SEISMIC HAZARD VULNERABILITY
ON GUAM

A Summary

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TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

0.1. SCOPE

This report is a simplified summary of Earthquake Hazard Vulnerability Study: Guam, Mariana Islands prepared by Dames & Moore, Inc. (D & M) for the Civil Defense/Emergency Services Office, Government of Guam and submitted in December 1994. The original report was reviewed by the Guam Seismic Advisory Council and deemed to be a document that would be technically inaccessible to a majority of the intended readership. The GSAC felt that the content, organization, and terminology needed major simplification and restructuring if the report were ever to be "user friendly" to those government agencies and private sector firms that would most likely need the enclosed information. It is expected that this work will act as a *Summary Report* for those not well versed in current seismic and tectonic terminology and that it be used as one of several tools for planning, teaching, consulting, and/or training in these subjects.

An original D & M report is appended to the original of this summary report and archived at the Office of Civil Defense. Copies of this summary, without the original D & M report, can be obtained from that office. As in the original study, this summary is not based on a comprehensive field investigation program by the author. We drew heavily from statements and publications of a number of experienced geoscientists to prepare this summary, as well as from our fifteen years of geologic experience on Guam and in the other Mariana Islands.

We eliminated certain text material and diagrams and graphs, but retained methodologies, results, interpretations, and conclusions from the original, although we felt obliged to add several alternative viewpoints. Rather than reproduce all the figures and diagrams appearing in the original report, we refer a number of them by their appropriate D & M Figure, Table, or Plate Number. We also feel that the treatment of seismic hazards and risk response presented in the original report needed to be shortened and generalized.

We present a modified seismic hazards map as a "fold out" in the body of the text for rapid reference to text material. Copies of a wall-size edition of the map can be obtained at cost from the Water & Energy Research Institute of the Western Pacific at UOG. Finally, our report includes a short glossary of words first appearing in the text in *italicized* form.

D & M. cite five tasks accomplished by their technical report:

1. *Developed a summary of the tectonic setting and recorded earthquake history of the Mariana Islands Arc region.*
2. *Mapped, at 1:50,000 scale, the active and dormant faults, and geologic hazards.*
3. *Established of a Guam-specific response spectra for use in developing building requirements.*
4. *Estimated the statistical probability of strong earthquakes that could occur on or near Guam.*
5. *Recommended future research activities that would be helpful in identifying earthquake hazards and susceptibility on Guam.*

We reorganized and simplified materials from the D & M "Tasks" into the following Chapters.

1 *Geologic Framework*
2 *Faults and Earthquakes*
3 *Seismic Hazards*
4. *Conclusions & Recommendations*

Guam has experienced countless aftershocks from the "Great Earthquake" of August 8, 1993, in addition to several significant tremors judged to be spatially unrelated to that event. Many otherwise informed citizens and the local media continue to offer explanations for the untested premise that Guam is lately experiencing an unusually high frequency of earthquakes. Scientists on Guam and elsewhere are being asked to give reasons for this perceived increase. Our position is that there is no scientific evidence to support the premise. Earthquakes have always been and always will be an integral part of this island's environment. They appear to be random and unpredictable events, occurring within a statistical probability frequency distribution that can be, as yet, only imperfectly modeled. We believe, however, that effects of large earthquakes, including occurrences of seismically triggered hazards, general levels of destruction, and injuries, and deaths, can be anticipated from this model and from our collective experience, and within limits mitigated through sound planning and engineering.

0.2. PREVIOUS RELATED STUDIES ON GUAM

0.2.1. ISLAND GEOLOGY

The geology of Guam was comprehensively reported by Tracey et al (1964) from several years of field studies by a large party of geologists in the decade following WWII. Much of what we know about the age and origin, and the composition, spatial distribution, and evolution of rock formations on Guam are detailed in U.S. Geological Survey Professional Papers 403-B through 403-H, and summarized in 403-A. Although there are unavoidable shortcomings in those studies arising from conflicts with the more recent *Theory of Plate Tectonics* and other modern scientific ideas, they are nevertheless the basic documents on which all subsequent geologic research and reports on Guam, including this summary, have been based. They represent an enormous resource of information for agencies, planners, consultants, students, etc.

0.2.2. ISLAND EARTHQUAKES

A general review of earthquakes, hazards, and mitigation was prepared for GovGuam, Disaster Preparedness Planning Section of the Bureau of Planning in 1977-78, through a Federal Grant from the then Department of Health and Urban Development (DHUD). The four volume series proved helpful in preparing this report. Volume 1, "Earthquakes: Their Nature and Effects on Guam" is a particularly useful pamphlet, containing considerable historical data and is written in an easily read style and format.

0.3. ACKNOWLEDGMENTS

The writers acknowledge their appreciation to Juan B. Rosario, Director of Guam Civil Defense-GESO and Benny J. Cabrera, Earthquake Program Manager and Joanne Hoffard, Region 9, Federal Emergency Management Agency (FEMA) for their encouragement and financial support for this project. We also thank Mr. Fred Otte, Environmental Manager and Engineering Coordinator, Shell Guam, Inc., Mr. Tom Polevich, Environmental Geologist, Juan T. Rosario Associates, and Mr. Victor Wersch, Hydrogeologist, Guam Environmental Protection Agency, for reviewing and correcting this manuscript. Finally, we gratefully thank Dolores (Dee) Santos, UOG/WERI for expertly changing the raw manuscript into a WERI technical report format.

CHAPTER I

GEOLOGIC FRAMEWORK

I.1. INTRODUCTION

Guam is one of six islands in the Mariana Island Arc system south of Anatahan that have had generally similar geologic histories. All six, Farallon de Medinilla, Saipan, Tinian, Aguijan, Rota, and Guam are extinct volcanic edifices that during their long and episodic upward growth acquired a veneer (up to 175 meters) of *limestone*, a rock made of the cemented skeletal remains of tiny marine organisms composed primarily of *calcium carbonate*. The slowly emerging volcanic structure acquired this cap of limestone by remaining submerged in shallow marine waters as the organisms accumulated for many millions of years.

Guam has been under construction for about 43 million years and has evolved through two consecutive time periods that featured, respectively, dominance of volcanism (43 to 15 million years ago) and co-dominance of coral reef formation and *terrigenous* erosion (the last 15 million years). Indeed, several intervals of time experienced appreciable overlap of all three geologic processes: volcanism, major coral reef development, and terrigenous erosion. Yet, despite changes in the dominant geologic processes, sudden deep *crustal* movements and resulting shock waves and ground shaking, what we call earthquakes, have always plagued Guam.

I.1.1. PLATE TECTONICS

Volcanoes, earthquakes, oceanic trenches, and arc-shaped island chains such as the Mariana Islands are among the more perceptible signals of the earth's basic thermal and kinetic instability. Over the past thirty-five years those signals and their origin have become codified into the Theory of Plate Tectonics, a paradigm that now appears as Chapter 1 in most elementary geology textbooks. It is staggering to list how many environmental, economic, and political issues and concerns in the world relate to various aspects of this theory, and no more so than on Guam and in the Mariana Islands. It would take volumes to summarize the theory and applications to our island, and thus the reader is referred to several standard geology texts for this information. A few of these texts are listed separately in the references. We will, however, borrow generously from the Theory of Plate Tectonics, while keeping technicalities to a minimum. The main geographic components are as follows.

I.1.1.1. Mariana Island Arc

Volcanism generally is concentrated along the Mariana Ridge, a mostly submerged topographic high on the sea floor, 50-100 kilometers west of the Mariana Trench (Figure 1). All the Mariana Islands, those that are younger and still volcanically active such as Pagan, and those to the south that are volcanically extinct like Saipan and Guam, lie on this Mariana Ridge (Figure 1). Collectively, the islands, seamounts, Mariana Trench to the east, Mariana Trough to the west, and other regional seafloor features, including the bedrock and oceanfloor sediments, are referred to as the Mariana Island Arc System. The region encompasses over 1,200 kilometers longitude and over 1,500 kilometers latitude, and coincides generally with the region shown in D & M, Figure 2.1. In the north, the Mariana Island Arc System merges with the Izu-Bonin Island Arc, to the south the Mariana Arc intersects the Yap Island Arc.

I.1.1.2. Plates and Basins

Figure 2 indicates the approximate position and the names of the two principal tectonic plates that have been converging to form and modify the Mariana Islands. They are the Pacific Plate east of Guam and the Philippine Sea Plate including Guam and west of Guam[1]. Plates are rigid slabs of *lithospheric* bedrock, perhaps a hundred kilometers thick, that move slowly in response to thermal convective activity below. Rates of movement vary worldwide, but range generally between 1 and 8 cm/yr. Plates are bounded laterally by other plates in one of four general spatial arrangements: a) "straight on" plate convergence such as in the case of much of the Mariana Island Arc, b) *oblique convergence*, as exemplified by portions of the Mariana Arc, producing long lateral fracture or *rift* systems called *strike-slip faults* that will be discussed later in this report; c) divergence (spreading center) such as along the East Pacific Rise; and d) three-plate intersections called *triple junctions.* Regardless of the geometry, however, plate-plate interactions are responsible for almost all major earthquakes.

A portion of the Philippine Sea Plate, the region lying immediately west of Guam and east of the West Mariana Ridge (Figure 2), is called the Mariana Trough, and more generally is an example of a *backarc basin*. The Mariana Trough extends from around 12 degrees north latitude to its junction with the Izu-Bonin Arc to the north near 24 degrees latitude. It can be visualized as symmetrical halves spreading laterally (at about 2 cm/yr) away from a north-south centerline. Seismic activity in the trough region is relatively low. The phenomenon of spreading in the backarc basin creates new bedrock beneath the seafloor sediments, and for that reason geophysicists have given the basin the tectonic plate designation of Mariana Microplate, to distinguish it from the surrounding Philippine Sea Plate that is comprised of much older bedrock.

I.1.1.3. Transform System

Figure 2 indicates the trend of a series of *transform faults* or simply transforms, that extend from the Mariana Trough across and slightly south of Guam, into the *forearc* to the Mariana Trench. These features are similar in origin and size to the great transform systems in California and Luzon (Figure 2), and other tectonically active areas. They form by oblique plate convergence.

I.1.1.4. Mariana Trench and Subduction

The Mariana Trench lies east and southeast of Guam. Between Guam and the Mariana Trench is an active seismic area called the *forearc* or *forearc basin*. The Mariana Trench and forearc basin are formed by the northwest movement of the Pacific Plate and its convergence against and subduction beneath the Philippine Sea Plate (Figure 3). The Trench reaches depths of about 11,000 meters, the deepest feature on the planet and marks approximately the flexure in the subducting Pacific Plate.

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[1] Philippine Sea Plate is now more commonly used than Philippine Plate

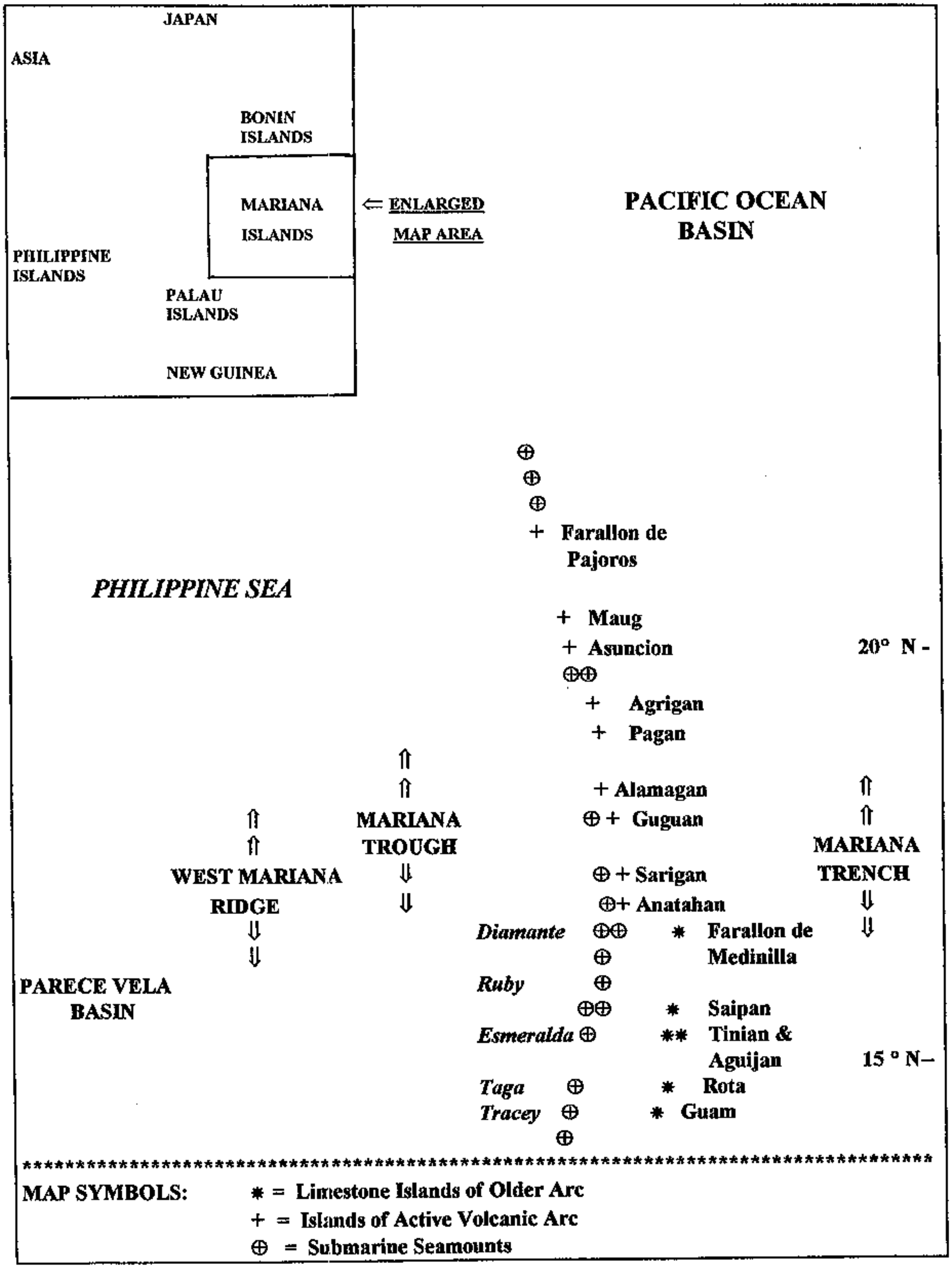


Figure 1: Regional Map of Mariana Islands & Principal Submarine Seamounts: Approximate scale = 1:1,000,000, The West Mariana Ridge, Mariana Trough and Mariana Trench trend southwest below about 16° N lat.

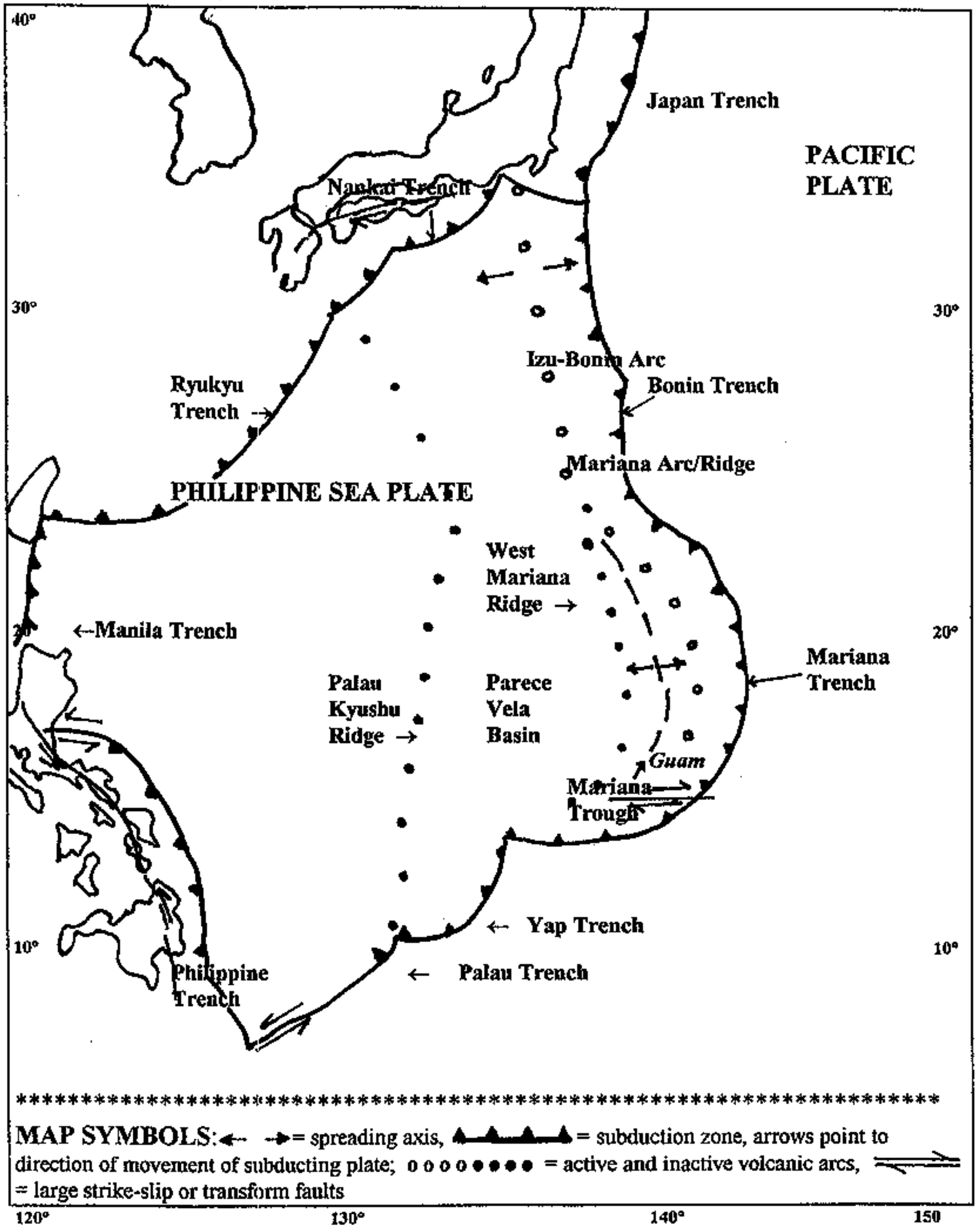


Figure 2. Schematic Map of Philippine Sea Plate: Principal Tectonic Features are Indicated. Approximate scale 1:25,000,000

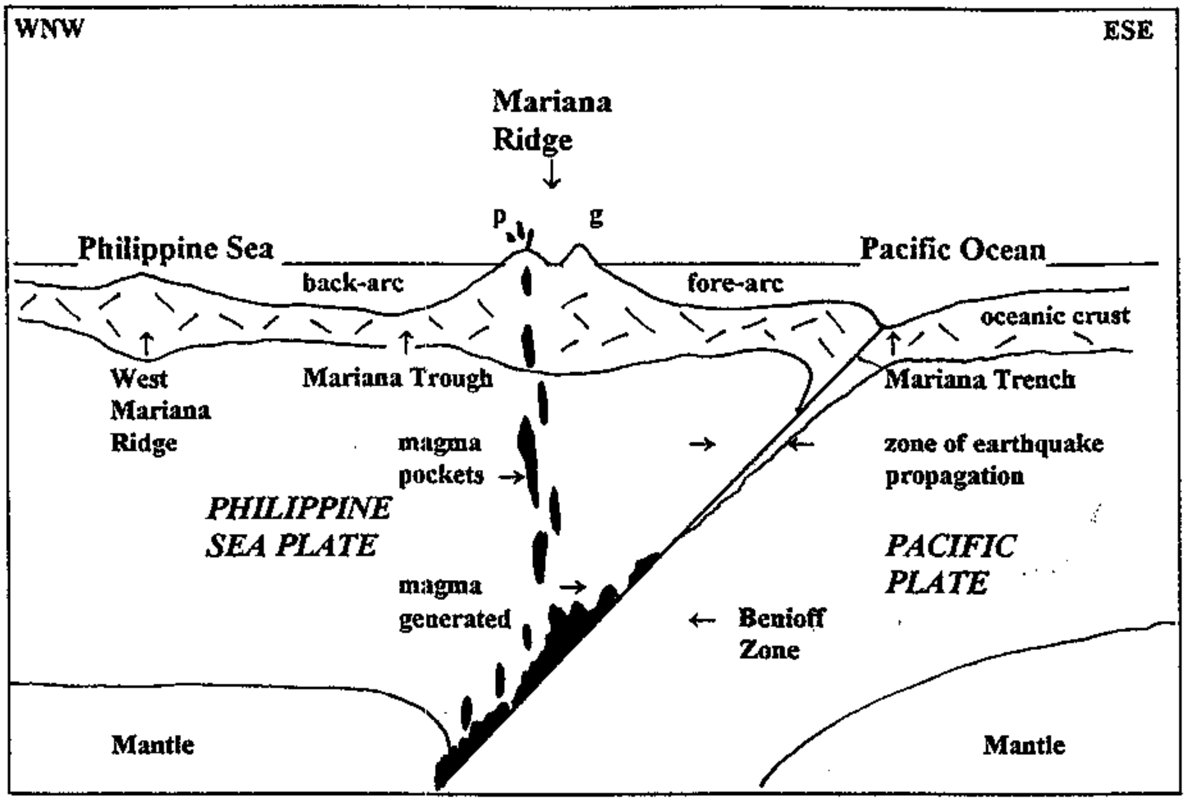


Figure 3: Generalized Schematic Cross-Section through the Mariana Island Arc. Showing Key Tectonic Elements. The vertical scale is exaggerated. g = Guam, Saipan, etc., the older limestone-covered islands on the Mariana Ridge; p = Pagan and the other active volcanic islands and submarine seamounts to the north and west of the older arc.

The geographic location of the trench follows a curved line that bends sharply westward south of Guam (Figure 2). Curvature reflects systematic variation in rates of convergence and subduction, and the angle of subduction from south to north along the trench. These variations are also probably responsible for geographical concentrations of earthquakes and for historic patterns in earthquake magnitude and frequency. When combined with rates of convergence of the Pacific Plate, the accumulated rate of convergence along the Mariana Trench is around 5.5 cm/yr.

The first evidence of *subduction* was reported in a famous paper by Benioff (1948) He showed with graphs of depth of earthquake origins (foci) plotted against distance from trench to volcanic arc, the existence of what he interpreted to be a fault system dipping from the trench under the active volcanic arc (Figure 3). Today, we realize that this zone, now called the *Benioff Zone,* is approximately the top of the subducting slab of *lithosphere.* It is along this zone, or in adjacent plates themselves that most of the earthquakes affecting Guam originate.

I.2. VOLCANISM & VOLCANIC ROCKS

I.2.1. MAGMAS

The volcanic rocks that form the bulk of Guam and the all other islands in the Mariana chain, were created from *magmas,* molten rock generated by melting of subducted oceanic crustal rock and sea floor sediments. Magmas formed between 500 to 650 kilometers depth and migrated upward through fracture zones in the earth (Figure 3), eventually to extrude as *lava* onto the seafloor, sometimes violently, and sometimes as slowly oozing flows. Over time, successive eruptions have created localized volcanic edifices on the ocean floor, several of which continued to grow upward to form huge *seamounts* and later, islands. Other seamounts have remained submerged but could evolve upward to form islands in the future.

I.2.2. BEDROCK FORMATIONS

The volcanic rocks under Guam vary in composition, texture, strength properties, water content, and critically, in the manner in which they weather, erode, and maintain a given slope. These properties jointly determine much of the vulnerability of a given ground location or broad area of terrain to seismic shock waves. The variation in behavior of volcanic rocks can be traced directly to the style of volcanism that created the rocks, specifically the manner by which the magmas were extruded and solidified, and the location where extrusion occurred. Volcanic rocks on Guam were created during three long periods of time, called Geologic Epochs and their outcrop distribution is indicated on the geologic map, Figure 4.

I.2.2.1. Eocene Volcanic Rocks (43-38 million years ago)

All the islands began life as active volcanoes along a linear rift on the ocean floor about 43-40 million years ago. Eocene volcanism featured *basalt* flows very similar to those being extruded on the "Big Island" of Hawaii today. The rocks can be observed on sea cliffs and road cuts between Toguan Bay and Agat on the southwest coast. The geologic unit is designated now as the Facpi Formation (Reagan and Meijer, 1984), although in the original studies of Stark (1963) and Tracey et al (1964), it was termed the Facpi Member of the Umatac Formation. The Facpi Formation is considered the oldest or *basement* rock of Guam.

I.2.2.2. Oligocene Volcanic Rocks (38-23 million years ago)

Volcanism style changed in the Oligocene Epoch, when beginning about 38-35 million years ago highly explosive submarine eruptions heaped tens of cubic kilometers of fine *ash* and coarser debris onto the flanks of the growing basaltic seamount. That long period of explosive submarine activity is evidenced today in many outcrops of the Alutom Formation throughout central Guam, notably on Nimitz Hill, Mt. Alutom, and Mt. Tenjo, along the Cross Island Road, in the Ylig River watershed, and in the north, at Mt. Santa Rosa near Yigo. During this same general time, basalt magmas intruded into the older Facpi Formation flows along *faults* and fractures. Resulting rock structures are called *dikes* or *sills*, and now stand out in bold relief along many sea cliffs and on adjacent wave-assaulted platforms in southwestern Guam.

I.2.2.3. Miocene Volcanic Rocks (23-15 million years ago)

The final volcanic chapter of Guam was written in the late Oligocene and early Miocene Epochs. Between 25 and 15 million years ago, southern Guam experienced tremendous explosive eruptions of volcanic debris that is similar in many respects to the earlier Alutom volcanic rocks. Outpourings of basalt flows also accompanied the Miocene volcanism. These youngest volcanic rocks, called the Bolanos formation, can be seen today throughout much of southern Guam, with excellent outcrops exposed on Mt. Sasalaguan, Mt Schroeder, and generally the entire Geus, Inarajan, Agfayan, Bubulao, and Ugum-Talofofo River watersheds.

When Bolanos eruptions ceased, about 15 million years ago, almost all of southern Guam was above sea level and blanketed with volcanic rocks. Notable exceptions were the present southeastern coast between Yona and Inarajan which was then under several hundred feet of ocean, and the present day Talofofo River valley, perhaps as far west as the Fena River valley, which was then an extensive *estuary,* following an ancient fault trend. In the north, the Guam seamount dropped away into seas punctuated only by two small islands that were localized bumps on the Guam seamount, formed during the Oligocene volcanic event and later faulted upward. Those Miocene islands are now Mt. Santa Rosa and Mataguac Hill in Yigo.

I.2 3. VOLCANIC TERRAIN

Volcanic rocks weather rapidly in the tropics to a clay-sand residuum. As result, the volcanic southern half of Guam consists mainly of highly dissected terrain. Slopes are frequently steep, often nearly vertical, but even gentle slopes tend to be unstable. This inherent instability will be addressed later in this report. Slopes are covered variously with a savanna grass community, ravine forest vegetation, or they may lack vegetation altogether.

Guam's volcanic terrain included numerous perennial stream systems, the four largest being the Ylig, Talofofo-Ugum, Inarajan. and the Pago-Lonfit Rivers. A glance at any drainage map of Guam would reveal that trunk and tributary drainage directions are strongly aligned in a rectangular or rhombic grid, implying that stream flow and channel erosion are controlled by oriented zones of weakness in underlying bedrock, presumably faults and/or *joints.* These structures are described in Chapter 2.

Picture

I.3. REEFS AND LIMESTONES

Coral reef development on Guam assumed major importance during the Miocene Epoch, about 15-10 million years ago. From that interval until about 2 million years ago, reef tracts grew in shallow seas and lagoons that blanketed almost the entire area that is currently northern Guam as well as the perimeter of southern Guam. Over the past 2 million years, in response to Guam's continued upward emergence, all coral reef development has shifted to the perimeter fringe of the island, where reef evolution has been strongly influenced by the pronounced swings in sea levels that have affected coastlines around the world, as a response to cycles of polar-continental glaciation.

I.3.1. LIMESTONE FORMATION

Over time, limestones evolve from reefs through physical and chemical changes brought on from reactions between reef skeletal materials and rain and groundwater percolating through the rock. As a result of these processes, ancient reefs around Guam became hard, frequently cavernous limestone bedrock, quite different superficially from original reef structure. Chemical attack on the bedrock is facilitated by the presence of many natural bedrock fractures and abundant *pores* that disperse surface waters downward to great depths, where they may dissolve great volumes of carbonate bedrock forming intricate and extensive cave systems. Taken to the extreme, cave formation may leave limestone overburden locally unsupported and vulnerable to ground subsidence, or even collapse. Resulting closed surface depressions are called *sink holes, sinks*, or more generically, *dolines,* and the regional terrain referred to as *karst.*

I.3.2. LIMESTONE TERRAIN

There are a variety of separately mapped limestone formations on Guam. They represent different ages and origins of formation, but all have support a similar geomorphology that is easily differentiated from that formed over volcanic rocks. The separate formations are shown on Figure 4 in shades of blue and green.

Areas of Guam underlain directly by limestone bedrock have distinct terrains. Three in particular are widespread and could involve distinctive earthquake responses: a) limestone plateau, b) terrace and scarp perimeter, and c) the karst terrain region.

I.3.2.1. Limestone Plateau of Northern Guam

The northern three-eighths of the island, principally generally north of Agana, are an elevated limestone plateau. Similar terrain also occurs along a two-to-five kilometer wide coastal strip from Yona, south to Inarajan. The northern limestone plateau averages about +120 meters in elevation but gently rises to the north to reach almost +200 meters on the extreme northern and northeastern edges. The high permeability of the limestone bedrock under the plateau allows rain to rapidly infiltrate to the water table (lying near sea level) at rates reaching several hundred meters/hour. As a result, there is a general absence of any natural standing water and surface drainage on the northern limestone plateau.

The generally monotonous physiography of the limestone plateau is broken by individual and clusters of sinkholes and several conspicuous clifflines that represent *faultline scarps.* The latter result from faulting and erosion and will be discussed later in this report. Broken and recemented limestone, called *limestone breccia*, characterize the limestone along these faultlines.

I.3.2.2. Scarp and Terrace Terrain

Over the past 2 million years, sea level fluctuations have alternatively promoted, slowed, stopped, and/or shifted perimeter reef growth landward or seaward. Reef growth patterns and a generally upward rising island have combined to create notable elevated terraces separated by steep *scarps* or cliffs around our northern coast. Terrace surfaces form over long periods of constant sea level when the entire reef system widens and grows seaward; scarps result from vertical shifts in the relative position of the island and sea level.

Scarp and terrace terrain occurs along the fringes of the entire northern coast and along most of the southeastern coast, where the limestone plateau abruptly terminates and the terrain steps downward through a flight of from three to six terraces to a general rocky shoreline. At least one additional terrace is now slightly submerged, covered with modern reef growth and beaches, while perhaps two totally submerged terraces lie offshore beyond the modern reef. The scarps and terraces at elevations between +10 and +200 meters are *Pleistocene* in age, having formed between 2 million and 125,000 years ago. Terraces at or below +10 meters elevation, appear to have developed through more recent reef building, about 125,000-130,000 years (Randall & Siegrist, 1996).

I.3.2.3. Karst Terrain

Doline dominated terrain occurs in the middle eighth of the island, bordering Route 10 from Barrigada to Chalan Pago, and Route 4, from Agana to Pago Bay is a region that lies between sea level and +50 meters, and is notable for its sink holes and other complex solution features, and often flashy, interrupted drainage, and "dead-end" surface drainage. Bedrock is a highly *argillaceous* reef limestone that is sufficiently impermeable to support locally intermittent surface drainage, much of which eventually feeds into Agana Swamp via both overland runoff and subterranean passageways.

I.4. UNCONSOLIDATED SEDIMENTS

In addition to the two major classes of bedrock on Guam, limestone and volcanic rock, significant local accumulations of modern sediments occur in southern Guam. These deposits are derived ultimately from a) *in situ* weathering of volcanic bedrock and eventual transport downslope and downstream of the *detritus*, and/or b) transport and concentration of reef carbonate particles in nearshore environments, and c) artificial land reclamation and stabilization projects. Many such deposits are seasonally or even permanently saturated with water, and may be highly sensitive to shock waves generated in earthquakes.

I.4.1. SAPROLITE

Many volcanic outcrops in southern Guam are composed of *saprolite*, a soft, highly weathered rock-like material that forms as a thick mantle (several tens of meters) above the less weathered volcanic bedrock below. Saprolite appears from a distance to the untrained observer to be bedrock, but it has been totally transformed through chemical changes to a weak, soft, and spongy material. This weathered cap on bedrock gives the pronounced low-velocity seismic wave signal reported in several *seismic refraction* studies on Guam. In the D & M report, "stiff soil" is used for saprolite caps on volcanic rock Saprolite thickness may reach 25 meters.

I.4.2. COLLUVIUM

Colluvium is weathered rock material transported downslope by gravity. A deposit of colluvium may consist of a single isolated boulder, a pile of boulders (called *talus*), but more generally is an unsorted mixture of sands, silts and clays that has been gravity-transported. Gravity failure of any slope is invariably promoted by the increased weight of water retained in the soil and saprolite during the rainy season, and colluvial deposits frequently are water-saturated.

I.4.3. ALLUVIUM

Alluvium refers to unconsolidated rock particles that have been transported and deposited by moving water (also ice and wind). Water-deposited alluvium tends to be sorted by size (or mass), exhibit distinct stratification, and may be fresh-, brackish-, or marine-water-saturated. Alluvial sediments occupy channels and floodplains of many lower valleys in southern Guam; build deltas seaward into estuaries, and are transported along the coast by longshore marine currents and deposited as beaches, on reef platforms, or swept offshore.

In rivers and on the inshore portions of deltas, alluvium is primarily *terrigenous* detritus originating from erosion of weathered volcanic rocks. It tends to be rich (20-40% weight) in silt- and clay-size particles and usually is saturated with fresh, brackish, or marine pore waters. Notable examples include Agana swamp, a riverine alluvial deposit where sediment pores are saturated with fresh water, and the lower Talofofo and Inarajan River valleys and estuaries where sediments are saturated respectively with brackish and marine waters.

I.4.4. ARTIFICIAL FILL

Large tracts of coastal terrain are underlain by several meters of artificially deposited sediment. These areas may have been constructed by dumping and bulldozing of discarded World War II material and rubble, or they may have been built primarily by pumping in dredged marine sediment. In the latter case, the alluvium will be composed primarily of reef carbonate detritus of varying sizes, but containing a high percentage of silt-size "fines"(less than .0625 mm in diameter). In many places the artificial fill is water saturated. The behavior of this material when shaken is cause for alarm, as will be discussed later. The largest deposit of man-made alluvium on Guam is the nearly continuous artificial fill that forms most of the area between and including Polaris Point and Cabras Island, west of Marine Drive, on the central western coast.

CHAPTER II

FAULTS AND EARTHQUAKES

II.1. FAULTS

A fault is a bedrock fracture along which opposite sides have moved. Thousands of bedrock faults criss-cross Guam, the other Mariana Islands, and the bordering oceanic regions. They result ultimately from collisional stresses and rock failure brought about through convergence of the overlying Philippine Sea Plate (Mariana microplate) and the subducting Pacific Plate.

II.1.1. NOMENCLATURE

The movement along the fault is called the *slip* (Figure 5A-5E). Faults are usually depicted in texts as planar features, and the characterization of a fault plane is a useful oversimplification. Faults are three-dimensional structures, and the compass direction of the trace of the fault (trend on a map), assumed for simplicity to be a line, is called its *strike* or bearing. Figure 6 indicates the strike of the largest mapped faults on Guam. If the fault slip is predominantly parallel to the strike, the fault is termed a *strike-slip fault* (Figure 5E). If an object on one side of the fault moves to the right during faulting, when observed from the other side of the fault, the structure is termed a right-handed or right-lateral strike-slip fault (Figure 5E). A left-handed or left-lateral strike slip fault produces movement to the left when observed across the fault plane.

The slope of the fault plane, as measured by the acute angle that it makes with a horizontal plane, is called its *dip angle* or *dip*. If the movement is predominantly up or down the fault plane, the structure is termed a *dip-slip fault* (Figures 5A-5D). Both strike-slip and dip-slip faults are major deformational rock structures in the Mariana Island arc and both are associated with the generation of earthquakes.

II.1.2. FAULT ZONE

Often the fault plane is sufficiently "open' to allow passage of groundwater; equally as often, the fault plane has been cemented shut by mineralization, preventing free flow of groundwater. Large faults tend to affect bedrock properties along strike and over wide areas on either side of the fault plane: Affected rock, often called the *fault zone* or *shear zone,* is variously bent, crumpled, broken, recemented (mineralized), splintered, gouged, pulverized, or even baked from the friction associated with movement.

II.1.3. FAULTS ON GUAM AND IN THE MARIANA ARC

Faults are tangible symptoms of crustal unrest and the cause of seismicity. The strike and types of fault movement in the Mariana Islands are a function of the angle at which the Pacific Plate is colliding with the Philippine Sea Plate, the rate of subduction, and the dip of the Benioff Zone. Those parameters have changed considerably over the past 40 million years, and they vary geographically along the entire 1,500 kilometer length of the Mariana Island Arc. Further, the strike of a given fault may change over time as the angle of plate collision changes: Thus, fault trends are not only inconsistent between locations on the Mariana Ridge, they may vary significantly within a small area of a single island, especially if the faults are of different ages or the same fault has been active for long periods of time. On Guam (Figure 4 & 7), some faults slice across bedrock of all ages while others appear to cut only older formations. We can only safely infer that faulting and earthquakes have taken place since the seamount began growth over 40 million years ago, and likely will continue to do for as long as the island arc exists.

The following fault types are in evidence on Guam and throughout the arc.

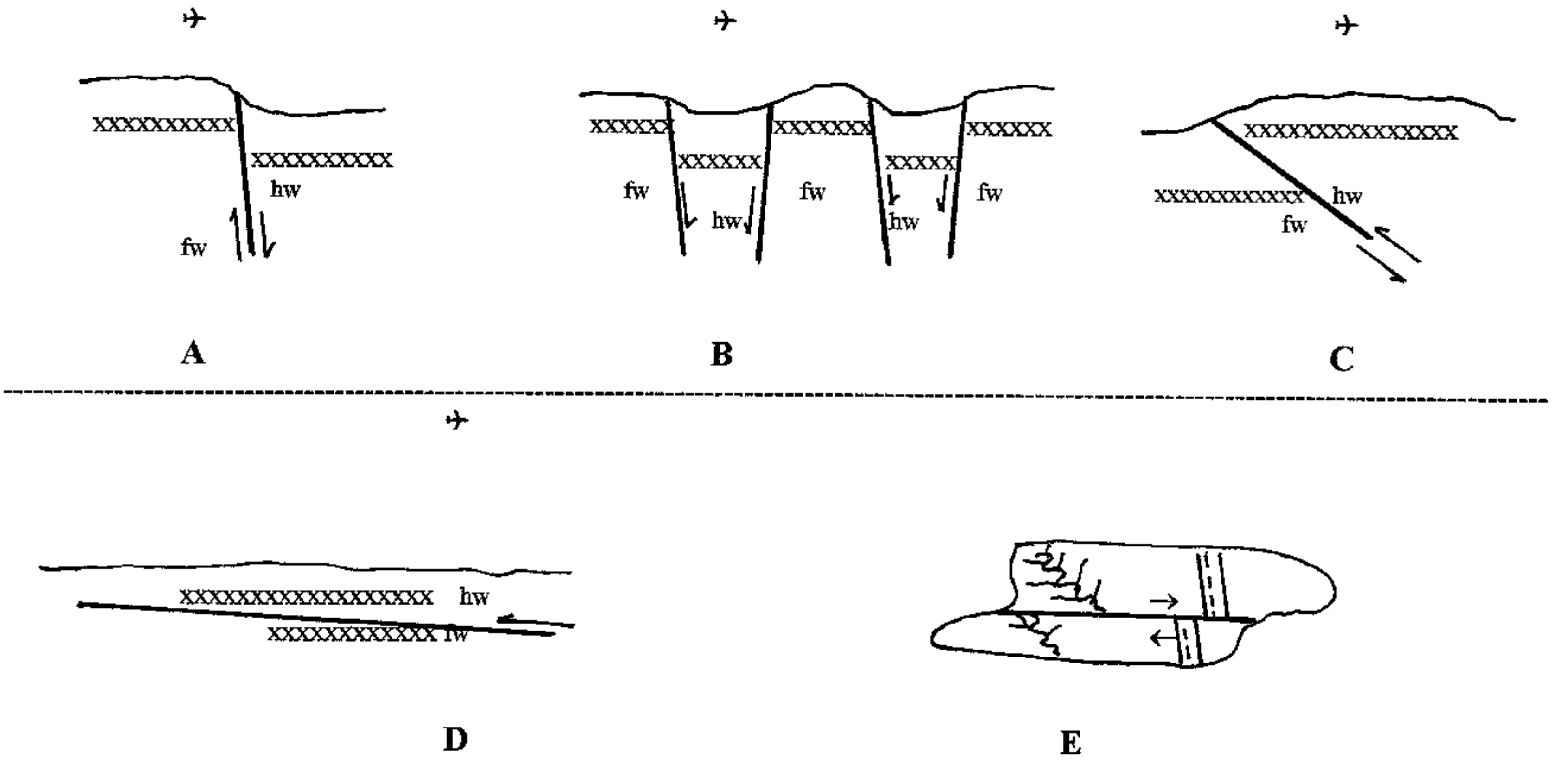
II.1.3.1 Normal Faults

One very common type of dip-slip fault in the Mariana Islands is called a *normal* or *gravity fault* (Figure 5A & 5B). In this type, the block of rock riding above the fault (hw = *hanging wall*) moves down with respect to the opposite block (fw = *footwall*). Because the hanging wall moves down with respect to the footwall, any cliff or fault scarp formed will be on the footwall. Normal faults tend to be associated with crustal tilting and other vertical crustal movements as well as tension (extensional) movement. Moreover, normal faults commonly have very high dips, and many are essentially vertical.

Tracey et al (1964) mapped several prominent normal fault zones on Guam and several other zones of inferred normal faulting (Figures 4, 6 & 7). Others have been subsequently identified by the writer. None of the fault zones is known to necessarily begin or end on land. The inference (Tracey et al, 1964) that all the major faults on Guam are normal faults is probably not correct.

From Figure 6 we can see the trend of the largest normal faults on Guam: The Adelup-Pago Point Fault separates the volcanic south from the limestone plateau; the Tamuning-Yigo Fault strikes generally south-southwest from Mt Santa Rosa in Yigo, along Latte Heights, past the Won Pat International Airport, to the Tamuning-East Agana boundary; the Cabras Fault strikes from about Facpi Point northeast along the west coast toward Piti Bay; the Talofofo Fault Zone (actually multiple parallel normal faults) strikes from the Pacific Ocean at Talofofo embayment west-northwest past Naval magazine and Santa Rita, and possibly continues along the southern coast of Orote Peninsula; and the Cocos Fault strikes along the southern coast and defines the Mamoan Channel at Merizo. In addition, Tracey et al (1964) mapped several shear zones in the north for which they assumed normal fault movement.

Other presumed normal faults indicated on Figure 6 include the prominent structure that drops down the tip of Orote Peninsula, one or more faults or splinters of a fault zone that strikes trend across Ypao-Saupon (old hospital) headland in Tamuning, a prominent fault zone that strikes northwest-southeast through NCTAMS and "Double Reef" on the northwest coast. In addition, Tracey et al, (1964) mapped at least two prominent faults in the Tarague embayment on the northern end of Guam, a prominent structure that truncates the eastern side of Aga Point in the south, striking inland to the Inarajan watershed, and several prominent faults trending northwest in the Inarajan-Fintasa River system, from near the Village of Inarajan to well beyond the Ugum River valley.



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Very dark line indicates the trace of the fault in the plane of the paper; hw = hanging wall; fw = footwall; arrows indicate the relative principal slip directions; and the separation between layers with the same rock symbol indicates amount of slip.

Figure 5. Fault Types. A & B are Normal or Gravity Faults; C is called a Reverse Fault; D is a Low Dip-Angle Reverse Fault, usually called a Thrust Fault, and E is termed a Strike-Slip Fault (right-handed). A-D are Vertical Sections, E is in Plan View. Scales vary from <1:1 up to 1:15,000,000.

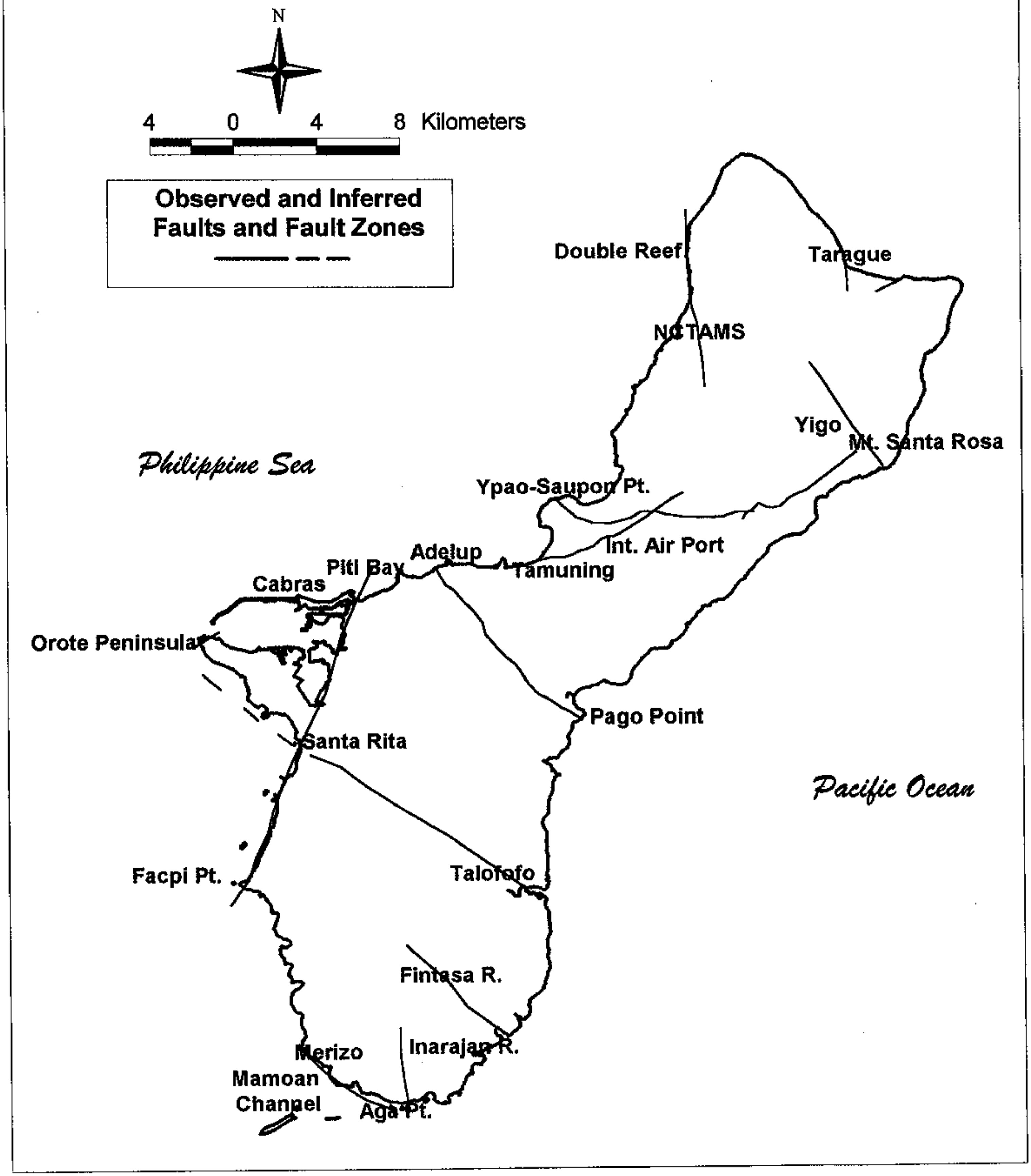

Figure 6. Generalized Fault Map of Guam

All faults shown are probably normal faults, but several have a strike-slip component.

II.1.3.2. Reverse Faults

A reverse fault is a dip-slip fault where the hanging wall moves up with respect to the footwall (Figure 5C). Reverse faults can have any dip, but many are termed *thrust faults* or *thrusts*, reverse faults with dips less than 5 degrees (Figure 5D). Reverse faults and thrusts are typically associated with zones in the crust that are subject to major compressional stress and when the rocks break, one block, the hanging wall, "thrusts' over the other block (Figure 5D). On Guam, small high angle reverse and thrust faults, with maximum apparent slips measured at several tens of meters, can be seen in all three volcanic formations. In the south, they occur in the volcanic rocks on the flanks of Mts. Schroeder, Tenjo, and Jumullong Manglo, along the Agat-Umatac Road, along the southwestern coast between Umatac and Toguan, and in central Guam on Mts Chachao and Alutom.

Reverse faults on Guam and other islands in the Marianas were considered in earlier geologic reports to be both less pronounced and less significant seismically than normal faults. Nevertheless, they obviously represent a location of crustal weakness and historic movement, and at the very least, should be noted and considered before siting man-made structures. However, thrust faulting is hypothesized to be the dominant type of fault movement east of the islands in crustal rocks within the *forearc zone* near the Mariana Trench, where direct effects of plate-plate compressional and shear forces are at a maximum (Figure 3).

II.1.3.3. Strike Slip Faults

Strike slip faulting creates immediate lateral offsets of the land, without necessarily any significant scarp formation along the strike (Figure 5E). The famous San Andreas fault in California is an example of a right-lateral strike-slip fault. Hengesh (1995) in the D & M report hypothesizes the occurrence of strike-slip movement to account for the August 8, 1993 earthquake. He further asserts that the Adelup-Pago Point fault described above as a normal fault has a strong strike-slip component. Others have indicated large strike-slip faults running more or less perpendicular to the trend of the arc, from the Mariana Trough eastward into the forearc (Karig & Rankin, 1983).

It is entirely conceivable, based on many other tectonic areas of the world that large strike slip faults change their sense of motion along strike and/or over time and gradually become dip-slip faults. Besides the San Andreas fault, many other notable earthquake-associated faults in the Pacific Rim are strike-slip faults. It is not uncommon to have a total slip exceeding 500 kilometers on large strike-slip faults. On the regional tectonic map displayed earlier as Figure 2, the reader can note two large strike slip faults resulting from oblique plate convergence: the Luzon fault that strikes northwest-southeast through the Philippine Islands and the large strike slip fault striking through the southern perimeter of the Japanese main islands. Movement on the latter in 1995 caused the devastating Hanshin-Awaji (Kobe) Earthquake.

II.1.4. FIELD IDENTIFICATION OF FAULTS

It is obviously important for a number of reasons to be able to locate and trace faults, and many faults leave more than enough clues on the surface to pinpoint their existence. One can read an elementary field geology or geophysics text to appreciate the many ways that the existence of a fault or faults may be revealed, not including the earthquake itself. Nevertheless, at least three major devastating earthquakes in the past decade, Loma Prieta, California (1989), Kobe, Japan (1995), and Northridge, California (1995) were caused by movements along faults that were hitherto unknown, despite the fact that each quake was centered in an area noted for large and active faults and an area that had been intensely mapped by geologists and geophysicists. The inability to locate and map faults arises from the fact that many never break the surface, even during an earthquake. This was the case with the three earthquakes mentioned above and with the August 8,1993 earthquake on Guam. . Additionally, scarps or offsets resulting from surface faulting may be quickly obscured through erosion or covered with surface sediment in only a few years.

II.2. EARTHQUAKES

An earthquake is the phenomenon of ground shaking, caused by a sudden release of energy. Earthquakes that concern the inhabitants of the Mariana Islands are those caused by the breaking and movement (brittle failure) of a volume of rock along a fault zone, i.e. a planar zone of weakness in the outer part of the earth. Released energy (strain energy) radiates out from the source and is transmitted through rock and soil as a complex spectrum of shock waves, called seismic waves.

Earthquakes are transient reflections of regional-scale tectonic forces and crustal movements. During a large earthquake, one observes considerable horizontal ground movements, but the underlying subcrustal (*upper mantle*) mechanism is principally vertical movement of thermal convection currents.

The ability of a rock body to slip in spite of the enormous friction between rock faces along a fault is thought by many to be related to progressive, sometimes rapid, intensification of microscopic cracks and intergranular openings in a strained rock before failure. This *dilatancy* allows migration of water into the dilating rock and increases the *pore water pressure* to "lubricate" the system. (Hubbert & Ruby, 1959). The earthquake in this model only occurs after water has entered the dilated rocks.

II.2.1. FOCUS AND EPICENTER

The source of seismic shock waves often shown simplistically as a point on cross-section through the earth, is called the hypocenter or focus. For artificial earthquakes (e.g. from bomb explosions), this point is essentially at the surface. The foci for natural earthquakes range from very nearly the surface to perhaps 700 kilometers depth. On average, shallow focus earthquakes (<70 kilometers depth) are more frequent and more destructive than intermediate (arbitrarily, 70-300 kilometers depth) and deep focus earthquakes (> 300 kilometers depth).

It is very convenient when discussing earthquakes to name the epicenter, a point on the earth's surface directly above the focus, but often the epicenter is popularly known by the name of the nearest town or city (e.g. Anchorage Earthquake, 1964). For bomb-generated earthquakes, of course, the epicenter is equivalent to the focus.

II.2.2. REGIONAL CONSIDERATIONS

The foci of many earthquakes in the vicinity of the Mariana Islands follow a general pattern that has been recorded in all island arcs (D & M Figures 2.5 & 2.6). Depths of focus increase systematically along the descending Benioff Zone, away from the trench and forearc toward the volcanic ridge. This relationship continues well into the *backarc* until earthquake activity along the Benioff Zone ceases. Thus we see intuitively a fundamental relationship that escaped geologists until perhaps thirty-five years ago, i.e. the exact interrelationship between seismicity and volcanism in an island arc. When the relatively cold rigid slab of oceanic crustal rock moves down along the Benioff Zone, to the hotter interior of the earth, it first undergoes brittle failure with episodic release of strain energy, until it reaches depths of about six or seven hundred kilometers where no longer can it undergo brittle failure, and thus melts to a magma (thermal failure).

Plate-plate collision and subduction then are the ultimate cause of the stress that produces rock failure and earthquakes in island arcs. The stress may cause strain to build up in the subducted plate, in the overriding plate, or both, and released in a number of directions depending on the angle of collision and the velocity and angle of subduction.

II.2.3. SHOCK WAVES

Earthquake shock waves can be classified broadly into body waves and surface waves. Body waves propagate within the rock or soil; surface waves travel near the ground surface. Both can cause extensive damage.

II.2.3.1. Body Waves

Body waves move through rock and soil at a velocity that depends on the physical properties of the rock material, specifically *density* and the elastic properties of *bulk modulus* and the *modulus of rigidity* The two types of body waves are a) the faster moving *primary waves* (called *P waves*) and b) the slower moving *secondary waves* (called *S waves*). P waves arrive first in all earthquakes, and are felt first in most earthquakes. Their motion is the same as a sound wave wherein they alternately compress and dilate the rock and are able to pass through solid rock, soil, liquids, and gases. The effect of P waves is similar to a sonic boom that rattles windows. Because a fraction of P waves emerge from the ground and vibrate the atmosphere, they may be audible to animals and humans if frequencies are in the proper range of the ear (about 14-16 cycles/second).

S waves shear rock sideways, or at right angles to their direction of propagation, and are not transmitted through liquids or gases because neither is elastic to shear. The effect of S waves is to shake the ground both horizontally and vertically and for that reason S waves can be very destructive. However, although both P and S waves are invariably felt in strong earthquakes on land, only P wave motion is recorded onboard ship.

When P and S waves reach the surface, a high percentage of their energy is reflected right back into the rocks below, so that the surface layers are affected almost simultaneously by waves moving up and descending reflected waves.

II.2.3.2. Surface Waves

Surface waves are also of two types, Love waves and Rayleigh waves. Both are slower than Body waves. The motion of Love waves is similar to that of S waves, but with no vertical displacement; they move from side to side in a horizontal plane and at right angles to their direction of propagation. Love waves produce horizontal shaking and can be very damaging to building foundations, but they do not propagate through liquids. Rayleigh waves, the slower than Love waves, move like an ocean wave. As in water waves of oscillation, affected rock particles move in a elliptical fashion in a vertical plane pointing toward the direction of movement.

Rayleigh waves will move water within a body of water such as a lake; Love waves affect only solids and thus stop at the water's edge, but they push on the sides of the body of water inducing sideways water movements as in vibrating wave tank.

II.2.3.3. Reflection and Refraction

When shock waves hit an interface between two bodies of rock, A and B, with differing physical properties, part of the wave energy will be reflected back into A, and part refracted as the wave passes across the interface and continues to be propagated through B. As a further complication, each reflected and each refracted wave generated at an interface will be split into a new S and P wave. Thus an enormous, almost infinite number of body waves can be generated from a major earthquake and all the rock boundaries crossed. The result can be major and seemingly chaotic ground shaking and a confusion of seismograph lines near the epicenter of a large shallow earthquake.

I.2.4. EARTHQUAKE SIZE

A variety of measurements have been utilized to gauge the "size" of an earthquake. They range from perceptions, to observed damage to architectural structures, to measurements directly related to ground motion and indirectly to energy released, to measurements related to the fault slip, basic properties of affected bedrock, and the area of faulting.

II.2.4.1. Intensity

Earthquake intensity has been used to assess earthquake 'size' by observing damage to built structures, perceived disturbances to the ground during shaking, and the reaction of certain animals to movements. In modern times, several scales based on observations and perceptions have been codified and are in wide use. All are based on an *ordinal scale* or one in which consecutive intervals are of unequal size. In practice after canvassing an impacted region for earthquake intensity observations and impressions, one then connects points of similar intensity on a regional map (called isoseismals) and the source of an earthquake (epicenter) is thus estimated. Maximum intensity values equate with the size of the earthquake, and the rate at which isoseismals change in value on the map (gradient) are a response to how rapidly shock wakes are dampened with distance, and thus correlate with changes in the physical nature of the rock and sediment.

The most widely used intensity scales are the Rossi-Forel Scale (RFS) first used in the 1880's and the Modified Mercalli Intensity scale (MMI), first published in 1902. The MMI is in fact a modification of the RFS. The RFS contained ten intensity values while the MMI scale contains twelve discrete intensity values ranging from MMI = I, that signifies "Not felt except under especially favorable circumstances" to MMI =XII that signifies "Damage total. Waves seen on ground surface, lines of sight distorted, and objects thrown into the air"! The Modified Mercalli Intensity Scale was subsequently adapted to local construction conditions in California and most of the United States.

The MMI scale and local modifications continue to be important in assessing the relative size of earthquakes in many areas where instrumentation cover is generally lacking and where a long historic baseline record of such observations is in existence. MMI values are widely used as well by insurance companies, underwriters, structural and design engineers, and others interested in seismic vulnerability and risk. They are also very useful in research into the relationship between surface or bedrock geology and the various types of earthquake-related phenomena.

However, the utility of the MMI scale requires a number of unbiased observers, and a major flaw is that the greatest intensity value is too often selected, thereby biasing upward the local rating for the earthquake intensity. Secondly, slope failures of any type resulting from an earthquake give the quake a very high rating on the MMI Scale. Yet slopes can fail during small tremors if they are near the threshold of movement. In fact, they fail without any recorded seismic event as exemplified recently at Sokehs on Pohnpei Island and near Santa Rita, on Guam.

II.2.4.2. Magnitude

For many years the size of earthquakes has been universally measured by the Richter Magnitude Scale, first introduced by C.F. Richter in 1935 for local earthquakes in California, and subsequently modified and generalized to earthquakes anywhere, at any distance from the epicenter. *Magnitude* was originally defined (so-called Richter magnitude) in terms the common logarithm of a complex mathematical function involving maximum ground motion or *amplitude* (measured on a seismograph in hundredths of millimeters) at a distance 100 kilometers from the epicenter. An increase of one unit on the Richter scale means a tenfold increase in amplitude. Richter perfected the scale later by making allowances for wave attenuation with distance and for different seismograph scaling factors. Either the P or S wave could be used with the original Richter procedure.

Subsequently, magnitude has been refined into M_s, a reading based on maximum surface wave amplitude, and M_b, magnitude based on the largest amplitude of body waves, (usually P wave amplitude). M_b and M_s are related empirically as shown below in Equation (1), but general experience indicates that M_s more closely agrees with our perception of the "size" of a given earthquake and is more commonly cited.

$$\mathbf{M_s = (1.59\ M_b) - 3.97} \qquad \textbf{(Richter, 1958)} \qquad \textbf{[1]}$$

Theoretically there is no upper or lower limit to a Richter magnitude reading although an earthquake's upper size is constrained by the strength of crustal rocks, and its lower limit by the sensitivity of the seismograph (a reading of -3.0 has been recorded!). In terms of magnitude, the largest earthquake recorded in modern times had an $M_s = 8.7$[1] and occurred on June 12, 1897 near Assam, India. Several notable 20th Century earthquakes are listed here below with their M_s given for reference.

YEAR	EPICENTER	M_S	COMMENTS
1906	San Francisco	8.3[2]	Great San Francisco fire
1920	Kansu, China	7.6	180,000 deaths from landslides
1923	Kwanto	8.2	143,000 killed in Great Tokyo fire
1960	Chile	8.5	Major tsunami damage in Hawaii
1964	Prince William Sound, Alaska	8.4	Major damage to Anchorage, large tsunami hits N. California
1976	Tangshan, China	7.6	About 650,000 deaths
1985	West central Mexico	8.1	Liquefaction and shaking devastate downtown Mexico City
1988	Spitak, Armenia	7.5	25,000 killed. Poor construction, liquefaction and landslides
1990	Gilan Province, Iran	7.7	40,000 killed, from soil liquefaction & poor construction
1995	Hanshin-Awaji, Japan	7.3	Devastated city and waterfront of Kobe: 5,400 killed
1995	Northridge, California	6.8	Fault plane unknown before earthquake, 10 billion dollars in damage

M_s can be used to empirically calculate the approximate energy in *ergs* or *joules* released during an earthquake, and for surface waves, that empirical relationship is:

$$\mathbf{Log_{10}E\ (ergs) = 1.5M_s + 11.8 \qquad (Bolt,\ 1978) \qquad [2]}$$

From Equation 2 we can estimate the energy released from the 1993 Guam earthquake ($M_s = 8.1$) as about $10^{23.95}$ ergs or about 1/10 to 1/100 of the 10^{25} to 10^{26} ergs of strain energy released on average every year from all earthquakes worldwide. In contrast, an earthquake of magnitude of $M_s = 7.1$ will release an estimate $10^{22.45}$ ergs of energy. Thus we see that an increase of only one unit on the M_s scale translates to an increase of about $10^{1.5}$ in terms of energy released or 31.6 times the energy. An increase of two units on the M_s scale (e.g. 6.0 to 8.0) translates to an increase of almost 10^3 ergs, an almost 1000 fold increase in released strain energy.

Earthquake magnitude measurements have the advantage over earlier intensity assessments in that they don't depend upon population density, construction practices, or other factors related to man. They do require, however, the existence of a network of expensive and well-maintained seismic equipment and the experts to read the instrument data.

II.2.4.3. Seismic Moment

Seismologists in the past twenty-five years have turned more to a number called the *seismic moment* to assess the "size" of earthquakes. This measurement is equal to the integrated product of the following parameters: rigidity of the bedrock, slip along the fault, and area of faulting. The

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[1] Estimated from MMI and seismograph records.

[2] San Francisco (1906), Kansu (1920), and Kwanto (1923) estimated from MMI and seismograph records

measurement of seismic moment is based on a complex smoothing of the seismic spectra that, to describe, is well beyond the scope of this report A new magnitude M_w based on the seismic moment, extends the Richter scale by more accurately indexing strong earthquakes, and as a result, M_s of many historic earthquakes have been revised upward or downward to produce the new values of M_w. For example the Prince William Sound (1964) and San Francisco (1906) earthquakes had surface magnitudes of 8.4 and 8.3 respectively, but the former has a seismic moment at least 100 greater. Recalculation of surface wave magnitude adjusted for seismic moments revises the San Francisco earthquake downward to $M_w = 7.9$, and the Alaskan quake upward to $M_w = 9.5$.

There are several advantages to using seismic moment magnitudes. The correlation between M_w and slip can provide useful criteria for designing and constructing highways, pipelines and other structures that must cut across the trace of an active fault. Seismic moments can also be used to compute the velocity at which tectonic plates that are bounding the fault, are moving past one another. From this information and other geophysical data we can assess how much of the relative motion of the plates accounts for earthquakes and how much is dissipated as *aseismic creep*. For example, seismic moment analyses has shown that much of the plate motion in the Mariana arc is dissipated as aseismic creep.

II.2.4.4. Recurrence:

The frequency with which earthquakes affect any one location or region is obviously an important, but yet an elusive parameter. Agencies charged with mitigation and general preparedness, and the public at large, need sound estimates, but these are dependent upon accurate and extensive records. The general relationship for recurrence comes from Richter (1958) who derived the function from empirical analysis of an extensive time series of seismic events in California. The length of the record can be extended back in time by estimating magnitudes from MMI. The Richter recurrence equation is

$$\mathbf{Log_{10}\, N = a - bM} \qquad \mathbf{[3]}$$

where N is the number of seismic events in a given region, over an extended period of record, equal or exceeding magnitude M, and a and b are constants specific to the region and/or fault zone.

II.2.4.5. Aftershocks & Foreshocks

Major earthquakes are succeeded in following hours (up to many months) of seemingly random sequences of generally progressively smaller earthquakes called *aftershocks*. The total number of aftershocks may easily exceed a thousand but the most damaging usually occur within hours of the main shock. The origin of aftershocks has been debated for many years and no consensus has been reached. Nur and Brooker (1972) argue that aftershocks are the result of slippage following the slow migration of pore waters into the dilated region of bedrock surrounding the original slippage.

Foreshocks are small earthquakes that precede the main shock. They have been detected in sufficient instances as to give some promise as a possible earthquake predictor.

II.2.5. EARTHQUAKES ON GUAM

Guam experiences an enormous number of earthquakes, originating within 100 kilometers of the island (D & M, Figures 2.4, 3.1, 3.2, 4.1, 4.2). They can be classified tectonically into quakes a) originating along the Benioff Zone between the subducting and overriding plates (interplate earthquakes), and b) originating within either the subducted or overriding plate (intraplate earthquakes) (D & M, Figure 3.1).

It is further possible to partition the population of earthquakes affecting Guam on the basis of geographic-tectonic distinctions: Here we can distinguish between earthquakes originating a) in the backarc generally west of Guam where active crustal spreading takes place, and b) those originating under Guam and further to the east in the forearc region. The latter can be subdivided on the basis of frequency and density into the concentrated subpopulation of earthquakes south and southwest of Guam, and the relatively diffuse population northeast of Guam, but still within the forearc.

II.2.5.1. Size

MMI have been cataloged for Guam from first-hand experiences since the introduction of that scale in 1902, augmented by damage and phenomena descriptions prior to 1902. A partial listing of these events appears in D & M as Table 4.1. M_s of earthquakes affecting Guam since the introduction of the Richter scale, and earlier tremors estimated from MMI values provide nearly a century of magnitude readings. The record indicates about a thousand earthquakes of $M_s = 4.0$ or greater since 1902.

II.2.5.2. Descriptions

A number of historic earthquakes have been especially noteworthy in terms of size or damage.

January 25, 1849: Damage to Agana and nearby town; one death due to tsunami; estimated local MMI: VII-VIII.

September 22, 1902: Estimated Magnitude 8.1; widespread damage in Agana; stone masonry houses completely destroyed; with a few exceptions, nearly all masonry buildings had considerable damage; numerous landslides reported; many bridges collapsed; estimated local MMI: VIII-IX. This earthquakes has been the most damaging since records have been maintained.

December 10, 1909: Estimated Magnitude 7.4; epicentered 250 km southwest of Guam; some additional damage reported in Agana; the Women's Hospital, built of local masonry and mortar, had to be torn down; estimated local MMI: VII-VIII.

October 29, 1936: Estimated Magnitude 7.75; epicentered about 125 km [78 miles] southwest of Guam; plaster fell, walls were cracked, ornamental tiles fell; estimated local MMI: VII-VIII.

November 1, 1975: Magnitude 7.1; epicentered 20 km [12.5 miles] north of the island; damage on Guam reached one million dollars; many businesses lost stock from shelves; a number of structures were damaged; estimated local MMI: VIII.

January 27, 1978: Magnitude 5.2; epicentered near central east coast of Guam; caused considerable damage to the island; many homes and at least two government buildings were damaged; estimated local MMI: VII-VIII.

February 13, 1983: Magnitude 6.3; epicentered about 40 km [25 miles] north of the island; minor damage reported in northern Guam; one person slightly injured at Tamuning; estimated local MMI: VI.

August 8, 1993: Magnitude 8.1; epicentered about 60 km [37.5 miles] south of the island; caused 1 indirect death and comparatively little damage for an event of that size. This earthquake is the most recent large event to affect Guam. The USGS and Harvard University pinpoint the center of energy release to be about 60 km south of Agana. Waves emitted by the quake indicate a plane dipping at about 15 degrees with a strike roughly at N65E. The main shock was release at the southwestern end of a rectangular plane 40 km wide and 120 km long (Figure 4.3). Global Positioning Systems indicate that Guam shifted about 20 cm to the southeast and subsided about 10 cm.

April 24, 1997. Magnitude 5.7 followed five seconds later by magnitude 6.3. The first quake was considered to be an aftershock of the August 8, 1993 great earthquake. The second, quake was epicentered at 14.0°N latitude and 144.89°E longitude, or about 27 miles west of the neighboring island of Rota and about 28 miles north of the Guam Seismic Observatory at Potts Junction. This second quake originated at a depth of about 65 miles and had a measured $M_G = 6.5$. On April 30th, a magnitude 5.0 earthquake occurred at focus of only 5.5 miles near Rota. The April 24 earthquake so weakened the Upi elementary school that it was partially razed.

May 9, 1997: Magnitude 6.1. Caused island-wide power outage.

II.2.5.3 Recurrence ~~on Guam~~

D & M calculated earthquake regional recurrences of earthquakes around Guam based on pre-1963 data and again, post-1963 data, the latter from the National Oceanographic and Atmospheric Administration (NOAA). The examined area extends about 200 nautical miles around Guam. Guam's earthquake recurrence equations calculate as:

$$\mathbf{Log\ _{10}N = 5.596 - 0.599M\ (pre\ 1963\ data)} \qquad [4]$$

$$\mathbf{Log\ _{10}N = 5.016 - 0.549M\ (post\ 1963\ data)} \qquad [5]$$

Plugging an earthquake M value of 6 or greater into Equations [5] and [6], will generate recurrence numbers N for Guam of between 50 and 100 expected earthquakes, within that 200 miles radius during a 170 years interval as covered by both sets of data.

CHAPTER III

SEISMIC HAZARDS

III.1. INTRODUCTION

Seismic hazards refer to earthquake-related phenomena that potentially place lives and property at risk. Seismic hazards usually but not necessarily have rapid and unexpected onsets, and operate over short time frames. Although they seem to be "a surprise" at the time, in fact, based on our collective experiences and common sense, they should not be too unexpected. This chapter describes hazards that were observed as a result of the Great Earthquake on August 8, 1993, as well as hazards that were not observed during that event, but which have historically or prehistorically occurred on Guam, thus should not be discounted. We also present a map of seismic hazards, a modification of D & M's Map, and finally a summary of the philosophy and general methodology of seismic hazard analysis.

III.1.1. FACTORS AND TYPES

Seismic hazards on Guam may take many forms, e.g. catastrophic slope failure, subsoil liquefaction, tsunamis, etc., Triggering mechanisms, severity, duration, and extent are dependent on several factors as outlined below.

III.1.1.1. Factors

- ***Physical Characteristics of Affected Site*:** Includes site elevation and topography, drainage, properties of near-surface foundation materials such as type, composition, and strength, vibration, and elastic properties of bedrock or unconsolidated sediment, and water saturation.

- ***Faulting*:** Includes style, e.g. strike-slip vs. normal vs. thrust fault, duration, direction, slip, and whether fault plane ruptures the surface.

- ***Earthquake Parameters*:** Epicenter, focus, M_s and M_w, amount of slip, area of rupture.

- ***Wave Travel Paths*:** The path through the earth (distance and properties of rock and soil) taken by seismic waves determines the degree of attenuation or dampening of the shock wave amplitudes, and the general area impacted.

- ***Built Structures:*** The location and structural integrity of man-made structures including buildings, bridges, pipelines, etc.

III.1.1.2. Types

Bolt (1978) presents the "main" seismic hazards, recognizing that no one location is necessarily subject to all of the following:

- ***Shaking:*** Includes differential ground settlement, landslides and mudslides, soil *liquefaction,* ground lurching, and avalanches.

- ***Displacement along a Fault:*** Rupture of the ground surface and formation of scarps and offsets

- ***Coastal Flooding:*** Tsunamis and Seiches

- ***Stream Flooding:*** From failed dams and levees, and backup from watershed slope failures

- ***Fire:*** Major urban hazard

Seismic hazards on Guam and the other limestone islands in the southern Mariana arc could conceivably include all of the above, depending upon factors described in the first outline above. However, we will limit the following discussion to *slope failures* and soil liquefaction, the two primary hazards occurring during the last great earthquake of August 8, 1997. Areas prone to those hazards are delineated on the Seismic Hazard Map (Figure 7). Both hazards are usually a direct and immediate response to *ground acceleration* beyond certain threshold limits for extended periods of time. Additionally, we also offer a brief review of some of the other hazards mentioned by Bolt (1978) that were not evidenced in that 1993 earthquake, but which should be considered somewhere between possible and probable when an earthquake of similar magnitude strikes Guam in the future.

III.1.1.3. Strong Motion, Acceleration and Attenuation

Severe and violent shaking usually goes by the term *strong motion* and is recorded on a strong motion seismograph. A seismograph that directly records ground acceleration is called an *accelerometer or accelerograph.* Ground acceleration is scaled against the 1.00g gravitational acceleration through a vacuum, of a falling sphere from rest state. Acceleration measured in firm ground for moderate-sized earthquakes usually ranges between 0.05 and 0.25g. Measurements of ground acceleration have been correlated with indices on the MMI scale (Richter, 1956), and this calibration is commonly used by seismologists and geologists to cross-check observations and seismic hazard models.

Ground accelerations have both vertical and horizontal components, the latter being larger and a more reliable estimate of the MMI.. These measurements are heavily relied on by architects and engineers concerned about the structural integrity of buildings during earthquakes. Ground motion and the duration of time over which the ground is in motion above certain threshold values of acceleration are also considered very important factors in assessing structural vulnerability.

Dissipation of ground motion with distance from the source is called *attenuation.* This can be observed on seismographs that record horizontal ground acceleration. Attenuation can be modeled mathematically for a given rock body of known properties, earthquake magnitude, and path and distance traveled. It is a key input to most seismic hazard models.

D & M assumed that rock properties affecting ground motion attenuation on Guam could be operationally classified into one of two groups: a) Soft Rock or Stiff Soil made up of volcanic flows, volcaniclastic rocks, and coral limestone and b) Medium Stiff Soils that include colluvium, alluvium, and artificial deposits. The basis for this classification were velocities of S waves measured from various seismic surveys done on island. Their data set for southern Guam, however, was limited to one site.

III.2. RECENT SEISMIC HAZARDS ON GUAM

The most obvious seismic hazards in the recent $M_s = 8.1$ earthquake were slope failures and liquefaction of unconsolidated sediments. There was no direct evidence of movement of the island's major faults nor any significant tsunami effect. Ground shaking intensity was minimal, although, according to D & M (1994) the duration was uncharacteristically long for a shallow event such as this. Most of the visible liquefaction occurred in low-lying and artificial fill areas, although some ground fissures, liquefaction, sand volcanoes, and differential settlement occurred elsewhere. About a dozen significant rockslides occurred on the northern plateau and terrace and scarp terrain, and dozens of small landslides occurred in the south. The modern platform reefs in Apra Harbor and reef margins elsewhere lost several large blocks off the oversteepened reef fronts. Several small *neotectonic faults* on the elevated reef platform at Ylig and Aga registered minor movement. Possibly some minor displacement occurred in volcanic outcrops in the Upper Inarajan River valley. Several caves visited by the writer in the Ipan Talofofo area in the week following the earthquake of August 8, 1993, had considerable fresh destruction of stalactites that probably resulted from that event.

Three feet of subsidence around Piti power plant, liquefaction of the fill behind the sea wall on the Naval base which shoved the wall into the harbor, collapse of a Naval canteen due to liquefaction, and spreading, subsidence, and buckling of the quay at the Guam Commercial Port were among the geotechnical casualties. Otherwise, structures near such ground displacements performed satisfactorily. The most significant structural damage occurred in the Tumon Bay area where three hotels were severely affected. Half of Guam's bridges received at least moderate damage. Utility networks performed relatively well, with the exception of water pipes experiencing about 100 breaks throughout the island.

III.2.1. SLOPE FAILURES

Probably the largest single cause of deaths associated with earthquakes over the past several hundred years, and most certainly in rural environments has been catastrophic slope failures. Many of these slope movements occurred on hillsides that had given no apparent early warning of instability. Other occurred on slopes that had relatively benign movements for many years and were considered stable.

Slope failures take many forms but they are ultimately caused when *driving forces* on a slope = (mass of the slope) x (gravity) exceed the sum of all *resisting forces* on that slope. Resisting forces include both the natural bonds that adhere various rock and soil materials to one another, and man-made restraints that secure slopes. Slopes, where driving forces even slightly exceed resisting forces, are going to fail, slowly or rapidly, and often with catastrophic results. Seismic events usually accelerate the process but although the ultimate cause of slope failure may not necessarily be an earthquake, the latter is often a proximate cause. Even slopes where the ratio is not 1.0 prior to an earthquake can fail in a major seismic event.

We may not judge with certainty which slopes will fail during the next tremor, but it can be fairly obvious when a given hillside is nearing its threshold of movement: Some combination of the following field observations should be evidenced: steep slopes, water-saturated soils, thick saprolite, continued intense rainfall, concentrations of seeps and springs, slip planes, disrupted tree growth, dead trees, absence of any vegetation, presence of joints and faults in bedrock outcrops, deep chemical weathering of bedrock, high percentages of clay in soil and saprolite, and/or inappropriate land-use activities, such as gross undercutting off the toe of a slope, poor agricultural and forestry practices, failure to put in sufficient drains, etc.

Slope failures can be classified as to their general velocity and the type and condition of material moving. For a comprehensive treatment, the reader is advised to consult one of the standard engineering/environmental geology texts referenced at the back of this report. Those that were recorded in the August 8 earthquake are: *soil slips, mudflows, debris flows*, and *landslides* in the volcanic terrain and *rockfalls, rockslides*; and landslides in the limestone area, and *slumps* in colluvium and alluvium.

III.2.1.1. Volcanic Terrain

Downhill movement of hillsides in the volcanic terrain of southern Guam occurs on nearly all non-horizontal slopes if other conditions of failure are met (see above). Almost all slopes have failed to some degree at one time, and almost all are candidates for future failure. With few exceptions, slope failures appear to be controlled by discrete zones or layers of water saturated clays, that serve to diminish the resisting force. Often clays are the swelling-shrinking types that promote further instability. Planes of slippage can be seen, after-the-fact as bare soil "scars", throughout slopes in the south. Prior to failure, they can be often detected by the presence of a line of small seeps. Slope drainage is an essential, but commonly overlooked mitigation procedure.

Construction near the base of-slopes that involve cutting back the toe should be discouraged in southern Guam, as should other activities that decrease failure resistance or add to the mass. The custom of cutting into the base of the slope to enlarge the property below can promote catastrophic slope movements. The principal slope failures in southern Guam are listed below and all are exacerbated by earthquakes.:

Soil Slips: Abrupt sliding or rotational slumping of a unit of topsoil is called a soil slip. The top several decimeters of soil are involved and the result is a pronounced bare "scar" on the slope and an obvious zone reaching a maximum of about ten square meters of crumpled soil and dislodged or dislocated vegetation. Soil slips are not so much a hazard to life as they are a disruption of the environment, but they are a signal of a generally unstable slope that could give way with a larger-scale movement in a seismic event.

Mudflows: Flowage of a viscous, high density, mud-water slurry, usually down a pre-existing ravine or valley, and often involving a considerable component of weathered boulders that are rafted along on the movement. Mudflows on Guam rarely exceed ten square meters, but a few in the badlands areas exceed an acre and are several meters thick. They produce a flat, lobe-shaped deposit. Mudflows frequently block stream drainage temporarily. Large mudflows could create major flooding.

Debris Flows: Similar to mudflows but dominated by large individual clasts, intermixed within a sticky muddy matrix. Debris flows slide forward to produce very chaotic topography. Recent debris flows are found throughout the badlands in the Ugum, Bubulao, and upper Inarajan River watersheds and reach about an acre in area. Large debris flows can devastate a valley and disrupt drainage permanently.

Landslides: Rapid or slow downhill sliding of a predominantly dry mass of weathered sediment and rock. Landslides produce elongated, wedged shaped deposits, often damming streams in the process.

Slumps: Mass movement of soil or soil and saprolite wherein there is backward rotation of the entire block, called a slump block. Slump blocks are a major feature in the badlands and savanna grasslands.

III..2.1.2. Limestone Terrain: Slope failures in limestone terrain are less diverse and much less frequent, but constitute nevertheless a localized seismic hazard.

Rockfalls and Rockslides: The free fall and sliding and tumbling down a steep incline by individual limestone boulders off fault scarps are relatively common in northern Guam. Both processes appear to be favored by highly *brecciated*, jointed bedrock in addition to the near vertical scarps. Several localized rockfalls and rockslides occurred on the plateau following the August 9, 1993 Great Earthquake, and still others have occurred since within earthquake-weakened rock sections during heavy rains. Several relatively large slides of mainly boulders occurred during the August 8, 1993 earthquake. On Marine Drive in East Agana, a small rockslide destroyed several parked vehicles. One large fall-slide combination obliterated the large (est 2 million gallons per day) coastal spring at Janum on the northeast coast. A major rockfall at Mergagan Point on the north coast closed a large popular sea cave on the edge of Andersen Air Force Base.

III.2.1.3. Unconsolidated Sediment: Unconsolidated deposits rarely achieve the height to undergo the more common types of slope movement described above. However, even on nearly flat surface fluidized sediment may move laterally. These phenomena are called flow landslides or earthslides. Another exception is along surf-exposed strands where undercutting causes occasional slumping off low lying cliffs. Also, some of the unconsolidated colluvial deposits of mud or debris described above may be remobilized during subsequent large quakes and move further downslope.

III.2.2. LIQUEFACTION

Liquefaction is a process of loosely-packed, granular materials losing their shear strength and assuming fluid-like characteristics. It results from increased pore-water pressure caused by extreme shaking. Fluidization allows an unconfined sedimentary deposit to spread out laterally, gradually slowing as it loses pore-water pressure. If confined beneath overburden, however, two mechanisms may simultaneously take place: pressurized pore-water acts to escape vertically, and can literally bore through the overburden to explode onto the surface in geyser-like fountaining of water and sediment. This instantaneous dewatering produces a cone-shaped structure called a *sand volcano*. Simultaneously, fluidized deposits can rapidly ooze laterally or vertically, resulting in spreading and cracking of the ground surface, and causing both collapse and uplift.

The magnitude of the seismic event, distance, ground motion and different geologic conditions affect liquefaction differently. Liquefaction and the ground surface deformation can be extremely damaging to manmade structures . Vertical movements may be as much as 10 meters, while lateral movement may be almost 100 meters. As an example, in Anchorage, Alaska, during the Prince William Sound earthquake in 1964 (Mw 9.5), the clay-silt layer underlying Anchorage and suburbs underwent partial fluidization, and major sections slid over twenty meters into the estuary. This produced multiple breaks or scarps in overlying strata and on the ground of as much as five meters in height, and an area of over forty hectares variously dropped down or lifted up. Scores of homes and commercial buildings were destroyed.

Liquefaction may be promoted by the chemistry of the sediments as well as level of water saturation. Under Anchorage, fluidized clays of estuarine-marine origin contain sufficient sodium to disperse the clay and allow them to flow like "silly putty" when severely shaken. Since 1964, State and Federal Surveys have tried to identify deposits of similar marine clays. Such clays may exist on Guam.

Liquefaction during the August earthquake involved carbonate gravels, sands and muds that appeared to be dredge spoil from the adjacent reef platform and embayments. Sand volcanoes, small ground scarps, lateral spreading, and surface collapse variously occurred in and around the Guam Commercial Port, Dry Dock Island, SRF Beach, Sasa Bay, Mariana Yacht Club, Piti Power Plant, Sasa Bay coastline the former USO facility. All these locations are sited on artificial fill, albeit some modified over time to look natural, and all underwent visible and sometimes destructive and costly surface disruption from liquefaction.

Because modern unconsolidated deposits are the principal units susceptible to liquefaction, areas on Guam which are potentially at risk are fairly well defined. The lowest potential of liquefaction susceptible materials includes lagoon and estuary deposits. Moderate potentials are alluvial valley sediments which drain into bays or estuaries where offshore reefs are not present. The highest potentials occur at beaches, artificial fills, and other water laid sand and sand-mud environments. These areas are marked on the Seismic Hazards Map and are relatively site specific.

Liquefaction on Guam, however, is not necessarily restricted to areas of Guam mapped as alluvial or artificial deposits. Snorkeling in Tumon Bay during the morning following the Great

Earthquake of August 8, 1997, the writer counted at least twenty-five separate remnants of sand boils or sand volcanoes on the reef platform. Following the next tidal cycle that afternoon (August 9) the centralized "eruptions' had all but disappeared, but the sand had redistributed in "windrows" parallel to the prevailing currents. These deposits gradually lost definition over the next several days. Liquefaction and upward movement of sand probably originated in large sediment-filled valleys in the cavernous Pleistocene limestone substrate below the modern reef. Upward movement was facilitated by the fractures that criss-cross the reef. How this phenomenon translates to the failure of built structures along lower Tumon has yet to be established, but Wersch (1997, Pers. Comm.) of the Guam Environmental Protection Agency reports that boring logs indicate a contributing cause to the failure of the Royal Palm Hotel to be liquefaction of sand deposits within karstic Pleistocene bedrock

III.3. POTENTIAL HAZARDS ON GUAM

A variety of seismic hazards not witnessed in recent earthquakes have a varying potential for affecting Guam. That potential cannot be quantified, and locations for those hazard can only be approximated from the geology and *geomorphology*. Potential hazards with the highest likelihood of occurrence and for causing serious damage and injury are ground surface rupturing along fault planes and tsunamis. Other hazards with less potential include ground subsidence or collapse over weakened cavernous limestone bedrock and river flooding from a variety of earthquake-related factors.

III.3.1. SURFACE RUPTURE ALONG FAULTS

Bulging, stretching or lateral and vertical movement of the ground surface are common characteristics of surface fault ruptures. Fault ruptures may also be simply defined as "cracks" or displacements on the earth's surface due to underlying shaking or movement. No documented fault rupture occurred on August 8, 1993, but it is obvious from the number of fault scarps and displacements that surface rupture has occurred in the past. The writer did observe many minor displacements (1-5 cm) in the volcanic *shale* outcrops in the upper Inarajan and Fintasa River valley on a field trip in late August, 1993. They all appeared to be fresh fractures, but there were no previous baseline observations from which to calibrate this finding.

III.3.1.1. Historic and Ancient Fault Movements on Guam

It would be ideal to have a firm estimate of the frequency, rate of fault movement, average slip per earthquake., etc. It would simplify planning and land use decisions. unfortunately we have only indirect estimates based on many assumptions about that remain untested. The following section describes fault movements that have occurred along major faults on Guam in the past. Quoted rates of movement are D & M estimates based on terrace uplift models advanced by Lajoie (1986) (See D & M Appendix E). Actual values have significance only that they confirm the obvious, that the island has been generally emerging for at least several million years, and that separate regions of the island are emerging at different rates. The latter assertion implies the existence of, or potential for, faulting or tectonic creep along hinge lines that are not now showing conclusive field evidence for faulting.

Adelup-Pago Point Fault Zone: The Adelup-Pago Point Fault trends from approximately Pago Point on the east coast to Adelup, and marks basically the separation between southern volcanic and the northern limestone terrain. Based on the displacement of specific rock units and estimated comparisons of uplift rates of terraces to the north at Pagat Point and Lates Point with those of the south at Talofofo Village, it appears that the Adelup-Pago Point Fault has had the most significant displacement in its past than any other known fault on Guam. D & M estimated that there is a vertical slip-rate of approximately 0.4 mm/yr between Talofofo Village and Pagat Point. Further, D & M indicated that there is evidence of on-going strike-slip movement on this fault implying that it is capable of producing significant surface deformation. D & M also pointed out that the estimate of Lates Point uplift is only slightly higher (.04 mm/yr) than Talofofo meaning that deformation is occurring between the two northern points of Pagat and Lates, although no faults in the area have been located.

Talofofo Valley Fault Zone: The Talofofo Valley Fault zone extends northwest from Talofofo Bay to Santa Rita-Agat, and perhaps farther, along the southern coast of Orote Peninsula. The fault displaces rock formations as old as Oligocene and as young as the modern and *Holocene* age reef. A Holocene age terrace (last 10,000 years) to the north of Talofofo Bay and a presumably Pleistocene terrace to the south, both of which are at nearly the same elevations, also indicate recent activity along the fault. Vertical slip rates of 0.15 mm/yr have been estimated by D & M for this zone.

Mt Santa Rosa Fault Zone: The Mt Santa Rosa Fault Zone runs from Janum Point to Marine Drive (Highway 1) near the entrance to Andersen Air Force Base. This fault offsets Pliocene limestones as well as modern and Holocene age *alluvial fans*. It is also suspected that movement along this fault formed an escarpment along the fault and tilting of the nearby limestone terraces. Differences in uplift rates between Pagat Point and Ritidian Point may be attributable to movement on this fault are estimated by D & M at 0.5 mm/yr.

Tamuning-Yigo Fault Zone: The Tamuning-Yigo Fault extends from Mt Santa Rosa southwest to Agana. It displaces Miocene and Pliocene limestone formations. Beginning at the airport and continuing north to Mount Santa Rosa, a northeast facing topographic escarpment gradually decreases in height. The Mt Santa Rosa fault marks the end of the Tamuning-Yigo fault, however, other northeast trending fractures to the north of the Mount Santa Rosa fault appear to exhibit a right lateral slip and may have originally been part of the Tamuning-Yigo fault. This would indicate a) that the Tamuning-Yigo fault zone is older than that of the Mount Santa Rosa fault, and b) that it changes along strike northeastward from a normal fault with essentially dip-slip motion to a strike-slip fault with right-lateral motion. D & M estimate a minimum vertical uplift rate of 0.4 mm/yr at Tumon Bay and the east coast of Guam.

Cocos Fault Zone: The Cocos Fault is an inferred fault in Tracey et al. (1964). The structure trends west-northwest, separating southern Guam and Cocos Lagoon. It likely coincides in part with the extremely linear and deep Mamoan Channel at Merizo. Mannell Channel farther to the east also is probably fault controlled. This fault is parallel to the Talofofo Valley Fault and the Adelup-Pago Point Fault and according to D & M derived from the same stress phenomenon.

The movement offsets the Miocene volcanics behind Merizo and Pliocene Mariana Limestone from the Geus River to Aga Point. The downthrown block of the Cocos Fault is covered by Cocos Lagoon.

III.3.1.2. Fault Movement Implications

D & M estimates that the uplift rates on Guam range from 0.20 to 0.50 mm/yr, at least since the beginning of the Pleistocene, about 2 million years ago. Their estimates are founded on the number, spacing, elevation, and presumed age of coastal limestone terraces that they assert can be correlated with sea level stands throughout the world. These estimates are somewhat higher than those that this writer has calculated for the north end of Guam (0.08-0.10 mm/yr) during the past 125,000 years (Randall & Siegrist, 1996). However, although these movements appear very small, a slip of even 0.5 mm/yr can result in earthquakes up to magnitude 7.0.

In California, similar faults pose serious hazards to humans and structures and are therefore identified and avoided. D & M strongly suggests continued investigation and study of Guam's fault zones so as to better plan and prepare concerned agencies and individuals.

III.3.2. TSUNAMIS, SEICHES, AND COASTAL FLOODING

On average, one destructive *tsunami* strikes a coastline each year in the world. Considered particularly vulnerable are the low lying coastal areas around the Pacific rim, particularly east-facing coastal Japan, the Indian Ocean and the Mediterranean and Caribbean seas. Tsunamis are long wave-length water waves (several hundred kilometers wave length) that move at velocities of as high as 550 kilometers/hour. In shallowing waters, train of tsunami waves slow down and their amplitudes increase, thereby generating the risk to life and property.

Because of it close proximity to a oceanic trench where large-scale thrust faulting and displacement of the seafloor are common, Japan's Pacific coast is considered the most at-risk coastal zone in the world for tsunamis. In addition to close proximity to large active dip-slip faults on the seafloor, other considerations favorable for high amplitude tsunamis include gradually shallowing water and funnel shaped embayments along the coastline. Normally, large tsunamis are not restricted to a single wave crest, and as many as five successive destructive waves from the same earthquake have been recorded in Hawaii.

The August 8, 1993 Great Earthquake some produced minor coastal flooding that indicated a small local tsunami effect, but on the Japanese coast the wave reached a height of almost 1 meter. The strike-slip motion (Hengesh, 1995) of the movement causing the August 8 earthquake, probably did not displace the seafloor to any extent. The coastline of Guam remains at risk to tsunamis because of it proximity to the forearc-Mariana trench where thrust faulting does occur, though not to the extent as with the Nankai and Izu trenches facing eastern Japan. The abrupt shallowing of Guam's coastal seas and the almost continuous perimeter reef structure militate against, but do not prevent destructive tsunamis.

Tsunamis are by no means solely produced by earthquakes. Submarine volcanic eruptions (rarely) and submarine landslides (commonly) can displace a sufficient volume of seafloor and water as to produce destructive tsunamis. Risks of a large submarine volcanic eruptions triggering destructive tsunamis on our shores is very small, but it is not zero. The western coast of Guam faces several active submarine volcanoes that are only a few tens of kilometers away. Warning times from a large eruptions would be vary short.

Seiche is an oscillating wave system set up in a closed basin such as a lake or inland sea. They also commonly set up in swimming pools during large earthquakes. In a large earthquake much of the water in a reservoir at capacity could surge over the lip of the dam, weakening the dam, and flooding and destroying property downstream. With the obvious exception of the Fena reservoir in the U.S. Naval Magazine in southern Guam, the semi-enclosed Apra Harbor, and perhaps Umatac Bay, there are no large bodies of water in which a destructive seiche wave would set up.

III.3.3. GROUND COLLAPSE IN LIMESTONE TERRAIN

Sinkhole Collapse: Sinkholes are quite frequently observed along coastal terraces. Usually small (10-30 meters diameter) and shallow (10 meters depth), sinks are notable on the 10 and 65 meter (40 feet and 200 feet) terraces at Tarague in the north, and on the 10 meter (35 feet) terrace at Janum and Campanaya in the northeast. Several sinkholes, recently visited by the author on the Tarague terraces (Randall & Siegrist, 1996), had obviously expanded by subsidence and rockfalls off the sidewalls.

Surface collapse in limestone terrain that has high seismic activity, for example in Bosnia and Croatia, is not uncommon. As mention previously, much of northern Guam is honeycombed with large caves. Many follow faults or fracture trends, while others appear to be random expressions. A potential always exists for a destruction of pillars and other supports and sudden collapse of the ground surface into a shallow cavern system during a large earthquake. Judging from our analysis of all sinkhole dimensions on Guam, a collapsed sink would probably measure between 10 and 30 meters in diameter, and 5 to 10 meters in depth.

III.3.4. RIVER FLOODING

Streams in southern Guam are relatively short, have steep gradients, and with several exceptions, lack significant floodplains. Larger ones have tidal reaches and all are subject to flash discharge, bank full stage, and overbank flooding during typhoons.

Many rivers are vulnerable, especially in their headwaters, to being temporarily dammed by large landslides and other forms of slope failure. This could cause immediate and serious upstream flooding, and following the rapid, inevitable failure of such a water-logged landslide dam, flooding and mass destruction downstream, where human populations tend to be higher. Landslides and faulting have also been known to divert flow permanently.

Both the one important dam on Guam (Fena) and the major diversion (lower Ugum River) are potentially vulnerable to disruption if not destruction from faulting and landslides. Further, at least one future dam site that had been evaluated by consultants for potential development into a reservoir (Inarajan River) is vulnerable to faulting, landslides, and major flooding downstream. (Dumalaing et al, 1997).

III.4. SEISMIC HAZARDS MAP OF GUAM

D & M presented a Seismic Hazards Map of Guam that they prepared as an overlay to the U.S. Geological Survey 1:50,000 scale topographic map of Guam (USGS, 1977). Faults and geologic formations were transcribed from Tracey et al (1964) and photogeology came from 1:26,000 airphotos flown by Perry Associates of Agana, Guam during 1992-1994. The map appears as Appendix C in D & M.

The D & M overlay shows not only the distribution of visible and inferred faults, bedrock and alluvial formations, but also locates landslide and liquefaction hazards and most probable tsunami impact sites. Hazards are classified as high, moderate, and low. For this report, the D & M map was digitized and re-issued in color using ARC VIEW at the computer laboratory at WERI/UOG. An 11 x 17 inch map (Figure 7); a full-size copy (wall size) is available from WERI/UOG at cost. For simplicity, the topographic base map was not reproduced, but all the information on the original U.S. Geological Survey map was digitized and could be retrieved along with a considerable amount of Guam's infrastructure information to produce a series of colored maps relating seismicity to many geographically distributed variables. Such variations can also be obtained at cost from WERI/UOG on request.

Figure 7 indicates a number of faults, of various types, especially in the Bolanos Formation in southern Guam, that do not appear on Figure 6 in this report. Many of these have been mapped over the past several years at UOG/WERI in connection with water resource studies.

The distribution of seismic hazards so mapped must be interpreted as a generalization, and prudent land-use, construction, and zoning decisions usually (should) require site-specific geotechnical investigations.

III.5. SEISMIC HAZARD ANALYSIS

III.5.1. STATISTICAL APPROACH

Seismic hazard analyses are today based on probability and statistics (Reiter, 1991). Such concepts as hazard, vulnerability, and risk are assigned probability values of between 0 and 1.0. Analyses are based on an assumption that destructive earthquake magnitudes follow a frequency distribution model such that the occurrence of a destructive earthquake is both a rare and random event within any time small interval of time chosen. Whether destructive earthquake occurrences actually follow this model is still not agreed upon, its simplicity and apparent applicability in many regions appear to favor its continued use.. From tables found in many elementary statistics texts and an extensive data base of earthquake magnitudes in a region, one can calculate the probability of exactly none, one, two, three, etc, or the probability of at least one, two, three, etc. earthquake of any magnitude occurring within any pre-selected time interval. The model thus affords a degree of comfort to those who believe that destructive earthquake occurrences (and their peak ground motion, level of destruction, and risk) can be predicted on the basis of pure statistics

Probable earthquake magnitudes (or moments) can be used to predict probable ground motion (ground acceleration) at any specific site. This is the essence of most approaches to hazard analysis. It requires factoring in a great deal of basic geologic and geophysical information, much of which is lacking for the Mariana Islands. From the probability of the occurrence of a given level of ground motion, one can estimate the probability of exceeding a given level of ground motion at that specific site during some pre-established time interval. This latter is the key to risk analysis, a procedure similar in concept to that used in river flood recurrence or exceedence models.

To get to seismic risk analysis from earthquake magnitude and ground acceleration data, one sometimes develops an intermediate vulnerability model that estimates probable damage to buildings, infrastructure, or injury, etc. given the initial probability values established for ground motion (Risk Management Solutions (RMS), 1995a and 1995b). Damages are usually quantified by computing ratios of repair costs/replacement costs. Detailed construction and structural data and occupancy data are needed to complete the analysis. Thus, as in hazard analysis, the product of vulnerability analysis is also a probability. Under RMS, vulnerability probabilities can also be factored into models to compute risk. A risk analysis incorporates data on financing, structure of risk, insurance, re-insurance, and subjective evaluations or policies of acceptable risks. Again, the products of this analysis is a probability.

III.5.2. METHODOLOGIES AND RESULTS

III.5.2.1. Probabilistic Seismic Hazard Analysis

Methodologies for analyzing hazards differ, but D & M used a combination of algorithims and assumptions that they call the Probabilistic Seismic Hazard Analysis (PSHA). The procedure developed seismic hazards in the region surrounding Guam. D & M hoped to used this analysis as input to a risk assessment analysis for the island of Guam itself. Other methodologies are basically similar and all rely on solid input data, while all are weakened appreciably, if not fatally, by a lack thereof.

As detailed in D & M Appendix B, the method depends on existence of a large database of historic earthquake information including magnitudes and origins, a fundamental knowledge of regional and local geology and tectonics, including fault locations and physical properties of bedrock and surficial sediment, identification of all significant regional seismic sources (locations), plus fulfillment of two critical and basic assumptions, namely:

a) A simple probabilistic function can be established to characterize adequately recurrence of destructive earthquakes within five designated contiguous areas of the Mariana Arc region, broken down into smaller subareas. The smaller subareas are called "seismic sources" by D & M.

Picture

D & M call this the magnitude frequency problem, and settled on the Poisson distribution as their statistical model of destructive earthquake occurrences.

b) Equations can be generated that satisfactorily describe ground motion attenuation for a specific magnitude seismic event originating at each seismic source within the larger Mariana Arc region. D & M computed equations from shallow crustal sources. Equations representing subduction Benioff zone sources were "borrowed' from other subduction zones that have been better studied.

The PSHA model then calculates probabilities that destructive earthquakes of certain magnitudes will occur and recur at various seismic sources in the region. These are integrated with attenuation equations to derive probabilities of equaling or exceeding certain levels of ground motion at any and all sites considered. Recurrence is used to compute exceedence probabilities in the risk analysis.

II.5.2.2. Risk Analysis

D & M estimated the probability that maximum or peak ground acceleration (PGA) would be exceeded over various time periods. They define two scenarios. The *Operating Basis Earthquake* (OBE) as an earthquake that produces a ground motion with a probability of exceedance equal to 0.50 (50%) in 50 years. Probability of exceedence means the probability that a given value will be surpassed. In the OBE scenario, ground motion should be minimal and most structures should remain fully functional. Any damage should be easily repairable.

In contrast, they define the *Design Basis Earthquake* (DBE) as an earthquake that produces a much larger ground motion, one with only an 0.10 probability (10%) of exceedance in 50 years. Essential facilities should remain operational and most buildings under the DBE scenario should withstand collapse during such an event. Significant structural and nonstructural damage should be acceptable as long as there is no risk of loss of life.

The following table represents exceedence probability values for bedrock and soils that are generally applicable to anywhere on Guam: They were calculated on the basis of return periods of 72 and 144 years for the OBE and 475 and 950 years for the DBE.

DESIGN AVERAGE ACCELERATIONS

Scenario	Return Period (Years)	PGA (g values) Rocks	PGA (g values) Sediments	Exceedance Probability (50-Years)	Exceedance Probability (100-Years)
OBE	72	0.22	0.21	0.50	0.75
OBE	144	0.29	0.27	0.29	0.50
DBE	475	0.43	0.38	0.10	0.19
DBE	950	0..52	0.46	0.05	0.10

CHAPTER IV

CONCLUSIONS AND FUTURE STUDIES

IV.1. GENERAL CONCLUSIONS

Earthquakes are a serious hazard to lives and property on Guam. They represent sudden releases of strain energy along faults that move in response to tectonic plate interactions. Earthquakes have occurred more or less randomly since the island-seamount first formed over 40 million years ago, and will continue to do so unabated into the future. There is no evidence of a recent increase or decrease in seismic activity in the Mariana Arc.

Signs of former crustal movements can be seen throughout Guam in the form of bedrock fracture zones and faults, but no fault movement ruptured the surface of the ground in the recent Great earthquake of August 8, 1993. The principal hazards, based on that event are slope failures and soil liquefaction. The former are especially prevalent in the volcanic terrain in southern Guam; the latter most likely occur in artificial and naturally deposited sediments along the west-central coast, but also may occur in estuaries and perhaps within large sediment pockets within cavernous limestones.

Seismic hazard analysis is handicapped by incomplete data bases and an absence of detail information about site conditions. nevertheless hazards can be mapped in a relative sense and risk assigned in terms of expectable strong motion. Ground shaking which may occur could reach moderate to medium high levels. With a 90 percent probability of not being exceeded in 50 years, peak ground acceleration was calculated to be 0.42 g for bedrock sites and 0.39 g for unconsolidated sediments. Without further investigations, it is not recommended, however, that UBC Seismic Zone Factors of 0.3 for Guam be raised to 0.4, unless other non-technical reasons may contribute to the decision.

IV.2. FUTURE STUDIES

Although the D & M report is a very important first step in assessing Guam's seismic setting, further work is needed on understanding and modeling seismic hazards. Future studies should prove very useful in building the necessary on-island and subduction zone data bases demanded by the assumptions implicit in the PSHA model. We list below a summary and rearrangement of the recommendations advanced by D & M in this regard, commenting that although none in particular requires instant attention, the combination are needed before planners, engineers, architects, and lifeline agencies can take comfort in their respective levels of earthquake preparedness.

IV.2.1. FIELD STUDIES AND INSTALLATION

IV.2.1.1. Remap and Interpret Activity Levels of Island Faults

Purpose: A detailed study of island faults and faulting events in the past 10,000 years (Holocene) is not only feasible but of critical importance. Special emphasis should be placed on locating and mapping Holocene age faults that have produced surface rupture at one time or another.

Implementation: This activity could be undertaken with supplementary air photos, perhaps digital imagery, shallow drilling and trenching, age-dating of rocks and mineralized areas, and field geologic mapping.

Benefits: Benefits will include improved information on active areas which should lead to better planning and construction practices. Schools, hospitals, fire stations and essential facilities may be placed outside of highest risk zones. Property damage and loss of life can be greatly reduced. Another real benefit would be better predictions of ground motion throughout the island.

IV.2.1.2.: Conduct Geophysical Survey of Site Conditions

Purpose: Delineate and define tectonic movement and shallow subsurface geology of key areas of Guam to update and distinguish between site classifications. This survey is needed in a number of areas, especially areas of high density, tall built structures, and lifeline buildings.

Implementation: Seismic reflection and refraction techniques and ground-penetrating radar surveys are the most cost effective methods to use for this purpose. Information placed in geographical data base as above.

Benefits: Improved detection of fracture zones, faults, joints, caves, large pockets of water-saturated unconsolidated sediment that are at risk for liquefaction.

IV.2.1.3. Install Strong Motion Instruments on Guam

Purpose: Strong motion data for Guam is virtually non-existent. Models used for the study of Guam and the Marianas Islands are derived from other tectonic environments. *Accelerographs* are needed to record data that could improve the preliminary attenuation equations and our understanding of this particular phenomenon.

Implementation: Coordination between GovGuam and Federal agencies (FEMA, U.S. Geological Survey) will be required to have proper motion instrumentation installed in the appropriate locations.

Benefits: An important step for updating and improving response spectra, a major parameter for safe construction of larger buildings.

IV.2.2. SYNTHESIS STUDIES

Recommended future studies that involve primarily archival, statistical, and computational activities are described below.

IV.2.2.1. Refine Seismic Hazards Model

Purpose: Integrate fault data from above into a highly resolved refinement of existing and future PSHA models.

Implementation: Develop a narrowly spaced grid (using geographical information system) of point sources for Guam, and throughout the immediate region.

Benefits: This grid will give the necessary control for improved seismic hazard forecasts and assessments, and ultimately to provide for more efficient "microzoning" within the more active subareas.

IV.2.2.2. Investigate Mechanism of August 8, 1993 Earthquake

Purpose: Refine our estimate of the exact tectonic location (interplate or intraplate), of the August 8, 1993 great earthquake and re-interpret aftershock data.

Implementation: Collect, examine, analyze and interpret all existing data.

Benefits: Additional analyses of existing data should allow a more accurate estimate of the expectable maximum magnitude earthquake for Guam.

IV.2.2.3. Review Instrument Data for Weak and Strong Records

Purpose: Improve the reliability of the preliminary attenuation equations for subduction zone events.

Implementation: Interpret, compare and continue accelerogram records.

Benefits: Increase understanding of attenuation equations to improve response spectra.

IV.2.2.4. Develop Seismic Hazard Maps

Purpose: Develop maps at a variety of scales and detail suited to the needs of planners, environmentalists, politicians, builders, teachers, etc. relating seismic hazards to geology, topography, demographics, infrastructure, etc., based on a geographical information systems.

Implementation: Update and include relevant information in the geographical data base as it becomes available. Collect new information as needed.

Benefit: The public will become aware and knowledgeable about hazards, especially about high risk areas already developed or targeted for future development.

IV.2.2.5. Review Archived Earthquake and Tsunami Data

Purpose: To develop an improved understanding of the historic seismicity of Guam. An accurate historic record provides the data set for continuously improving statistical models of earthquake activity, natural hazards, and damage estimates. Accurate records are also useful for planners, politicians, scientists, etc., for understanding seismic phenomena and for keeping the public informed.

Implementation: The information will be summarized into books, papers, public archives, CD-ROM, and other records for information to the public and within the seismic profession.

Benefits: Improve understanding of the seismicity of Guam and refinement of hazards.

GLOSSARY

Alluvial Fan Fan- or cone-shaped sediment deposit at the base of a mountain or escarpment, also where fast moving tributary meets main stream. Represents sedimentation of usually coarse detritus resulting from rapid velocity decrease of stream flow coming down off highlands.

Alluvium: Also **alluvial deposits**. Sedimentary deposits resulting from the operation of modern rivers and coastal currents. Consist of clays, silts, sands, and gravels of various compositions.

Amplitude: The height of a wave or wave form above its zero position.

Argillaceous: Describing material that is rich in clay and clay minerals.
That interval of geologic time between 38 and 23 million years ago

Aseismic Creep: Slow microscopic or submicroscopic elastic movement along a zone of crustal weakness involving no seismicity.

Ash: Volcanic dust less than 4 mm in diameter. Ash deposits may become cemented to form ***tuff*** deposits.

Basalt: A fine-grained, usually dense, black or very dark colored igneous rock. The principal rock formed from oceanic lava eruptions.

Backarc: Also **backarc basin**. A tectonic designation for the region that lies on the concave side of the arc, separated from the oceanic trench by a volcanic ridge. The Mariana backarc lies to the west of the Mariana islands.

Basement: The oldest rock in a region. The basement often is only seen by drilling.

Breccia (adjective brecciated): A rock composed of cemented clasts that are blocky or angular. Breccias can form from, a variety of process. On Guam. limestone breccias are frequently associated with fault zones, and are called fault breccias. Also, many of the volcanic rocks in the Bolanos Formation are composed of angular clasts of hard igneous rock within a matrix of soft volcanic ash. These are called volcanic breccias or flow breccias.

Bulk Modulus: Also **modulus of incompressibiliy**. Bulk modulus is the 3-dimensional elasticity or the elasticity of a volume of material.

Calcium carbonate: A chemical compound with the formula CaCO3. The mineral names for this compound are calcite and aragonite and each is an important component of reef organisms' shells

Clay: Sediment that is less than 1/256 mm (ca. 0.004 mm) in diameter.

Clay Minerals: One of a large group of hydrated aluminum silicate minerals structured into alternating atomic sized sheets or layers of silica and alumina ions and often crosslinked to another sheet of water and metal ions. Clay minerals are usually, but not always, clay size. Volcanic rocks on Guam weather to clay minerals.

Colluvium. Also **colluvial deposits**. Refers to an accumulation of rock, saprolite, and/or soil that has moved piecemeal or as a unit downslope, primarily in response gravity and the lack of resisting forces on the slope. Landslides and rockfalls create colluvium at the base of slopes.

Crust: An imprecise term used to include the rocks that comprise the upper several tens of miles of the earth. The crust under the ocean is considerably thinner than under continents. The bottom of the crust is defined at a major geophysical change in the properties of rocks.

Debris slide: Very common form of slope failure marked by a mud matrix and large clasts, with a high percentage of mud, and clasts generally not in contact with each other. Very common in badlands of Guam.

Density: The physical property of a substance measured as mass per unit volume. The density of most rocks is between 2 and 2.5 grams per cubic centimeter.

Detritus: In sedimentary geology: loose, unconsolidated particles of rock that are transported (by moving water, wind, etc.) and then deposited in quieter circumstances such as in a stream backwater, lake, bay, or ocean, either near or far from their original source.

Dike: An igneous rock body that formed when lava intruded into and cooled within pre-existing rocks. Resulting structures are tabular and cut across the pre-exiting rock structure. Dikes on Guam are usually basalt and can be commonly observed along the southwestern coast, where they may be about 2 to 3 meters thick and extend several hundred meters along in outcrops.

Dip: The acute angle between a geologic plane, such as a fault plane, and the horizon.

Doline: Also **sinkhole**. A generic name for all solution and collapse structures in karstic terrain and used interchangeably with sinkhole or sink. Originally the funnel shaped cavities that connect surface with underground caverns. Neighboring dolines commonly interconnect by wall collapse into valleys called *uvalas*.

Driving Forces: The combined forces promoting the downhill movement of soil or rock.

Eocene Epoch: That interval of geologic time between 54 and 38 million years ago, or between the end of the Paleocene Epoch and beginning of the Oligocene Epoch.

Erg: Unit of work (dyne-centimeters) in the cgs system of measurement. Can be used also as unit of energy (work/time) when time is one second.

Estuary: Coastal embayment or channel in which tidal forces are dominant. Often the drowned extension of a river. Talofofo and Tumon Bays are estuaries, the former being a drowned river mouth.

Fault: A fracture in a rock body along which their has been measurable movement

Fault Gouge: Finely powdered rock occurring with a few meters of a fault plane, often turned into water-bearing clay minerals by groundwater action, occurring along a fault zone. Frequently the cause of seeps and springs along a fault.

Footwall: The block of bedrock next to a dipping fault that lies generally below the fault plane.

Forearc: The tectonic designation for the region between the oceanic trench and corresponding volcanic ridge, located on the convex side of an island arc chain. The Mariana forearc is east of the Mariana islands.

Geomorphology: That branch of geology that deals with landforms and their evolution. Often used as a synonym for the overall landscape.

Gravity Fault: Also normal fault. A dip slip fault where the hanging wall moves down with respect to the footwall.

Hanging Wall: The block of bedrock next to a dipping fault that lies generally above the fault plane

Holocene: Also Recent. That interval of geologic time encompassing the last 10,000 years.

Island Arc: An arcuate chain of volcanic islands produced by plate collision and subduction. Island Arc System

Joint: A fracture in a rock that has seen only minor widening. Joints usually occur in clustered (sets) and in distinct patterns related to the stress field.

Karst Topography: Also karst or karst plateau. A limestone plateau marked by sinkholes interspersed with abrupt ridges and irregular protruding rocks, usually underlain by caverns and underground streams

Lava: Molten rock flowing or otherwise being ejected onto the earth's surface.

Liquefaction: Also soil liquefaction: Transformation of a water-saturated granular material into the liquid state through the release of excess pore water pressure. Soil and sand behave as a dense fluid rather than a wet solid mass of particles during an earthquake.

Lithosphere: Uppermost approximate 100 kilometers of the earth. Tectonic plates are lithospheric slabs.

Love wave: Seismic surface wave with only horizontal shear motion normal to the direction of propagation.

Magma: Molten rock within the earth.

Magnitude: A measure of earthquake size based on the logarithm to the base ten of a complex formula involving amplitude of ground motion, period of ground motion, depth of focus, and seismometer location with respect to focus. Magnitude is measured off a Richter Scale. Now universally used in place of qualitative intensity measurements that are site specific.

Micrometer: Also micron. 1 micrometer = 0.001 millimeters

Miocene Epoch: That interval of geologic time between 23 and 5 million years ago, or between the end of the Oligocene Epoch and the beginning of the Pliocene Epoch.

Mudslide: Slope failure in which colluvium is predominantly water saturated clay and silt.

Neotectonic: Very recent tectonic activity.

Normal Fault: See gravity fault.

Oblique Convergence: term used to describe tectonic plate convergence where the zone separating the two plates is not perpendicular to the direction of plate movement. The plates are in effect shearing past one another at some angle.

Oligocene Epoch: That interval of geologic time between 38 and 23 million years ago, or between the end of the Eocene Epoch and the beginning of the Miocene Epoch.

Primary Wave: Also **"P"** wave. Seismic body wave that propagates within a rock body and travels by compression and dilation of rocks.

Pleistocene Epoch: That interval of geologic time between 1.8 million years ago and 10,000 years ago, or between the end of the Pliocene Epoch and the beginning of the Holocene or Recent Epoch.

Rayleigh Wave: Seismic surface wave with ground motion only in a vertical plane containing the direction of propagation of the waves.

Reverse Fault: Dip-slip fault where the upper block, the hanging wall, moves over the lower blow, the fault wall.

Rift: a) A long, well-pronounced fault zone such as the San Andreas fault. b) intersection of a fault plane with the earth's surface.

Modulus of Rigidity: The ratio of the applied shearing stress to the angle of rotation it produces in a rock body.

Resisting Forces: In reference to slope failure, the sum of natural and artificial bonds and restraints that prevent mass movement of a slope.

Rockfall: Near vertical freefall of detached rocks of any size from a cliff face. Also used for the deposit so formed.

Rockslide: Sliding of newly detached rocks along steep slopes, faults, or bedding planes. Also used for the deposit so formed.

Rotational Slump: Downward slip of a mass of rock or unconsolidated materials and simultaneous rotation of the unit along one or more curved planes of weakness, called slip planes. A slip plane is often a fracture plane and marked by a concentration of clay and water.

Sand Volcano: Conical shaped accumulation of sand expelled vertically onto the ground during liquefaction of underlying sands.. These escape structures can reach heights of about a meter. Many observed around USO, and Piti and Cabras Power plants after August 9, 1993 Great Earthquake.

Saprolite: Deeply weathered rock that has not been disaggregated and moved. Saprolite retains many original rock features, but has been totally chemically transformed to clay minerals and other weathering products. Many volcanic rocks in southern Guam are capped by several tens of meters of saprolite.

Scarp: Cliff. May be formed by erosion, faulting, sedimentation or some combination.

Secondary Wave: Also "**S Wave**". Seismic wave generated within a body of rock that shears the rock sideways perpendicular to the direction of travel as it propagates through the rock. Secondary waves travel more slowly than primary waves and will not propagate through fluids.

Seamount: A submarine mountain, generally a volcanic cone that is rising up several hundred meters off the ocean floor. Almost every island in the Pacific Ocean is the top of a seamount.

Seismic Moment: A measure of earthquake size, the product of the amount of slip times the area of faulting times the rigidity of the bedrock.

Seismograph: An instrument that records the arrival times of all seismic waves and their amplitudes. The printed output is called a **seismogram.**

Seismotectonic provinces: A region encompassing common tectonic themes and earthquake frequencies.

Shale: A fine-grained, soft, well-layered, fissile, and easily split sedimentary rock. Shales normally have a high percentage of silt and clay sized particles (<.0625 mm). Much of the volcaniclastic rocks in southern Guam are shales comprised of volcanic ash and fine cinder.

Shear Zone: A generally linear volume of bedrock that shows signs of shear deformation as manifest by intense mineralization, brecciation, and formation of fault gauge. Several prominent shear zones are mapped in northern Guam

Shear Strength: The ability of material to resist a shearing force.

Sill: A rock body that is similar to a dike, except that a sill trends parallel to the main pre-existing structure in the host rock. A notable basalt sill occurs in the outcrops in the Alutom Formation in the Sasa River valley.

Sinkhole: Also **sink, doline, swallow hole**.

Slip: Also **fault slip**. The distance along the fault plane that a particular fault moved during a single episode of faulting.

Soil Creep: Also creep. Slow, essentially imperceptible, and generally continuous downhill movement of soil and saprolite. Usually accompanied by outward expansion of soil, tilting of trees, and displacement of built structures. Soil creep is a common feature on moderate slopes in the volcanic terrain of southern Guam.

Strike-Slip Fault: A fault where the slip is predominantly along the strike of the fault plane. Pure strike-slip faulting produces lateral offset of topography, but no vertical scarp. The San Andreas fault in California is a strike-slip fault.

Strong Motion: Ground shaking near an earthquake source consisting of large amplitude seismic waves of various types.

Subduction: Movement of one tectonic plate (subducted plate) under another tectonic plate due to plate density differences.

Talus: Also **scree**. Individual or a collection of boulders accumulating on the lower slope or the base of a scarp. On Guam talus is associated with rockfalls and rockslides.

Terrace: Flat, usually horizontal but occasionally tilted, land surface, bounded abruptly by steeper slopes on both sides. In profile, terraced terrain appears as steps. The southern islands in the Mariana arc have notable terraced terrain as a result of localized faulting, slow uplift and subsidence of the entire island, and periodic changes in worldwide sea levels.

Terrigenous: Terrigenous refers to the clay, silt, sand, and gravel detritus eroded from any landmass (terrigenous erosion). Slope failures and stream activity comprise terrigenous erosion.

Thrust Fault: Also **thrust**. A reverse fault where the fault plane dips at less than 5 degrees. In a typical thrust fault the overriding rock volume moves almost horizontally over the fault plane. Thrusts are associated commonly with the converging margins of two tectonic plates.

Translational Slide: Also **slab slide**. Slope failure where a block of bedrock and soil slide as a unit parallel to a bedding plane weakness in the bedrock.

Trench: Linear to gently arcuate, deep and relatively narrow depression in the ocean floor marking the locus of subduction of two converging plates. A trench lies to the ocean side of the forearc region. The Mariana Trench lies about 100 kilometers east and southeast of Guam.

Triple Junction: Zone of convergence of three tectonic plates.

Volcaniclastics: A general designation for rocks formed by the accumulation of either or both hot and cold particles of any size that are blown out of a volcano. Volcaniclastic rocks can form under the ocean (submarine) or on land (sub-aerial). The other major type of volcanic rock is a flow or flow rock. Submarine volcaniclastic rocks are the dominant form of volcanic rock on Guam.

Tuffaceous: Refers to volcanic rocks that contain an appreciable percentage of volcanic ash. Tuffaceous rocks tend to be soft, friable, easily eroded., and often unable to form stable slopes.

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