface streams on Guam are located on the southern half of the island (Mink and Vacher, 1997).

Jenson et al. (2006) further subdivided the physiographic provinces of Guam into five divisions: Northern Plateau, Basement Outcrops, Southern Coast, South-

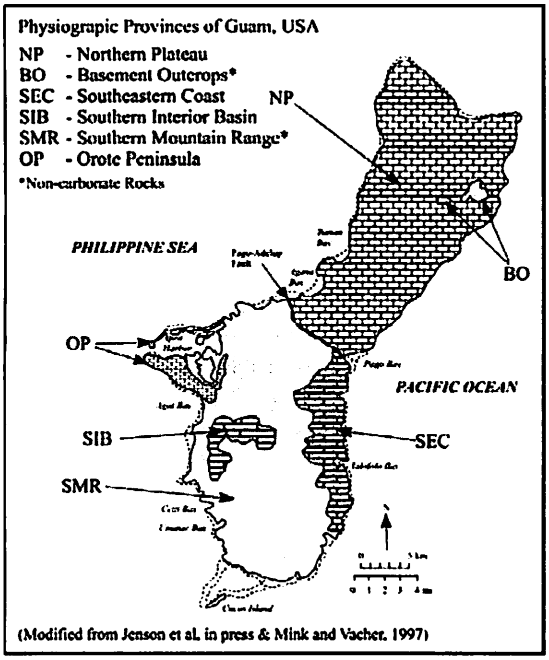

Figure 3. Physiographic map of Guam (Modified from Jenson et al., 2006).

ern Interior Basin, and Southern Mountain Range (Figure 3).

Rota Island.

Rota is located about 80 km north of Guam and has a surface area of about 96 km^2 and a coastal perimeter of about 52 km.

There are six physiographic provinces in three Regions. The regions are: Sinapalo Region, Sabana Region, and the Taipingot Peninsula. Sugawara (1939; and 1949) described the physiographic provinces in terms of their terrace level. The six terrace levels described include Sabana, Aburataruga, Shinaparu, Lugi, Taragaja, and Mirikattan. Keel (2005) divided the island into five regions: Sabana, Talakhya, Sinapolo, Taipingot Peninsula (Wedding Cake) and Songsong Village.

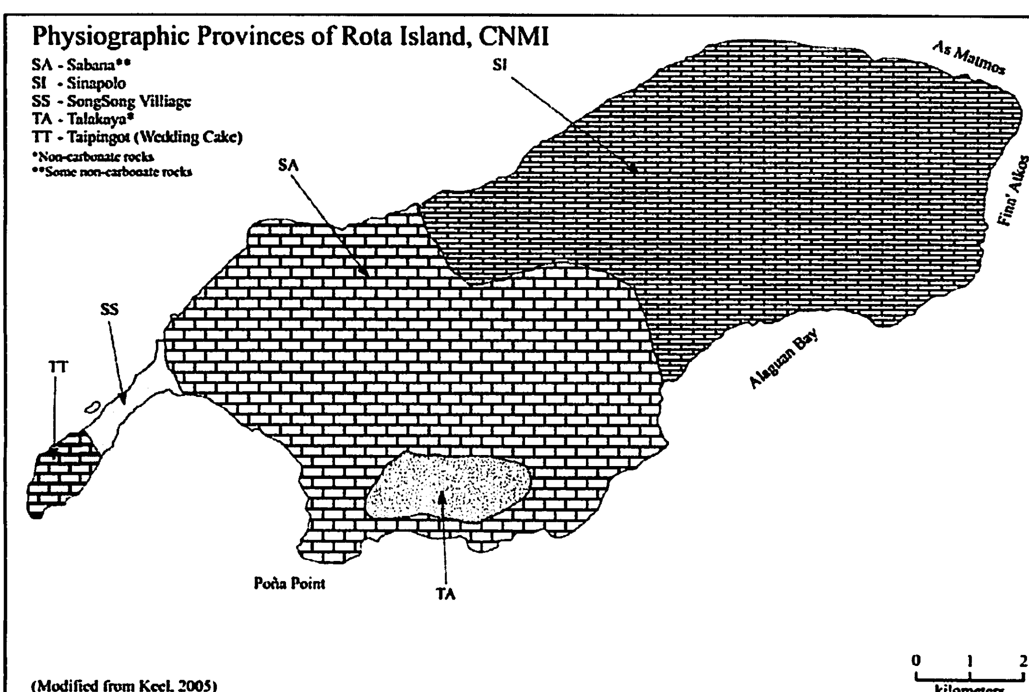

Figure 4. Physiographic map of Rota (Modified from Keel, 2005).

Stafford et al. (2005) reported volcanic outcrops in the Sabana and Talakhaya regions with the only surface streams occurring on the Talakhaya (Keel, 2005).

Aguijan Island

Aguijan has only about 7.2 km^2 of island surface, all of which are exposed Miocene and Pliocene age carbonate rocks, resting on an Eocene volcanic edifice (Tayama, 1936; Stafford, 2003). There are three concentric terraces on Aguijan at elevations 0-50 m, 50 – 100 m, and 100 – 150 m (Figure 5). No surface streams or beaches are present (Jenson et al., 2006).

Tinian Island

Tinian is approximately 102 km^2, and is the third largest of the Mariana Islands (Cloud et al., 1956). The island was divided by Doan et al. (1960) into five provinces separated by high-angle faults: Northern Lowland, North-Central Highland Central Plateau, Median Valley, and Southeastern Ridge (Figure 6). Stafford et al. (2005) reported four volcanic outcrops on Tinian near Sabanettan Mangpang, Bañaderon Lemmai, and Laderan Apaka (Figure 6). Streams flowing overland off of Bañaderon Lemmai provide for point source recharge into the karst system.

Saipan Island

Saipan is the second largest of the Mariana Islands and the largest of the 14 islands in the Commonwealth of the

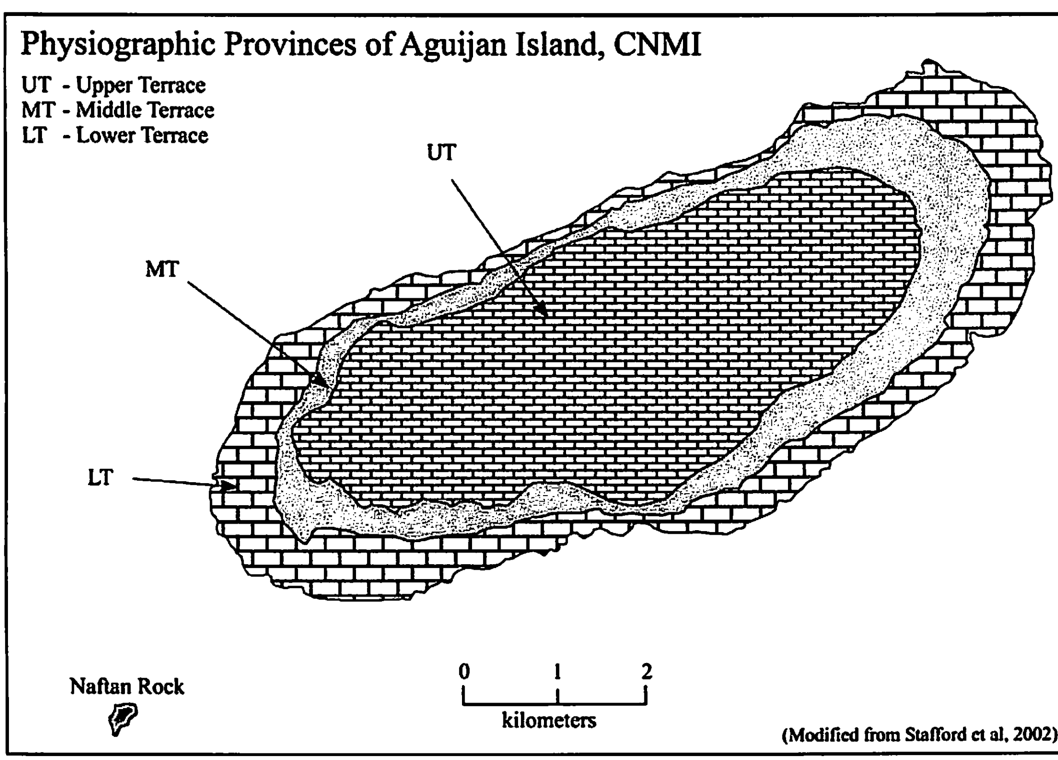

Figure 5. Physiographic map of Aguijan (Modified from Stafford et al., 2005).

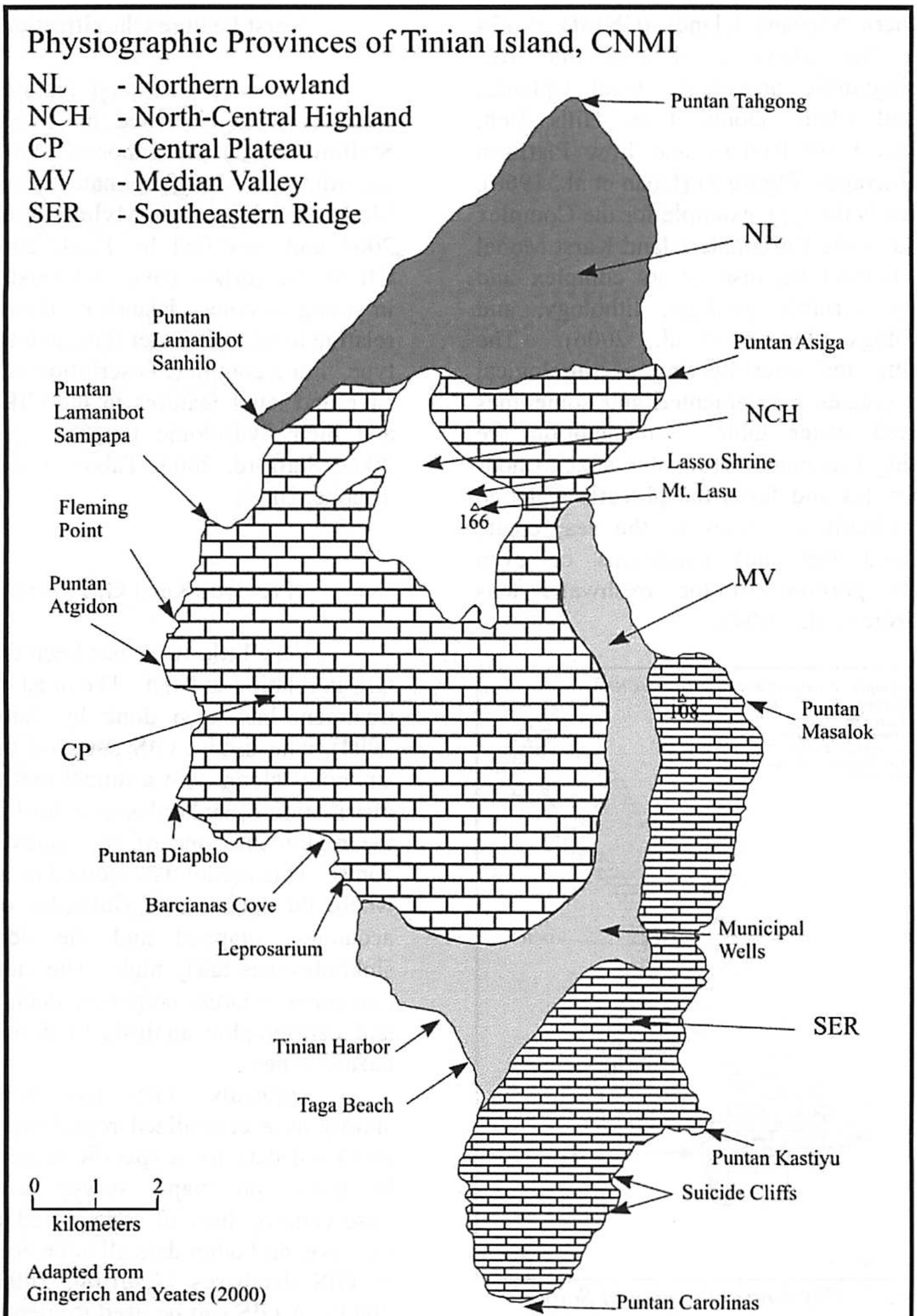

Figure 6. Physiographic map of Tinian (Modified from Stafford, 2003).

Northern Mariana Islands (CNMI) at 124 km^2. The island is divided into five physiographic provinces: Axial Uplands, Coastal Plain, Donni Clay Hills Belt, Coastal Fault Ridges, and Low Platform and Terraces (Figure 7) (Doan et al., 1960). Saipan is the type example for the Complex Island in the Carbonate Island Karst Model (see below) because of its complex and highly variable geology, lithology, and hydrology (Jenson et al., 2006). The faulting and interfingering of lithological units creates a fragmented and sometimes perched water table. In addition the faulting can place carbonates next to non-carbonates and force the phreatic water to take circuitous routes to the sea, create confined (artesian) conditions or even isolate portions of the freshwater lens (Mylroie et al., 2004).

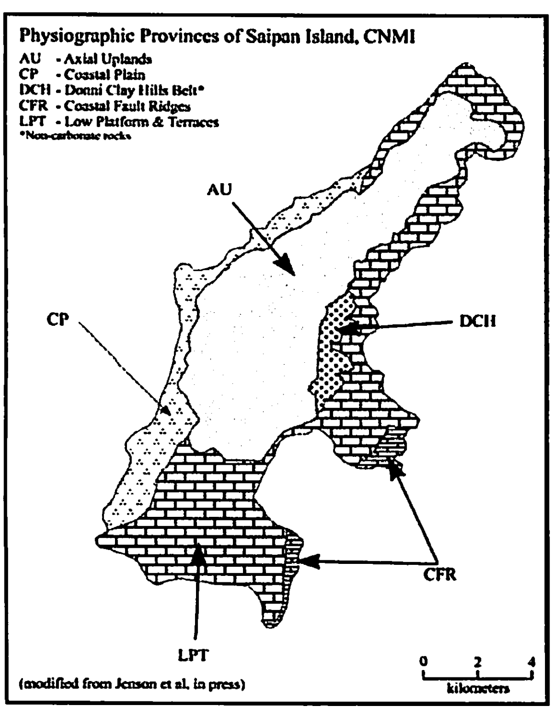

Figure 7. Physiographic map of Saipan (Modified from Jenson et al., 2006).

Karst Feature Classification

The cave and karst features in the database were classified by Keel (2005), Stafford (2003) and Taborosi (2000; 2004) according to the Carbonate Island Karst Model (CIKM) (*sensu* Mylroie et al., 2001; 2004 and modified by Keel, 2005). The CIKM categorizes cave and karst features in young carbonate islands by their position relative to the salt-water lens, and the island type. For a complete description of how the cave and karst features in the CIKM form and their hydrologic functions (see Keel 2005, Stafford, 2003, Taborosi, 2000, and Toepke, 2006).

Previous Karst GIS Work

Very little work has been done with GIS in relation to karst. The most extensive treatment has been done by Gao (2002; 2004), who used a GIS database of known sinkholes along with a model that used the distribution of sinkholes in order to classify the region into one of six relative hazard zones. This model was viewed as a success where the location of sinkholes had been accurately mapped and the density of sinkholes was fairly high. The model used lineament, nearest neighbor, decision tree, and cartographic analysis to delineate the hazard zones.

Typically, GIS has been used simply as a centralized repository of cave and karst data for a specific region. Cave locations and maps, survey data, field observations, lists of unexplored areas of the cave, and other data all have been stored in GIS databases (Addison, 2003; Iliffe, 2003). A GIS can be used to identify gross errors in field notes and to produce better maps (McKenzie and Veni, 2003), especially when data are entered directly into a GIS system, the use of GIS software can improve cave maps by reducing data errors in the survey.

Alternatively, a descriptive GIS of known caves can be used to identify where a cave resource is likely to be found. If a cave's entrance location is known and the location and size of cave passages is known, overlaying the cave map with the overlying topography can identify where the cave nearly intersects the surface. This information can then be used to identify places where additional field work should be performed in order to potentially find additional cave resources (McKenzie and Veni, 2003). Knowing where to focus exploration can greatly increase an explorer's probability of finding previously unknown caves. One team used GIS to map known cave and karst features in order to identify patterns in and distribution of karst features (Lyew-Ayee et al., 2003). Mylroie et al. (2005) produced a digital karst map of the known cave and karst features of Mississippi. ArcGIS was used to produce maps of counties with known caves as well as all other digital karst maps.

In addition to maps of cave features, GIS has been used for the mapping of karst features including karst-prone geology, and specific karst features such as sinkholes and karst drainage basins. Paylor et al. (2003) used GIS to map the karst prone geology and sinkholes of Kentucky. This statewide map can then be used by the public and both public and private organizations to identify potential environmental and developmental issues. In addition to using GIS to map sub-surface features, GIS has been used to map surficial karst features and sometimes their connection with sub-surface features. One such project is the Florida Cave Database. The National Speleological Society Cave Diving Section and others that map underwater cave passages provided subsurface data for this project. Included in the database are fields such as ownership, entrance locations, conduit size and trend, and direction of water flow. After the data were acquired, an attempt was made to correlate the sub-surface features with known sinkholes and other surficial karst features (Denizman, 2004).

There are significant issues in mapping the flow of water through karst systems because the flow of groundwater in karst aquifers differs from traditional aquifers in speed, direction, and distance that the water travels. Subsurface waters may flow for many kilometers at rates comparable to that of surface streams and may cross under surface divides. Glennon (2003) used GIS to develop a model to better understand and predict the flow of groundwater in karst aquifers.

Lindsay and Smart (2004) used a GIS to map the level of the water table and to identify underground watersheds in terms of quality, quantity, flow directions, divides and conduits. Part of the reason for the mapping of karst groundwater is to map potential contamination risks (Lindsay and Smart, 2004; Singhal and Samuelson, 2004). Other uses for karst aquifer mapping are for governmental planning (Paylor et al., 2003), freeway route selection (Florea and Gulley, 2004; Griffin and Florea, 2004), and creating management zones to redirect urban development (Veni, 2004).

Planning of development in karst regions reduces the environmental impact of human activities and can also be used to help guide development activities. One of the major issues facing planners in karst areas is the high risk of groundwater contamination due to the potential of rapid and unfiltered transport of contaminated water to unknown destinations. In addition to the work done by Paylor et al. (2003), other workers such as Kostka et al. (2004) have used GIS maps to help governments create development plans and change zoning to better reduce the risk of future groundwater contamination.

METHODS

Database Development

A relational geodatabase (GDB) in 3NF was developed to store spatial and non-spatial information for each of the cave and karst features in the descriptive GIS. The tables in this database are: ACCURACY_INFORMATION, CAVE_TYPES, CAVES, HYDROLOGIC_FUNCTION, ISLANDS, PROVINCES, and SURVEY_GRADE. The ACCURACY_INFORMATION table contains the accuracy of the location information and information as to how the location of the cave or karst feature was obtained; CAVE_TYPES contains information as to the karst feature type (e.g., Flank Margin Cave, Closed Depression, etc.); HYDROLOGIC_FUNCTION stores information on whether the feature serves to recharge the groundwater or if the feature is discharging groundwater, and optionally, at what rate; ISLANDS contains information specific to each island; PROVINCES contains information on the physiographic provinces; SURVEY_GRADE contains information as to the accuracy of the survey performed on the karst feature; and CAVES holds the information on the caves and karst features for the islands including the location information.

Each table has a surrogate (artificial) key as its primary key. Foreign keys to ACCURACY_INFORMATION, CAVE_TYPES, HYDROLOGIC_FUNCTION, PROVINCES, and SURVEY_GRADE were created in the CAVES table and a foreign key to ISLANDS was created in the PROVINCES table.

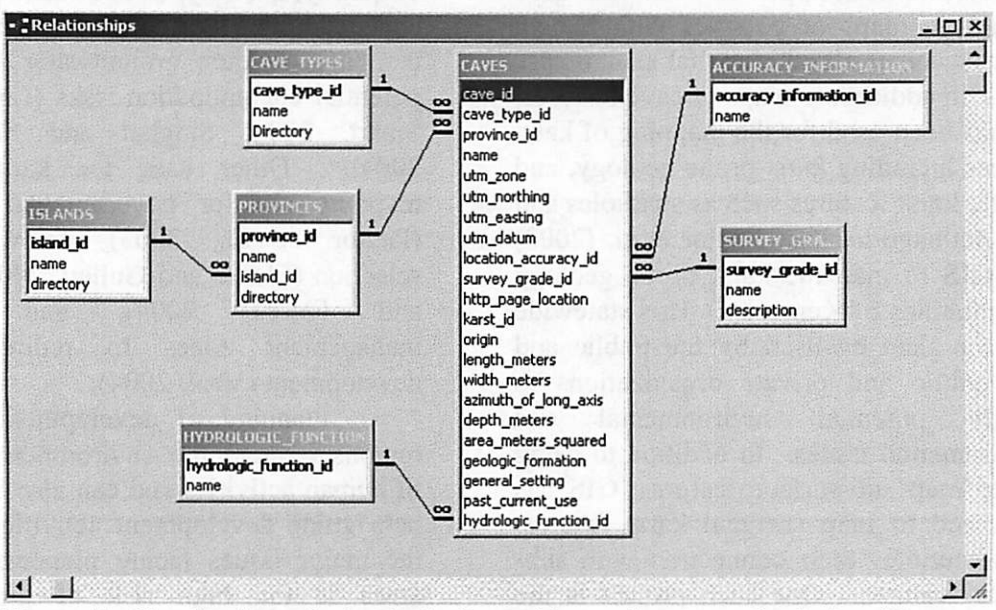

Figure 8. Geodatabase design including tables, columns, and relationships.

To speed retrieval, individual indexes were created on each of the primary and foreign keys as well as each of the name columns. The database design is shown in Figure 8.

To speed retrieval, indexes were created on all of the name columns as well as on the primary and foreign key columns.

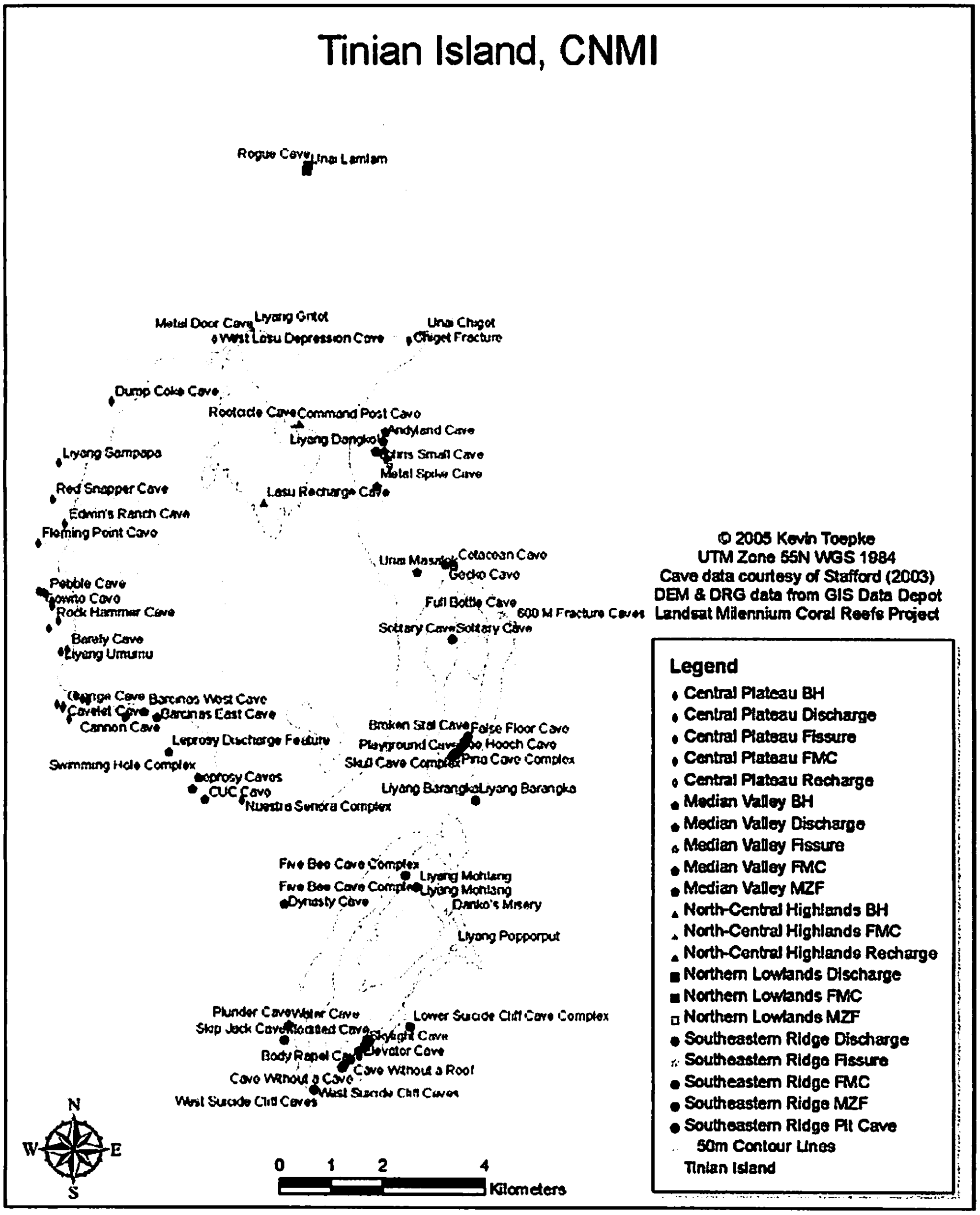

Figure 9. Map of the cave and karst features of Tinian Island, CNMI with island outline and 50 m contour.

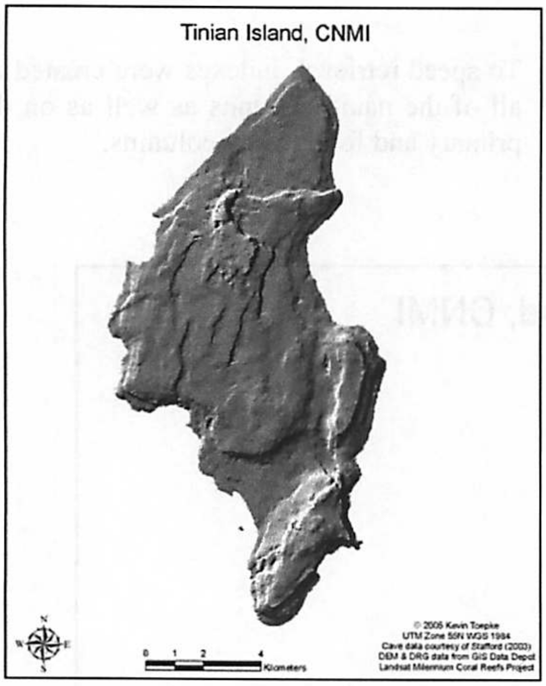

Figure 10. Hillshade of Tinian.

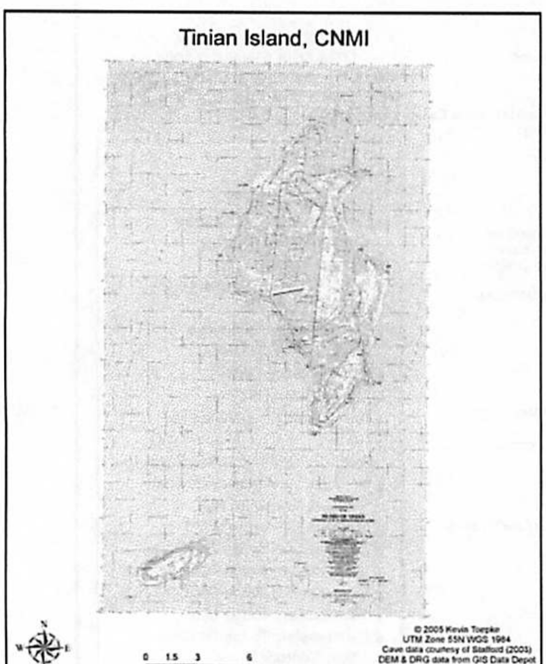

Figure 11. Map of Tinian and Aguijan Islands showing Digital Raster Graphics (DRG) Layer.

The data for this project has already been collected for various projects, including various Masters Theses by Mississippi State University (MSU) and University of Guam (UOG) students. The data for Rota was collected and organized by Keel (2005) for his project at MSU; Tinian and Aguijan by Stafford (2003) for his project at MSU; and Guam from Taborosi (2000, 2004) for his UOG project. Information on most of the caves of Saipan was not available for this project. The data were acquired via personal communication from each author and directly from the theses.

The same process was followed for each of the datasets compiled in this database. The data were validated based on received locations, maps, descriptions and fieldwork. The data then were organized into a series of directories based on island, physiographic province, feature type, and individual feature, as appropriate. The cave data was also loaded into the Geodatabase.

For purposes of this paper, only examples of Tinian will be shown. The same types of figures were created for the other four islands.

Once the cave data were organized, the digital data were organized by island and the DEMs were used to generate hillshades, island outlines, and topographic maps and hillshades at contour intervals (Figure 10). For each island, a map showing the location of each karst feature was created from the data in the Geodatabase. Each feature type was given a distinct symbol/color combination for ease of identification; the generated island outline and 50 m contour lines were added for reference (Figure 9).

Once the maps were produced and the data were organized and vetted, a series of HTML pages was created--a homepage for the entire database, as well as an introduction page for each island, as well as

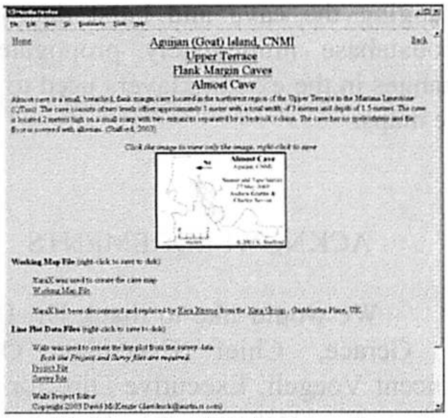

Figure 12. Sample HTML page for a cave.

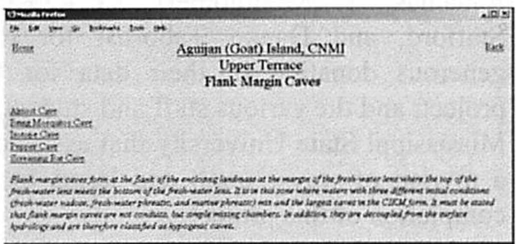

Figure 13. Sample HTML cave type page.

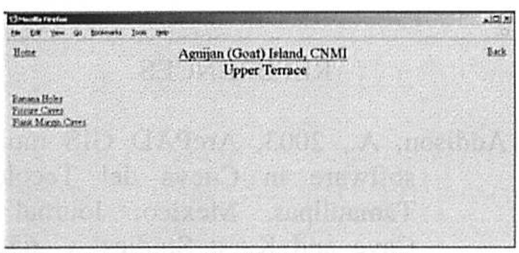

Figure 14. Sample HTML page for a physiographic province.

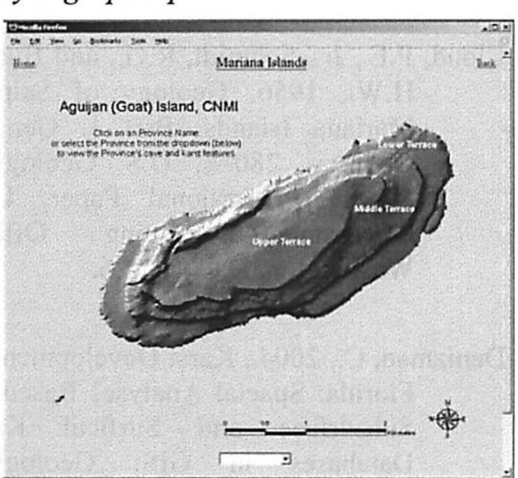

Figure 15. Sample island home page.

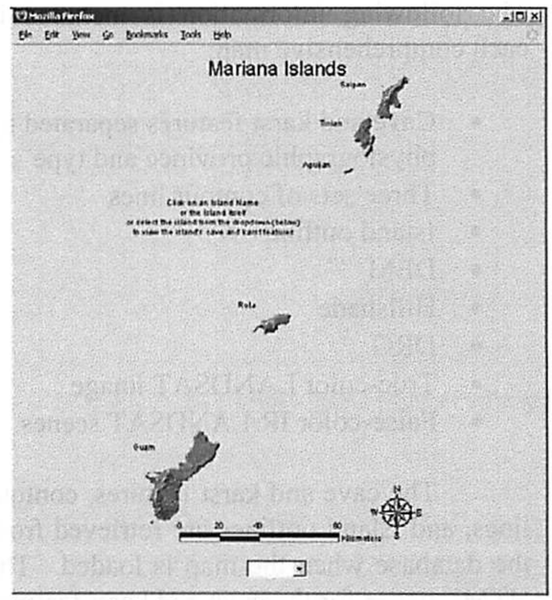

Figure 16. Project homepage.

pages with phyisiographic provice information, cave type within the province, and karst features present. These HTML pages were then linked to the maps via the http_page_location field in the Geodatabase. Samples of the pages created are in Figures 12-16.

CONCLUSIONS

A relational database of cave and karst information, including five comprehensive maps (one for each island), and a series of HTML pages were produced. The geodatabase contains point information for all known cave and karst features in the Marianas, three sets of contour lines (10, 25, and 50 m intervals) for each island stored as polylines, and island outlines stored as polygons. The point information of Saipan is incomplete because the data for only four cave features was received.

The following information is included in each comprehensive map:

- Cave and karst features separated by physiographic province and type
- Three sets of contour lines
- Island outline
- DEM
- Hillshade
- DRG
- True-color LANDSAT image
- False-color IR LANDSAT scenes

The cave and karst features, contour lines, and island outlines are retrieved from the database when the map is loaded. The HTML pages for the cave and karst features contain the feature descriptions, maps, and links to the digital survey project files and the working map documents. Additional web-publishing quality HTML pages were created to allow normal web navigation from the project's root directory.

The five maps and HTML pages along with the geodatabase provide a good start for organizing the cave and karst data of the Mariana Islands. They provide a "one-stop shopping" destination for information on the caves and karst of the Mariana Islands. This consolidation of information will allow researchers to identify future project locations and to more effectively target field activities. Additionally, the data from new projects can be integrated into the database. However, a good deal of extra work could be performed to enhance the geodatabase and maps, such as the addition of tables or fields and the incorporation of these new data into the maps.

Organizing the point, line, and polygon data in a relational geodatabase allows for simplified data management. Future researchers can modify the cave and karst data from a single place. Adding or changing the cave and karst data in the geodatabase immediately propogates the changes in the existing layers used to create the maps.

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