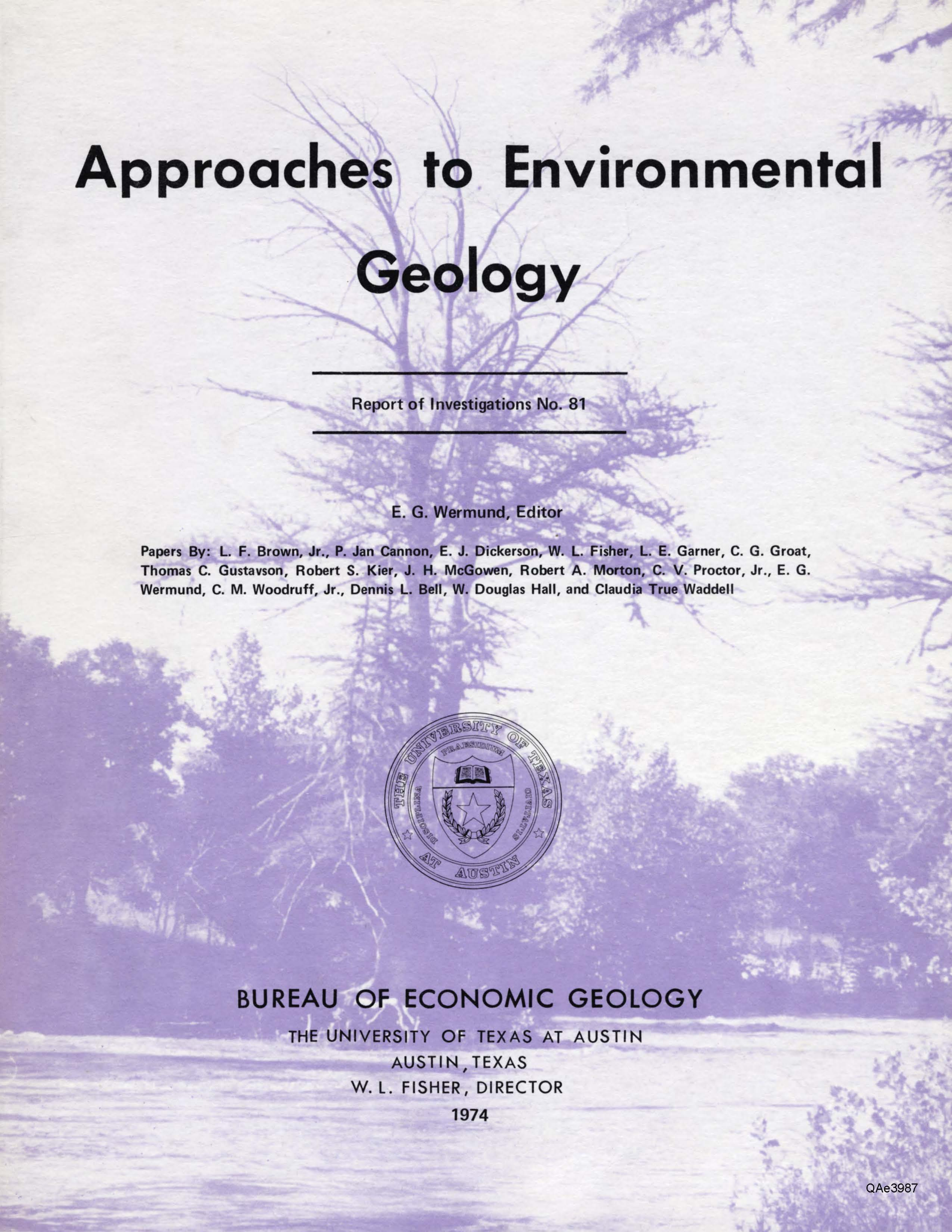

Approaches to Environmental Geology

Report of Investigations No. 81

E. G. Wermund, Editor

Papers By: L. F. Brown, Jr., P. Jan Cannon, E. J. Dickerson, W. L. Fisher, L. E. Garner, C. G. Groat, Thomas C. Gustavson, Robert S. Kier, J. H. McGowen, Robert A. Morton, C. V. Proctor, Jr., E. G. Wermund, C. M. Woodruff, Jr., Dennis L. Bell, W. Douglas Hall, and Claudia True Waddell

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APPROACHES TO ENVIRONMENTAL GEOLOGY

W. L. Fisher

"Environmental Geology" is by now a part of the vocabulary of most geologists. The term rather simply connotes the application of geology, geologic techniques, and geologic reasoning to the broad environmental concerns of society. The term is not, nor should it be, precisely defined. Environmental geology is clearly not a subdiscipline of geology, but it does embrace a large involvement and wide application of geology. There are several approaches that may be taken in the application of geology to environmental problems. The breadth of geology as a discipline and the range of problems of an environmental nature assure the variety. The approach of geologists who participate in or respond to environmental impact statements involving a specific problem or area differs from the approach of geologists who seek to develop data for baseline inventory and comprehensive planning. The objectives, and hence approach, of geologists in the public sector may well differ from the approach of geologists in the private and corporate sector. Geology applied to natural hazard environments (earthquake zones, landslides, and highly eroding shorelines) obviously nets a more dramatic product than geology applied to more subtle problems. Scale and scope modify the geologic approach, with regional analysis differing from local and specific applications. And finally, in addition to these inherent variations in approach, several more important factors must be considered: the long-term fate of environmental and resource management, the requisite kind and degree of management, and the existing technical options. The question ultimately is whether the geologic discipline should contribute only to management schemes established by others or should it also be involved in the development of management plans. Obviously, response to these broad questions will fundamentally influence approaches to environmental geology. Presentation of environmental geologic data is shaped by both the intended audience and the purpose, but it is also basically a product reflecting the geologic approach taken.

Approaches to environmental geology, as they are presented in this colloquium, are primarily the product of project-oriented, organized research conducted in the public sector. The Bureau of Economic Geology is a research component of The University of Texas at Austin; it also functions as a quasi-state agency (the State Geological Survey), but carries no regulatory responsibility. It is strongly allied to the academic and research mission of a large state university, but it is a functional part of state government.

The principal thrust of the environmental geology program at the Bureau of Economic Geology is the development of appropriate baseline inventories of the natural resources of the State. Emphasis is on (1) systematic environmental and geologic mapping, which may assume fundamental departures from traditional geologic mapping; (2) application of basic research to environmental problems; and (3) analysis of land and environmental resources in terms of carrying capacity. Inventory and analysis are conducted on both regional and comprehensive scales. Regional inventory embraces land diversity and types, carrying capacity, and current land use. Comprehensive inventory is conducted in detail; it is directed to the areas of the State where environmental problems are perceived to be most critical—the Coastal Zone, urban areas, water-related areas including aquifer recharge zones and lands bounding inland water bodies, and areas characterized by natural hazards (shoreline erosion, faulting, subsidence, and stream and hurricane flooding). Inventory and analytical elements of the program are aimed at both immediate and long-term needs.

Another part of the program involves participation in the preparation of environmental impact statements and in the review of such statements. In its role as a quasi-state agency, as a member of the State's Interagency Council on Natural Resources and Environment and the various committees and task forces of that Council, and in cooperative programs with state agencies carrying statutory obligations, the Bureau of Economic Geology participates in shaping and developing resource management planning. Response to legislative committees and staff, local units of government, numerous regional and local planning agencies, as well as the private and corporate sector, is a substantial part of the environmental geology program.

The utility of geology in resource management and, hence, the shape of environmental geology, must consider societal needs—immediate as well as long-term. These may not be rigorously defined, uniformly expressed, or even, in some cases, fully perceived. Thus, to the environmental geologist, falls not only the obligation to provide basic technical data and to evaluate these data in the most appropriate manner, but also the obligation to assist in defining and clarifying both immediate and long-term management needs. This, in turn, calls for an appreciation of how resource management programs and plans should be developed and a consideration of the basic options available.

The extent to which geology and geologists can contribute to resource management depends to a very great degree on the management approach taken. It appears that two basic options exist. One option, and certainly the one most commonly exercised to date, is to establish specific, and all too often arbitrarily defined, limits. This is what might be called the "tape and gauge" approach—no waste discharge above a specific level, no construction within so many feet of a shoreline or water body, no emissions above a particular level. The principal attraction of this approach is the relative ease by which it can be established, legislated, and enforced. Implementation of rigid, arbitrary standards has made environmental protection largely a legal task and in the process it has diminished technical (including geological) input into decisions and management. Thus, this arbitrary approach has yielded the same auto emission standards in the atmospherically inverted Los Angeles Basin as on the windswept prairies of the High Plains. In fairness, such approach is conceivably the only response to what are perceived as *immediate* needs and existing legislative mandates.

But more viable and prudent options seem available in the longer term, options which also make geologic input more significant and certainly more fundamental. Accordingly, the second option calls for a more flexible basis to resource and environmental management, specifically the allocation and adjustment of resource use to the natural or technically enhanced carrying capacity of land, water, and air. An historical and traditional example of this second approach has been utilized in agriculture. Clearly, agricultural scientists and farmers have been and continue to be the most effective land use managers known. Their goal is an obvious and simple one—productive use of land without misusing the land. Good farming adjusts to land capability because it is profitable and prudent to do so. If the element of soil fertility or soil capacity is expanded to include the entire range of physical, biological, and chemical attributes of land and water, and if the use element—agricultural productivity—is extended to embrace the whole spectrum of land and water use, a logical, technical basis for prudent land use and management seems evident. On this basis, for example, septic tanks could be permitted in lands capable of support, whether these lands be 20 yards or two miles from a lakefront. While this second option, the adjustment of use to carrying capacity of an environment, allows necessary resource use consistent with desired environmental quality, it does require a bigger investment in the inventory and analysis of lands and waters. Such inventory and analysis can be a major thrust of environmental geology and, accordingly, a fundamental place for geological application.

The environmental geology program of the Bureau of Economic Geology is designed to develop applicable geologic data for both immediate and long-term needs. The case studies presented in Approaches to Environmental Geology represent completed or ongoing projects conducted in different parts of a diverse State. While common basic orientation has been assumed, specific approaches have been designed in each area. A goal of this colloquium is to relate the experience of an environmental geology program conducted as an organized research effort in the public sector.

ENVIRONMENTAL INVENTORY: INNOVATION IN GEOLOGY AND GEOLOGIC PRESENTATION

L. F. Brown, Jr.

A PERSPECTIVE

Growing environmental concern continues to affect the economics, technology, and public image of American industry as few other events since the beginning of the industrial revolution. This concern coincides with a critical shortage of mineral and energy commodities, which can be satisfied only by more intensive exploitation of material resources. Environmental control, on the other hand, promises substantial changes in production and extraction techniques practiced by mineral-energy companies.

Few issues involving natural resources have been so clearly focused, and seemingly so diametrically opposed, as the mineral-energy crisis on one hand and the equally important environmental quality crisis on the other. Geologists occupy a unique position relative to both of these crises. Geology has made a significant contribution to mineral-energy exploration and exploitation. At the same time, geology has the capability to make similar contributions toward maintaining rational environmental guidelines as intensified and competitive land, water, and mineral-energy resource use accelerates during the rest of the 20th century. Mineral and energy companies will make full use of the best that geology can contribute in locating needed reserves; it is equally important that future environmental inventory-management systems devised by federal and state governments be based similarly on adequate, sound geological principles. Geology can contribute significantly to bridging the gap between required resource use and necessary environmental protection.

The role of geology in mineral-energy exploration and use is a traditional part of the profession; the proper, and most effective, role of geology in the environmental arena during coming decades is less clear, and perhaps its potential is not adequately recognized. The purpose of this report is to explore generally the critical need for extensive geologic input into evolving environmental inventory-management systems.

Near the end of the 1960's, Congress and many state legislatures enacted a variety of antipollution legislation to define and enforce acceptable pollution levels. This legislation had immediate impact on most industries. Future environmental legislation promises to be more pervasive, involving all aspects of land and water use. For this reason, most geological scientists, whether in industry, survey work, education, or consulting, may find themselves involved in some manner with land use dilemmas.

In the 1970's, several conclusions have clearly emerged from the environmental debate and controversy of the sixties. Although industrial, commercial, governmental, and scientific experts may disagree on specific aspects, all reasonable adversaries conclude that our nation must maintain a strong industrial posture with its necessary energy resource requirements, but that the natural environment must also be protected and maintained at an acceptable level of quality. Naturally, population growth is a key to the dilemma, but until population growth reaches an equilibrium, environmental quality will remain threatened. The crux of the problems facing the United States is arriving at a decision as to what constitutes acceptable environmental quality in the light of constitutional freedom of choice for all individuals.

During 1974 some version of a federal land use inventory bill may be enacted into law. Federal land use bills under consideration provide funding and guidelines for state land inventory programs, particularly in areas of environmental concern. These and other impending legislation promise to have extensive impact on industries involved in mineral and energy extraction that involves land and water use. That the federal government will ultimately insist on some land use management also seems certain. The kind of inventory system devised at this time by each state can have long-lasting effects on mineral, energy, and materials production and is sufficiently serious to warrant active participation of geologists in preparation of the programs. It is not, however, the sole responsibility of surveys; *every* earth scientist can assume his share of responsibility to see that future management programs, if enacted, are well constructed. It is important for each state to develop its own system by its own scientists and planners that best suits its unique requirements and natural character. Geologists can provide an important service to their state by insisting on proper input of geology into their state land use planning system.

At the grassroots and in the statehouse, geologists can assume an educational role. Political leaders, voters, students, and industrial colleagues are all genuinely concerned about the problem of maintaining environmental quality along with a high standard of living; geologists can help them plan ahead on the basis of *fact* and *reality*. Lawmakers and voters need to be provided with intelligent guidelines and alternatives in the mineral-energy resource and environment dilemma. Decision-makers need a basis for establishing rational land inventory systems; unless geologists incorporate their expertise and perspective of environmental resources into management legislation, others far less qualified may assume this role.

Two principal but differing routes for scientific resolution of the environmental dilemma are open to geologists in this decade—both are critical, in part overlapping. The first involves solving specific, current resource-environmental impact problems; the second involves comprehensive studies to delineate and inventory resources and environments in preparation for long-range planning.

In the first case, many specific regional or local site problems exist because of poorly planned or careless use of resources. These problems require realistic and equitable solution using the best geology, biology, chemistry, and engineering available. In many cases, adequate science and engineering exist, although this availability certainly does not preclude the need for continued research. Most legislative measures to date evolved from specific environmental impact problems; they set minimum standards or requirements normally within current levels of scientific and technical knowledge. Fair enforcement of pollution and other standards related to environmental protection provides an important means of solving current-use environmental dilemmas. Rational solution of site- and area-specific impact problems can be improved by continued scientific and technological reevaluation of standards, along with built-in flexibility of standards to fit the inherent variability of many natural systems.

Since impending federal legislation will undoubtedly result in required state land inventory systems which will serve as the basis for future management programs, a second, and perhaps more critical, role for geologists is to see that land use guidelines are properly conceived. Other scientists and planners are not necessarily qualified to contribute in many areas of traditional geological expertise that are critical to planning. Geological input, therefore, is more valuable than engineering or water resource geology, as important as these areas are; the application of most areas of geology is necessary to provide a basic understanding of our natural systems. Rocks that originated within ancient geological environments, as well as modern environments and associated physical (and many biological) processes, are all areas for valid geological inquiry. Environmental geology can be, therefore, more than strictly an engineering application; it can involve a broad spectrum of geologic concepts that are vital in understanding the earth and its many systems (fig. 1). Essentially, this view of environmental geology involves the projection of extensive areas of basic geology into environmental application. For example, geologists who have mastered subsurface geology in the search for oil reservoirs may be qualified to continue the search for favorable deep-basin reservoirs for waste disposal; geochemists and petrographers, in turn, may be needed to evaluate the interaction of waste liquids with the reservoir and its fluids. Geology applied to environmental problems, therefore, can be as broad as geologists' experience, imagination, and perception of problems.

Geologists can contribute their versatility and capability during this critical period of planning and legislation; land use guidelines and approaches currently under consideration may affect the exploitation of land and water resources for the rest of the century. Geology has the opportunity to provide a balanced perspective of use *versus* environmental balance by input into rational state and federal management programs.

Research on a variety of environmental problems in Texas by the Bureau of Economic Geology, The University of Texas at Austin, has provided a view of the environmental arena in a principal mineral-energy producing state (e. g., Fisher and others, 1972). In an effort to contribute geologic information for state planning, certain operating concepts and guidelines have been developed. There are probably as many viewpoints on environmental geology, what it is and its role, as there are workers. What follows, however, is a discussion of one viewpoint based on experience within a state geological survey which is actively involved in developing a statewide land inventory system, in preparing environmental atlases, and in cooperating with state and federal agencies and legislative committees in an effort to insure application of geology in future programs and legislation.

THE ENVIRONMENTAL CHALLENGE

At a time when scientific specialists are the rule in most disciplines, geologists may represent a

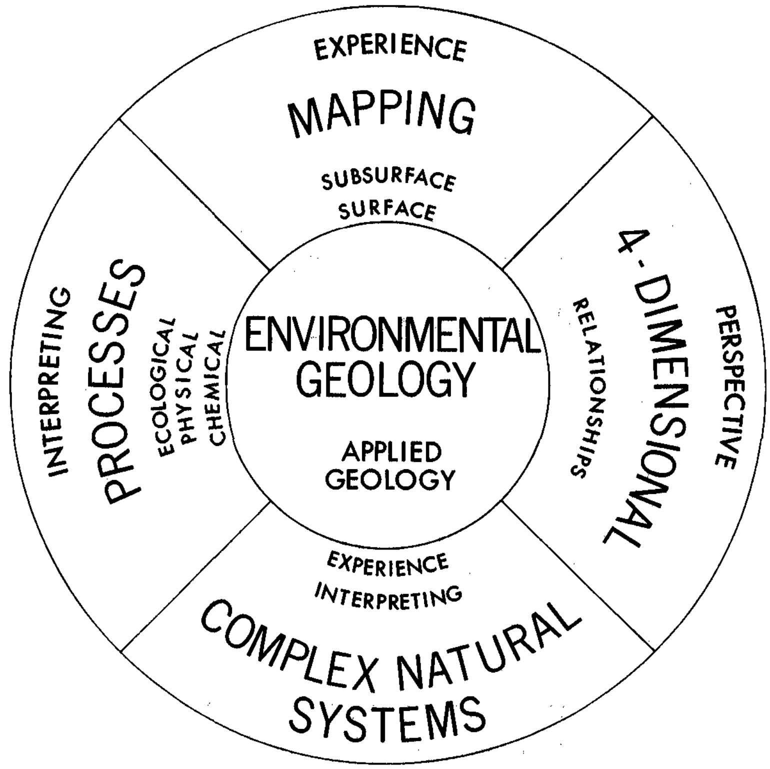

Figure 1. Environmental geology and its relationship to areas of traditional geologic expertise.

principal group of scientists who possess the broad viewpoint and general knowledge needed to react and retool *quickly* to provide critical leadership in the area of environmental management during the next two or three decades (fig. 1). This does not preclude the importance of and contributions by other scientists. A major thrust at this time toward defining and delineating environments and natural systems, however, requires the services of broadly trained, principally field-oriented scientists to prepare detailed maps of modern physical and biologic environments, as well as other properly conceived and innovative maps of the earth's surface and subsurface. The precise nature and spatial distribution of natural environments must be determined as quickly as possible if proper planning measures are to be devised for their protection and for acceptable exploitation. Knowledge of modern and ancient sedimentary facies or igneous and metamorphic units is of primary concern because of the common interrelationships between bedrock and environmental problems of many kinds.

It is an old geological adage that "Geology is what Geologists do." Geology becomes "environmental," therefore, when geologists use their knowledge in outlining and solving environmental problems. The term *environmental geology* may be displeasing to some geologists, but more importantly, the term serves to focus the attention of the nongeologist on the critical need for geologic input in planning and inventory. Environmental geology involves, by this definition, not only matters of site-specific impact problems, but also its application to the inventory of natural systems and the formulation of long-range guidelines for prevention of future impact problems (fig. 1). From the first course as undergraduates, geologists are taught the importance of observation, common-sense interpretation, cause and effect, clearly defining problems and solutions by maps and charts, interpolating and extrapolating limited data, regional synthesis, and field work. A critical phase of environmental research in this decade will involve extensive field study in the best tradition of the early geologists.

Except for a few recent graduates, most geologists working today on problems involving the environment were trained in traditional areas of the science. To contribute valid environmental information, geologists will be required to apply those quantitative skills introduced into curricula during the past decades, along with more tradi-

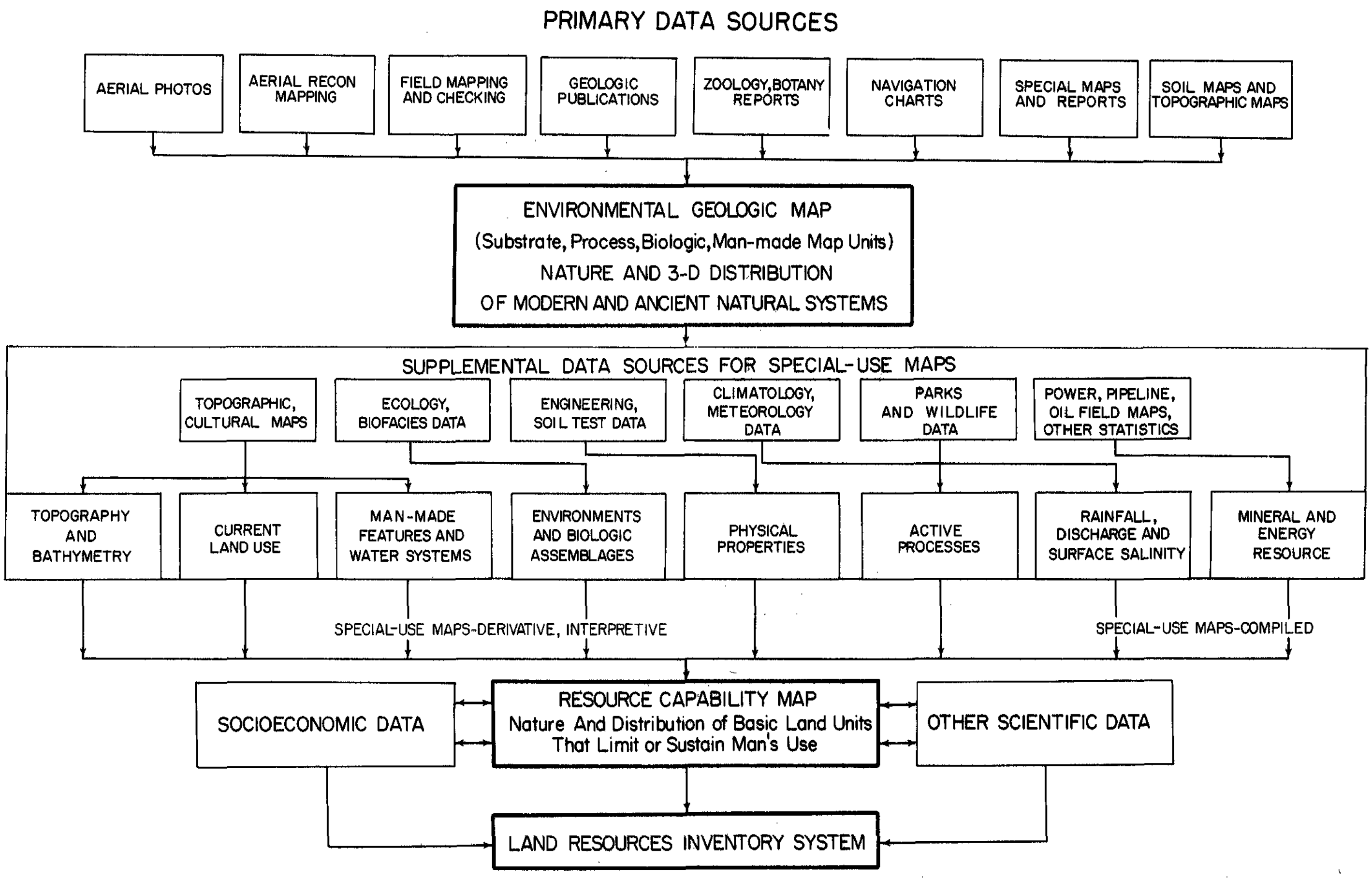

Figure 2. Role of traditional geologic data in developing a land resources inventory system.

tional geologic skills. Although many geologists may be required to reeducate and involve themselves in areas that are initially strange and poorly defined in terms of formal training, perhaps the single most important factor to success is viewpoint or state of mind. A geologist ultimately must sense the relevance and excitement of preparing maps and supplying interpretations that are urgently needed by environmental planning and enforcement agencies in order to make logical, fair decisions on impact problems and prevention.

A balanced environment with all its complexity will require the best research and application geologists have to offer. Here is an opportunity for a mature science to apply its rich heritage to some of the most vital problems ever faced by the human race. Geology possesses a tradition of four-dimensional perspective, process-related approaches, and appreciation of complex natural systems, coupled with a history of common sense and awareness of time and scale (fig. 1).

ENVIRONMENTAL GEOLOGY IS BASIC GEOLOGY

Applying geology to problems caused by interaction of man and earth does not necessarily require a new and unique body of knowledge, but the selection of basic geologic skills, approaches, and know-how which can be focused on a specific environmental problem (fig. 1). Traditional sources of information, as well as new areas of data, can be utilized; geologic mapping for environmental evaluation needs to possess a strong bias toward fundamental, process-defined, lithogenetic rock units. A proper geologic map is the key to derivative mapping, which in turn translates data and ideas for other disciplines (fig. 2).

Approaches and Techniques

A knowledge of physical, chemical, and biologic processes active within modern environments is critical if the environmental impact of various types of human activity is to be properly evaluated. In other words, natural environments with all their variability must be understood before proper management can be devised. Just as important, but perhaps less obvious to most nongeologists, is an understanding of rocks beneath the land surface (fig. 2). Relict igneous, metamorphic, or sedimentary rock bodies, which originated in ancient earth environments, may now determine to a great degree the suitability of land for various uses and human activities. These rocks may significantly dictate the nature of soils, wildlife, vegetation, ground water, deep disposal reservoirs, mineral-energy resources, and all manner of aspects important to the environmental, economic, and social quality of a region.

Too few scientists, much less nonscientists, seem to recognize the variability inherent in natural systems. Exceptions are field biologists and wildlife specialists who commonly possess this insight and most geologists who have a three-dimensional (or four-dimensional) grasp of rocks and natural systems. Proper environmental regulations, if developed, should be compatible with natural variation. Unnecessary controls or overdesign in a stable environment are just as inadvisable as indiscriminate use of delicately balanced environments. Requirements can be adapted to the capability or capacity of each geological environment or substrate. Geologists can provide information required to establish these kinds of rational environmental requirements.

Likewise, geologists are aware that change through time is not only natural but inescapable. Man may thwart nature for a while, but change will eventually occur. The concept of natural evolution of geologic systems is important when writing regulations for land and water use. Similarly, it is important that the nongeologist realize that many chemical elements and other earth materials popularly considered pollution are and have been distributed within natural systems throughout geologic time; continued extensive inventories, not only of water quality but of "sediment quality," are needed to determine natural levels of critical elements.

An individual researcher or a complex research organization can and do attack environmental problems with an array of traditional and contemporary tools and techniques. Complex chemical problems in ground water or bay and estuary contamination may require sophisticated apparatus, computers, and other techniques. Research on problems of air pollution likewise may require a highly specialized staff and elaborate equipment. Yet, mapping of many environmental factors can be carried out simply with topographic maps and aerial photographs by an experienced geologist or biologist (fig. 2). Investigation of dredge-spoil effects on marshes, for example, may require little more than a willingness to slog through knee-deep water with shovel and coring device. All degree of expenditures and specialized investigations are possible, but it is heartening that many *very* important tasks immediately ahead can be undertaken without excessive expense by using traditional approaches and techniques.

Geologic Mapping: An Environmental Inventory

Mapping the distribution of the basic elements of natural environments, their associated processes, and modern and/or ancient facies is imperative for a meaningful inventory of environmental systems (Fisher and others, 1972). Important elements may include such diverse features as septic systems, oyster reefs, *Spartina* marsh, sand dunes, agricultural lands, zones of shoreline erosion, ancient fluvial channels, point bar depositional sites, active alluvial fans, shallow aquifers, igneous intrusives, or potentially active faults. Perhaps an environmental problem may be a 10,000-square-mile general survey of possible sanitary landfill sites, or it may be a detailed ground-water pollution study of very local extent; in either case, appropriate delineation and mapping of the geologic components involved is the first logical procedure. That is, find out what factors or components are important and then determine their properties, distribution, and interrelations.

Environmental map units.—Mapping which provides functional, applicable results is the ultimate goal, whether mapping modern environments and facies or ancient rock bodies (fig. 2). Unfortunately, many geologic maps are not functional as environmental maps; maps based on faunal zones, for example, rarely offer any knowledge of the genetic constitution and distribution of rocks in an area of ground-water pollution or catastrophic engineering failures. No more helpful in environmental application are highly subjective and philosophical time-stratigraphic maps. Unfortunately, many formations on traditional geologic maps are names applied to undifferentiated rock sequences between two "contacts" or marker beds. There is a critical need for maps of lithofacies, metamorphic facies, igneous rock zones, landforms, all types of man-modified features, modern floral and faunal distribution, and any other genetic and/or process-defined feature. When any feature becomes of first-order importance to understanding the nature of the total environment, then it becomes a critical map unit. The name of the game is utility and innovation in mapping and map presentation, rather than precedence.

When mapping modern features such as active landslide areas, tidal flats, or flood plains, processes responsible for and operating in or upon an environment can be reliably inferred. Consideration of process and resulting facies supplies information that improves the predictability of properties that may limit or sustain a particular use. Similarly, in working with ancient geologic materials, maps of lithogenetic units, whether sedimentary facies, metamorphic belts, or igneous differentiation zones, allow prediction, extrapolation, and interpolation of many physical and chemical properties, geometry, and other peculiarities that geologists are qualified to interpret. Recognition and mapping of lithogenetic rock units provide, therefore, insight into the nature and distribution of properties important in inventory, environmental planning, and problem solutions.

Maps which chart the three-dimensional distribution of rock units provide an optimum framework for environmental work in sedimentary rocks. For maximum utility, geologists can apply the concepts of three-dimensional, laterally gradational geology and can group rock bodies into genetic systems which facilitate the interpretation of critical properties. This type of mapping, with some modification, can also be applied to metamorphic and igneous rocks. Although superior modern technology is vital, it does not alleviate the need for traditional geologic methods. Innovative maps based on principles unique to geology can play a key role in focusing the contributions of many specialized areas of science on the common problem of environmental quality.

The map: basic geologic document.—Constructed of lithogenetic, process-defined rocks and fleshed out with data from many areas of science, the environmental geologic map can become a fundamental document on earth materials and processes (fig. 2). It can illustrate clearly the distribution of modern and ancient sedimentary facies, as well as fundamental igneous and metamorphic units when applicable. Such a map supplies the geologist with basic information about modern processes, as well as data for interpreting ancient processes responsible for critical properties exhibited by bedrock. Later observations, analyses, and specialized studies can then be interrelated using the environmental geologic map as a skeletal framework.

The environmental geologic map can also serve as a record of the current status of dynamic modern environments and processes, as well as a permanent record of exploitation, erosion, and human modification. Maps of physically dynamic areas such as rivers, coastal zones, slumping mountainsides, and active faults provide a base line of reference by which approximate rates and kinds of charges can be determined. Evolution of a dynamic geologic environment can be monitored by periodic mapping which shows the average or significant direction and rate of change; daily monitoring devices, which record small-scale, commonly reversing changes, can be tied to a long-term, regional framework.

A total system of complex, interrelated modern sedimentary processes and environments can be monitored efficiently and inexpensively by sequential mapping, especially using aerial photography and other remote sensing techniques. Precise quantitative measurements made at instrument stations can be related properly and in perspective with the whole system of related modern environments. Similarly, mapping systems of ancient rocks in terms of lithogenetic systems provides insight into the rate and kind of processes responsible for the rocks, giving the geologist a tool with which to estimate better the potential properties of bedrock, such as porosity, permeability, geometry, strength, probable hydraulic character, and many others.

The environmental geologic map can serve as the common denominator for communication among environmental geologists, soil scientists, engineers, biologists, marine scientists, and other related specialists (fig. 2). A map showing the distribution of natural systems and the three-dimensional picture of ancient rocks and inferred processes interrelates diverse areas of scientific specialty. Certain soils, for example, develop on specific rocks and sediments. These soils and parent bedrock determine to a considerable degree the nature of engineering properties, the kind of vegetation (along with micro and macro climate), and wildlife of the area. Ecosystems, which are tightly interwoven with physical and chemical environments, in turn, may be related to landforms, sediment rocks, or bay-estuarine substrates that are displayed on environmental geologic maps.

Technical input from other scientists can be integrated through the display of the information on maps. Economists, planners, public utilities specialists, power suppliers, sanitary engineers, lawyers, legislative councils, and untold numbers of other persons in the governmental and private arena can plot, plan, refer, and digest available environmental input when it is projected and displayed in relation to the basic environmental elements of the area or region. The environmental map can, therefore, become a common language, a vehicle which has the potential to interrelate many divergent specialists and allow their collective contributions to be focused simultaneously on a problem. It also provides a principal source of accurately located data for computer modeling studies and environmental data banks.

Derivative Mapping

The environmental geologic map occupies a unique and important role in environmental studies by serving as the prime source of readily derived interpretative maps (fig. 2). Properties that are primarily related to geologic materials and processes can be derived from the basic environmental map.

Interpolate and extrapolate.—Maps that exhibit the distribution of factors needed for engineering, wildlife management, hydrology, and other purposes can be obtained by analyzing data from closely spaced coring or observation stations. Tens of thousands of shallow cores or data localities in an area of 20,000 square miles, however, would be necessary to prepare a map based entirely upon a network of sample and observation stations. Qualified geologists can rapidly map modern and bedrock units using aerial photographs, well data, and a knowledge of the geometry and genetic nature of rock units; then vital properties of these geologic units that are determined at selected coring and sampling sites can be extrapolated to similar units. Such properties can be reasonably interpolated for all areas within the boundary of the facies or rock unit. Local variations in the properties of a single lithogenetic unit normally occur, but in many cases it is likely that the map would display accurately critical characteristics, such as a shrink-swell or high permeability, for perhaps 90 percent of the area. On-site drilling would be necessary before construction or other final utilization of the area, but a derived map of shrink-swell or permeability provides a rapid and efficient means of advance planning.

Extrapolating and interpolating properties derived from selected testing sites throughout large areas is what geologists are best trained to do. This is the principal tool in oil or mineral exploration by which minimum data are used to evaluate large tracts of land without concentrated coring or testing. Limited data can be extended to provide useful guidelines for the engineer, the sanitary landfill authority, the hydrologist, or the wildlife expert. Derivative mapping extracts and extends every bit of useful earth information.

Translation of Geology.—The derivative map can be the means of translating basic geology into a form that can be utilized better by a wide variety of persons interested in the environment and its proper exploitation and conservation. For example, public utilities are plagued in some areas by corrosion of pipes and cables. Corrosion is, in part, a second-derivative property of the soil and its chemistry, which in turn commonly relates to bedrock; a map of the bedrock of underlying sediments on which highly corrosive soils develop may become a derivative map of corrosion potential. When selected testing shows that corrosion is primarily restricted to soils developed from one or more rock units, these geologic units then define the limits of various degrees of corrosion potential.

Derivative maps can be as esoteric as a map of areas favorable for the growth of an ornamental plant species to maps as practical as load-strength limits for heavy construction. It is up to geologists to communicate and translate for the nongeologist. Hesitance on the part of other scientists to acknowledge that geology can provide hard, useful, reliable facts generally can be overcome with practical examples. For example, a geologist certainly cannot convince an engineer that geology has something to contribute to the solution of a problem if the geologist is ignorant of engineering problems and responsibilities. When something is learned of engineering limits, wildlife tolerances, water quality levels, and other vital properties, geologists can then hope to contribute significantly to other areas of environmental application. Communication is possible when the nongeologist is approached on his own terms and in his own specialized language.

RESOURCE CAPABILITY: GEOLOGIC APPLICATION IN RESOURCE AND ENVIRONMENTAL MANAGEMENT

Because of the growing concern over land and water resources, land uses, and associated problems of environmental quality, the United States is moving toward federal and, perhaps, state land use legislation. Management of private lands and waters will not be popular, especially with most geologists, but our society has become so complex and our resources so overtaxed that some guidelines appear inevitable. It is absolutely imperative that geologists take an active role in land use planning programs at this time, for geologic input is essential to any balanced land use system.

Geology can help supply the kind of data and inventories that will allow for preventive maintenance of the environment and land resources. Geologic input can help to insure proper multiple land use, development corridors, preservation areas, economic trade-offs, management of renewable resources, and intelligent conservation of expendable resources. In other words, geologists are just as qualified to assume roles of leadership in environmental and resource management as any other profession. Leadership is needed to develop the most effective management of natural environments, processes, and resources. If future development and utilization of natural resources—land, water, biota, and mineral-energy resources—are consistent with natural capabilities and limits of the environment, many impact problems can be precluded or minimized.

Since society neither can accept total and absolute preservation, nor can it condone unmanaged, unrestricted exploitation, flexible environmental guidelines will permit maximum but wise use of resources, consistent with minimal environmental imbalance and natural variability. Flexible guidelines are far more realistic than highly restrictive, rigid codes. To develop such guidelines consistent with the legitimate resource needs of our society requires an adequate inventory, description, and delineation of these natural units, followed by evaluation of their capability for varied uses. This leads to the concept of *natural resource capability* (Brown and others, 1971). Resource capability is a logical step beyond environmental geology; it is the application of the science in governmental decision-making machinery where ideas can become reality (fig. 2).

Any realistic land use program must inevitably depend on geographically delineated land units that allow for precise legal definition, codification, and performance requirements. Maps containing such units can allow planning to proceed intelligently and fairly far ahead of development and resource use. Resource capability provides the scientific framework by which performance standards can be legally stated, enabling users to have the option of preventive engineering and other procedures which will insure against undesirable environmental impact. Such a program permits fundamental decisions on land and water management to be made early and to be made with full cognizance of the scientific factors. Integration of geology into state planning and inventory programs is an essential step that needs to be taken by geologists. This is, perhaps, the single most important, ultimate role that individual geologists, geological societies, and associations can assume.

A resource capability unit is an environmental entity—land, water, area of active process, or biotic assemblage—defined in terms of the nature, degree of activity, or use it can sustain without losing an acceptable level of environmental quality. Alternative, and somewhat synonymous, terms for the generally similar concepts include "performance standards" and "environmental resource units" (Turner and Coffman, 1973). Units are established by recognizing elements of first-order environmental significance, whether they be physical, biologic, or chemical. These land and water elements may include, among others, (1) physical units (geologic substrate and soil units) where physical properties and substrate composition are of primary importance; (2) process units, such as flooding, sheetwash, dune migration, landsliding, or faulting where physical processes are dominant factors; (3) biologic units such as reefs, marshes, swamps, and timbered areas where biologic activity and habitation assume first-order significance; (4) geomorphic and structural units where unique landforms or active structural activity such as faulting or subsidence are critical; (5) geohydrologic units in which aquifer recharge or discharge is a first-order factor; and (6) man-made units such as dredged channels, filled land, and urbanized areas where man's activity has resulted in important environmental modification.

Resource capability units are derived by interpretation of environmental geologic units. Although many environmental derivative maps can be prepared for various specialists and interest groups, the resource capability map is a very special derivative that can be prepared exclusively for decision-makers, such as planners, legislators, judges and others charged with developing or enforcing environmental resource use standards. Capability units can be evaluated in terms of any current or potential land and water use, providing an impact prediction system far in advance of actual use.

Application of the capability concept, whatever name may be applied or specific name implied, offers a potent tool to planners, politicians, and economists. Decisions based on political and economic factors can be rooted in full recognition of the fundamental natural limitations or attributes of the area. Maximum use with minimum environmental degradation can be planned within the realities of politics, economics, and societal problems. Whether such a system, when and if devised, will be used by the body politic is open to speculation, but for certain, the politician will have no choice if geologists fail to help provide him with a rational system for land use decisions.

CONCLUSIONS

One of the most critical problems facing the world during the last decades of this century will be the effect of an expanding population with its needs for water, sanitation, recreation, and varied land use, coupled with complementary mineral-energy extraction and industrial expansion. A paradox exists between a concern about the ultimate supply of natural resources necessary to maintain the present Western lifestyle, and a growing concern about the impact of accelerating exploitation on environments and ecosystems. Environmental knowledge is the key to proper balance between exploitation and conservation.

Environmental geology is, above all else, the practical or functional application of the science to critical environmental problems; geologists have for years similarly applied the science to mineral exploration and investigations of earth history and processes. More and more geologists will begin filling an increasing number of positions involving environmental problems; these tasks will require the best in research and application that the science of geology has to offer.

A major thrust is needed at this time to define and inventory natural environmental systems, their present status, and the impact of human modification. A principal geological tool in controlling pollution, diminishing resources, indiscriminate land use, and unnecessary or excessively rigid controls on private or corporate activity will be properly conceived and innovative geologic maps. The United States is poorly covered by geologic maps of adequate scale and proper concept for solving impact problems and for developing long-range inventories of land resources.

Maps need to be composed principally of lithogenetic units, even if they do not conform to traditional maps or formally accepted nomenclature. For example, first-order environmental units may include sediments or rock units such as fluvial channel-fill sand or reef limestone; vegetational units such as salt marsh or grass-stabilized dunes; landforms such as tidal deltas or highly dissected badlands; process-defined units such as landslide areas, active faults or flood plains; and numerous man-made units. Lithogenetic maps allow rapid derivation of special-use environmental maps for a broad spectrum of scientists and nonscientists. Three-dimensional extrapolation and interpolation of physical properties allow prediction of the behavior of material under varied land use, thus introducing natural land and water capability to decision-makers.

Geologists can insure that environmental management is based on flexible guidelines or capability in harmony with the variability and realities of modern environments and ancient substrates. Rigid controls that do not account for natural geologic variations are scientifically improper; over-control is just as serious as undercontrol. Geologists possess important and unique talent for helping to separate environmental fact and reality from emotionalism. The time to introduce geological expertise into land use programs is *now,* before emotionalism and popular misconceptions about scientific solutions become incorporated into a rigid system of environmental acts that exclude the fundamental, critical geologic realities of the environment.

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TEXAS STATEWIDE RESOURCE CAPABILITY MAPPING AND INVENTORY

Robert S. Kier

INTRODUCTION

Concern over land and water use and environmental quality has sparked considerable interest in development of programs charting optimum use of natural resources consistent with the ability of environments to sustain human activity. Requisite for such programs is comprehensive knowledge of physical, chemical, and biological characteristics, limits on use, and interrelationships of and among various land and water areas. Certain resources are capable of extensive and intensive use; others are delicately balanced, but are extremely productive and essential; still others are finite and nonrenewable, and need to be managed properly in order to maintain use commensurate with their rate of renewal or with awareness of their ultimate depletion. These different kinds of resources and environments need to be identified, their areal extent and distribution determined, and their various uses evaluated if we are to assess natural ability of land and water areas to support man's impact.

Because no environment is isolated, a regional perspective is necessary to: (a) ascertain the attributes, distribution, and diversity of land and water resources, the relationships among these resources, and their overall natural capability for use; (b) identify critical areas under population and industrial pressure where detailed studies are most needed; and (c) provide a firm foundation for regional planning and interrelate subareas within the region where differing, but more detailed, studies may have been performed. If implemented on a statewide basis, this kind of inventory also serves to partially fulfill requirements contained in pending federal land use legislation.

The concept of resource capability developed by Brown and others (1971), derived from experience gained in mapping environmental geologic units in the Texas Coastal Zone (Fisher and others, 1972, 1973a), provides a basis for a natural resource inventory. Analysis of resource capability considers basic facets of land—geology, pedology, biology, and current land use as it pertains to the capability of land and water areas to sustain present and potential use. This analysis allows delineation of areas with like natural ability to withstand similar kinds and rates of use without deteriorating environmentally beyond an acceptable level, and of areas that are subject to natural processes, such as flooding, erosion, or subsidence, which are potentially troublesome to human activity.

As such, resource capability analysis provides an environmental base line against which to measure the consequences of man's activities assuming no technological improvements have been performed. Of course, carrying capacity can be enhanced by engineering modifications, but natural capability determines the extent and scope of modifications needed to make a land or water area suitable for a particular use.

Resource capability units are similar to environmental resource units (ERU's) proposed by Turner and Coffman (1973) in their review of environmental geology. Despite Turner and Coffman's implications to the contrary, environmental resource units are defined in essentially the same way as resource capability units; their definition lacks only consideration of current land use as an indication of natural capability. Furthermore, and again in contrast to Turner and Coffman's statements, the fundamental concept, reasoning, and methodology of resource capability analysis is not limited to the Coastal Zone. The principals can be applied to any given region—lowlands, interior plains, mountains, desert—at any given scale and level of detail. Capability analysis is also independent of the classification scheme used.

A resource capability map (1:500,000) of the State of Texas is nearing completion. Seventy-eight land and water units are depicted and have been grouped, as listed in table 1, according to their fundamental significance as: (a) aquifer units—areas of recharge to different kinds of aquifers; (b) substrate units—geologic and soils units with distinctive physical attributes; (c) physical properties units—lands with unique physical characteristics, such as high shrink-swell potential and slope instability, leading to particular use problems; (d) geomorphic and structural units—terraces, badlands, and karst areas, where form and slope affect land use; (e) physical process units—land and water areas, such as flood plains, sand dunes, and hurricane-surge channels, where dynamic processes dictate or should dictate aspects of use; (f) biologic units—wetlands, reefs, and the like, whose biologic habitation, activity, and productivity are delicately

Table 1. Statewide land resources classification.

A. Aquifer Units
   1. Recharge sand
   2. Upland recharge sand
   3. Perched coastal aquifers
   4. Recharge limestone
   5. Localized fractured-granite aquifer

B. Substrate Units
   1. Hard, massive limestone
   2. Hard, thin-bedded limestone
   3. Marl
   4. Mixed limestone and marl
   5. Chalk
   6. Caliche with soil cover
   7. Caliche
   8. Hard sandstone and conglomerate
   9. Mixed hard sandstone and clay
   10. Clayey sands
   11. Mixed sandstone, clay, and coal
   12. Kaolin-lignitic clay
   13. Greensand-ironstone
   14. Gypsiferous red beds
   15. Gypsum-anhydrite
   16. Fractured, steeply dipping rocks
   17. Granite
   18. Ash
   19. Lava flow
   20. Mixed volcanic rocks (ash and lava)
   21. Gravels with volcanic rocks
   22. Bedrock gravel
   23. Bolson fill
   24. Flint gravel (terrace deposits)
   25. Limestone gravel
   26. Limestone-clastic sequence

C. Physical Property Units
   1. Unstable clay—moderate to good cropland
   2. Unstable clay—poor cropland
   3. Unstable clay and hard limestone
   4. Unstable sandy clay
   5. Moderately permeable clayey sands
   6. Loose surficial sand

D. Geomorphic Units and Structural Features
   1. Stony mountain land
   2. Terraces

Table 1 (continued).

3. Levee and crevasse deposits
4. Inactive alluvial fan and slopewash deposits
5. Badlands
6. Red beds—plain
7. Red beds—moderately to deeply dissected
8. Stairstep topography
9. Caliche-limestone karst and gypsum collapse areas
10. Salt domes (shallow or piercement)
11. Faults

E. Process Units
1. Flood plains
2. Alluvial fans
3. Playas
4. Alkali flats
5. Blowouts
6. Windblown sand
7. Sand dunes
8. Clay dunes
9. Tidal delta and tidal inlets
10. Wind-tidal flats and tidal flats
11. Bay-margin shoals, delta-front sands, and bay-margin sand
12. Mainland beaches, spits, and storm berms
13. Potential hurricane-surge channels

F. Biologic Units
1. Fresh marsh
2. Swamp (including peat bogs)
3. Brackish to salt marsh
4. Grassflats
5. Reefs (including living, dredged, and dead remnants)

G. Bay, Lagoon, Estuarine, and Open Gulf Units
1. River-influenced bay
2. Restricted bay
3. Open bay
4. Open bay—tidally influenced
5. Interreef flats
6. Shoreface sands
7. Shelf

H. Man-Made Units or Features
1. Surface water storage area (lakes and reservoirs)
2. National forests and parks
3. Urban buildup areas
4. Subaerial spoil and made land
5. Submarine spoil

Table 2. Factors considered in assessing resource capability of land and water areas of Texas.

1. Nature of area—type of unit
   - A. Hydrologic—areas of recharge for important aquifers
   - B. Substrate—physically defined, but no special limiting parameters
   - C. Physical property—special limiting physical properties
   - D. Geomorphic—land shape or configuration, important in recognition of area and in determining capability
   - E. Process—natural processes presently occurring in these areas
   - F. Biologic—floral and faunal communities that determine capability
   - G. Bays, lagoons, estuaries, and open Gulf—capability is related to bottom material, faunal and floral communities, and coastal processes
   - H. Man-made—man-made land or culturally defined areas with special natural or legally determined capability
2. Geometry of unit—surface or subsurface
3. Distribution—local or regional
4. Topography and slope, structures, and surface drainage
5. Physical properties
   - A. Composition, dominant minerals, and type of cementation
   - B. Foundation strength
   - C. Shrink-swell
   - D. Plasticity
   - E. Porosity and permeability
   - F. Corrosion potential, pH
   - G. Erosion potential—kind
   - H. Solubility
   - I. Hardness
   - J. Compressibility
   - K. Rippability and ease of excavation
   - L. Blasting characteristics
   - M. Fill potential and ease of land shaping
   - N. Slope stability
6. Additional factors
   - A. Aquifer potential
   - B. Faulting
   - C. Flood potential
   - D. Floral types (natural)
   - E. Faunal types (natural)
   - F. Soil development including dominant soil types found on each capability unit
   - G. Current land use
7. Additional discussion
   - A. Geologic units included in each capability unit
   - B. Possible uses

balanced and of paramount importance to man's well-being; (g) bay, lagoon, estuarine, and Gulf units—submerged coastal lands defined by the nature and distribution of bottom sediment, salinity patterns, circulation, tidal influence, depth variations, turbidity, fresh-water influx, distribution of biotic communities, and water chemistry; and (h) man-made units—areas of spoil and urbanization where man's activities have completely altered the environment or created new environments with their own natural capabilities.

The purpose of this report is to describe: (1) the derivation of the land and water resource units in the State of Texas, the types of data used in assessing resource capability, and the methodology used in the analysis; (2) the map base, format, and accompanying text; and (3) the potential utility to planners and managers of the map and text and of the possible special purpose maps that can be derived from the land and water resources map.

DERIVATION OF RESOURCE CAPABILITY UNITS

A resource capability unit has been defined as an environmental entity—land or water, process, biota, or physically defined area—delineated according to its fundamental natural properties and to the nature and degree of use it can withstand without losing acceptable environmental quality (Brown and others, 1971). Principal factors that determine natural capability or carrying capacity are many and diverse, especially over a large area containing many different kinds of environments, such as Texas. Among these factors are (a) susceptibility to flooding; (b) physical properties of soils and substrates, such as shrink-swell conditions, foundation strength, corrosion tendency, degree of permeability, and types and number of fractures; (c) slope, relief, and geomorphic form; (d) erosional and depositional processes by water, wind, and more direct gravitational movement such as in landslides; (e) biologic habitation, tolerances, productivity, and stability; (f) active and potential faulting and subsidence; (g) natural water quality and movement; (h) geometry and distribution; and (i) mineral resource potential. Specific factors considered in assessing resource capability of Texas are outlined in table 2.

Evaluation of natural capability units is also tied to the types and intensity of activities that take place on the land and in or on the water. Present and anticipated land and water uses are varied, but certain activities serve as examples. These are: (1) solid and liquid waste disposal; (2) channelization, ditching, and draining; (3) construction of buildings, highways, light and heavy industry, jetties, groins, piers, and seawalls; (4) surface and subsurface extraction of raw materials; (5) filling and land reclamation; (6) devegetation and other alteration of natural flora; (7) farming and grazing; (8) use of herbicides, pesticides, and insecticides; and (9) impounding of surface water for future use or storage of wastes. A flow diagram illustrating the process of resource capability evaluation is presented in figure 1.

By considering all factors—physical, chemical, and biological, active or passive—and the effects that current and potential land and water use have upon an area, the natural carrying capacity of that area is assessed. The influence of each factor and use is weighed on an area-by-area basis, with constant reassessment to assure completeness and consistency. The resulting product shows the distribution of fundamental, environmentally significant, natural units. Resemblance to traditional geologic maps reveals the strong influence of geology on natural capability of land and water areas.

In evaluating natural capability of land and water areas in Texas, all available information was used, including published and unpublished reports, maps, and observations. Approximately 250 published references and innumerable unpublished reports, manuscripts, and notes were consulted in considering natural carrying capacity of land and water areas in Texas. Descriptions, properties, distribution, and variability of more than 450 formal and informal geologic and biologic units and more than 150 recognized soils units were compiled and analyzed in this process.

Original mapping for most of the geologic maps used in delineating the areal distribution of many of the capability units was at scales of 1:62,500 (1 inch = 1 mile) and 1:24,000 (1 inch = 2,000 feet); mapping of many of the soils units was at even larger scale. Where few or no data existed, capability units were mapped directly on stereo aerial photos at a scale of 1:62,500. Where no photographic coverage was available, topographic maps were used to map the capability units. In all, nearly 10 man-years of effort have been expended on this project covering the 267,339 square miles of Texas, not including time spent in original geologic, biologic, or soils mapping, frequent consultation among the staff members, or final preparation for printing of the land and water resources map.

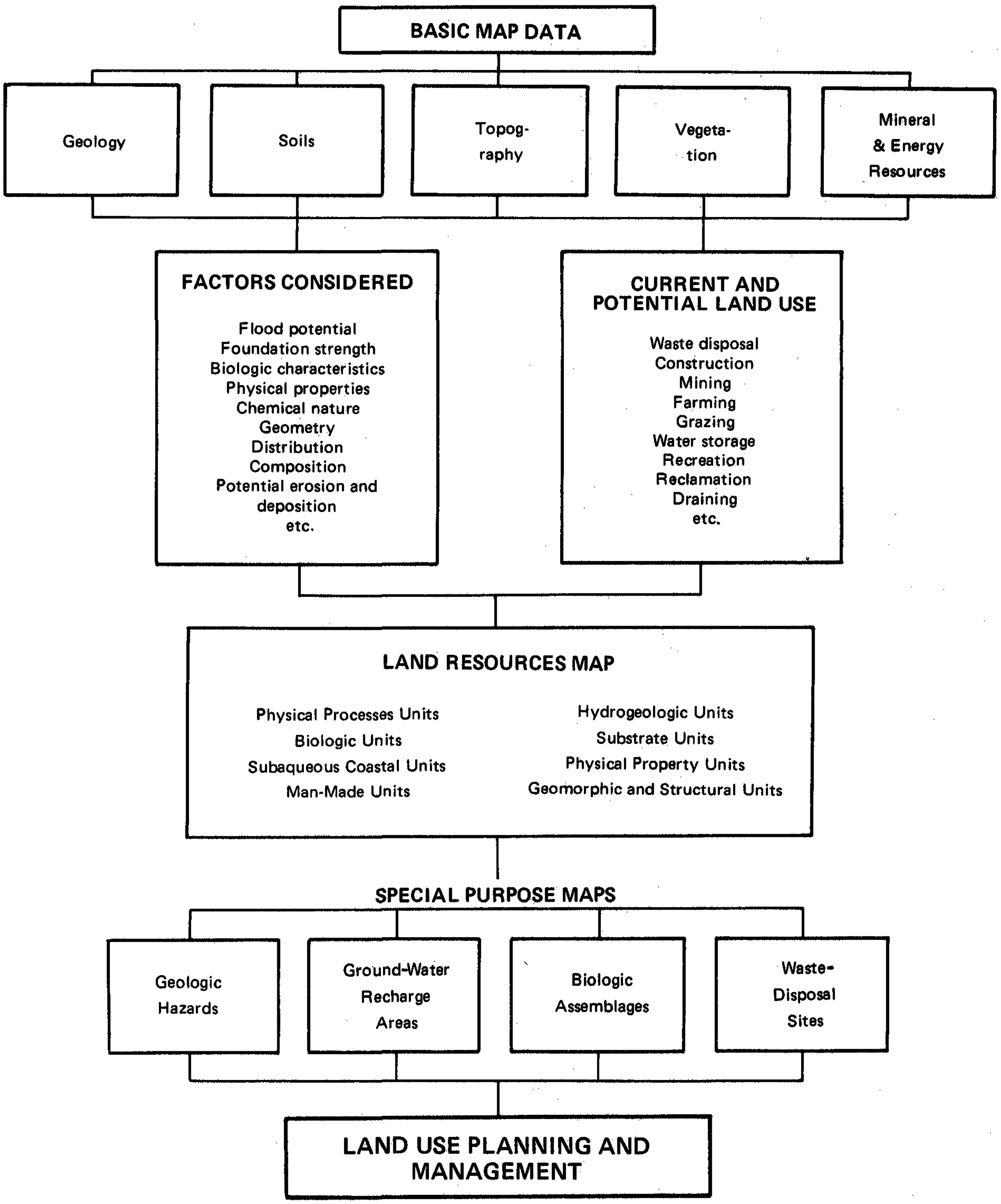

Figure 1. Flow diagram illustrating process of resource capability analysis.

Analysis of resource capability of Texas was generally a team effort; no one person has sufficient expertise to encompass all aspects of capability analysis. The mapping team, although geologists by formal training, maintained an interdisciplinary approach throughout the project. Nearly all of the research staff at the Bureau of Economic Geology contributed their knowledge of the State's geology, soils, fauna and flora, and land use patterns to assessing natural carrying capacity of the various land and water areas.

LAND RESOURCES MAP

Base

The base for the Land Resources Map of Texas is the standard U.S. Geological Survey 1:500,000 (1 inch = 8 miles) topographic map of the State. The topographic contour interval is 200 feet with supplemental 100-foot contours in the Coastal Zone. Cultural features included on the base are parks and national forests, roads, railroads, city and county boundaries, and urbanized areas. Water features shown include streams, drainage ditches, canals, and natural and artificial lakes and reservoirs.

The U.S. Geological Survey map was last updated in 1965. For the purposes of the Land Resources Map, more recent information on cultural and water features that are also capability units was desirable. Reservoir configurations and pool elevations of water bodies larger than approximately 500 acres in surface area were updated to early 1973 using maps of existing and planned reservoirs from the Texas Water Development Board. Urban buildup areas were updated using the most recent aerial photo coverage available from the Texas Highway Department. New state and national parks were also added.

Map Units

The 78 land and water resource units of the State (table 1) are depicted on the Land Resources Map with distinct colors and letter-number symbols to facilitate map interpretation (fig. 2). Where possible, map colors of capability units with similar environmental properties—hydrogeologic, geomorphic, etc.—are from the same region of the color spectrum. Two units, recharge limestone and urban buildup areas, are shown by overprint patterns on other capability units. National parks and forests are delineated on the cultural base.

Format

The large—nearly 8½ by 6½ feet—Land Resources Map is divided into four quadrants corresponding to the four parts of the U.S. Geological Survey base. The map legend, along with 10 auxiliary maps, is in the southwest quadrant, in the position of Mexico. The 10 maps are drawn at an approximate scale of 1 inch = 130 miles; they summarize (1) physiography, (2) soils, (3) vegetation types, (4) general geology, (5) mineral resources, (6) energy resources, (7) climatic conditions, (8) major river and coastal basins, (9) location of major aquifers, and (10) distribution of structural basins.

Each capability unit is described in the legend by its characteristics, limiting factors and uses, and compatible activities. Descriptions are in nontechnical terms, but are sufficiently detailed to adequately describe properties and proper use of the unit.

Auxiliary Maps

The 10 small maps in the southwest quadrant of the Land Resources Map depict aspects of land capability that cannot be shown on the larger Map. This information is important in assessing the full environmental impact of man's use of land and in helping to relate rather finely delineated capability areas on the large Map to the grosser regions of the State. Generalized illustrations of two of the maps are contained in figures 3 and 4 to show the level of detail that each of the auxiliary maps will have. Brief descriptions of these maps follow:

Physiographic Provinces.—Physiography of the State of Texas depicted by line drawing and colors showing the general physiographic regions of the State. Data source: adapted from Raisz, 1952; Arbingast and others, 1967; and Godfrey and others, 1973.

Generalized Geology.—Generalized geology of the State grouped according to age and rock type, including (1) Quaternary, (2) Pliocene, Miocene, and Oligocene, (3) Eocene, (4) Cretaceous (Gulf Series), (5) Cretaceous (Comanche Series), (6) Jurassic and Triassic, (7) Permian, (8) Pennsylvanian and Mississippian, (9) Devonian, Silurian, Ordovician, Cambrian, and undivided Paleozoic strata, (10) Precambrian, and (11) undifferentiated igneous rocks. Data source: Oetking and Feray, 1959; and various published and unpublished maps from the Bureau of Economic Geology and the U.S. Geological Survey.

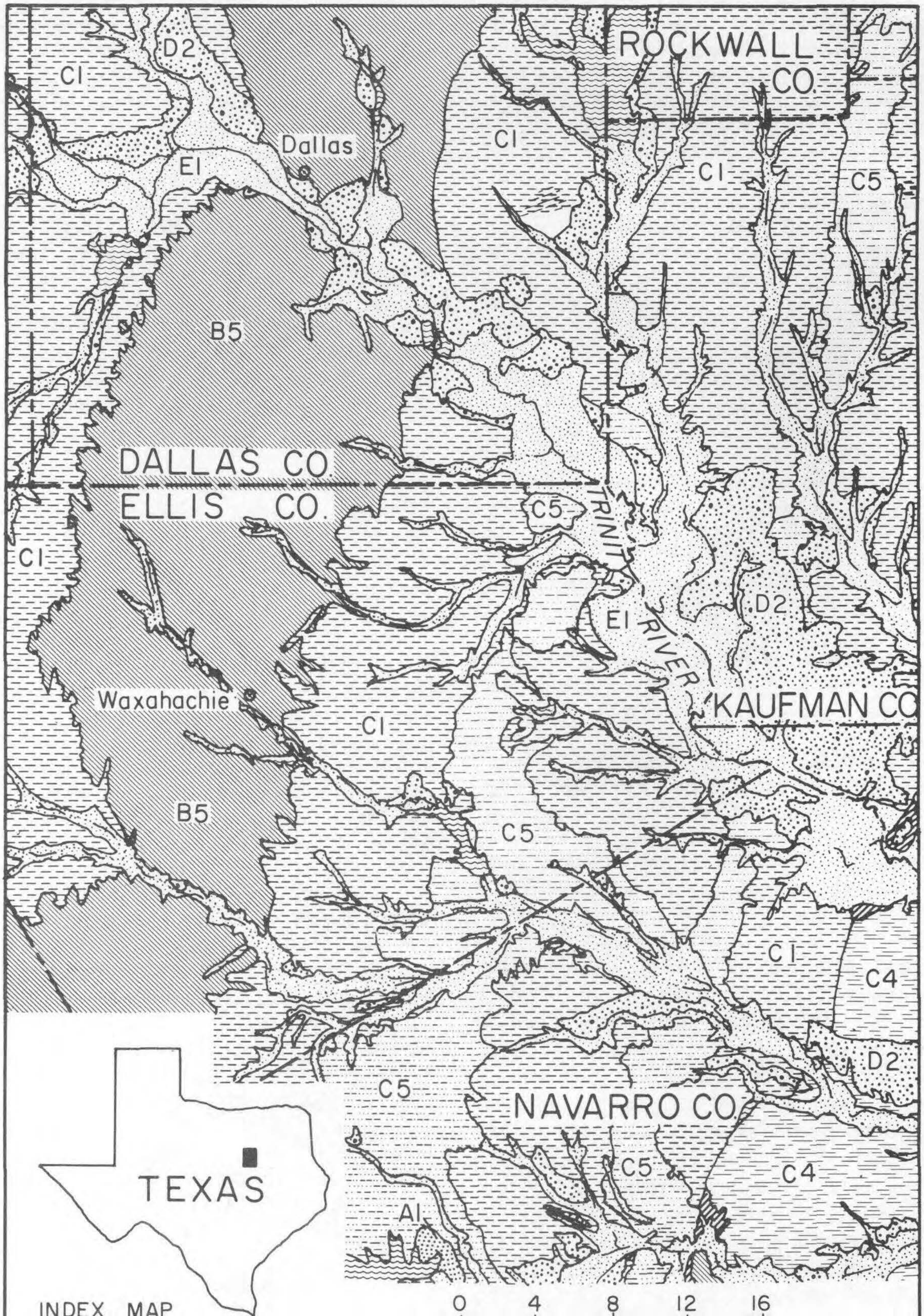

Figure 2. A small area of the Land Resources Map, near Dallas, Texas.

Generalized Soils Map.— Delineation of 36 soils groups of associations based on similar characteristics, limitations, and uses, and also combined according to physiographic areas. Data source: modified from Godfrey and others, 1973.

Vegetation Regions.—Delineation of general vegetation regions in the State, including (1) plain grassland, (2) blackland prairie, (3) coastal prairie, (4) desert shrub savanna, (5) mesquite-chaparral savanna, (6) juniper-oak-mesquite savanna, (7) mesquite savanna, (8) oak savanna, (9) oak forest and prairies, (10) longleaf pine forest, (11) oak-hickory-pine forest, and (12) oak-hickory forest. Data source: Arbingast and others, 1967; Tharp, 1944; Chambers, 1952; Kuchler, 1964; and The Dallas Morning News, 1966.

Generalized Structure Map.—General structural framework of the State showing locations of (1) strong uplifts—mostly buried, (2) moderate uplifts, (3) moderately deep basins, and (4) deep to very deep basins and deep-well disposal reservoirs. In addition, the area of active or potentially active faults in the Coastal Zone is shown. Data source: Oetking and Feray, 1959; and Bureau of Economic Geology.

Major River and Coastal Basins.—Delineation of the 15 major river basins and 8 major coastal basins in the State. Data source: Texas Water Development Board.

Major Aquifers.—Recharge areas and downdip limits of fresh water in major aquifers of the State, including (1) alluvium, (2) Gulf Coast, (3) Ogallala, (4) Carrizo-Wilcox combined, (5) Edwards (Balcones fault zone), (6) Edwards-Trinity combined (Plateau), and (7) Trinity. Data source: Texas Water Development Board.

Mineral Resources (fig. 3).—Distribution of known and potential mineral resources of the State, including (1) gypsum, (2) talc, (3) ceramic clay and coal, (4) ceramic clay and lignite, (5) bentonitic clay and pumicite, (6) metallic minerals, feldspar, mica, fluorspar, and barite, (7) limestone, (8) chalk, (9) shell, (10) salt (domes), (11) copper, and (12) sulfur (other than salt domes). Map also shows locations of active or recently active surface mines for many of the above resources and for gravel, graphite, iron ore and ironstone, sand, granite, asphalt, and trap rock. Data source: compiled from numerous published and unpublished sources, including Brown, 1959; Fisher, 1965; Fisher and Rodda, 1967; Garner, 1967; Halbouty, 1967; Zimmerman and Thomas, 1969; McAnulty, 1972; and Groat, 1973.

Energy Resources (fig. 4).—Energy resources that are depicted include known (1) major oil fields, (2) major gas fields, (3) surface and subsurface coal deposits, (4) surface and near-surface lignite deposits, (5) subsurface lignite deposits, and (6) uranium ore concentrations. Locations of active lignite strip mines and active or recently active uranium mines are also shown. Data source: numerous published and unpublished sources, including Mapel, 1967; Fisher 1963, 1965; Finch, 1967; Eargle and others, 1971; Netzeband and Girard, 1966; and Vlissides, 1964.

Climatic Conditions and Potential Hurricane-Flood Zone.—General climatic conditions of the State depicted by lines showing mean annual temperature, precipitation, and evaporation over approximately a 30-year period. In addition, the map shows the area potentially flooded by hurricane-driven surge and tides. Data source: Arbingast and others, 1967; Texas State Climatologist, 1966; Lowry, 1960; and Bureau of Economic Geology.

Text

The text that accompanies the Land Resources Map is designed to provide more specific data than is contained in the map legend. Included chapters discuss (1) the meaning of resource capability units—definition, nature and use, variability, and relevancy in environmental application; (2) the Land Resources Map—base, format, approach, data sources, and how to use the map; (3) the capability units—description, properties, encompassed geologic formations and soils units, engineering characteristics, attributes and limitations, and variability within the units; (4) the 10 auxiliary maps; and (5) the role of a natural capability inventory in land planning and management.

Descriptions of each capability unit contain available data about the (1) nature of the area, (2) geometry of the unit, (3) distribution, (4) topography and slope, structures, and surface drainage, and (5) physical properties, as well as additional factors and discussion (table 2). These are the kinds of information needed to adequately characterize the various areas of the State for proper planning of the best uses of natural resources.

UTILITY OF THE LAND RESOURCES MAP

The Land Resources Map of Texas serves three important purposes:

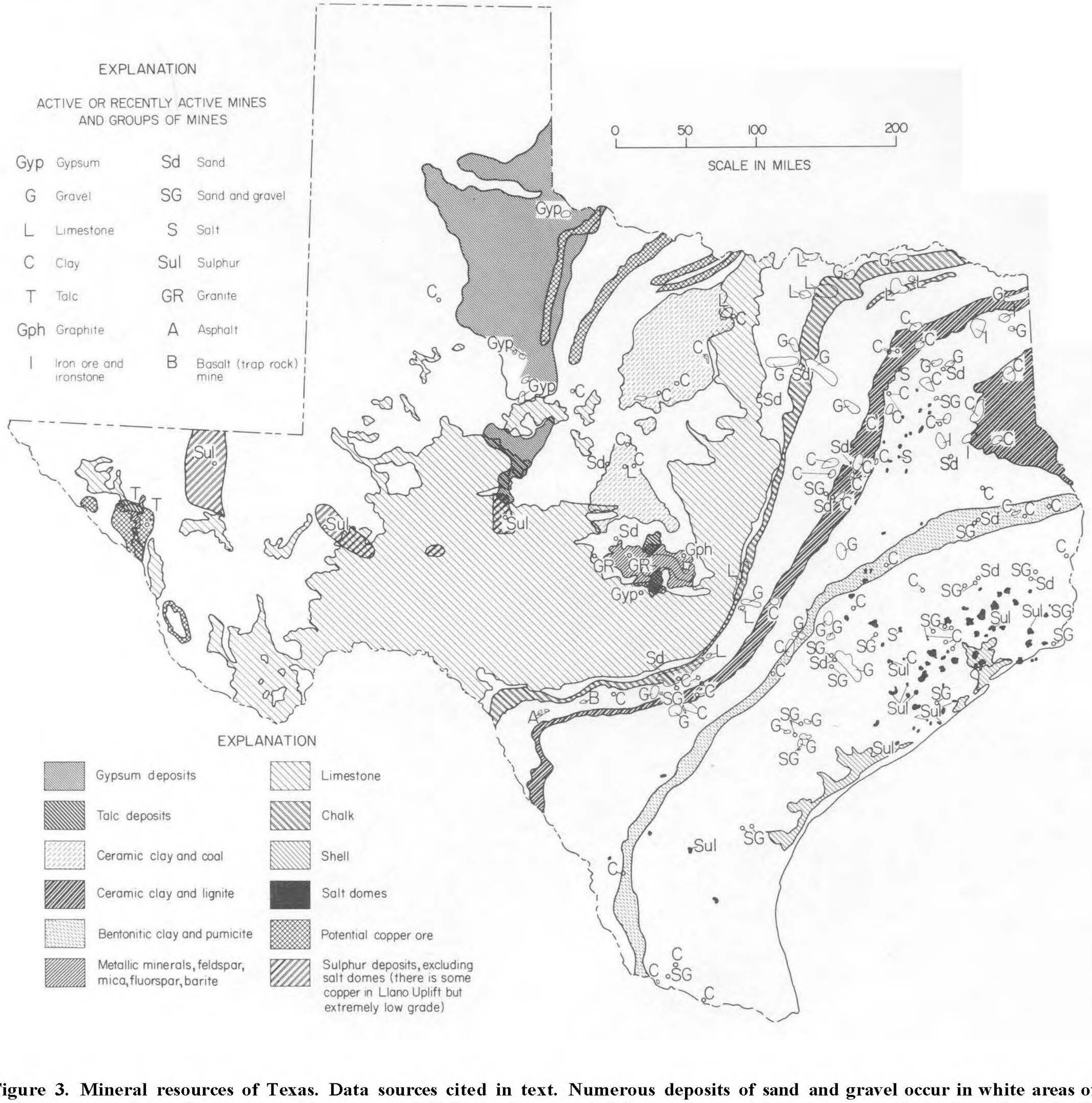

Figure 3. Mineral resources of Texas. Data sources cited in text. Numerous deposits of sand and gravel occur in white areas of the map, but are not shown for cartographic reasons. Caliche is also quarried for road material in numerous places throughout the State. Ironstone occurs south of the band of bentonitic clay and pumicite in East Texas, but is used exclusively for road metal and also is not shown.

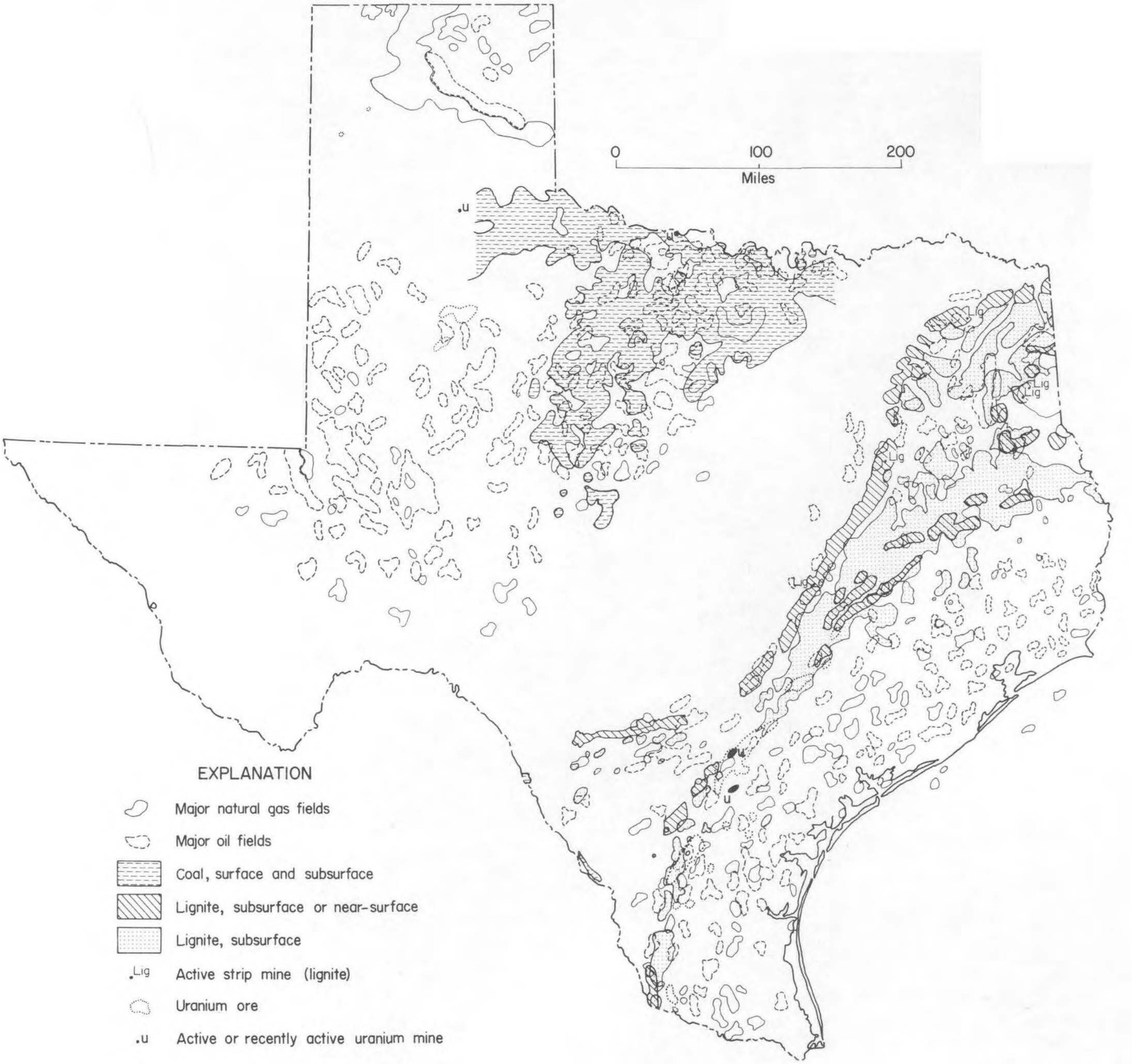

Figure 4. Energy resources of Texas. Data sources cited in text.

(1) It provides a comprehensive, inclusive overview of the State's natural land and water resources, their distribution, attributes, limitations on use, and relationships between units. If local and state land use plans are to be fair and effective, the planners must clearly understand how each region interrelates with other regions and how management decisions in one area can affect environmental quality in another area.

(2) It focuses attention on the nature and distribution of critical environments under intense population and industrial pressures and in need of more detailed study. Delineation of critical areas is called for in Federal land use bills. The environmental geology of the Texas Coastal Zone has already been mapped and described (Fisher and others, 1972, 1973a); analysis of natural carrying capacity of these coastal lands and water bodies has been started by Team Plan Incorporated (Mathis and others, 1972) and by the Bureau of Economic Geology (Fisher and others, 1973b; Proctor and others, 1973; and also Kier and Bell, p. 152–183). Similar consideration of physical properties of land areas has commenced between the rapidly developing Dallas-Fort Worth region and the San Antonio area. Studies of the Greater Waco area at Baylor University (Flawn, 1965; Burket, 1965; Elder, 1965; Spencer, 1966; and Font and Williamson, 1970) and of the Austin area at The University of Texas at Austin (L. E. Garner and K. P. Young, personal communication; and also Garner, p. 101–122) are already complete. Studies of the Capitol Area Planning Council region (Woodruff and Lentz, 1973) and investigation of the area bordering Interregional Highway 35 (by several graduate students at Baylor University) are underway.

(3) It provides fundamental facts on which to base regional planning and environmental management, and serves to integrate fragmented but more detailed studies throughout the State. These studies by several individuals at different institutions (see above) must be brought to a common denominator if they are to have meaning to planners and managers.

The Map and information contained in the accompanying text can also form the basis for several thematic maps depicting special aspects of the State's natural resources. Among the maps that can be easily and quickly generated with some additional data are (1) the distribution of sand and gravel resources, commodities of very short supply in parts of Texas; (2) the location and extent of flood plains and/or other natural hazards, such as active or potentially active fault zones; (3) a revised floral assemblage map of Texas and a faunal assemblage map of the State; (4) the location and kind of threatened environments in the State; (5) the distribution of ground-water recharge areas; and (6) the kind and location of substrates suitable for solid waste disposal. These maps can then be used to help outline and locate particular resource problems for detailed study. When combined with an up-to-date current land use map (under construction at the Bureau of Economic Geology), much valuable natural resource information will be readily accessible to individuals, to industrial and service firms, and to state agencies.

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ENVIRONMENTAL GEOLOGIC ATLAS OF THE TEXAS COASTAL ZONE

L. F. Brown, Jr., and W. L. Fisher

INTRODUCTION

The Texas Coastal Zone is marked by diversity in geography, resources, climate, and industry. It is richly endowed with extensive petroleum reserves, sulfur and salt, deepwater ports, intracoastal waterways, mild climate, good water supplies, abundant wildlife, commercial fishing resources, unusual recreational potential, and large tracts of uncrowded land. The Coastal Zone is a vast area of about 20,000 square miles, including approximately 2,100 square miles of bays and estuaries, 375 miles of Gulf coastline, and 1,425 miles of bay, estuary, and lagoon shoreline. About one-quarter of the State's population and one-third of its economic resources are concentrated in the Coastal Zone, an area including about six percent of the total area of the State.

The Texas shoreline is characterized by interconnecting natural waterways, restricted bays, lagoons, and estuaries, low to moderate fresh-water inflow, long and narrow barrier islands, and extremely low astronomical tidal range. Combined with these natural coastal environments are bayside and intrabay oil fields, bayside refineries and petrochemical plants, dredged intracoastal canals and channels, and satellite industries. The attributes that make the Texas Coastal Zone attractive for industrialization and development also make it particularly susceptible to a variety of environmental problems. The Texas Coastal Zone is thus balanced between maintenance by natural physical, chemical, and biological processes, and effects of industry, urban concentration, and coastal land development.

Parts of the Coastal Zone are among the fastest developing industrial, urban, and recreational regions in Texas; the Zone is at best a precariously balanced natural complex of dynamic environments with a history of almost yearly hurricane impact. Adequate plans to meet the potential problems of pollution, land and water use, and conservation are critically needed to insure proper development of this vital Texas region. A regional analysis and inventory of the total coastal resources of Texas is vitally important and must be based on accurate maps of physical and biological environments, landforms, areas of significant processes, genetic sedimentary or substrate units, and man-made features. The Environmental Geologic Atlas of the Texas Coastal Zone (fig. 1) is designed to present information on the nature of the Coastal Zone, what is happening to it, and at what rate changes are taking place. Such information is needed for long-range resource planning and management. Mapping is the fundamental base necessary to provide answers to these critical questions.

Role of Environmental Geology in the Coastal Zone

Development of guidelines for proper and prudent management of the Texas Coastal Zone depends upon adequate knowledge of the nature and distribution of natural environments, land and water capability, and man's impact on the Coastal Zone. Processes and environments are a fundamental part of the geological character of this dynamic region. Many areas of the Coastal Zone are changing under man's accelerating impact. Because the Zone is balanced in terms of erosion and deposition, hurricane impact damage, salinity variations within bays and estuaries, plant stabilization of sediments, and a myriad of other critical features, man's impact can significantly affect the natural environmental balance. At the same time, the necessity of resource use in man's modern industrial society is obvious. Development, exploitation, and industrialization practices, however, should be compatible with the natural limitations imposed on the region by its physical, chemical, and biologic setting.

Regional climatic, sedimentary, biologic, and physical process variations along the Texas Coast clearly preclude a rigid coastwide system of resource management. Any fair system of management must be based upon the concept of natural local and regional variation of environments; correspondingly, flexible guidelines should be firmly based upon these variations in properties, composition, and behavior under various land uses. Environmental geologic maps provide the fundamental data needed to create such a system of resource management.

One principal goal of the Environmental Geologic Atlas of the Texas Coastal Zone is to obtain an understanding of the natural systems *before* human impact irreversibly changes the character of the Zone. Only by the understanding of the natural coastal system can proper and

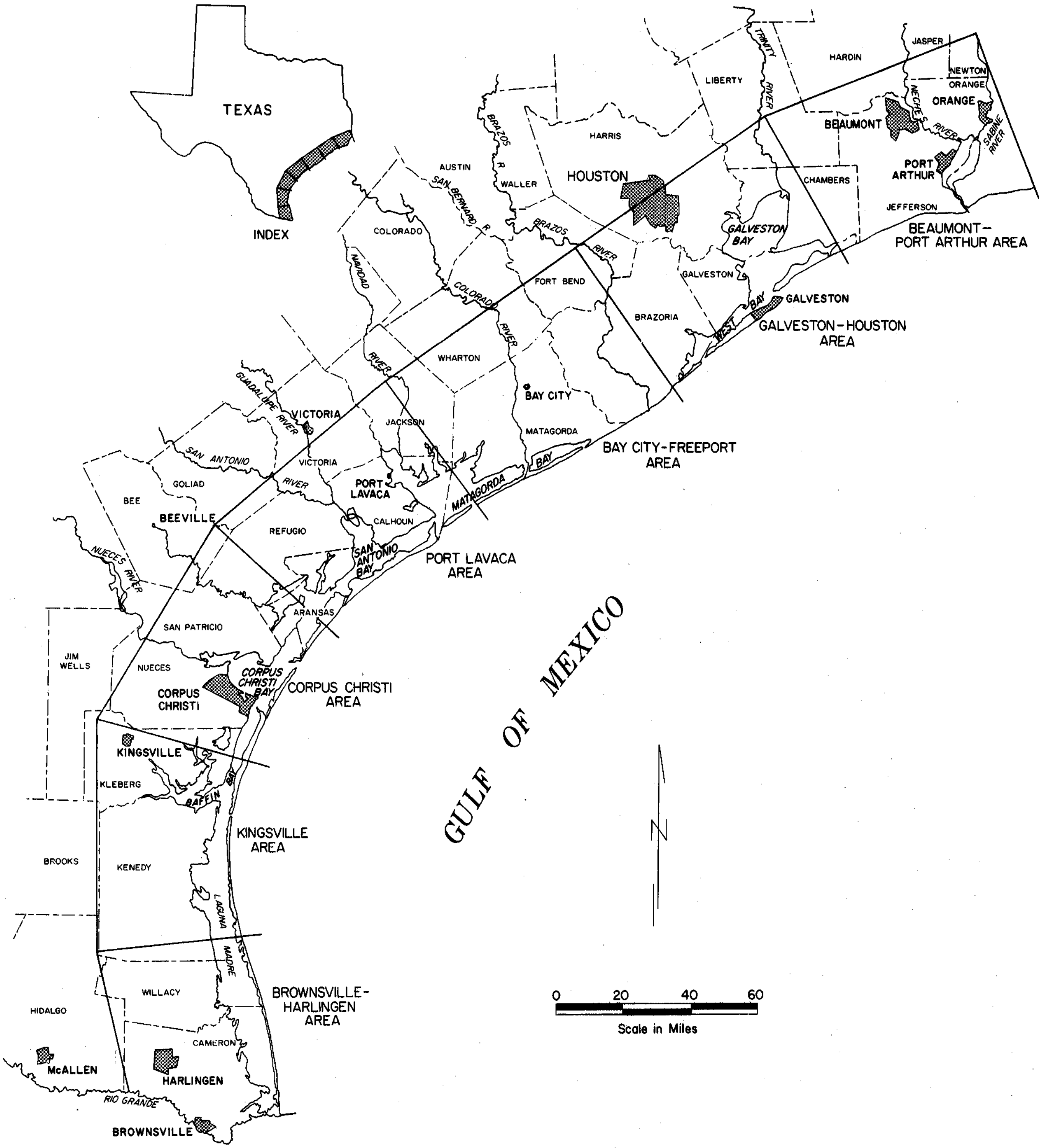

Figure 1. Index of the Environmental Geologic Atlas of the Texas Coastal Zone. After Fisher and others, 1972.

compatible use of the region be determined. Maps of environmental units along the 400-mile-long Coastal Zone provide a benchmark with which to evaluate future changes and to diagnose appropriate use of the coastal regime.

Wise conservation should include the proper use of Coastal Zone resources within prudent guidelines that will insure minimum modification of the environmental quality of the region. For this reason, each kind of land use should be evaluated in terms of its potential effects on the geological and biological units of the Zone. Proper use will result when each of man's coastal activities are properly located in such a manner as to insure necessary minimum environmental damage.

The key to proper land and water use is the basic inventory of the coastal environments, sediment types, processes, and biological conditions. The Environmental Atlas provides this fundamental information that can serve as the basis for evaluating coastal legal problems, socioeconomic problems, industrial development, pollution, recreational needs, problems of public and private ownership, and other factors involving the natural framework of the Coastal Zone.

Several aspects of the Texas Coastal Zone make a long-term resource management program imperative; in turn, this requires a thorough knowledge of the environmental geology of the Coastal Zone. Since the Coastal Zone is the center of rapid geological and physical changes coupled with a rapidly expanding population, an Environmental Atlas provides a current record of the status of dynamic coastal environments and processes, as well as a permanent record of exploitation, erosion, and human modification. Dynamic environments can be monitored by periodic mapping that indicates the significant direction and approximate rate of physical, biological, and chemical changes. The environmental map is the common denominator for communication among coastal scientists through which technical input can be integrated and applied. Just as important, economists, planners, utilities specialists, power suppliers, sanitary engineers, lawyers, legislative councils, regional councils of governments, and many other groups can better plan, plot, refer, and digest environmental data using the Atlas maps.

The Coastal Environmental Atlas Project

The Environmental Geologic Atlas project was initiated in 1969 when the need for a thorough regional analysis of natural processes, environments, lands, water bodies, and other coastal factors became urgently apparent. Without an adequate environmental inventory, further specialized scientific studies, as well as regional planning for improved use of coastal resources, could proceed neither efficiently nor effectively. Because of impending environmental problems in the region, staff members of the Bureau of Economic Geology assigned the project a high priority and proceeded with the mapping in the summer of 1969. Approximately 25 man-years of geologic and cartographic effort were expended in the four-year period of preparation.

The Coastal Zone, defined from the inner continental shelf to about 40 miles inland, includes all estuaries and tidally influenced streams and bounding wetlands. For purposes of presentation, the Zone was divided into seven areas (fig. 1) from the Texas-Louisiana boundary southwestward to the Rio Grande: (1) Beaumont-Port Arthur, (2) Galveston-Houston, (3) Bay City-Freeport, (4) Port Lavaca, (5) Corpus Christi, (6) Kingsville, and (7) Brownsville-Harlingen. Each of these seven coastal areas is covered by a separate Environmental Geologic Atlas (fig. 2) containing a descriptive text, statistical tables, an environmental geology map (scale 1:125,000), and eight special-use environmental maps (scale 1:250,000). The seven Coastal Atlases cover approximately 20,000 square miles.

GEOLOGY AND GEOLOGIC HISTORY

The Texas Coastal Zone is composed of several active, natural systems of environments—fluvial and deltaic systems, marine barrier-strandplain-chenier systems, and bay-estuary-lagoon systems, as well as an eolian (wind) system in South Texas and marsh-swamp systems in the more humid middle and upper coastal regions. Geologists are also aware that the Coastal Zone is entirely underlain by sedimentary deposits that originated in ancient but similar coastal systems. These ancient sediments were deposited by the same natural processes that are active in shaping the present coastline; for example, longshore drift, beach swash, wind deflation and deposition, tidal currents, wind-generated waves and currents, delta out-building, and river point bar and flood deposition.

Active and relict coastal systems (fig. 3) may be divided into three principal groups based on their relative ages: (1) natural systems that originated more than about 30,000 years B.P. (before

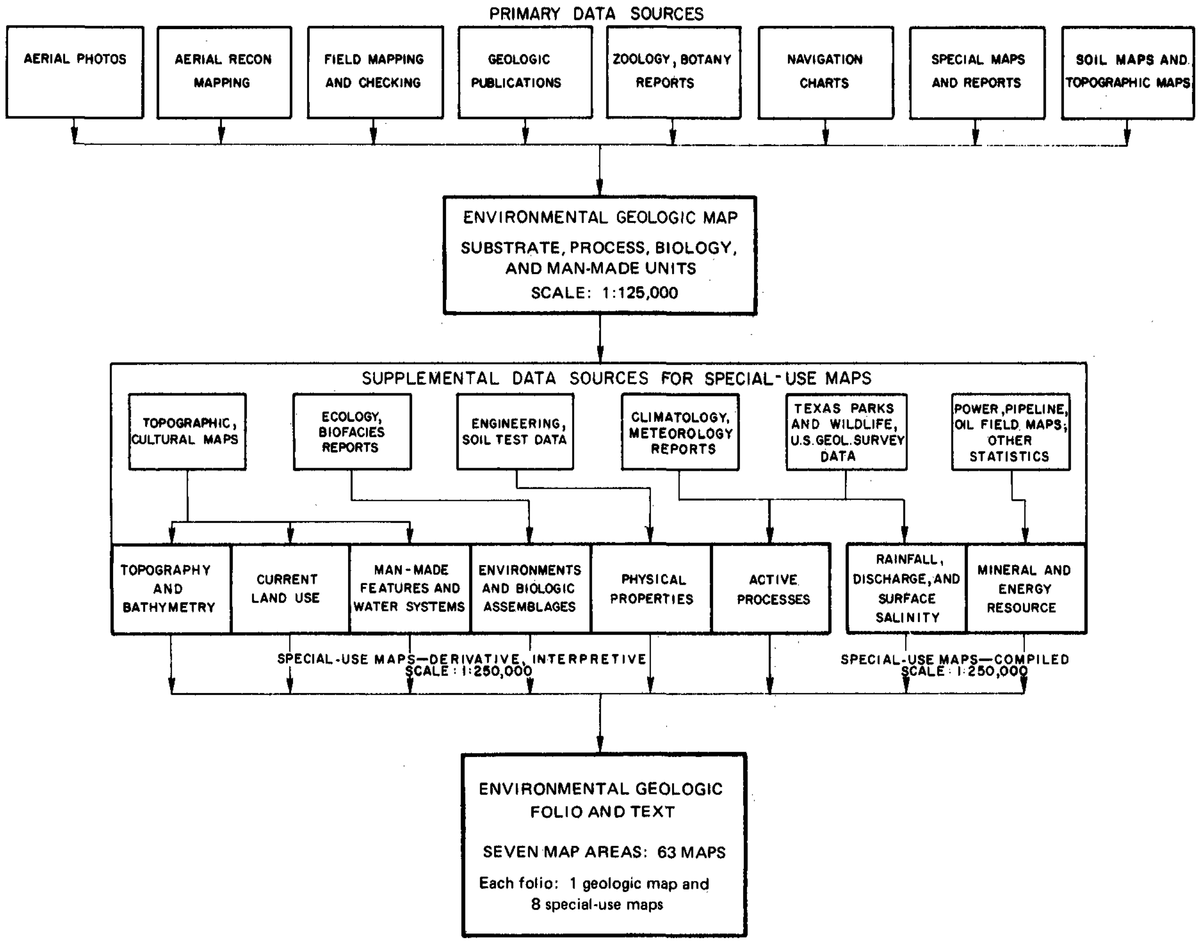

Figure 2. Sources and flow of data for the Environmental Geologic Atlas of the Texas Coastal Zone. After Fisher and others, 1972.

present) during interglacial periods of the *Pleistocene* ice age; (2) natural systems termed *Holocene* that originated between approximately 18,000 and 4,500 years B.P.; and (3) natural systems herein termed *Modern* that have been developing since about 4,500 years B.P. and are currently active.

Modern coastal systems are characterized by a distinctive suite of natural environments in which certain geologic processes result in deposition of unique sedimentary deposits. These deposits are similar in every respect to older sedimentary deposits of Pleistocene or Holocene age and, therefore, can be interpreted to have originated within genetically similar but ancient environments. For example, Modern river or fluvial systems are composed of levee, point bar, and flood-basin environments, in which certain types of sediment are deposited by specific geologic processes. Similarly, point bar, levee, and flood-basin deposits of Pleistocene or Holocene age can be interpreted as having been deposited in similar environments within an ancient river system.

A knowledge of processes that are active within Modern environments is critical if the environmental impact of various types of human activity is to be evaluated. Stated simply, natural environments must be properly understood if they are to be managed and protected. Just as important environmentally, but perhaps less obvious to most citizens, is an understanding of the ancient sedimentary substrates underlying the Coastal Zone. These relict deposits of ancient systems of coastal environments determine to a great extent the suitability of coastal lands for various uses and human activities. Similarly, the sedimentary

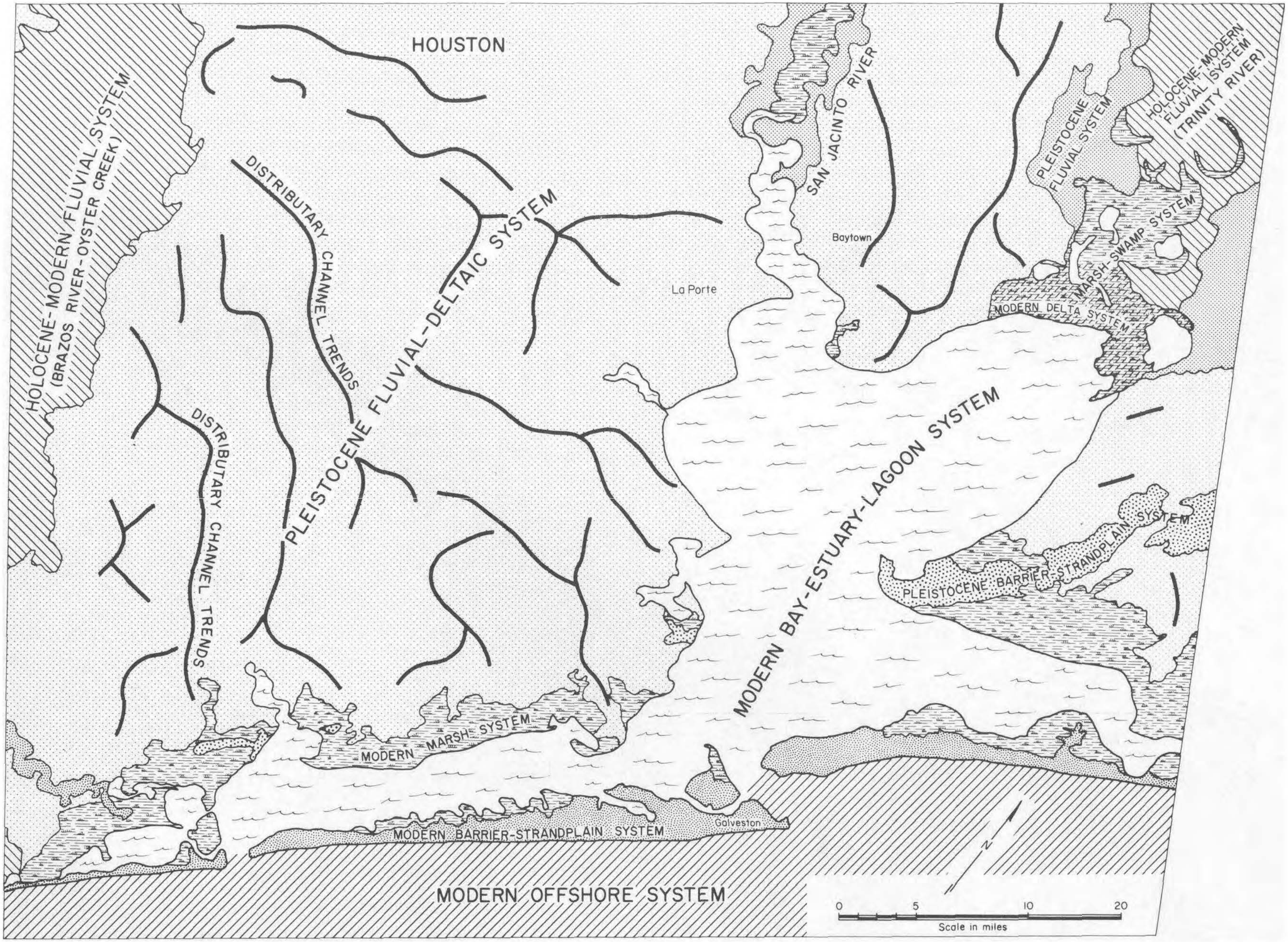

Figure 3. Natural systems defined by environmental mapping in the Galveston-Houston area. These systems are composed of genetically related environments, sedimentary substrates, biologic assemblages, areas of significant physical processes, and man-made features. Simplified from the Environmental Geology Map of the Atlas. After Fisher and others, 1972.

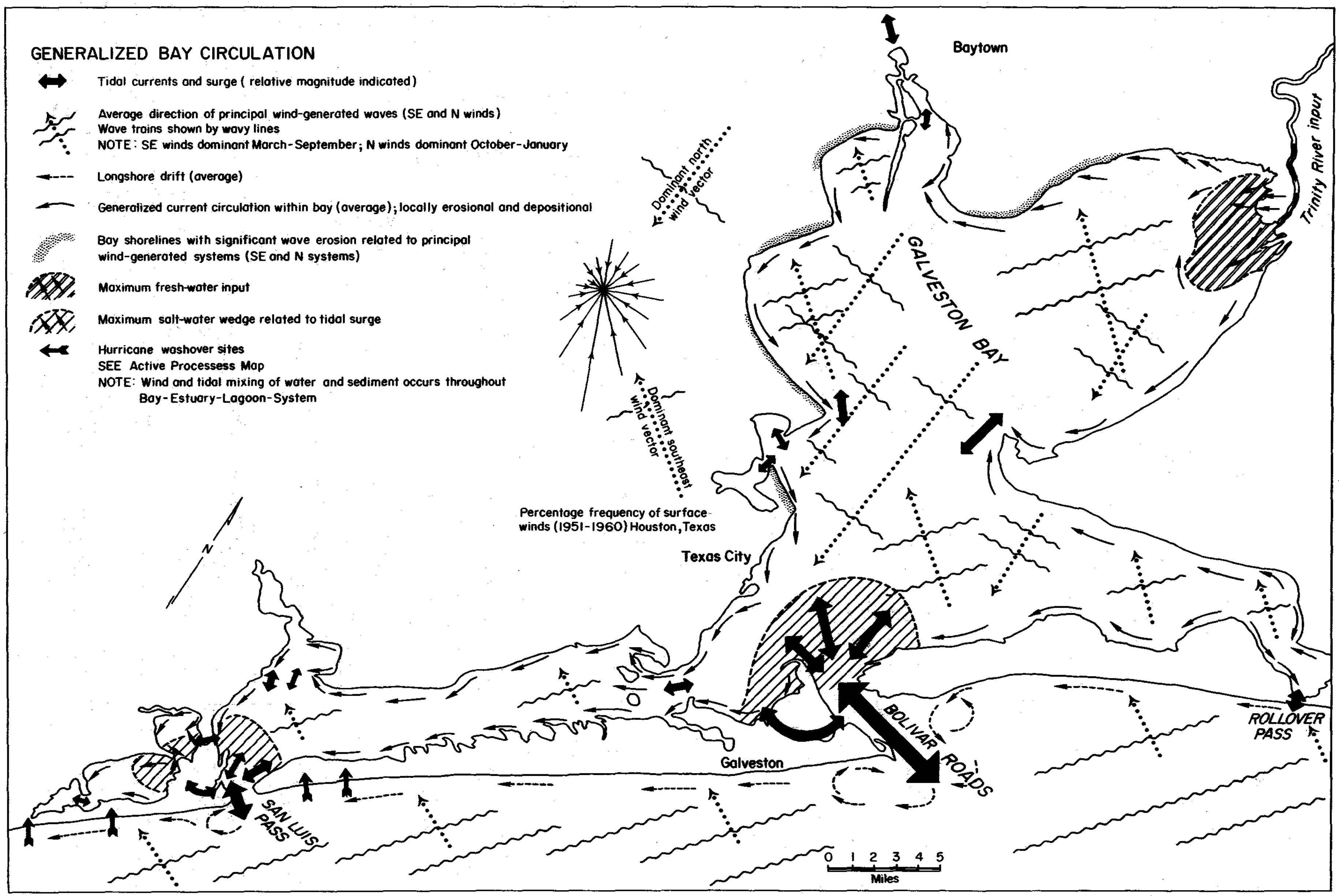

Figure 4. Circulation, waves, sediment transport, and other physical processes, bay-estuary-lagoon system, Galveston-Houston area. After Fisher and others, 1972.

deposits of these older Pleistocene and Holocene systems dictate the nature of soils, wildlife, vegetation, ground water, natural resources, and all manner of aspects that are important to the environmental quality of the region. For these reasons, it is critical that the nature of the environments, processes, and sediment substrates for all *active* coastal systems and all relict sedimentary substrates for all *ancient* coastal systems be determined and mapped so that a scientific basis for environmental management can be developed.

A principal goal of the Environmental Geologic Atlas of the Texas Coastal Zone is to present the nature of active environments and relict sedimentary deposits. An appreciation of the geologic history of this dynamic region will enable the reader to envision the sequence of geologic events that has created and shaped the present Texas Coastal Zone. The geography of the region has evolved slowly through time as climate, sea level, and other environmental factors have changed. The present Coastal Zone is, therefore, but one frame in a kaleidoscope of changing rivers, shifting beaches, and subsiding plains. Past geologic events and current geologic processes join in characterizing the nature of the *total* coastal environment, as well as to point inevitably to future changes that man must learn to understand, predict, and manage. In short, the Coastal Zone is characterized by natural change; man's activities may significantly affect the rate and direction of these changes.

CLIMATE AND DYNAMIC COASTAL PROCESSES

The climate of the Texas Coastal Zone strongly dictates the relative importance of many significant geological processes. A principal factor is the direction and intensity of persistent winds that control the orientation and size of wave trains approaching the shoreline (fig. 4). In turn, the angle at which waves strike the coast affects the nature of longshore drift. The direction of wind-driven currents and waves in relationship to the orientation of tidal passes may increase or diminish the magnitude of astronomical tides that coincide with the wind activity. The amount of open-bay fetch and the direction of wind-driven tides within a bay also control the effectiveness of wind-tidal activity; for example, broad fetch and persistent wind aligned with the axis of a narrow, funnel-shaped bay result in high wind tides. The angle at which hurricanes strike the coast, likewise, affects the magnitude of floodtides, especially in narrow upper bay areas. The duration and intensity of winds control the nature and direction of bay currents that erode, transport, and deposit sand and mud. Bay shorelines strongly reflect the depositional or erosional character of currents, just as longshore drift smooths the seaward side of strandplains and barrier islands.

Just as important as wind in controlling coastal processes is the combined and interrelated effect of rainfall, evaporation, and temperature. Effective precipitation controls the nature and density of coastal plants, which are critical in a climatic regime where wind is a primary factor. Plants stabilize coastal sands that, if unvegetated, will be deflated and transported as eolian or wind dunes. The density of vegetation is especially critical in stabilizing and shielding coastal barriers and shorelines against hurricane impact. Effective rainfall and associated plant cover also stabilize inland soils.

ENVIRONMENTAL GEOLOGY MAP

Environmental geology units for the entire Coastal Zone (fig. 1) were interpreted from and plotted on three hundred and twenty 7.5-minute Edgar Tobin Aerial Surveys photomosaics and corresponding U. S. Geological Survey topographic maps, both at a scale of 1:24,000, or approximately 2.5 inches per mile. All environmental maps are printed on a regional base map of the Coastal Zone constructed especially for the Atlas by the Bureau of Economic Geology. The base map was compiled from 7.5-minute U. S. Geological Survey quadrangle maps; 5-foot topographic contours, available bathymetric contours, updated culture, and all paved roads are included.

Mapping involved extensive aerial photographic interpretation, field work, aerial reconnaissance, and utilization of available published data for the region. General sources and flow of data used in mapping are shown in figure 2; specific sources of data are noted in the text. Interpretation and mapping of environmental geologic units were based on a genetic grouping of the major natural and man-made features of the Coastal Zone. Units mapped were interpreted to be of first-order importance to the environmental character of the Zone. First-order environmental units include the following: (1) a wide variety of sedimentary substrates (sand, mud, shell) and associated soil units displaying distinct properties and composition; (2) units displaying a variety of natural processes, including storm channels, tidal passes,

Table 1. Environmental geology map units, Texas Coastal Zone.

HOLOCENE-MODERN SYSTEMS

Fluvial-Deltaic Systems

Meanderbelt sand, tree-covered, inactive, entrenched stream
Meanderbelt sand, prominent grain, inactive, non-entrenched stream
Fluvial sand and flood-basin mud, undifferentiated, inactive, non-entrenched stream
Meanderbelt sand and silt, sparsely grass- and shrub-covered, inactive within an entrenched stream
Interdistributary silt and mud, locally includes bay, lacustrine and crevasse splay
Flood basin, overbank mud and abandoned channel, mud-filled, inactive, within entrenched stream
Levee deposits, fresh-water, marsh-covered
Levee and crevasse splay deposits, silt, sand and mud, grass-covered
Levee and crevasse splay deposits, silt, sand and mud, tree-covered
Delta-plain mud and sand, sparsely grass-covered
Delta-plain mud and sand, grass-covered
*Delta front and channel-mouth bar sand shoal (active and abandoned)
*Prodelta mud and silt
Point bar, sand, tree-covered, along active streams
Point bar, sand, bare or sparsely vegetative, along active streams
*Abandoned channel and course, mud-filled
*Abandoned channel and course, swamp-covered, mud-filled
*Abandoned channel and course, fresh-water, marsh-covered, mud-filled
*Marsh, salt-water, mud and locally sand substrate
*Marsh, fresh- to brackish-water, mud and locally sand substrate
*Marsh, fresh-water, mud and locally sand substrate
*Swamp, mud and locally sand substrate
*Tidal creek, fresh- to brackish-water, marsh-covered, mud-filled
*Tidal creek, mud-filled
*Wind-tidal flat, sand and mud, transitional between bay and stream
Small active, headward-eroding stream, tree-covered to barren
*Berm and beach ridge, abandoned, sand and shell
*Fan and fan delta, sand, subaerial

Barrier-Strandplain-Chenier and Offshore Systems

Shelf mud and sand, mottled
Shoreface, mud, burrowed
Shoreface, sand and muddy sand, burrowed
Coastal mudflat, subject to tidal inundation
Beach, sand and shell
Barrier flat, sand and shell, very sparse grass
Beach ridge and barrier or strandplain flat, grass-covered, sand and shell
Sandflats and/or coppice sand-dune fields, active
Fore-island blowout dunes and back-island dunes, sand, active
Fore-island dune ridge, sand
Chenier beach ridge, sand, grass-covered
Chenier flat, sand and shell, grass-covered
Strandplain-barrier oak motte
Stabilized blowout dune complex, sand, grass-covered, hummocky
Washover channel, sand-filled, inactive
Washover channel, sand, active
Washover fan, sand, subaerial, vegetated
Washover fan, distal, sand, subaerial, barren, active
Ebb-tidal delta, mud and sand, subaqueous
Ebb-tidal delta, sand, subaqueous, proximal to channel
Ebb-tidal delta, mud and sand, subaqueous, distal to channel
Flood-tidal delta, mud, subaqueous
Flood-tidal delta, mud and sand, subaqueous, distal to channel
Flood-tidal delta, sand, subaqueous, proximal to channel
*Tidal channel, mud and some sand, active
Tidal channel, sand, active
Tidal channel, mud- and sand-filled, inactive
Inlet-related shoal, sand, accretionary in passes
Wind-tidal flat, subaerial, burrowed
Tidal flat, sand
*Swale between beach ridges, mud-filled
*Swale between beach ridges, fresh- to brackish-water, marsh-covered, mud-filled
*Marsh, salt-water, mud and locally sand substrate
Back-island sandflats with small migrating dunes, unvegetated
Wind-deflation trough and storm runnel on barrier flat, sand

Marsh-Swamp System

*Marsh, salt-water, mud and locally sand substrate
*Marsh, brackish-water, closed system, mud and locally sand substrate
*Marsh, fresh- to brackish-water, mud and locally sand substrate
*Coastal lake or pond, partially or completely mud-filled
*Marsh, fresh-water, and poorly drained depressions, mud and locally sand substrate
*Swamp, mud and locally sand substrate

Bay-Estuary-Lagoon System

*Fan and fan delta, sand, subaerial, along bay margin
*Berm or beach ridge, abandoned, sand and shell (P/M)
Bay- or lagoon-margin sand, locally with mud and shell, subaqueous
Bay- or lagoon-margin sand and mud; shell berms, beaches and spits, active, subaerial
Bay-margin oolites and quartz sand
Bay-margin quartz sand and calcite-coated grains
Sand shoal with some oolites
Bay and bay-margin sandy mud, mottled, some shell
Grassflat, muddy sand with shell
Bay sand with mixed shell
Bay and lagoon mud, mottled, some mixed shell
Bay sand with oyster shell
Bay mud with oyster shell
Bay sand
Bay mud and silt
Bay and lagoon sand, muddy
Bay mud, laminated, rare shell
Bay sand and muddy sand, locally with oyster shell
*Prodelta mud and silt
*Delta front and channel-mouth bar sand shoal (abandoned and active)
Oyster reef
Oyster reef flank, sand or mud, abundant shell
Interreef mud with oyster shell
Serpulid reefs and related shell-rich sand and beach rock
Wind-tidal flat, sand, loose, rarely flooded
*Wind-tidal flat, sand and mud, extensive algal mats, alternately emergent-submergent
Wind-tidal flat, mud and sand, algal-bound mud, gypsiferous, firm
Wind-tidal flat, mud and sand, algal mats, depressed relief, wet and soft

Wind-tidal flat, sand and mud, barren to sparsely vegetated, subaerial
Marginal residual sand apron on windward side of rincons and potreros, wind-deflation lag deposit
Eolian accretionary bars and ridges, sand and clay, on wind-tidal flats
Transitional zone, wind-tidal flat to eolian sand sheet, wind deflation

Eolian System

Active dune complex, sand, commonly banner dunes with small barchans
Active dune blowout areas, sand, local depressed relief, eolian grain prominent
Sand sheet with strong relict grain of base-leveled dunes
Sand and loess (silt) sheet with no relict grain
Moderately stabilized dunes, sand and loess (silt) sheet, brush-covered
Well-stabilized dune sands, live oak-covered
Sand and loess (silt) sheet deflation area, active
*Clay-sand dunes, accretionary, active
*Clay-sand dune complexes, inactive (H/M)
*Loess sheet, thin, silty, overlies calichified Pleistocene fluvial sand (H/M)
*Loess sheet, thin, discontinuous, silty, overlies Pleistocene deltaic mud and calichified sand (H/M)

~~Other Map Units~~

Point bar (fluvial) accretion grain
Beach ridge (barrier-strandplain-chenier) accretion grain
Spoil heap or mound, subaerial
Reworked spoil, subaerial
Spoil, subaqueous
Made land
Barchan dune orientation in banner dune complex
Longitudinal dune orientation in back-island dune field
Beach ridges, accretionary, relict (barrier-strandplain)
Wind accretion ridges, rincons and potreros
Serpulid reefs

~~Fluvial-Deltaic Systems~~

Meanderbelt sand
Flood-plain mud
Flood-plain mud veneer over meanderbelt sand
Distributary sand and silt
Interdistributary mud
Interdistributary mud with sand veneer
Delta-front mud and sand, veneered by thin mud
Delta-front mud and sand
*Abandoned channel and course, mud-filled (P/M)
*Abandoned channel and course, swamp-covered (M)
*Abandoned channel and course, fresh-water, marsh-covered (P/M)
*Tidal creek, fresh- to brackish-water, marsh-covered (M)
*Tidal creek, unvegetated, mud-filled (M)
*Tidal creek, fresh-water, marsh-covered (M)
*Tidal creek, grass-covered, mud-filled (P/M)
*Marsh, fresh-water, and poorly drained depressions, mud and sand
*Upland oak motte
*Loess sheet, thin, overlies Pleistocene fluvial sand (M)
*Loess sheet, thin, discontinuous, overlies Pleistocene mud and sand (M)
Circular to irregular depressions on distributary/fluvial sand (P/M)
*Clay-sand dunes, active (M)
*Clay-sand dunes, inactive (H/M)
Lakes and ponds, coastal, mud and sandy mud-filled (P/M)
*Beach ridge and berm, margin of lakes, shell (P/M)
*Swale between beach ridges, margin of inland lakes, mud-filled (P/M)

~~Barrier-Strandplain Systems~~

Barrier-strandplain sand, tree-covered
Barrier-strandplain sand, grass-covered
Live oak-covered beach ridge, relict
Swale between beach ridges, unvegetated, mud-filled (P/M)
Swale between beach ridges, grass-covered, mud-filled (P/M)
Sheet sand, locally mud-veneered, back side of Pleistocene strandplain
Well-stabilized dune sand, dense live oak mottes (M)
*Marsh, fresh-water and poorly drained swales, mud- and sand-filled (M)

* Unit may occur within more than one system
M Modern
P/M Pleistocene to Modern
H/M Holocene and Modern

tidal flats, fluvial channels, wind erosion, and other dynamic properties of significance in maintaining and modifying the coastal environments; (3) biologic features such as reefs, marshes and swamps, subaqueous grassflats, and plant-stabilized sediment where biologic activity is of principal importance; and (4) man-made features such as spoil heaps, spoil wash, dredged channels, and made land where man's activities have resulted in significant environmental modification. Approximately 125 specific environmental geologic units are recognized and mapped in the Texas Coastal Zone.

Environmental geology map units are grouped into higher order natural systems (fig. 3). Systems such as fluvial-deltaic, barrier island, and bay-estuary-lagoon, for example, include a variety of natural substrate, biologic, or process units and environments that are genetically interrelated as to origin and distribution within the Coastal Zone. Man-made features are separately grouped to differentiate clearly natural and artificial features. The origin of the various natural units in the Coastal Zone determines their main features, composition, and character; hence, their origin is basic to consideration of resource evaluation and use. Natural systems delineated (table 1) include (1) fluvial-deltaic, a series of relict Pleistocene substrates (fig. 5) and Modern environments and substrates formed both by older and present-day

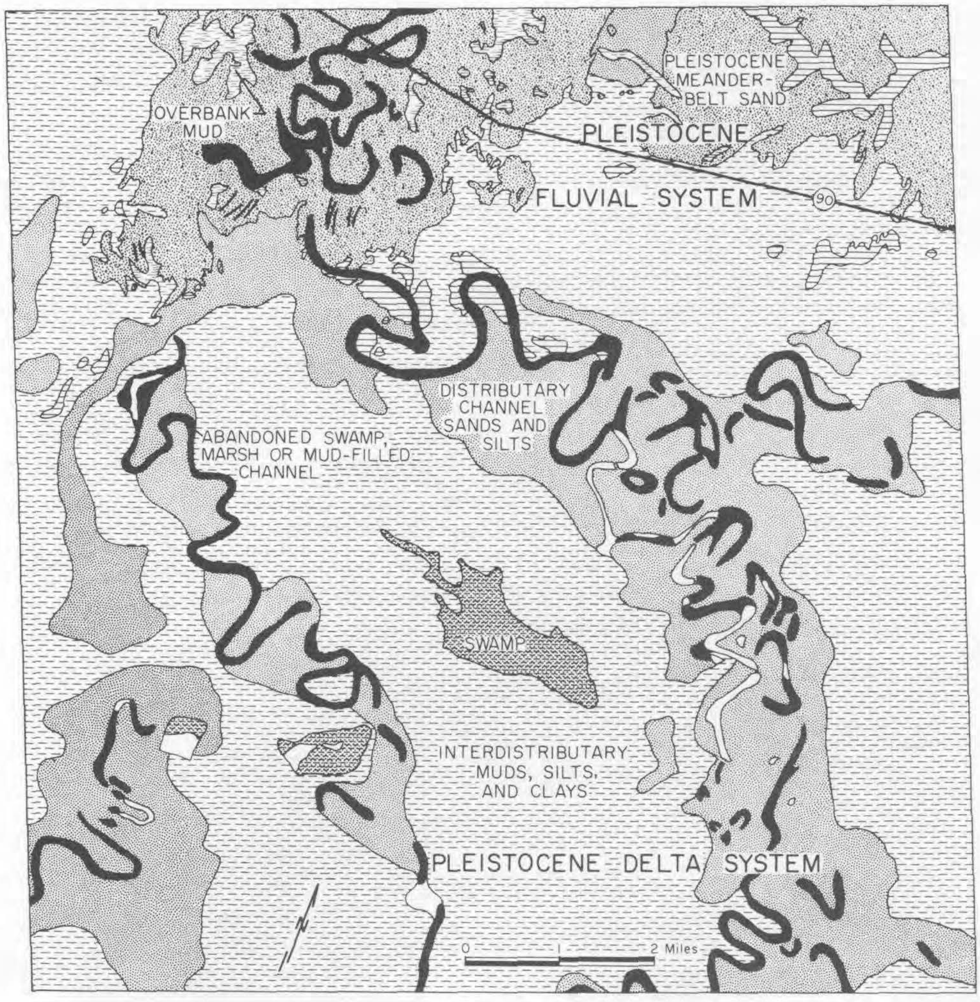

Figure 5. Pleistocene fluvial-deltaic facies, coastal uplands in vicinity of Devers, Beaumont-Port Arthur area. Meanderbelt sands appear to grade coastward into elongate belts of sand and silt that were deposited principally during delta building. After Fisher and others, 1973.

rivers and deltas (fig. 6); (2) barrier-strandplain-chenier, a suite of relict Pleistocene substrates (fig. 7) and Modern environments and substrates formed at the interface of the land and Gulf (figs. 8, 9); (3) marsh-swamp, including a variety of Modern, permanently wet, grassed and wooded lands of the low-lying coastal areas (figs. 6–10); (4) offshore, embracing various units of the Modern barrier island shoreface and inner continental shelf developed seaward of Gulf beaches (figs. 8, 9); (5) bay-estuary-lagoon, consisting of Modern subaqueous or submerged environments formed between the mainland and the barrier islands (fig. 11); (6) eolian, consisting of a variety of wind-dominated facies which occur primarily in the coastal bend region south of Corpus Christi (fig. 12); and (7) man-made features such as spoil and made land (fig. 10).

Environmental geology maps are presented at a scale of 1:125,000, or 2 miles per inch. Compilation work maps (1:24,000) are maintained on open file at the Bureau of Economic Geology. The currency of aerial photographs, topographic maps, and navigational charts used in the project can be determined by reference to index maps, which provide specific information on the date of photography and map or chart revision. Edgar Tobin Aerial Surveys photomosaics provided uniform coverage of the entire Coastal Zone.

Remapping in future decades with updated aerial photography and other multispectral remote sensing devices carried by aircraft and satellites will provide a valuable historical reference to rates and degree of both natural and man-made changes in the Coastal Zone. The Atlas is, therefore, an open-ended document which can be updated to maintain a current record of the change and modification of the region. It is also anticipated that the Atlas will serve to stimulate interest in and provide the environmental base line for many more specialized and localized studies addressed to specific pollution, land use, ecology, economic, and resource problems.

SPECIAL-USE ENVIRONMENTAL MAPS

Following preparation of the Environmental Geology Map for each of the seven areas of the Coastal Zone, a series of Special-Use Environmental Maps was prepared to present more specific information for a variety of potential users. The series of eight maps is designed for direct and specific use in the evaluation and proper utilization of the natural resources and environments of the area. They were constructed through (1) interpretation and derivation of units mapped for the Environmental Geology Map, (2) compilation of data from diverse sources projected onto the environmental base map, and (3) a combination of both derived and compiled data (fig. 2). Selection of the kinds of special-use environmental maps was based on a survey of the greatest need and potential use by both professional and lay people concerned with proper resource use and environmental management (table 2).

The series is composed of the following maps: (1) Physical Properties; (2) Environments and Biologic Assemblages; (3) Current Land Use; (4) Mineral and Energy Resources; (5) Active Processes; (6) Man-Made Features and Water Systems; (7) Rainfall, Stream Discharge, and Surface Salinity; and (8) Topography and Bathymetry. They comprise only a basic series of maps; a variety of other specific-use maps may be prepared by overlaying or combining any of the environmental map units (table 1). For example, the pipeline network of an area can be compared directly with the distribution of active and potentially active surface faults to identify those areas where faulting might result in damage to or rupture of the pipeline. Likewise, current land use can be compared to areas of hurricane flooding to determine kinds and amounts of land use affected. Map units can be grouped according to physical properties (Physical Properties Map) and then evaluated in terms of various land uses (table 3). Statistical analyses of all units and features included on the Environmental Geology Map and the various Special-Use Environmental Maps are summarized in tables.

Physical Properties Map

The special-use map delineating physical properties is designed to provide regional data for a variety of physical uses applicable both to land surface and to approximately 60 feet below the surface. Specific types of uses and activities that can be evaluated from these data are primarily those involving construction, excavation, drilling, channelization, and waste disposal. Table 3 includes an evaluation of the degree of suitability of each physical properties group for potential engineering uses.

The many geologic, biologic, active process, and man-made map units of the basic Environmental Geology Map are graded and organized into major

Table 2. Special-use environmental map units, Texas Coastal Zone.

PHYSICAL PROPERTIES MAP

Group I. Dominantly clay and mud
Group II. Dominantly sand
Group III. Dominantly clayey sand and silt
Group IV. Coastal and estuarine marshes, fresh to brackish
Group V. Inland swamp and fresh-water marsh
Group VI. Tidal flat and salt marsh
Group VII. Made land and spoil
Group VIII. Transitional wind-tidal flat and eolian sand sheet
Group IX. Clay-sand dunes and dune complexes
Group X. Eolian sand sheet
Group XI. Active sand dunes and dune complexes
Group XII. Loess sheet, silt and fine sand
Pit or quarry
Sludge pit or miscellaneous waste-disposal pit
Sewage-disposal site
Solid waste-disposal site
Salt dome, shallow piercement
Active or potentially active fault

CURRENT LAND USE MAP

Agriculture, cultivated land and orchards
Range-pasture
Woodland-timber
Swamp-timber
Live oak mottes
Fresh-water marsh
Saline- and brackish-water marsh
Residential-urban
Industrial, refineries, rail yards
Park and recreational facility, formally defined public facility
General recreational land, public beaches
Wildlife refuge, formally defined, government operated
Government land, federal and state, excluding recreational
Transitional area between wind-tidal flat and eolian sand sheet
Undifferentiated urban land, greenbelts
Made land
Spoil
Barren land
Oil and gas field
Education site
Pit or quarry
Solid waste-disposal site
Pipeline
Offshore petroleum production platform
Airfield
Salt dome
Sulfur production site
Brine production site
Liquid petroleum gas storage
Sludge pit
Sewage-disposal site
Artificial reservoir

ACTIVE PROCESSES MAP

Lower shoreface and shelf
Normal surf and breaker zone
Site of active or potentially active hurricane washover
Shoreline, erosional
Shoreline, depositional
Shoreline in erosional-depositional equilibrium
Shoreline, artificially stabilized
Area of slow to moderate bay deposition
Area of rapid deposition within bay
Area of active reworking and redistribution of spoil
Area of shoaling, moderate to high wave energy
Area of moderate erosion to slight deposition, tidal channel
Area of wind-tidal flooding
Area of intensive wind deflation
Eolian sand dunes, active
Oyster reef deposition
Inland lake, area of wave erosion and beach-ridge accretion
Area inundated by marine water. Hurricane Carla
Area inundated by marine water, Hurricane Beulah
Area inundated by river flooding and rainfall runoff, Hurricane Beulah
Hurricane Carla recording tide or river gage
Hurricane Carla recording site, still high water mark
Hurricane Carla storm surge and river flooding, debris or driftline
Hurricane Beulah recording tide or river gage
Hurricane Beulah storm surge and river flooding, debris or driftline
Hurricane Beulah recording site, still high water mark

MINERAL AND ENERGY RESOURCES MAP

Sand, includes all subaerial sandy deposits
Mud, includes all subaerial muddy deposits
Oyster reef
Oyster shell, dredged from bottom of bay
Serpulid worm reefs
Pit or quarry
Oil or gas field
Salt dome
Sulfur production site
Liquid petroleum gas storage site
Brine production site
Salt dome oil field
Cement plant
Lime plant
Aluminum plant
Petrochemical plant
Power generation plant
Utility line or cable
Pipeline
Offshore petroleum production platform

ENVIRONMENTS AND BIOLOGIC ASSEMBLAGES MAP

Subaqueous Environments and Assemblages

Shelf, open marine
Lower shoreface
Upper shoreface, surf zone
Shoreface adjacent to tidal delta
Inlet and tidal delta
Bay margin, shoal water
Bay and lagoon margin, seasonally hypersaline
Grassflats, shallow bay margin, dense grass
Grassflats, hypersaline, sparse to moderate grass
Subaqueous sandflats
Open bay, lower end with tidal influence
Open bay with reefs
Enclosed bay with reef
Enclosed bay away from tidal or river influence
Enclosed hypersaline bay or lagoon center
Restricted hypersaline bay and lagoon margin
Restricted bay center, hypersaline
River influenced bay, low salinity
Sand and oolite shoal
Reef, dense oysters
Reef flank and margin, oysters
Serpulid reef (relict) and interreef shoals
Subaqueous spoil
Fresh- to saline-water bodies

Subaerial Environments and Assemblages

Beach, swash zone
Vegetated barrier flat, foredune ridge, blowouts
Unvegetated coastal mudflats
Vegetated strandplain flat, foredune ridge, and beach ridge
Washover channel, fan, and wind-deflation trough and storm runnels
Active dunes, coppice dunes, blowouts
Sandflats, wind-tidal
Eolian ridges and active clay-sand dunes
Salt-water marsh
Brackish-water marsh
Brackish- to fresh-water marsh
Swamp
Inland fresh-water marsh
Frequently flooded fluvial areas
Berms along bay-lagoon margin
Intense wind-deflation and wind-tidal activity
Prairie grasslands
Poorly drained depressions, mud substrate
Poorly drained depressions, sand substrate
Loose sand and loess prairies
Live oak mottes and groves
Brushland
Made land
Grass and locally scrub oak-covered ridges
Mixed pine and hardwood forest
Small prairies in forested uplands
Fluvial grassland
Barren land

RAINFALL, STREAM DISCHARGE AND SURFACE SALINITY MAP

Calculated average surface salinity
Extreme low surface salinity
Extreme high surface salinity
Salinity measurement station, data for graphs
Salinity measurement station, data for contouring
Rainfall recording station
Discharge measurement station

MAN-MADE FEATURES AND WATER SYSTEMS

Man-Made Features

Urban and residential areas
Industrial areas
Made land
Subaerial spoil
Subaqueous spoil
Jetty or pier
Pipeline
Offshore production platform
Airfield
Solid waste-disposal site
Sewage-disposal site
Seawall
Sludge pit
Undifferentiated urban land

Water Systems

Open ocean
Tidal inlet and pass
Lagoon, bay and estuary
Transportation canal and channel
Tidal-affected stream
River or stream
Slough or abandoned course and cutoff
Lake or pond (perennial)
Lake, pond, or playa (ephemeral)
Drainage or irrigation ditch and canal
Artificial reservoir
Wind-tidal flats

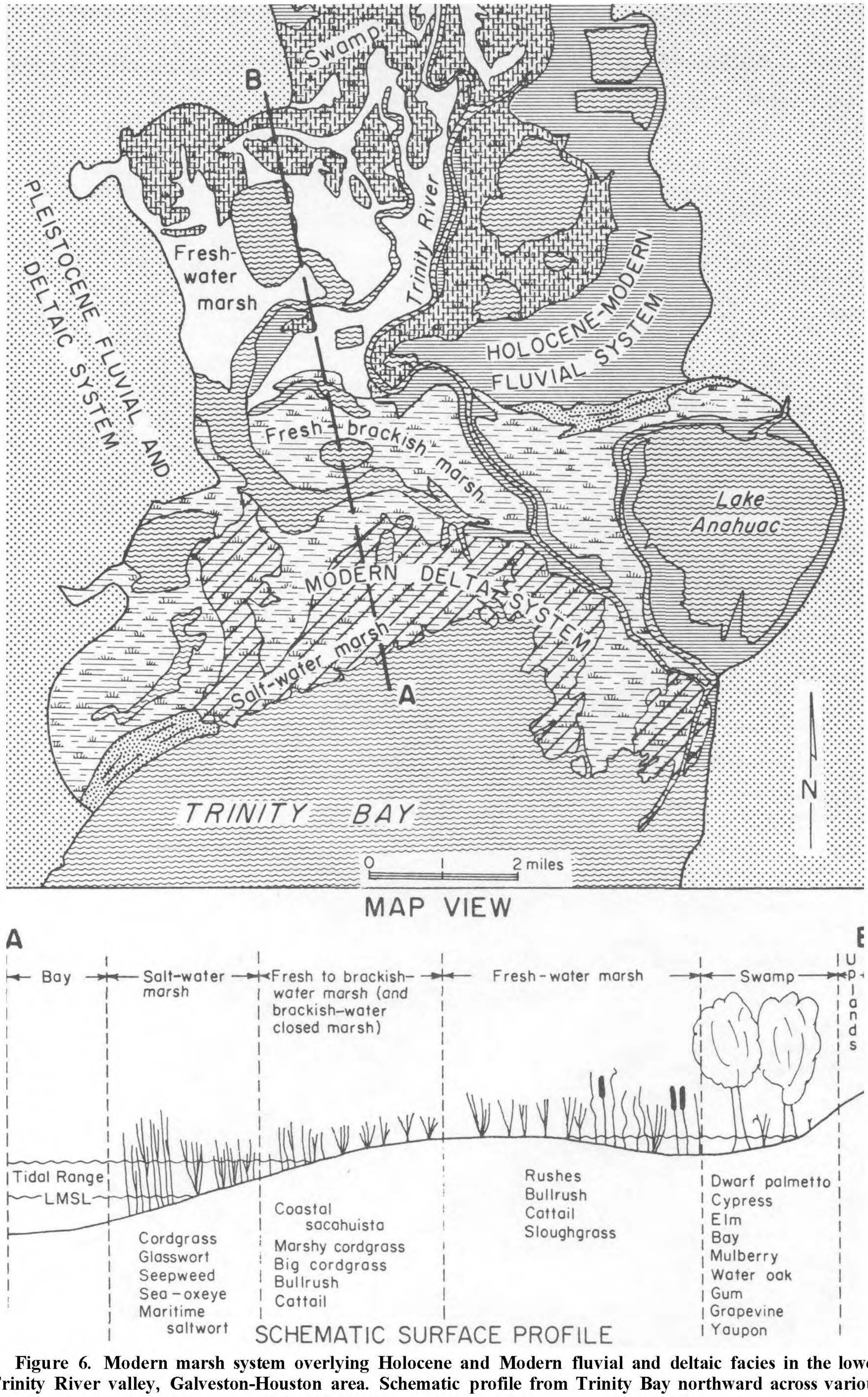

Figure 6. Modern marsh system overlying Holocene and Modern fluvial and deltaic facies in the lower Trinity River valley, Galveston-Houston area. Schematic profile from Trinity Bay northward across various marsh and swamp environments of the Wallisville area. After Fisher and others, 1972.

groups (table 2); each group is composed of units having common physical features and properties. Principal physical properties groups and land areas outlined on the Physical Properties Map include (1) areas of dominantly clay and mud soils and substrates, (2) areas of dominantly sand soils and substrates, (3) areas with soils and substrates consisting primarily of clayey sands and silts, (4) fresh- to brackish-water coastal marshes, (5) inland fresh-water marshes and wooded swamps, (6) tidal flats and salt marshes with frequent tidal inundation, and (7) made land and spoil. Additional physical properties groups occur in the eolian-dominated areas of South Texas (Kingsville, Brownsville-Harlingen, and Corpus Christi areas).

All these units have been derived from basic map units on the Environmental Geology Map by applying quantitative test data to the areally defined and mapped environmental geologic units (fig. 2). Land units are characterized in a qualitative manner only; available test data are too limited and too local in distribution to ascribe precise quantitative parameters to the various units throughout the entire area. Data presented on the Physical Properties Map of the Atlas should not be substituted for specific site testing and evaluation, but they can be used to grade large tracts of land for a particular suitability.

In addition to the major physical land types shown, principal zones of active or potentially active surface faults are defined. Current waste-disposal sites, pits and quarries, and sludge pits are also plotted.

Environments and Biologic Assemblages Map

The Environments and Biologic Assemblages Map depicts the distribution of major biologic

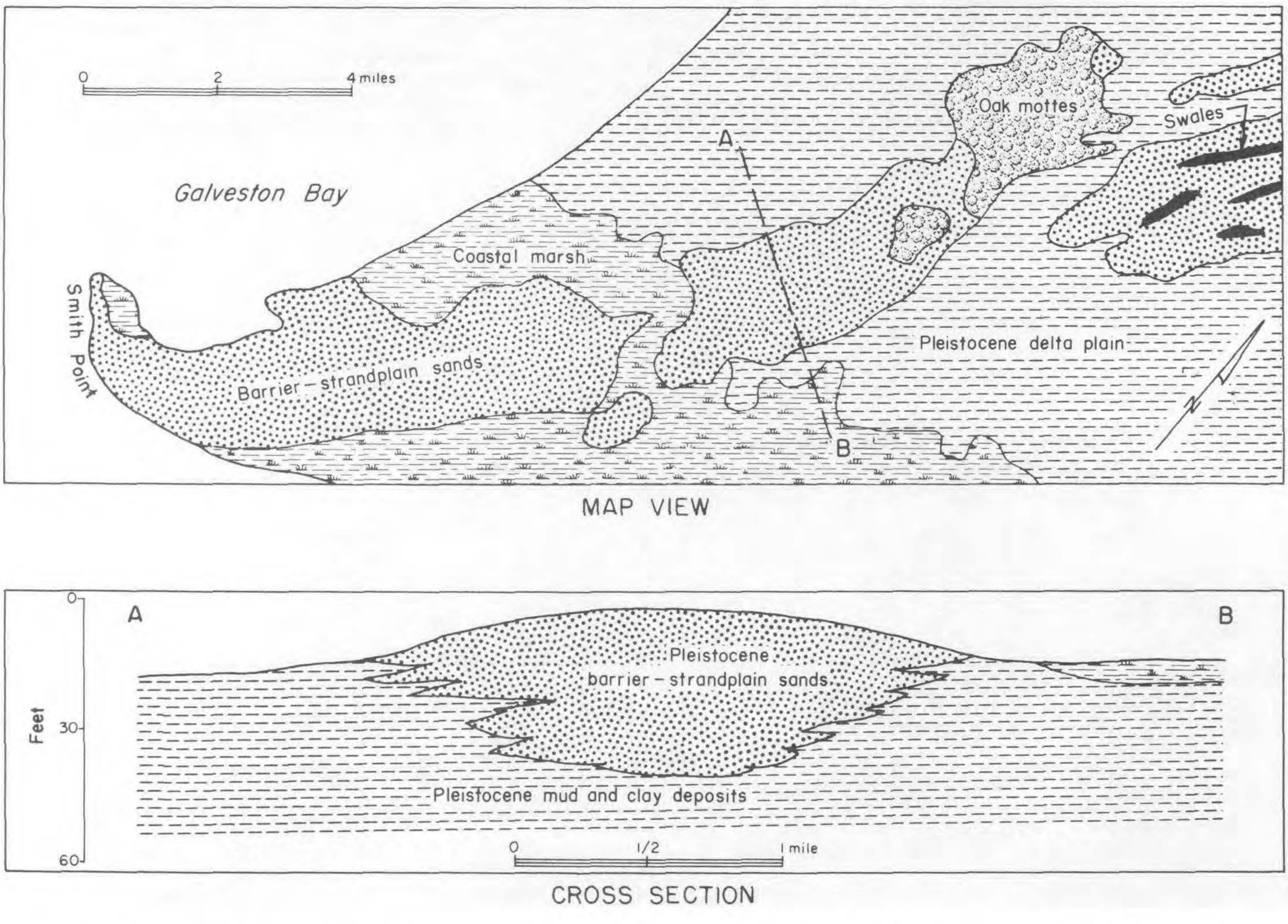

Figure 7. Pleistocene barrier-strandplain sands, Smith Point area, Chambers County, Texas. After Fisher and others, 1973.

communities and the environments they inhabit. These include (1) subaqueous environments and assemblages of the bays, estuaries, tidal passes, shoreface, and open shelf, defined primarily by assemblages of fixed or mobile benthonic (bottom-dwelling) organisms, which are chiefly faunal; and (2) subaerial environments and assemblages, defined primarily by land vegetation. A number of the biologic assemblages are of first-order environmental significance and, accordingly, appear as specific map units on the basic Environmental Geology Map. These include such units as reefs, the various wetland environments, and most of the Modern grass-covered barrier-island and associated units. Other natural environments have been derived from the basic Environmental Geology Map by utilizing previously known and compiled information on animal and plant distribution in the Texas Coastal Zone (fig. 2). Several environmental geologic units are occupied by single biologic assemblages. For example, the Pleistocene delta distributary channel sands and interdistributary muds originally supported extensive coastal prairie grasslands, but much of this assemblage and natural

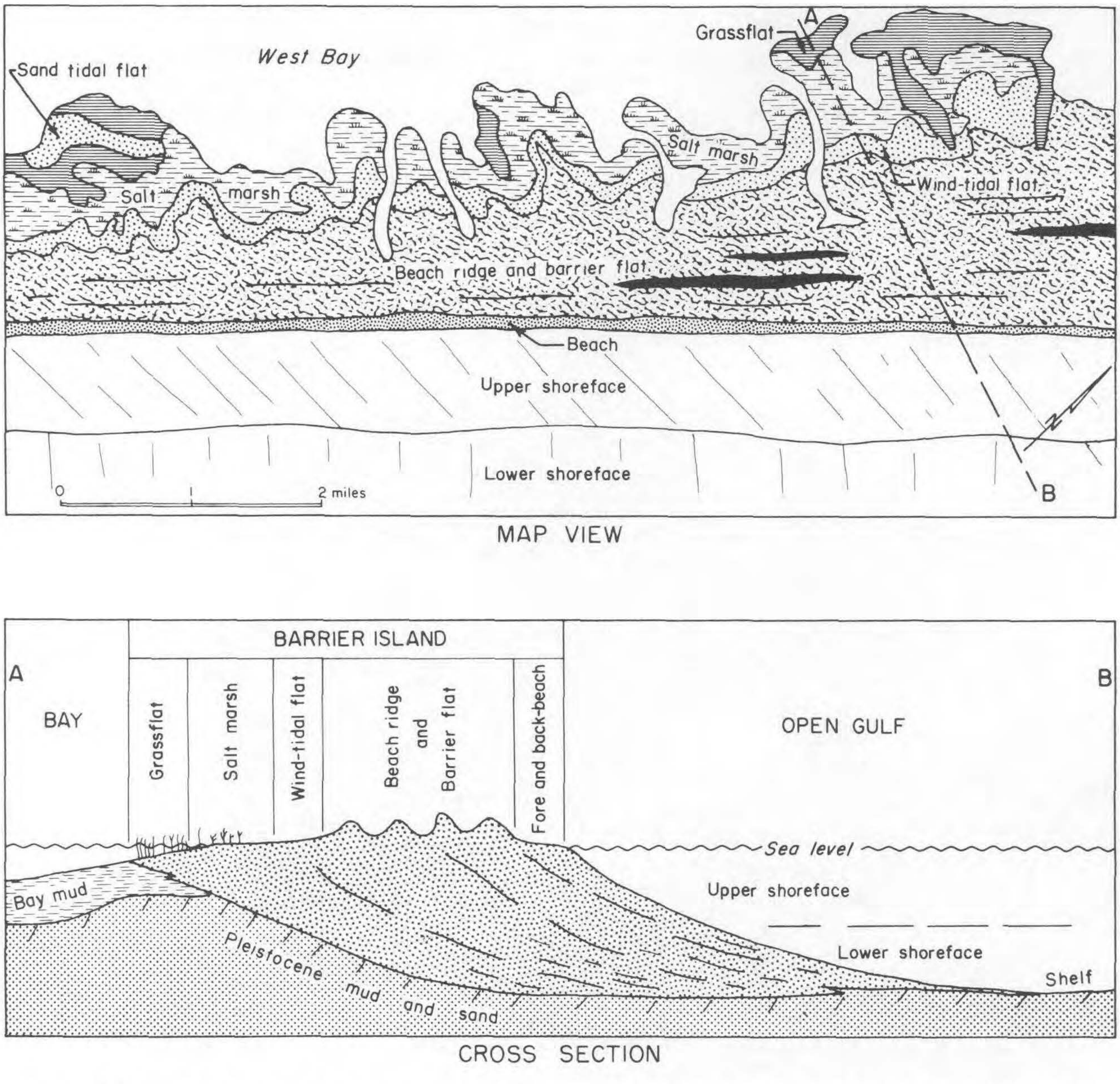

Figure 8. Modern barrier-bar environments and facies, Galveston Island. Cross section after Bernard and others, 1970. After Fisher and others, 1972.

Table 3. Evaluation of the natural suitability of physical properties groups for various coastal activities and land uses, Galveston-Houston area, Texas. After Fisher and others, 1972.

Suitability is evaluated on the basis of natural properties and may be improved by special engineering and construction methods. Significant properties considered as positive criteria for evaluating land-use suitability (+ = satisfactory; - = unsatisfactory; o = possible problems):

(1) Road construction: earthen structures and fill material--low shrink-swell potential, low compressibility, and low plasticity.
(2) Road construction: base material—low compressibility, low shrink-swell potential, and high shear strength.
(3) Road construction: grade material—low compressibility, low shrink-swell potential, and high shear strength.
(4) Fill material: topsoil—loam or sandy/siltv clay composition.
(5) Fill material: general, below topsoil—silty/sandy clay composition with low to moderate shrink-swell potential.
(6) Foundation: heavy—high load-bearing strength, low shrink-swell potential, and good drainage.
(7) Foundation: light—low shrink-swell potential.
(8) Underground installations—low shrink-swell potential, high load-bearing strength, and good drainage.
(9) Buried cables and pipes—low shrink-swell potential and low corrosivity.
(10) Excavatability—ease of digging with conventional machinery.
(11) Waste disposal: septic systems—moderate permeability, low to moderate shrink-swell potential, and good subsurface drainage.
(12) Waste disposal: solid waste—low permeability and good surface drainage.
(13) Waste disposal: unlined liquid waste retention ponds—low permeability.
(14) Earthen dams and dikes: low permeability, moderate shear strength, and moderate compressibility.
(15) Water storage: unlined reservoirs or ponds above ground-water level—low permeability.
(16) Water storage: reservoirs or ponds below ground-water level—high permeability.

GENERAL PHYSICAL PROPERTIES	PRINCIPAL ENVIRONMENTAL GEOLOGIC MAP UNIT	LAND USE: ROAD CONSTRUCTION			FILL MATERIAL		FOUNDATIONS					WASTE DISPOSAL			WATER STORAGE		
		(1) Earthen structures and fill material	(2) Base material	(3) Grade material	(4) Topsoil	(5) General—below topsoil	(6) Heavy	(7) Light	(8) Underground installations	(9) Buried cables and pipes	(10) Excavatability	(11) Septic systems	(12) Solid waste	(13) Unlined liquid waste retention ponds	(14) Earthen dams and dikes	(15) Unlined reservoirs or ponds above ground-water level	(16) Reservoirs or ponds supplied by ground water
Group I Dominantly clay and mud, low permeability, high water-holding capacity, high compressibility, high to very high shrink-swell potential, poor drainage, level to depressed relief, low shear strength, high plasticity, high to very high acidity, high corrosivity	Interdistributary muds, barrier-strandplain-chenier swales, abandoned channel-fill muds, overbank fluvial muds, mud-filled coastal lakes and tidal creeks	—	—	—	o	—	—	o	—	—	+	—	+	+	o	+	—
Group II Dominantly sand, high to very high permeability, low water-holding capacity, low compressibility, low shrink-swell potential, good drainage, low ridge and depressed relief, high shear strength, low plasticity	Beach, foredunes, barrier-strandplain-chenier vegetated flats, Pleistocene barrier and strandplain sands	+	+	+	o	+	+	+	+	+	+	o	—	—	—	—	+
Group III Dominantly clayey sand and silt, low permeability, moderate drainage, moderate water-holding *capacity, low to moderate com*pressibility and shrink-swell potential, level relief with local mounds and ridges, high shear strength	Meanderbelt sands, alluvium, levee, crevasse splay, distributary sands, bay-margin sand *and mud, Pleistocene fluvial,* distributary, delta-front sands	+	+	+	+	+	o	+	o	+	+	+	o	o	+	o	o
Group IV Coastal marsh, fresh to brackish, very low permeability, high water-holding capacity, very poor drainage, depressed relief, low shear strength, high plasticity, high organic content, subject to salt-water flooding, high to very high corrosivity	Fresh to brackish and closed brackish marsh, marsh-filled abandoned coastal lakes and tidal creeks	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	+
Group V Inland swamp and marsh, permanently high water table, very low permeability, high water-holding capacity, very poor drainage, very poor load-bearing strength, high organic content, subject to frequent flooding, very high acidity	Swamp, inland marsh, marsh-filled channels	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	+
Group VI Tidal flat and salt marsh, permanently high water table, very low *permeability, high water-holding* capacity, very poor drainage, very poor load-bearing strength, very high corrosivity, subject to frequent tidal inundations	Tidal flat and salt marsh	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Group VII Made land and spoil, properties highly variable, mixed mud, silt, and sand, reworked spoil commonly sandy and moderately sorted with properties similar to those of Group III	Subaerial spoil heaps or mounds, subaerial reworked spoil, subaqueous spoil, made land	HIGHLY VARIABLE: USE WITH CAUTION															

environment has been modified and converted into agricultural lands (compare with Current Land Use Map).

The Environments and Biologic Assemblages Map is not meant to be a biologic assay of the area but rather to show areal distribution of the type and number of major environments that are defined by dominant biologic assemblages. In short, it outlines the natural condition of the Coastal Zone. Comparison with current land use readily shows the extent of man's modification of the natural biologic environment.

Current Land Use Map

A number of factors in the Texas Coastal Zone contribute to diversified and extensive land and water use. The Zone is endowed with extensive mineral resources, notably oil, gas, and chemical raw materials (sulfur, salt, and lime), which

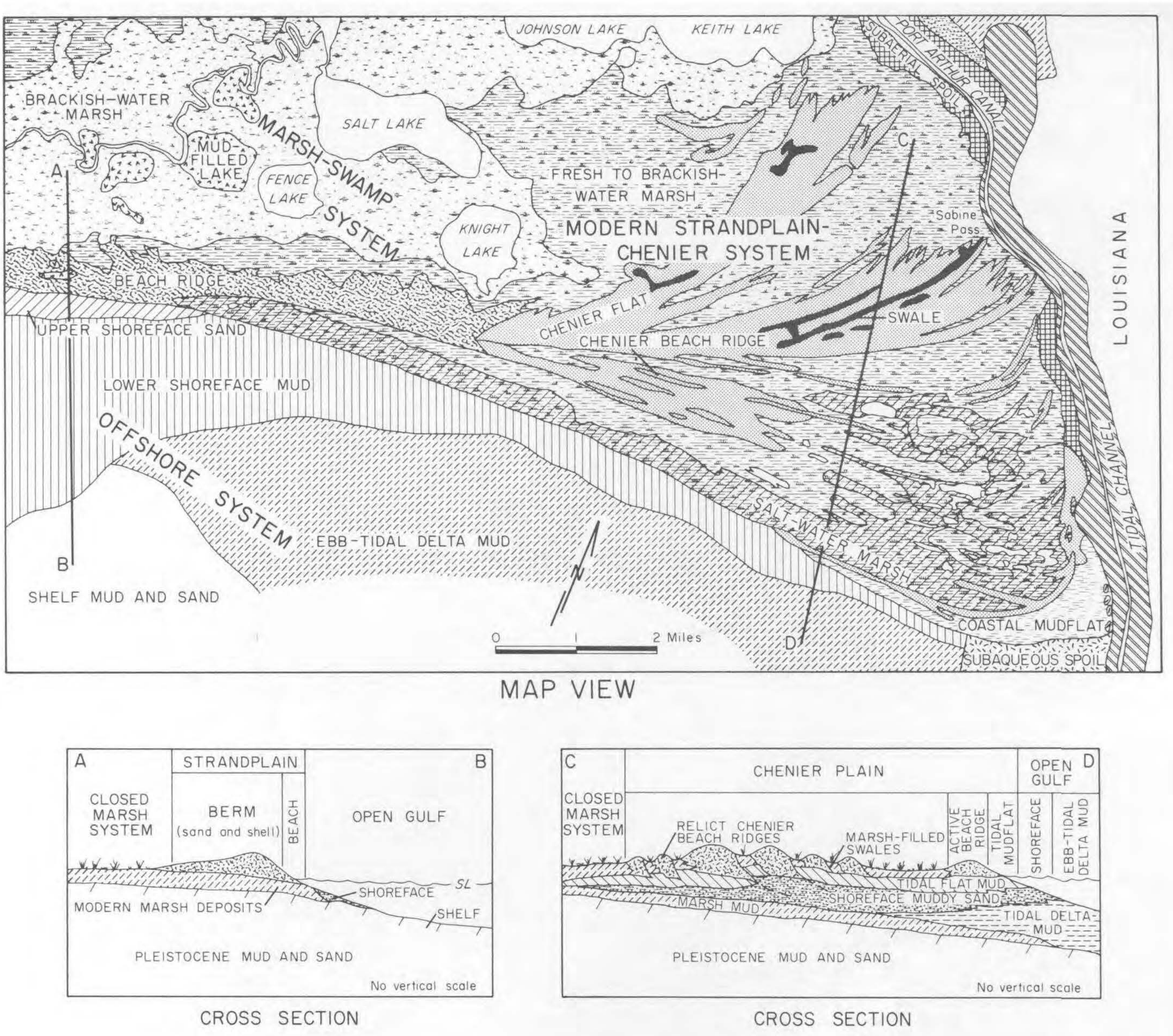

Figure 9. Modern strandplain-chenier and offshore systems along Gulf of Mexico, Beaumont-Port Arthur area. Chenier beach ridges were deposited along muddy coastline near Sabine Pass; sandy strandplain deposits occur southwestward of cheniers where muds are less abundant. Generalized cross sections contrast strandplains and chenier plains. After Fisher and others, 1973.

support one of the major petroleum-refining and petrochemical centers of the world. It is an area with fertile and productive lands that support extensive agriculture. And, finally, it embraces major port facilities with extensive intracoastal waterways and ship channels that have led to a high-volume flow of imports and exports.

Many of the factors that have led to diverse land and water use in the Coastal Zone have also led to current and potential limitations and conflicts. Many of the resources of the area have varied uses, both present and potential. For example, water bodies are used simultaneously for transportation, commercial and sport fishing, recreation, oil and gas well locations, pipeline routes, as a source of fill for real estate developments, and as a part of a waste-disposal system. Certain of these uses are obviously in conflict. The natural area is one of rapid and dramatic physical change involving active shoreline processes, hurricane flooding and damage, subsidence, and surface faulting; these dynamic changes interface with a variety of land and water uses. Further, the area embraces a fundamental legal boundary with the shore zone largely privately owned and the bay, estuary, and offshore areas publicly owned. Because the legal boundary is also a high-energy geological boundary, actions taken by one proprietor have an immediate and significant effect on others.

Current land use is classed in major use categories on the Current Land Use Map of the Atlas. Most of the information utilized in compiling the map was taken or derived from 7.5-minute U. S. Geological Survey topographic maps and similar Edgar Tobin controlled photomosaics (fig. 2); supplementary data were obtained

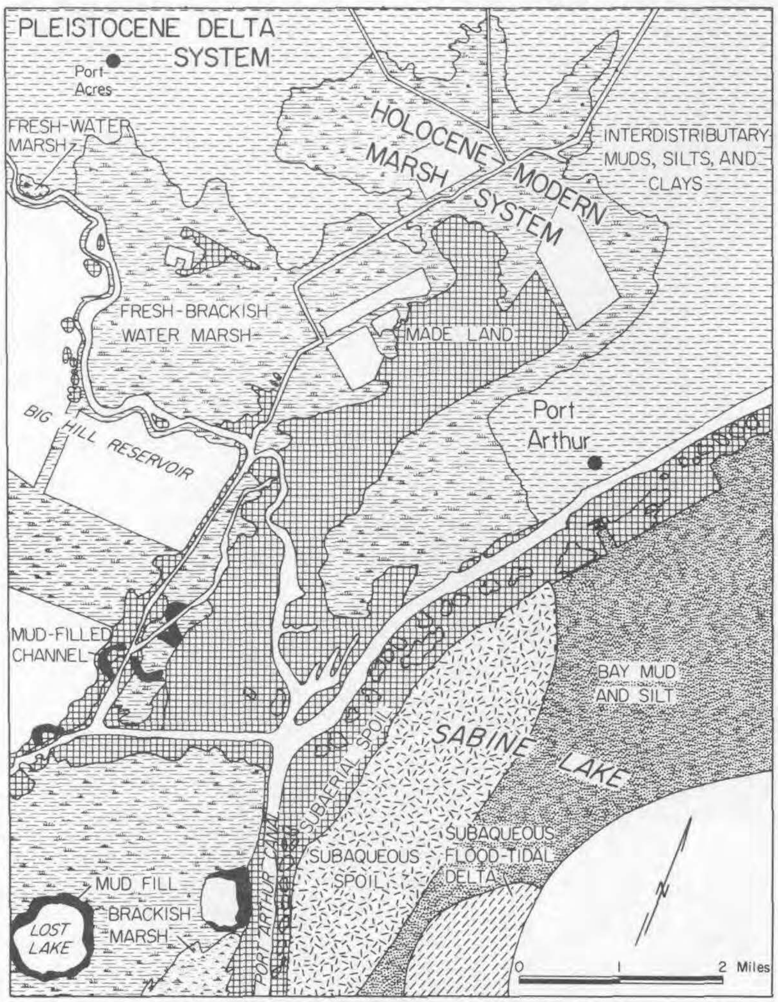

Figure 10. Extensive areas of made land cover former marshlands in the Port Arthur area. Subaerial and subaqueous dredge spoil has been dumped into the western end of Sabine Lake. After Fisher and others, 1973.

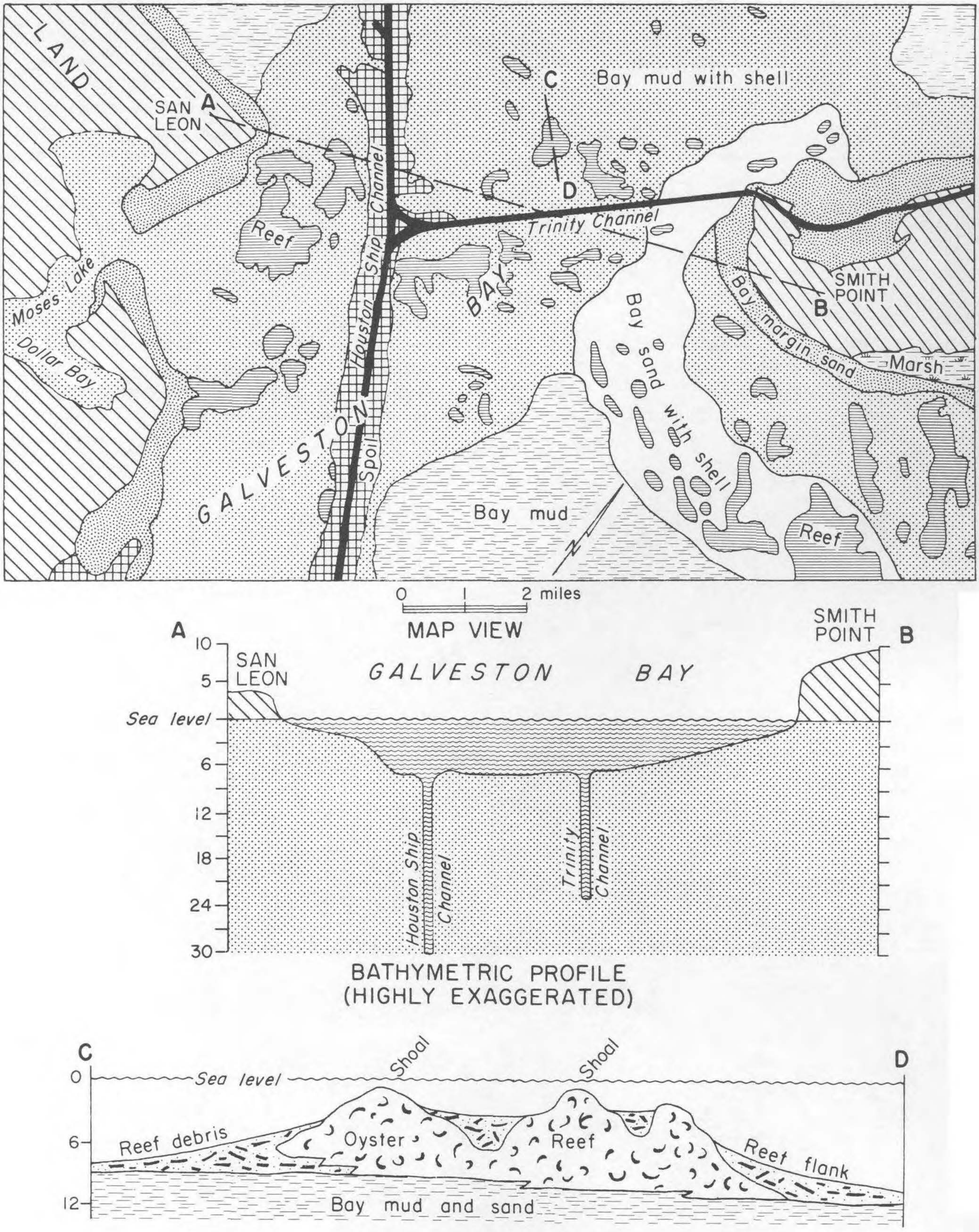

Figure 11. Modern bay-estuary facies within Galveston Bay. Bathymetric profile illustrates man's impact on the bay floor; the nature of living oyster reefs is shown by schematic cross section. After Fisher and others, 1972.

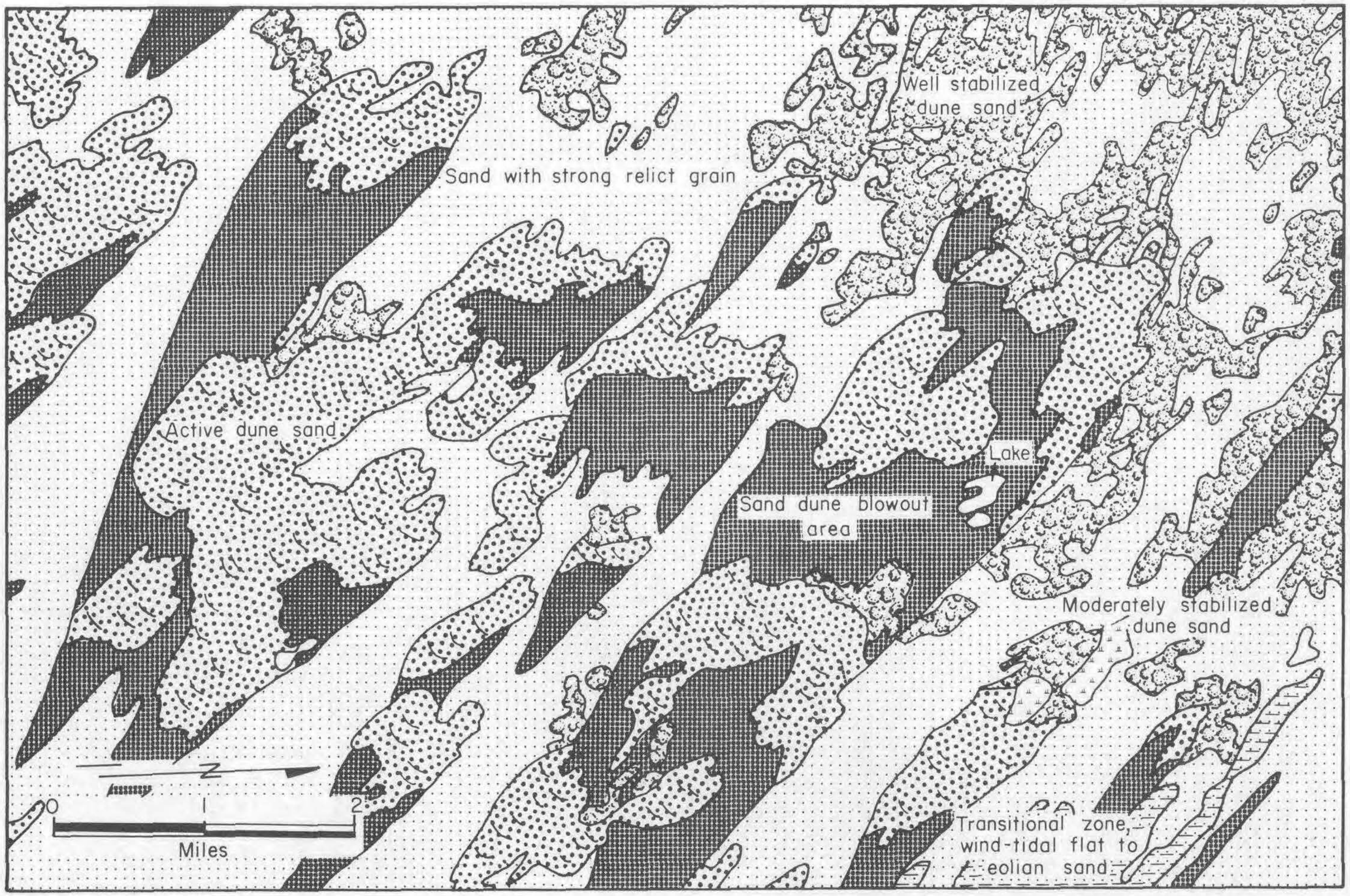

Figure 12. Banner dune complex, eolian system, Kingsville area. Banner dunes are composed of small barchan dunes.

by field observation and by derivation from the Environmental Geology Map. Base materials available for the entire area are generally on the order of a decade old. Where more recent base materials on a detailed scale existed, they were used to bring land use as up-to-date as possible; updating should be completed at least every decade or whenever new coastwide aerial photography becomes available.

Major classes of current or, in some cases, potential land use include (1) agricultural lands, (2) timber or wooded lands, (3) marshes or grassed wetlands, (4) urban lands, (5) government lands (State and Federal), (6) formally designated wildlife refuges, (7) general recreational lands, (8) made and reclaimed lands, (9) dredged spoil lands, and (10) artificial surface reservoirs. The major classes—agricultural, timber, marsh, and urban lands—are divided into smaller land use units. The Current Land Use Map shows location and distribution of oil and gas fields, educational sites, shallow piercement salt domes, sulfur mines, salt or brine plants, LPG storage sites, pits and quarries, sludge pits, sewage-treatment and disposal sites, solid waste - disposal sites, offshore petroleum production platforms, and airfields. Major pipeline, transportation-navigation, and irrigation-drainage networks are indicated.

Mineral and Energy Resources Map

Most of the Texas Coastal Zone is richly endowed with mineral and energy resources. Chief among these resources are oil and natural gas, which serve not only for fuel but also provide raw materials for many petrochemical processes. In addition, the Zone contains important resources of chemical raw materials—sulfur and salt, and shell for lime. The abundance of these chemical and petroleum raw materials and their occurrence in a zone with ocean access make this area one of the major petrochemical and petroleum-refining centers of the world.

The Mineral and Energy Resources Map of the Atlas shows the occurrence and distribution of all known mineral deposits, including oil and gas fields, salt domes, sulfur deposits, clay deposits, and general fill and aggregate materials. Also shown are existing pits and quarries, cement plants, brine production sites, and sulfur production sites. All shallow-piercement salt domes and moderate to deep-seated domes that have been proved by drilling, as well as those used currently for the underground storage of LPG, are indicated. The energy-distribution network is outlined by all major pipeline transmission facilities, major power or utility transmission lines, and power generation stations.

Active Processes Map

The Active Processes Map of the Atlas outlines the major physical and biological processes of the Coastal Zone that are critical for a variety of land and water uses. The main features of the map are a delineation of areas inundated by hurricane-surge floods and characterization of the bay and Gulf shorelines in their present state—erosional, depositional, or stabilized. In addition, such features as depositional rates within the bays, subaqueous areas of high energy, areas of extensive reef development, and areas of spoil reworking are indicated.

Man-Made Features and Water Systems Map

The Man-Made Features and Water Systems Map of the Atlas combines on one sheet the various features of the Coastal Zone that are the products of man's construction activities and the various kinds of surface water systems, including both natural and artificial water bodies. Presentation on a single map is for cartographic convenience.

Rainfall, Stream Discharge, and Surface Salinity Map

The Rainfall, Stream Discharge, and Surface Salinity Map of the Atlas summarizes certain salient climatic features. Data were selected for the three-year period, 1965-1967, for which detailed and continuous coverage exists.

Topography and Bathymetry Map

The Topography and Bathymetry Map included in the Atlas is a basic tool in the evaluation of land and water use and capability. Topography is indicated on the map with a distinct but graduated color pattern for each 5-foot interval of ground elevation. Elevations range from zero or sea level to approximately 100 feet in the most inland portions of the Coastal Zone. Topographic control used for this map (scale 1:250,000) and on the Environmental Geology Map, (scale 1:125,000) was compiled from U. S. Geological Survey detailed 7.5-minute topographic maps at the scale of 1:24,000.

Table 4. Coastal Zone land and water resource units—use and capability. Evaluations are based on natural capability which can be improved by engineering. Blank areas represent either no environmental problems or the use is not applicable on the particular resource capability unit. After Brown and others, 1972.

RESOURCE CAPABILITY UNITS		ACTIVITIES	Liquid Waste Disposal			Solid Waste Disposal		Coastal Construction			Inland Construction											
			Surface Disposal of Untreated Liquid Wastes	Disposal of Untreated Liquid Wastes, Subsurface, Shallow	Maintenance of Feed Lots	Disposal of Solid Waste Materials	Construction of Offshore and Bay Platforms	Construction of Jetties, Groins, Piers	Construction of Storm Barriers and/or Seawalls	Placement of Pipelines and/or Subsurface Cables ▲	Light Construction	Construction of Highways	Heavy Construction	Flooding (through dam construction)	Dredging of Canals and Channels, and Spoil Disposal ★	Excavation (includes extraction of natural materials)	Filling for Development	Draining of Wetlands	Well Development	Devegetation	Transversing with Vehicles (marsh buggies, air boats, dune buggies, motorcycles)	Use of Herbicides, Pesticides, Insecticides
WATER CAPABILITY UNITS	Bays, Estuaries, and Lagoons	River Influenced Bay Areas Including Prodelta and Delta Front	X	X		X	O	O	X	O					X		X		O			
		Enclosed Bay Areas	X	X		X	O		X	O					O		O		O			
		Living Oyster Reefs and Related Areas	X	X		X	X	X	X	X					X		X		X			
		Dead Oyster and Serpulid Reefs and Related Areas	X	X		X	O	O	X	O					X		X		O			
		Grassflats	X	X		X	X	X	X	X					X		X		X			
		Mobile Bay-Margin Sand Areas	X	X		X	X	X	X	X					X		X		O			
		Tidally Influenced Open Bay Areas	X	X		X	O	O	X	O					X		X		O			
		Subaqueous Spoil Areas	X	X		X	O	O		O							O		O			
		Inlet and Tidal Delta Areas	X	X		X	X	X	X	X					X		X		O			
		Tidal Flats	X	X		X			X	X	X	X	X		O	X	X		O			
LAND CAPABILITY UNITS	Coastal Wetlands	Salt-Water Marsh	X			X	X		X	X	X	X	X	X	X	X	X	X	O	X	X	X
		Fresh-Water Marsh	X			X			X	O	X	X	X	X	X	X	X	X	O	X	X	X
		Swamps	X			X				O	X	X	X	X	O	O	X	X	O	X	O	X
	Coastal Barriers	Beach and Shoreface	X	X		X		X	O		X	X	X		X	X			X		O	
		Fore-Island Dunes and Vegetated Barrier Flats	X	X	X	X			X		+	+	+		X	X			O	X	X	X
		Washover Areas	X	X	X	X		X	X	X	X	X	X		X		X		X			
		Blowouts and Back-Island Dune Fields	X	X		X				O	X	X	X		X				X			
		Wind Tidal Flats	X	X		X					X	X	X		O		X		O			
		Swales	X	X		X					X	X	X		X	X	X	X		X		X
	Man-Made	Made Land and Spoil	X	X	X	X							O							X		
	Coastal Plains	Highly Permeable Sands	X	X	X	X									O	X			O	X		X
		Moderately Permeable Sands	X	X	X	X									O	X			O	X		X
		Impermeable Muds	O							O	O	O	O						O			O
		Broad Shallow Depressions *	O								X	O	X						O			O
		Highly Forested Upland Areas *												X					O	X		X
		Steep Lands, Locally High Relief	X			X					O		O			X				X		O
		Stabilized Dunes	X	X	X	X						O			X	X			O	X	X	X
		Unstabilized, Unvegetated Dunes	X	X		X				O	X	X	X		X				X			
		Fresh-Water Lakes, Ponds, Sloughs, Playas	X			X									X		X	X	O			X
		Mainland Beaches	X	X		X		X	X		X	X	X		X	X	X		X	O		
		Areas of Active Faulting and Subsidence	O	O		O				X	O	O	X						O			
	Major Floodplain Systems	Point-Bar Sands	X	X	X	X					O				X				O	X		X
		Overbank Muds and Silts	X	X	X	X				O	O	O	O	O								O
		Water	X			X								O	X							X

X Undesirable (will require special planning and engineering)
O Possible problem(s)
\+ Barrier Flat only (no construction on dunes)

* Substrate variable
▲ Also occurs in Offshore Construction
★ Also occurs in Offshore Canals and Dredging

Bathymetric contours are shown at intervals of six feet, or one fathom, and are also represented by distinct gradational color patterns for ready determination of bottom relief and configuration. These contours are shown also on the Environmental Geology Map and were compiled from 7.5-minute topographic sheets and U. S. Coast and Geodetic Survey nautical charts. Depths range from zero or mean sea level to more than 30 feet. Deepest areas are within the active tidal channels, dredged channels, and the inner shelf. Depth of the navigation channels varies according to project depths and other specifications.

RESOURCE CAPABILITY: UTILITY IN LAND AND WATER MANAGEMENT

A basic goal of the Environmental Geologic Atlas of the Texas Coastal Zone is an adequate inventory of the natural resources of the Zone. Flexible management of the Texas Coastal Zone should be based on the natural capability of resource and environment units. Such units, termed *natural resource capability units* (Brown and others, 1971), have been derived from the maps included in the Atlas (table 4).

Particularly important to the maintenance of environmental quality are those properties and characteristics of natural resource units that limit their use for specific purposes or activities. Examples are: (1) potential for flooding by hurricane surges or by overbanking rivers; (2) unfavorable shrink-swell conditions; (3) tendency for corrosion of pipes and conduits placed in certain substrates; (4) degree of permeability, which determines the extent of transmission of pollutants into ground-water aquifers and nearby surface water bodies; (5) steep slopes, which are susceptible to gravity failure and extreme erosion from runoff; (6) extremely flat lands that are poorly drained and that pond water following heavy or prolonged rainfall; (7) impermeability, which exaggerates ponding and drainage problems; (8) persistent winds in arid areas, which cause wind erosion and migration of sediments in the form of dunes; (9) tidal flooding of broad, low-lying coastal flats by wind-driven water from bays, estuaries, and lagoons; (10) density of stabilizing vegetation on sand substrates, which maintains stability of sediments in high-energy wind and water environments; (11) wave energy dissipated along shorelines with resulting erosion and redistribution of sediments; (12) zones of active or potentially active faulting; (13) tendency for subsidence; and (14) erosional susceptibility of various sediments and soils to wind and water.

Evaluation of natural resource capability units depends upon the types of human activities that result in use of the units—currently or potentially. A wide variety of land and water use activities occur within the Coastal Zone (table 4); other potential activities will develop as population and urban-industrial expansion continues in the Zone.

Natural resource capability units display different capabilities and tolerances under the impact of human activities. For example, a highly permeable sand is a very poor host for a solid waste - disposal site simply because of its capability for transmitting wastes into aquifer systems, but the same permeable sand provides an excellent foundation for coastal structures. In turn, a relatively impermeable clay unit provides a secure host for solid waste disposal without aquifer pollution, but it is a very unsatisfactory foundation material. A brackish-water marsh not only can tolerate but is in fact defined on its capacity to accommodate changes in salinity; salt-water marshes, by contrast, can tolerate little fresh-water influx. A washover channel on a barrier island is a natural outlet for hurricane surges; it is an exceedingly poor site for construction. Many land and water resource units and their capabilities for particular uses are obvious; others are more subtle. A resource capability unit, therefore, must be evaluated in terms of each coastal activity; that is, environmentally significant physical properties may indicate that the capability unit will be severely affected by one activity, while another activity may prove to be entirely compatible with these properties.

By these examples it can be seen that in order to evaluate the impact of a specific coastal activity on a natural resource unit, it is necessary to evaluate the unit in terms of its limiting environmental capability properties. In this manner an activity can be evaluated in terms of the environmental stress it exerts on the resource unit; if the limiting environmental capability properties are compatible with the activities, no environmental impact will occur. On the other hand, if the activity adversely affects the resource unit because of the incompatibility of the activity and the limiting environmental capability properties, problems can be predicted and avoided or properly engineered.

Derivation of land and water capability maps from environmental geology maps provides an inventory of natural units that charts the distribu-

COASTAL WATER BODY AND LAND CLASSIFICATION

I. Bays, lagoons, and estuaries

- A. River-influenced bay
- B. Enclosed bay
- C. Reef and reef-related areas (absent)
- D. Grassflats (absent)
- E. Mobile bay-margin sands (absent)
- F. Tidally influenced open bay
- G. Subaqueous spoil
- H. Tidal inlet and tidal delta
- I. Wind-tidal flats (absent)

II. Major river systems

- A. Point-bar sands
- B. Overbank muds and silts (not illustrated)
- C. Water (including related lakes and sloughs)

III. Coastal wetlands

Salt marsh, fresh-water marsh, swamps

IV. Coastal plains

- A. Highly permeable sands
- B. Moderately permeable sands
- C. Impermeable muds
- D. Broad, shallow depressions (not illustrated)
- E. Highly forested upland areas
- F. Steep lands
- G. Stabilized (vegetated) dunes and sand flats (absent)
- H. Unstabilized (unvegetated) dunes (absent)
- I. Fresh-water lakes, ponds, sloughs, playas
- J. Mainland beaches (absent)
- K. Areas of active faulting and subsidence (not illustrated)
- L. Headward-eroding streams

V. Made land and spoil

VI. Coastal strandplain

- A. Beach and shoreface
- B. Vegetated strandplain and chenier flat
- C. Washover areas
- D. Active dunes (absent)
- E. Tidal flats (absent)
- F. Swales

Figure 13. Schematic map of land and water resource capability units, Beaumont-Port Arthur area.

tion of kinds and grades of natural resources. A schematic map of the Beaumont-Port Arthur area (fig. 13) illustrates the nature and distribution of land and water capability units; detailed, cartographically accurate maps can be constructed (derived from the Environmental Geology Map) to chart these vital environmental units. In any area these basic resource units can be evaluated in terms of current and projected human activities; the limits of their capabilities for various uses allow for the development of guidelines that will permit maximum use consistent with minimum environmental degradation.

A suite of special maps can be constructed from a basic natural resource capability map by evaluating all the units of a region in terms of all possible uses or activities; each natural resource unit on the map, therefore, can be graded as to capability for each specific use, providing a basis for evaluating the potential impact of an activity. In this manner, potential environmental stresses can be predicted far in advance in order to provide a firm, logical, and just basis for environmental management and decision-making with the full realization of the economic, political, and social alternatives.

USING THE DATA

Statistical Measurements

The areal extent of each map unit, the length of linear features, and the number of specific environmental units within each map area are listed in tables. For example, the area covered by fresh-water marsh or the area being used as rangeland was calculated and tabulated by counties. In addition, the percentage of each unit within an individual map area was determined. The total length of features, such as pipelines, erosional shorelines, or bay shoreline, was measured along with the number of specific sites on the maps, such as power generation plants, waste-disposal pits, and airports. The areal extent of units is listed in square miles; linear features are in miles. Measurement of areal data is based on point-count methods, cross-checked by planimeter techniques. Average values proved to exhibit greater than 90 percent accuracy. Linear features were measured by map-measuring wheels, and average values display greater than 95 percent accuracy. Accuracy of quantitative data is principally limited by the scale of the maps and the nature of the polyconic map projection.

Environmental Resource Subject Guide

An extensive, alphabetized index of information concerning the Coastal Zone has been compiled to afford easy access to desired information. The index provides a subject guide for locating information of a general nature, as well as information not specifically included in the map legends; both map and text sources are indexed. Following is an example of how this material may be used: One may wish to determine areas with very low permeability that would serve as satisfactory solid waste - disposal landfill sites. By referring to *permeability* in the index, the reader is directed to the Physical Properties Map, to specific pages in the text, and to a table evaluating land use suitability in the particular map area. In this manner, the areas of low permeability can be located on the Physical Properties Map. Reference to the text and to a table listing land suitability provides additional description and evaluation of landfill suitability. In addition, if the user wants to know the percentage of current solid waste - disposal sites within a map area that are improperly located, he can evaluate each site based on the properties at each location (Physical Properties Map) and then determine the percentage that are poorly located. Interpretation of data in this general manner will naturally depend upon the experience of the user in the specific subject of interest.

Generating Additional Data

For cartographic convenience and feasibility, basic data are presented on a series of nine maps. Combining information from two or more maps may provide additional insight into the nature of an area or provide a specific solution to an environmental problem. Many other special maps can be prepared by the user to present any combination of properties or characteristics necessary. For example, to evaluate an area in terms of potential for recreational parks, characteristics desirable for this particular land use must be defined. If the desired recreational land should be well drained, above hurricane tidal effects, vegetated with mixed pines and hardwoods, remote from oil fields, sulfur mines, pipelines, power lines, and industrial or residential developments, the coincidence of these several factors, obtained by overlapping the special-use environmental maps depicting these required properties, outlines areas suitable for this type of recreational development. All of the recreation requisites can be obtained from various maps of the Environmental Geologic Atlas of the Texas Coastal Zone; a map that shows the location and grades potential recreation sites can, thereby, be prepared by the user.

If an industrial site is desired within a region, the area can be analyzed using the Atlas. For example, reference to the Physical Properties Map outlines areas with suitable foundations and other related properties; the Current Land Use Map indicates the current use and approximate value of the land, as well as location of airfields or residential areas for employees; the Mineral and Energy Resources Map indicates availability of construction materials, pipeline facilities, railroads and highways, and principal power lines; the Topography and Bathymetry Map shows the slopes and land configuration which might bear on the site selection; the Rainfall, Stream Discharge, and Surface Salinity Map illustrates climatic data that might be critical; the Man-Made Features and Water Systems Map shows the nature of drainage systems, reservoirs, made land, and other related factors within the area; and the Environments and Biologic Assemblages Map provides information on the nature of vegetation at potential sites. In this manner, an environmental analysis may be made to evaluate a site or area for a specific, potential land use; or a broad area may be analyzed in order to locate or outline favorable sites for specific uses.

Other maps that may be made from the Atlas could outline areas of positive or negative suitability for a specific use; or the entire area could be grouped into various capability or use grades from excellent to poor on the basis of the number of desirable land factors which coincide. The varieties of special-use environmental maps that can be prepared from the basic Environmental Geology Map and units on the eight Special-Use Environmental Maps are essentially unlimited. By combining maps of the Atlas with other sources of economic, planning, industrial, transportation, or sociological data, a broad spectrum of environmental problems and management goals can be solved, or at least outlined and properly defined.

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ENVIRONMENTAL UNITS IN CARBONATE TERRANES AS DEVELOPED FROM A CASE STUDY OF THE SOUTHERN EDWARDS PLATEAU AND ADJACENT INTERIOR COASTAL PLAIN

E. G. Wermund

INTRODUCTION

The purpose of this paper is to show a philosophy and methodology for recognizing environmental geologic and resource capability units in carbonate terranes. First, resource capability or environmental units are derived for a case-study area in the southern Edwards Plateau with its adjacent interior coastal plain. Second, concepts learned from the case study are related to other geological provinces.

Brown and others (1971) have defined a resource capability unit as ". . . an environmental entity . . . defined in terms of the nature, degree of activity or use it can sustain without losing an acceptable level of environmental quality. . .These include (1) physical units ... (2) process units . . . (3) biologic units . . . and (4) man-made units. . ."

Physical units are identified from physical properties like composition, strength, and economic value. Process units are dominated by streamflow, solution, gravity slides, and the like. Biologic units result where certain fauna or flora (forests or prairie grasses, for example) assume first-order importance. Extensive quarrying and spoil heaps are significant man-made units. In carbonate terranes, derivation of environmental units is severely modified by climatic effects as they influence the karst process.

CASE STUDY—SOUTHERN EDWARDS PLATEAU AND INTERIOR COASTAL PLAIN

Problem

The Texas Water Development Board requested environmental geologic mapping of the Nueces, San Antonio, Guadalupe, and Lavaca River Basins, an area of more than 33,000 square miles. They asked that the mapping be completed in 3 years. Available base materials include: 100 percent of the area in 1:250,000 topographic maps, 80 percent of the area in 1:24,000 topographic maps, 100 percent of the area in 1:24,000 black-and-white controlled aerial mosaics, 100 percent of the area in 1:20,000, 1:40,000, and 1:65,000 black-and-white stereographic aerial photography, and about 4 percent of the area in 1:120,000 color stereographic aerial photography. Modeled after the Coastal Atlas of Fisher and others (1972), the environmental geologic mapping contract requires 8 maps that include environmental geology, physical properties, physical processes, slopes, economic resources, biologic assemblages, man-made features, and land use. Support includes employment of 4.5 geologists per year assisted by 5 half-time graduate assistants.

Southwest Texas was selected for environmental geologic mapping because this region contains important subsurface aquifers including the Edwards Limestone aquifer and the Carrizo Sand aquifer. Mapping was initiated in the north in the recharge zone for the Edwards aquifer and work will continue southward toward the Coastal Zone. In this way, the group is examining one physiographic province at a time. Time demands that the southern Edwards Plateau and the adjacent interior Cretaceous coastal plain be mapped in the first year—about 10,000 square miles (fig. 1). Therefore, mapping is limited to the interpretation of aerial photographs and topographic maps supplemented by brief field checks.

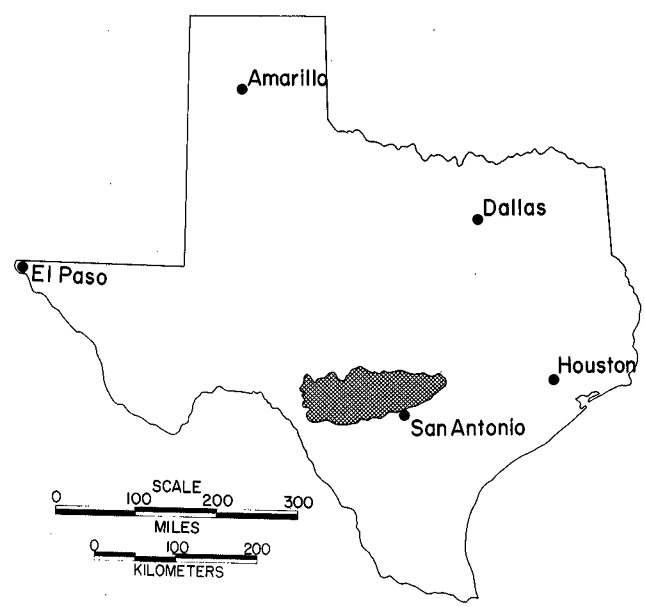

Figure 1. Location of the southern Edwards Plateau in Texas.

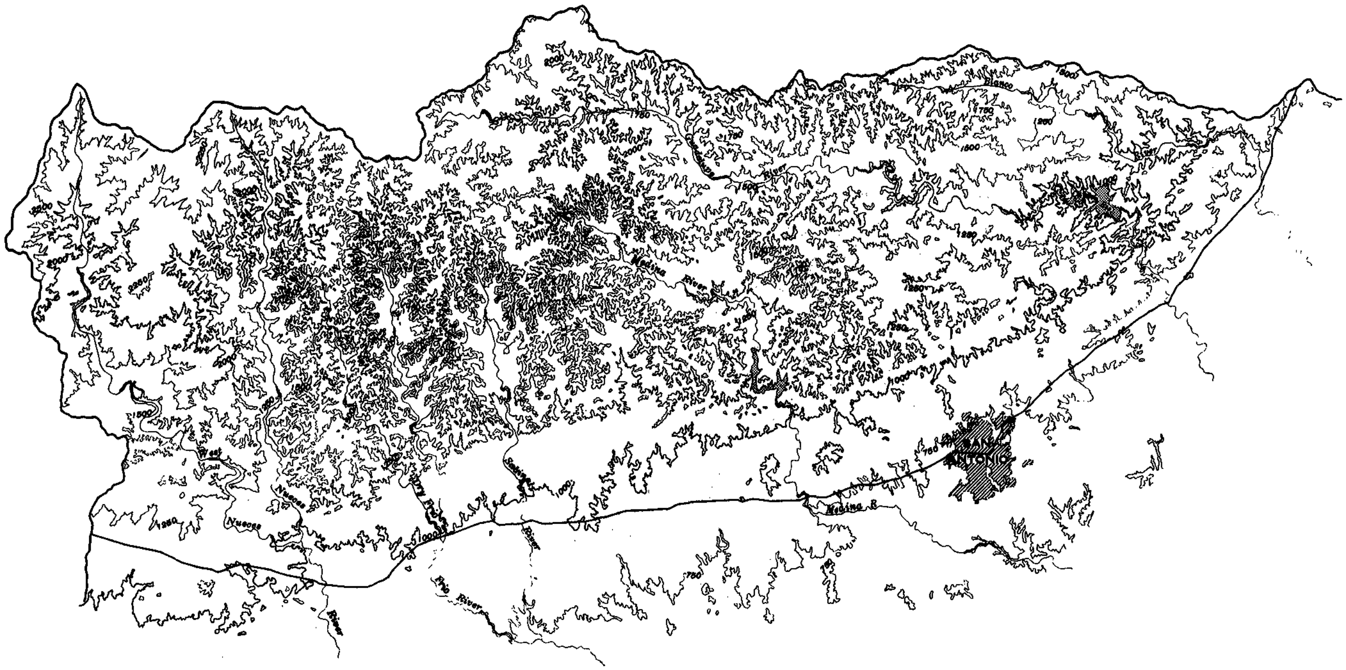

Figure 2. Topographic map of southern Edwards Plateau and adjacent interior Coastal Plain.

General Geology

The Edwards Plateau, according to Fenneman (1931), is held up by limestones lacking any fluviatile mantle. The maximum elevation of the plateau in this case-study region is about 2,400 feet, and the surface slopes gently both southward and eastward (fig. 2). The relatively level surface of the Edwards Plateau, which reflects nearly flat-lying rocks, is deeply incised by southward-flowing drainage in the Nueces River Basin and eastward-flowing drainage in the San Antonio and Guadalupe River Basins. Elevations are about 1,000 feet west of San Antonio and about 750 feet northeast of San Antonio where streams discharge from southern limits of the plateau escarpment onto coastal-plain rocks. Three different terrains are evident in the case-study region (fig. 2). Along the West Nueces and Nueces Rivers, most of the terrain consists of broad divides. Along the Dry Frio, Frio, and Sabinal Rivers, the terrain comprises both highly dissected divides and incised stream valleys. About the Medina and Guadalupe Rivers, most terrain lies in broad valleys and less occupies narrow divides.

Most of the streams that erode headward into the plateau form narrow valleys with steep walls of Cretaceous carbonate strata. These valley walls reach 400 feet high within one-half mile of the stream. Only the major streams develop valleys 3.5 to 5 miles wide. The wider valleys may have formed by both karst development and lateral cutting processes when there was greater rainfall than now (Pleistocene pluvials?). These modern wider valleys contain underfit streams which catch a present mean annual rainfall of 30 inches in the east and 22 inches in the west of the plateau. More significant is the character of the rainfall; 2 to 3 inches of rainfall in one hour from heavy thunderstorms is common.

Although a few outcrops of Del Rio Clay and Buda Limestone occur at higher elevations of the Edwards Plateau, only the Glen Rose and Edwards Formations crop out extensively (fig. 3, after V. E. Barnes and others, in preparation). The Glen Rose is more than 480 feet thick just north of Vanderpool near the center of the case-study region (Stricklin and others, 1971). At the same location, the Edwards Formation is about 360 feet thick (Rose, 1972). The Glen Rose Formation is formed of alternating beds of limestone, dolomite, and marly limestone; about 60 percent of the section consists of soft limestones. Conversely, the Edwards Formation is composed of limestone and dolomite with only 8 percent marly limestone in which clay beds rarely occur. Although the marly limestone of both the Edwards and Glen Rose Formations is rapidly weathered and eroded, it contains only a minor component of clay minerals.

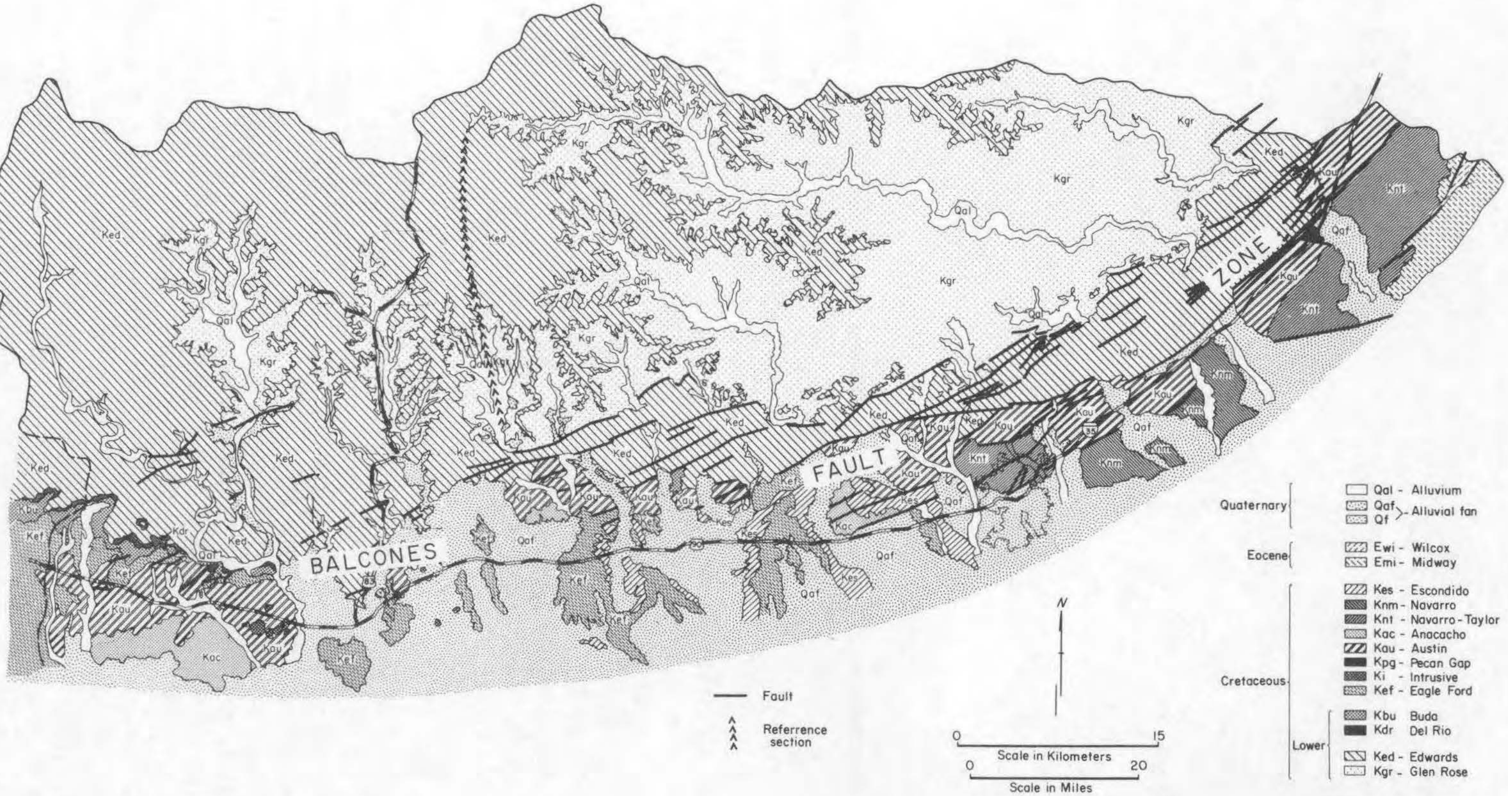

Figure 3. Geologic map of southern Edwards Plateau and adjacent interior Coastal Plain (after Barnes and others, in preparation).

With rare exceptions, our reconnaissance of the southern Edwards Plateau substantiates the lateral lithologic continuity of the Glen Rose and Edwards rocks described above. However, thick limestones do occur in the lower Glen Rose Formation in many places. Throughout the region, vertical and horizontal permeability paths developed in these limestones, as evidenced by joints and bedding planes that contain fissures enlarged by solution, older travertine-filled routes, and even caves. Such solution features are abundant in the Edwards Limestone, which appears to have a well-developed open system of fluid communication in outcrop and subcrop of the plateau.

The regional geologic map (fig. 3) illustrates a number of important regional features. The southern limit of both the Edwards and the Glen Rose outcrops is along the Balcones fault zone which strikes east-west in the western part of the map and nearly northeast-southwest in the eastern part. North of the major faults, broad valleys expose wider outcrops of the Glen Rose Formation. Valleys of alluvial deposits narrow immediately south of the faulting as streams incise the downdropped Edwards Formation. This can be seen on a succession of streams from west to east. Displacement along the Balcones fault zone is a maximum of about 1,700 feet in the eastern part of the map area (DeCook, 1963) and about 700 feet in the southwestern part of the area (Welder and Reeves, 1962). Maximum displacement along any one fault in the eastern part of the area is about 500 feet, whereas maximum displacement along any one fault in the southwestern part is about 200 feet.

South of the major Balcones faulting and south of the limiting Edwards outcrop, there is a marked change in the terrain. Maximum relief is about 100 feet in low rolling hills. The two types of outcrop that occur are (1) the normal succession of Upper Cretaceous rocks including the Austin, Taylor, and Navarro Groups made up mostly of chalks and terrigenous mud rocks, and (2) broad, extensive gravel and sand in the form of fan plains that appear just downdip of the Balcones faulting. At the base of the escarpment of the Edwards Plateau, these fans extend southward and eastward as broad and elongate plains of clastics developing a rich well-drained loamy soil.

Land Use

From reconnaissance one may readily distinguish the present uses of land in the southern Edwards Plateau (fig. 4). Six land use units are recognized: (1) "hill" country, (2) grazing land, (3) mixed grazing and cultivated land, (4) cultivated land, (5) urban and small communities, and (6) recreational areas. The hill country and grazing lands represent about 70 percent of the region. The above land use units are comparable to the resource capability units defined by Brown and others (1971) as present use is a critical aspect of resource capability units.

Each of the land use units previously mentioned has clear, identifiable properties as shown in table 1. Only two land use units are described as variable in bedrock, soil, slope, and vegetation. They are the recreational and populated units which are overprints upon other land use units. The Medina and Canyon Lake areas represent a special classification problem in that both areas support recreational and suburban activities. They are developing as permanent suburban communities of both dominantly retired military and commuting residents. San Antonio is only a short distance by automobile and a major military and commercial city in the southwest.

ENVIRONMENTAL UNITS IN THE SOUTHERN EDWARDS PLATEAU

Rationale for Environmental Construction

Previous environmental geologists generally derived environmental units from lithologic variations (Johnson and Smith, 1965; Danehy and Harding, 1969; Hayes and Vineyard, 1969; and LaMoreaux and others, 1971). Fisher and others (1972) are an exception in their derivation of hurricane process units. All, however, have considered topography or terrain as a separate problem, usually presented on a thematic map.

In the Edwards Plateau headwaters of the Nueces, San Antonio, and Guadalupe Rivers, the recharge process should be the dominant environmental factor regulating plans for current and projected land use. It is to be expected that recharge will always be the most important factor weighed and will never be preempted by residential and recreational needs of an expanding population. Therefore, the geological properties regulating the recharge process become the dominant inputs of environmental mapping. Variables affecting recharge and infiltration rates are: (1) rock composition, (2) fluid conduits reflecting porosity, permeability, and transmissivity, (3) soil and vegetation cover, (4) slope, and (5) the attitude of bedrock.

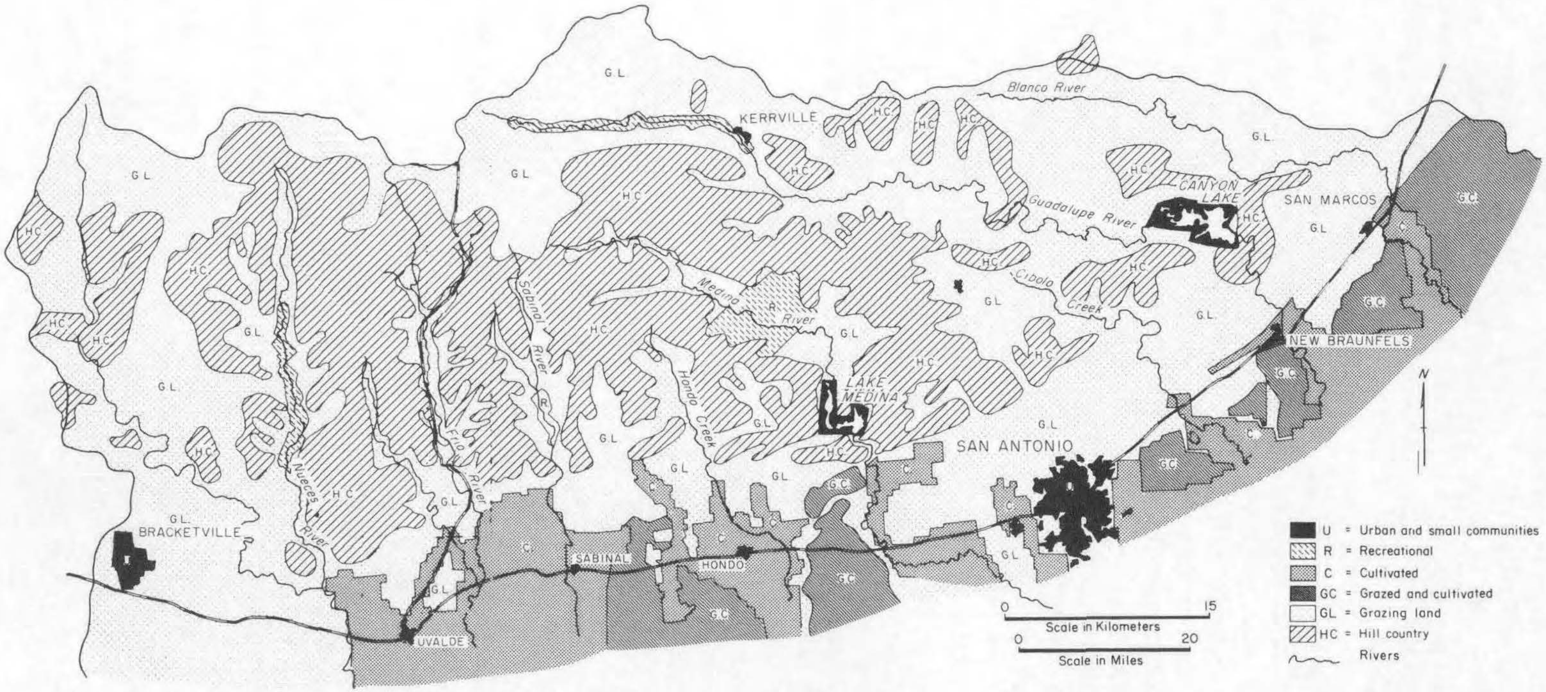

Figure 4. Land use map of southern Edwards Plateau and adjacent interior Coastal Plain.

Table 1. Present land use in the southern Edwards Plateau and adjacent inner coastal plain.

Units	Hill Country	Pasture	Mixed Pasture Cultivated	Cultivated	Recreation	City Town
Use	Scenic Hunting Hiking Few goats	Grazing cattle, sheep, and goats	Grazing or agriculture	Agriculture	Hiking Hunting Dude ranching Water activities	Community living
Maximum relief (ft.)	1500	500	100	20	1500	60
Slopes	Steep, generally $>15\%$ dissected	Moderate to flat, $<15\%$	Gentle to flat, generally $<10\%$	Very flat, generally $<2\%$	Variable	Gentle to flat, $<10\%$ in most cases
Bedrock	Limestone Dolomite	Marly limestone, dolomite, sandstone, shale, colluvium gravel, and alluvial gravel and sand	Shale Marl Chalk	Gravel Sand	Variable	Variable
Soil	Absent to thin dark clay confined to solution pockets and fractures	Variable thin clay of uplands to calcareous, friable loam of alluvial deposits	Calcareous clay, generally dark, thickness up to 2 feet	Oxidized, calcareous, friable loam	Variable	Variable
Vegetation	Open scrub juniper and live oak	Grassy prairie with scattered oak mottes and mesquite	Grass and mesquite, pecan and walnut on terraces	Grass, pecan, walnut	Variable	Replanted
Remarks	Cash crop is hunting leases	Thick caliche caprocks are common	Degree of slope and resistance to plowing affects use	Irrigation common	Concentrated along streams leading to summer housing	Lake developments about Canyon and Medina Lakes are a special problem

Table 2. Environmental units in the southern Edwards Plateau.

Unit	Karstic tableland	Karstic lowland	Deeply dissected	Moderately dissected	Upland rolling
Bedrock	Limestone Dolomite	Limestone Dolomite	Limestone Dolomite	Limestone Dolomite	Limestone Dolomite
Maximum relief (ft.)	40	100	800	100	40
Slopes	<5%	5-15%	>15%	5-15%	<5%
Soil	Dark, mildly alkaline clay	Dark, mildly alkaline clay. Thick in solution pits	Very thin dark clay	Stable alkaline clay	Dark clay of variable thickness
Vegetation	Grassy prairie Live oak mottes	Grassy prairie Live oak mottes	Sparse scrub juniper and live oak	Scrub juniper and live oak locally dense. Some open grass	Prairie
Structure Morphology	Joints with solution effects	Joints with strong solution evidence	Rock pavements Strongly jointed	Jointed	Some rock pavements
Man altered	Often root plowed	Some chaining and root plowing	None	Rare chaining Quarrying	Chained
Remarks	Sinkholes, shallow and often old	Both old and young sinkholes	Many cliffs of bare rock	Concave slopes	Flats are deeply dissected
Dominant Process	Recharge	Recharge	Runoff	Runoff Recharge	Recharge
Resource Capability Units	Recharge Carbonate Rangeland	Recharge Carbonate Rangeland	Rugged Carbonate Scenic	Recharge Carbonate Rangeland	Recharge Carbonate Rangeland

Table 2 (continued)—

Low rolling	Flood plain	Terrace	Alluvial fan	Colluvial	Mixed Alluvial-Colluvial
Limestone Alternating beds	Rounded gravel to mud-size clasts	Rounded gravel to mud-size clasts; may be caliche cemented	Subrounded gravel to mud; tough deep caliche cement to depths of 8 feet	Angular clasts of carbonate—caliche cemented	Angular and rounded clasts of carbonate from cobble to silt
20, often dip slope	20 where incised	20	60	100	40 to >100
<5%	<5%	<5%	5-15%	>10%	5 to >15%
Dark clay thicker on alternating beds	Calcareous, friable loam	Light, calcareous, friable, gravelly loam	None to thin, dark alkaline clay over thick caliche	Rubble area caliche	Barren in steeper colluvium to thick arable loam in high terrace
Juniper and live oak	Cypress	Dense to moderate stands of pecan and walnut	Sparse cedar and live oak	Generally barren	Prairie grass to oak-juniper stands
Some rock pavements	Jointed bedrocks	Torrential cross-bedding exposed in borrow pits	Creep scars of soil mass wasting over caliche	None	Creep scars and shallow fluvial gulleys
Tilled	Rare borrow pits	Caliche and gravel borrow pits	Caliche borrow pits	None	Lower part plowed; borrow pits
Some intermixed colluvium	Underfit streamflow in alluvium on bedrock floor	Sometimes cultivated. Prime housing site	Ubiquitous caliche. Often incised by a stream	Thick caliche, usually with incised streams	Always deep caliche. Individual alluvial units impossible to resolve
Recharge	Recharge	Recharge	Runoff	Colluviation	Runoff Recharge
Recharge Carbonate Arable Rangeland	Nonpermanent Recreational Flood plain	Arable Rangeland Gravelly loam	Sheetwash Caliche Gravel Rangeland	Colluvial Sheetflood Barren Caliche	Mixed alluvial-colluvial Rangeland

These five variables are primary factors, and the mapping methodology is a secondary influence determining the derivation of the plateau environmental units (Wermund and others, in press).

Where the rocks are carbonate, limestone, and dolomite, slope is probably the dominant property affecting recharge in the region. Variation in soil and vegetation development depends upon the slope and remains constant over different calcareous rocks, regardless of their attitude. Limestone and dolomite behave similarly as soluble, dense-fractured rocks. Their facies can only be separated by means of detailed ground mapping.

Steep slopes with convex hilltops are common in the many valley headwaters of streams dissecting the plateau. The steep slopes have rapid runoff nearly unimpeded by sparse brushy vegetation, and there is little infiltration into a rare, thin, and immature soil. On the divides with flattened slopes and in less dissected carbonates with concave slopes, denser vegetation retards runoff and thicker mature soil increases infiltration. Fracturing or jointing is also more important in the lesser slopes, but fracturing is consistently evident in the carbonates throughout the region. Where dense limestone and dolomite crop out on gradual slopes, sinkholes are common, reflecting recharge and infiltration. Some carbonate terrane has very gentle slopes reflecting the occurrence of soft limestone. This limestone is a rapidly weathering and eroding limestone containing a minor terrigenous clay component. As all the carbonate rocks have minimal southeastward dip (they are nearly flat), bedding attitude is treated as a constant not affecting the derivation of new environmental maps units (Wermund and others, 1974).

From the above recognition of varied carbonate terranes, six carbonate environmental units are named: karstic tableland, karstic lowland, deeply dissected, moderately dissected, upland rolling, and low rolling. As shown in table 2 and reflected by their names, geomorphology related to process is the dominant criterion for defining these carbonate environmental units. Slopes were determined from mapping slopes in percent.

Clastic terranes also constitute an important proportion of the plateau. In reality they are also composed of carbonates, but they are treated separately, having formed by colluvial and fluvial processes. They are also shown in table 2 as flood plain, terrace, alluvial fan, and mixed colluvial-alluvial environmental units.

Results of this study are best shown as a series of maps of the thick carbonate terrane, the carbonates in the fault zone, and the alluvial-colluvial landscape.

Thick Carbonate Terrane

In the hill country and highland grazing area of thick carbonate rocks, the karstic tableland, deeply dissected, moderately dissected, and upland rolling units dominate the scene. Comparative illustrations of these environmental units are shown as sets of topographic, environmental, and slope maps of identical areas.

The karstic tableland is more widespread in the western half of the study area. It is composed of mostly limestone with rare dolomite. This unit has very low topographic relief (fig. 5), generally less than 30 feet. No slopes are measured larger than 5 percent. Not only can standing water occur in scattered local sinkholes but there are local sags, not easily explained by solution, which may contain standing water. However, because of the soil development, water generally infiltrates. There is minor runoff from the karstic tableland along its dissected edge.

The dominant slopes off the dissected margin of the karstic tableland vary in steepness and form (fig. 5). From the nearly flat karstic tableland, the slope steepens gently and is nearly planar or concave in the moderately dissected unit. Therein, all the slopes are <15 percent and frequently <5 percent. Where there is a rapid transition from the level karstic tableland into the deeply dissected unit, slopes steepen abruptly and most are convex. Within the deeply dissected unit all slopes are >5 percent; valley walls of headward-eroding streams generally exceed 15 percent. Some areas of <5 percent are too small to map at the final scale and are therefore considered as part of the deeply dissected unit.

The purpose of figure 6 is to show a clearer separation of deeply dissected and moderately dissected units. The moderately dissected unit includes large areas of <5 percent slope, whereas the deeply dissected unit has only small areas of <5 percent slope occurring as narrow floors of steep-walled valleys. The moderately dissected unit contains rare slopes >15 percent, whereas much of the deeply dissected unit has >15 percent slope. Both units have slopes between 5 and 15 percent. No quantitative boundary of percent slope is established to separate moderately from deeply dissected carbonate terrane (fig. 6).

The moderately dissected unit has a thin stable soil which is relatively mature. Its soil will support

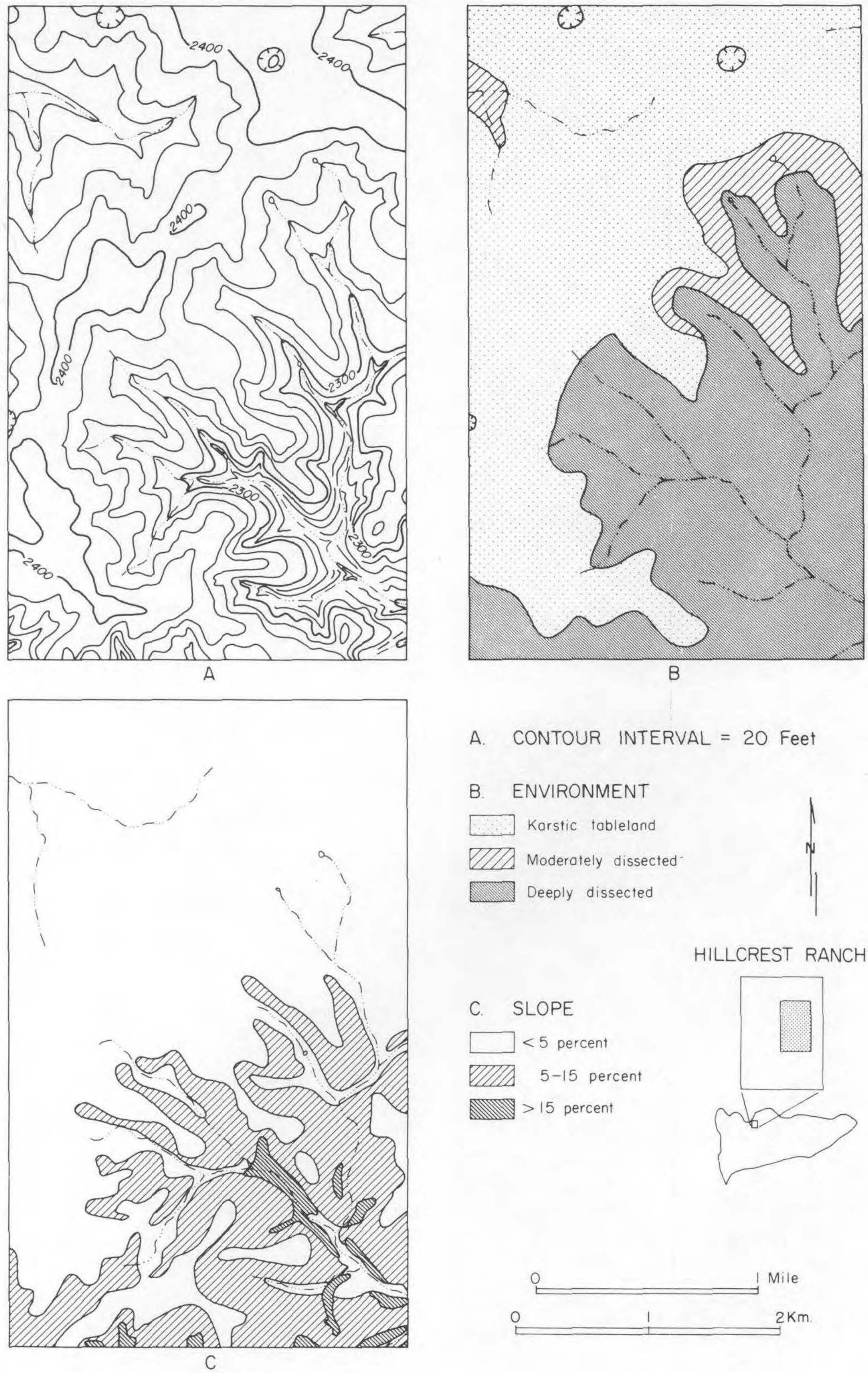

Figure 5. Contact of the tableland and dissected carbonate units showing A, topography; B, environmental; and C, slope units of Edwards Plateau.

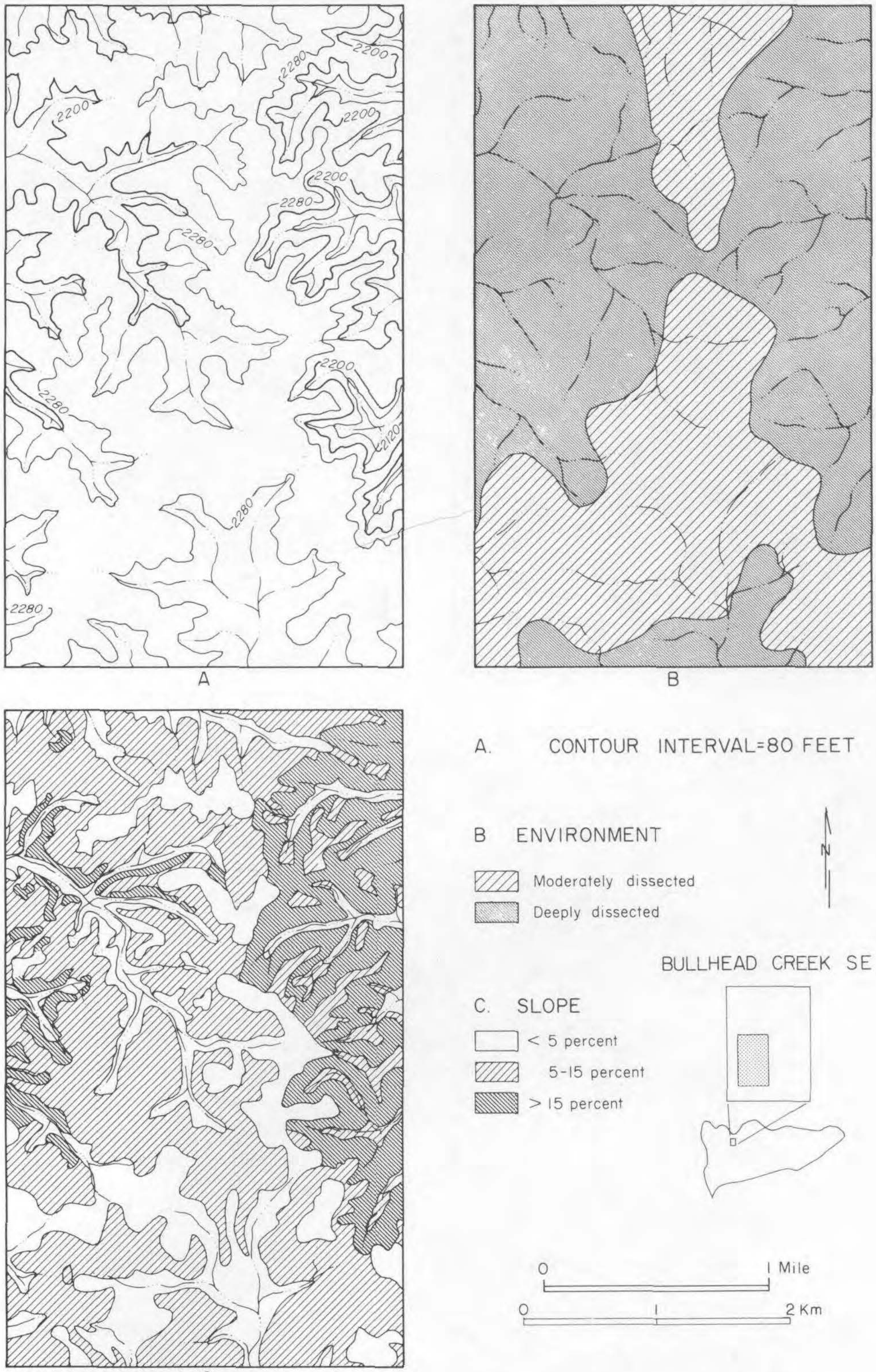

Figure 6. Contact of deeply and moderately dissected carbonate units showing A, topography; B, environmental; and C, slope units of Edwards Plateau.

grass and trees, and photography revealed that the surface was root plowed to remove the trees (fig. 6). Infiltration and recharge are more important than runoff here. The deeply dissected terrain has almost no soil and scrubby vegetation. Runoff is the dominant process for this unit.

Near headwaters of major streams in the eastern half of the area, an absence of older karst features is often reflected by the upland rolling unit (fig. 7). In some localities the upland rolling unit occurs on isolated divides having <5 percent slopes and no solution features. It always occurs on thick carbonate rocks. On the other hand, bedrock in the low rolling unit is generally a marly limestone giving rise to a recessive slope or to alternating beds of hard and soft carbonates. The predominant slopes are everywhere <5 percent (fig. 7) and may be gentle dip slopes. Where significant solution occurs, the topography becomes more rugged, leading to recognition of a karstic lowland unit.

In the fault zone, the downfaulted limestone shows fracturing and greater solution (fig. 8), and therefore has been noted as a separate environmental unit—the karstic lowland. The karstic lowland has slopes <15 percent; in areal extent the <5 percent and 5 to 15 percent classes of slopes are about equally represented. The sinkholes which occur in slopes of <5 percent may be young or old landforms and are frequently filled with clay. A reversal of topography can occur in clay-filled sinkholes; the topographic reversal is less than three feet. Even cursory inspection of aerial photographs of the karstic lowland reveals an increasing density of fracturing (lineations). This unit appears locally capable of rapid infiltration of precipitation into its moderate soil and has greater recharge than runoff overall.

Alluvial-Colluvial Landscapes

Figure 9 illustrates a representative distribution of the alluvial-colluvial environmental units: flood plain, terrace, alluvial fan, and the mixed unit. The flood plain occurs as a narrow, linear, slightly sloping area bordering underfit incised streams. The mapped flood plain is subject to high-frequency flooding. In the areas of incised meanders, the cutbank is one limit to the flood plain; on the point bar areas, there is generally a low terrace above the floor of the stream. The stream side of the low terrace, identifiable on stereo aerial photographs, equates with piles of old brush and litter deposited by floodwaters and observed in the field. Cypress trees that characterize the active flood plain are also identifiable on aerial photographs.

Perennial streams in the plateau are generally spring-fed. Most of the wider parts of the streams are generally the result of low man-made dams and concrete low-water crossings. Locally resistant limestone or dolomite beds form low dams and may pond water several feet deep a long way upstream. There is active recharge of bedrock throughout the flood plain both directly from the stream and indirectly through flood-plain alluvium.

The stream terraces occur as at least two and possibly three consistent mappable levels. Levels are not distinguished and only the terraces are mapped because they relate to the same alluvial process and are formed of the same materials everywhere. Physical processes, physical properties, slopes, resources, and land use are identical for each terrace level. The terraces, as well as the flood plain, everywhere include slopes less than 5 percent.

On stereo aerial photographs, the terraces are observed to clearly slope downstream. The terraces are never so level as to naturally pond water; generally terrace soils are so permeable that water will not pond. There are unusual areas where some terraces have caliche on the surface, and dissection of the calichified surface may develop swales which can hold standing water. Standing water is more likely in higher level terraces as they bear such heavy calichification that borrow pits are evident on the photographs at high terrace levels. Where there is widespread caliche in the terrace, runoff may exceed recharge. However, from field observations, the normal process on terraces is for recharge to dominate over runoff.

The alluvial fans are clearly distinguished by their fan shape. The head of the fan usually slopes >5 percent (fig. 7), but the predominant slope is <5 percent. Frequently, alluvial fans are cut by a relatively deep stream valley suggesting that the fans are older features than the modern drainage. In the field, deep calichification is observed with local sliding of new soil on top of the caliche. In photographs, caliche borrow pits are common in fans, and soil movement is noted as an irregularly rippled surface near the toe of fans. In addition to soil movement, there is a local colluvial contribution to the fans not readily apparent on photographs. The relative amounts of recharge versus runoff are regulated by the extent and degree of calichification in each fan.

As noted in table 2 of the environmental units, the mixed unit is a general identification of alluvial

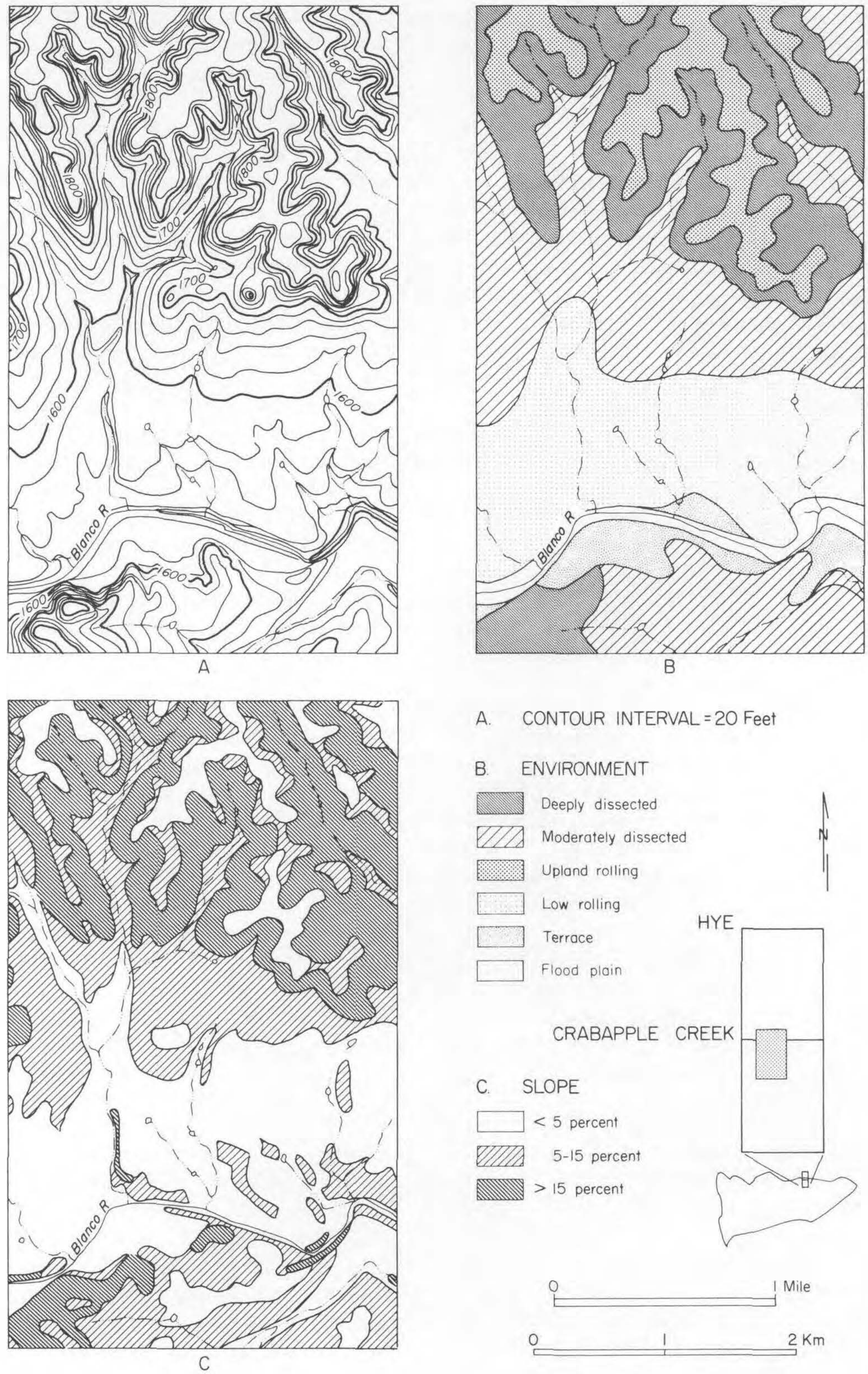

Figure 7. Comparison of deeply and moderately dissected with upland and low rolling carbonate units showing A, topography; B, environmental; and C, slope units of Edwards Plateau.

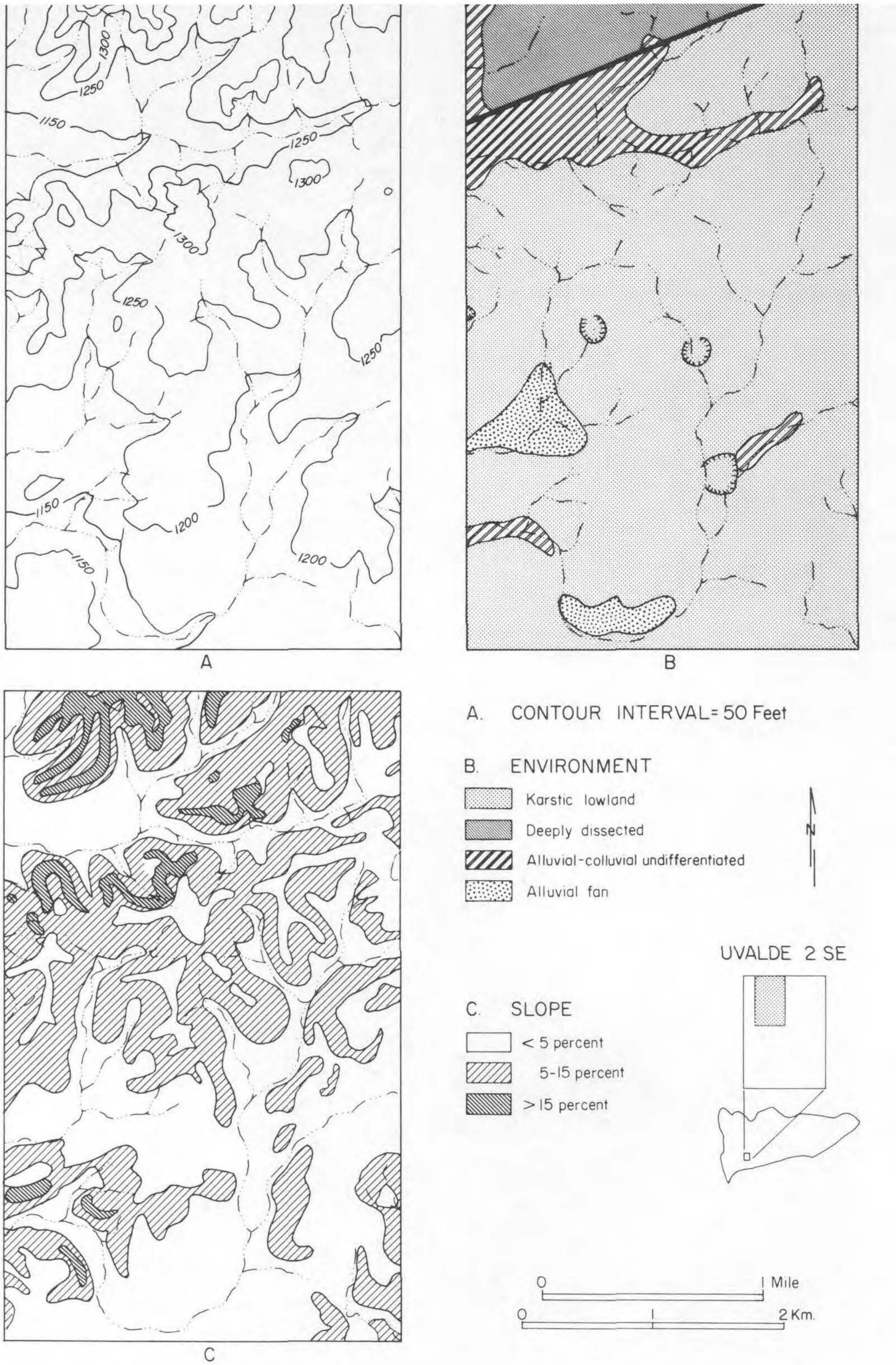

Figure 8. Balcones fault zone showing A, topography; B, environmental; and C, slope units of Edwards Plateau.

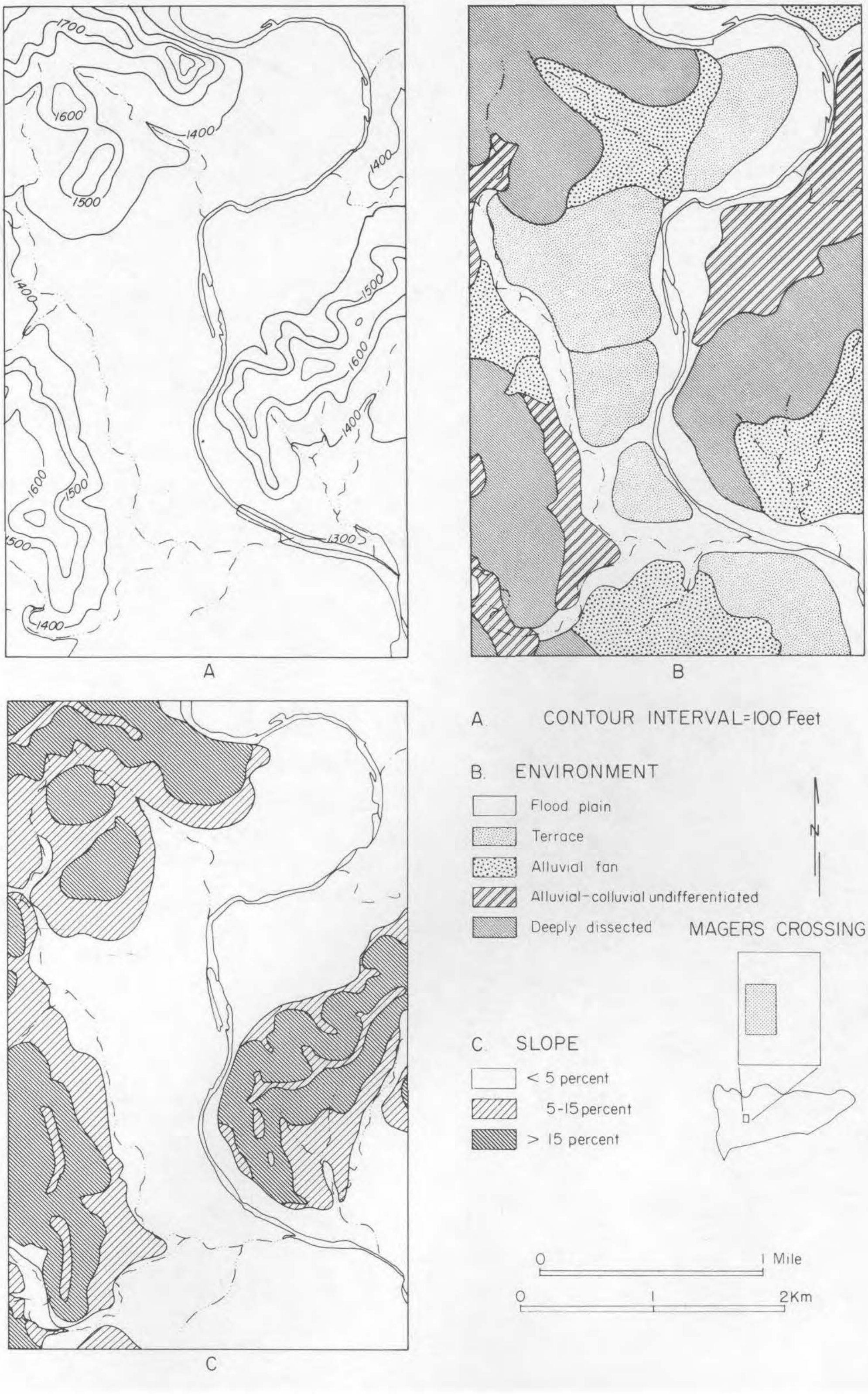

Figure 9. Alluvial valley showing A, topography; B, environmental; and C, slope units of Edwards Plateau.

and colluvial landscapes where it is not possible to accurately map flood plain, terrace, alluvial fans, and colluviation on aerial photographs. As might be expected, the shapes of mixed units are highly irregular. Slopes exceeding 5 percent are not uncommon on the mixed units. Generalizations regarding recharge and runoff would be inaccurate.

ENVIRONMENTAL UNITS OF THE ADJACENT INTERIOR COASTAL PLAIN

Rationale

The coastal plain is located south of most recharge into the Edwards Limestone aquifer. It is also south of both major faulting in the Balcones system and its corresponding topographic escarpment. Onto the coastal plain, the slope flattens markedly (fig. 2). Not only is the physiography different, so are the geology and man's activities on the land. There results a modification of the geological parameters which were significant in defining environmental units or resource capability units on the southern Edwards Plateau.

In the immediate area of the plateau escarpment, the single dominant element of the coastal plain is the fan plain (table 3). It is an apron of coalescing alluvial fans (Qaf in fig. 3) disgorged from the incised valleys of the plateau onto the adjacent low-relief plain; the fan-plain deposits both truncate and overlie Upper Cretaceous rocks (Kef, Ki, Kpg, Kau, Kac, and Kuf of fig. 3). This unit is an important self-contained aquifer of wedge-shaped widespread clastics commonly overlying impermeable shale. Therefore, it represents an area of both recharge and pumping. As a deep rich loamy soil develops on the fan plain, much of 2,000 square miles of lands irrigated by Edwards water is fan plain. It is clearly a particular and important environmental and resource capability unit.

Environmental units of the interior coastal plain, other than fan plains, stripped fan plains, flood plains, and terraces are derived on the basis of lithologic variations. The stripped fan plains are a special case of elevated older(?) fan plains stripped of their original soil profile leaving a dominantly gravel base. Sometimes a new soil has formed. Lithologic variations determine facies of known Upper Cretaceous formations. Environmental units are mapped as carbonate, chalk, sandstone, interbedded sandstone and shale, shale or mud, and volcanics (table 3). Properties such as shrink-swell characteristics or corrosive properties of shales, bedding thickness of limestones, and rippability of chalks determine the recognition of environmental units.

Distribution

Because the distribution of the regional facies of Upper Cretaceous rocks in the interior coastal plain case-study region is reflected by environmental units, muddy environmental units dominate the eastern and northeastern areas whereas carbonate units are most prominent in western areas—particularly west of the Nueces River. The units are most variable in the vicinity of San Antonio where units are affected by both the gradational contact of regional facies and minor faulting. Environmental units are more directly related to classical geological units in the coastal-plain province than in the plateau province. Therefore, environmental units related to definitions dependent upon compositional differences.

In the muddy environmental units northeast of San Antonio, the mud is corrosive with large shrink-swell ratios. Commonly, gravel caps mud-based hills (table 3). Depending upon the composition and distribution of the gravel, it may be recognized as either a stripped fan plain or stripped terrace environmental unit.

A complex of multiple environmental units of the interior coastal plain occur in a band between San Antonio and the Nueces River. An example of the distribution of numerous environmental units in a small area is shown in figure 10. Low-relief terrain is dominated by the fan-plain unit, as shown in the southern area. Maximum relief is dominated by volcanics which are quarried locally for basaltic trap rock. Moderate-relief hills are capped by a thin carbonate unit surrounded by shale. The shale outcrops west of San Antonio are stable units because of heavy calichification. Similarly the colluvial and alluvial units are cemented by caliche, sometimes to a depth of 12 feet.

West of the Nueces River, the entire section of Cretaceous coastal-plain rocks is dominated by carbonates. In this thick carbonate terrane, the units described in table 2 are again useful. As the lithology is relatively monotonous, the terrain becomes a prominent factor determining both land use and engineering properties. Also, as alluvial-colluvial units are similar in both the Edwards Plateau and interior coastal-plain provinces, these environmental units are employed in the same way in each province.

Table 3. Environmental units in the adjacent interior coastal plain.

Unit	Carbonate	Chalk	Sandstone	Shale or Mud
Normal relief (ft.)	20	10	40	10
Maximum relief (ft.)	100	40	40	80
Slopes	5-15%	<5%	5-15%	<5% abundant 5-15% common
Bedrock	Limestone. Usually 20 feet thick except in Nueces Basin thicker and massive	Chalk, about 15 feet, grades laterally into limestone	Indurated sandstone	Shale—some flaggy siltstone. Calichified west of San Antonio
Soil	Thin black clay	Black clay	Varied loam	Thick black clay
Vegetation	Cedar and live oak	Most diverse flora; has all types noted in paper	Post oak	Mesquite Prairie grass
Structure Morphology	Joint blocks sliding on underclay; associated with faulting	Rolling topography	Thick beds are crossbedded and jointed	Gently rolling topography
Man altered	Cleared of trees	Locally cultivated. Rare stock tanks	Cleared of trees	Stock tanks common, clay pits for bricks
Remarks	Maximum relief is in Nueces. In thick carbonates, go to units of table 2	Tough but not hard	Poorly indurated	Maximum relief results from gravel capping shale
Resource Capability Units	Floating thin limestone Rangeland	Jointed chalk Rangeland	Hard sandstone Rangeland	Stable Calichified Muddy Rangeland Pasture

Table 3 (continued)—

Interbedded Sandstone and Shale	Fan plain	Stripped Fan plain	Volcanic
60	10 (locally)	10 (locally)	60
100	160 (entire fan)	160 (entire fan)	200
>15%	<5%	<5%	5-25%
Variable sandstone; thickens in mud matrix	Gravel to mud clasts	Gravel mostly	Basalt
Loam and clay	Deep, calcareous, friable loam, Original soil	Thin to moderate calcareous friable loam, Late soil	Poor acidic soil
Mesquite Post oak	Prairie grass	Prairie grass	None
Jointed sandstones	Shallow residual braided channels	Shallow residual braided channels	Caves Some dikes
Stock tanks in shale, some root plowing	Tilled	Tilled or pasture	Rare quarrying
Sandstone; joint blocks float on shale	Widespread, all varied elevations. Braided pattern on surface of low channels (4′ deep, up to 20′ wide), active in yearly flooding	At higher elevations. Gravel behaves as cap-rock. Float onto underlying Cretaceous, especially muds	Makes up a minute area
Stable Interbed Rangeland Cropland	Arable gravel Aquifer	Gravel terraced Scrubby rangeland	Steep barren land Volcanics

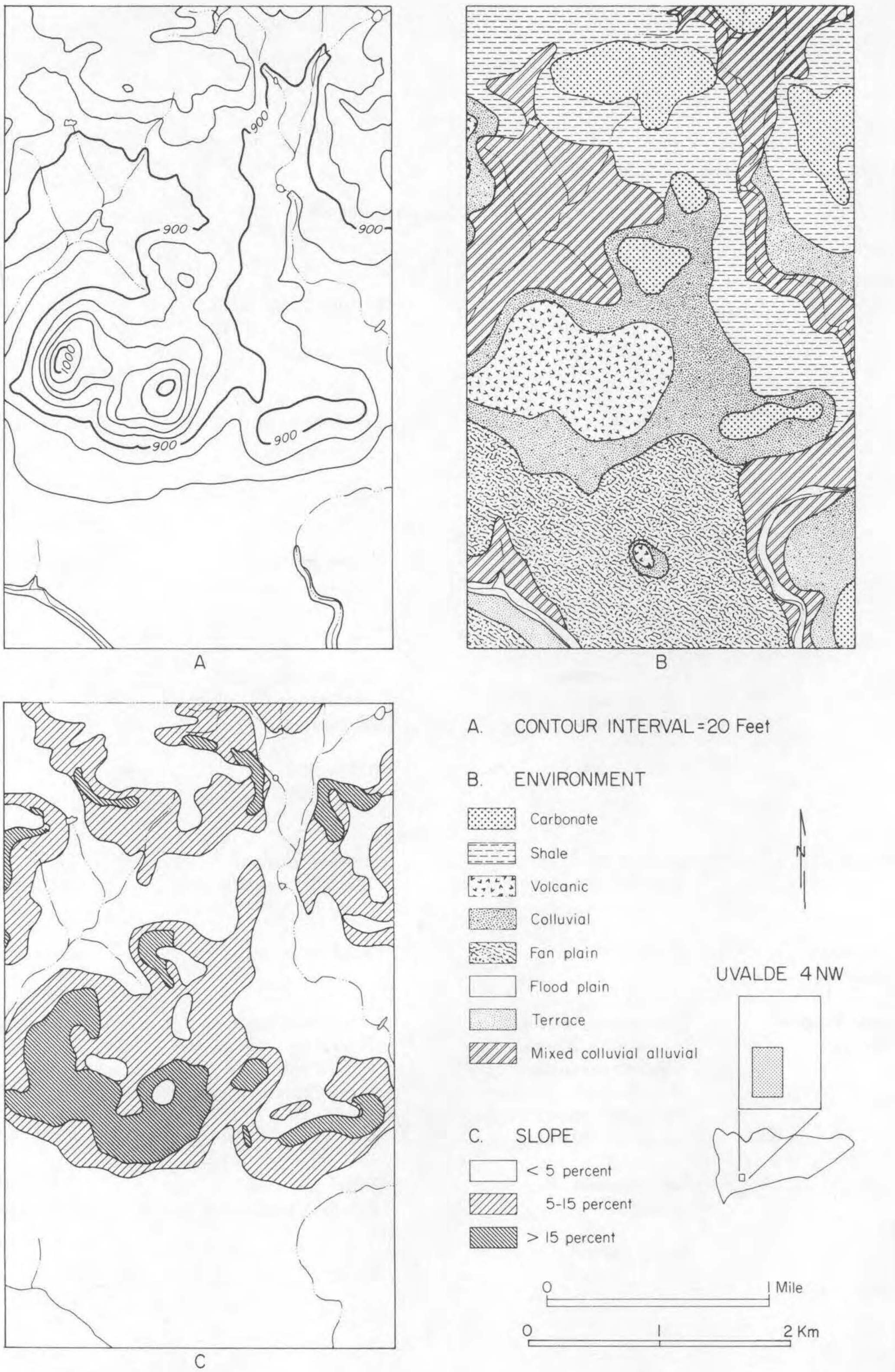

Figure 10. Adjacent interior coastal plain showing A, topography; B, environmental; and C, slope units.

ENVIRONMENTAL UNITS TRANSLATED INTO RESOURCE CAPABILITY UNITS

In the foregoing, environmental units were pragmatically defined from geologic parameters and strongly reflected the uses and needs of the land now and historically. For each terrane, both the historical adjustment by man and its potential productivity influence the derivation of environmental units as shown in the case study of the recharge zone for the Edwards Limestone aquifer. Man has till now sparsely settled this recharge zone, but additional uncontrolled human developments over the recharge zone can be degradational. Since affecting minimal environmental degradation is an essential part of defining resource capability units (Brown and others, 1971), it is worthwhile to translate environmental units into resource capability units.

In tables 2 and 3, environmental units are translated into resource capability units. The nomenclature reflects the bedrock, process if it is significant, and present use. For example, in table 2 the first item of karstic tableland is translated into a recharge-carbonate-rangeland, not always in identical order. In table 3, the sixth vertical unit is a fan plain, an environmental unit described as a resource capability unit—an arable gravel aquifer. Aquifer is indicative of a self-contained recharge process, and the very rich soil is emphasized. Certain environmental units need to be subdivided giving rise to more than one resource capability unit. An example is the shale or mud (table 3) which is a stable unit in areas of caliche formation. This same unit in a humid climate can be a very unstable plastic mud (an environmental unit) or an unstable mobile clay (a resource capability unit).

All the above definitions of environmental units and resource capability units reflect the base map scale of 1:24,000 to be presented at a 1:125,000 final scale. One should recognize that at smaller scales of mapping, much detail is lost; for example, in mapping Texas at a base scale of 1:250,000 for a final presentation scale of 1:500,000, nearly all the southern Edwards Plateau (fig. 1) would be mapped as a recharge carbonate.

CARBONATE TERRANES IN OTHER LOCALITIES

Based on mapping the resource capability units and environmental units of the Edwards Plateau in the case study, it appears valuable to apply this mapping experience to other localities. Examples of this application are shown in table 4 and figures 11–14. As man most densely populates the temperate humid regions, the first analogs are described from central and eastern United States. Areas of climatic extremes are discussed last.

In southern Indiana, the Upper Mississippian carbonates form an expansive outcrop. There the karst process has developed a mature terrain. An example of a carbonate resource capability unit dominated by sinkholes is illustrated by the West Corydon, Indiana, 7.5-minute quadrangle (fig. 11). In the internally drained sinkhole rangeland (resource capability unit), relief is low but most slopes exceed 15 percent. As most drainage is internal, it is doubtful that residual soil can maintain suitable moisture content throughout the year to permit farming. The rugged topography influences land use and, in the case of corridor structures like roads, makes engineering expensive.

A second example of a carbonate resource capability unit in a humid temperate climate is the Shenandoah Valley or Great Valley in the Appalachian Mountains. The Charles Town, West Virginia quadrangle is representative of one area in the Great Valley (fig. 12). Both a thickly mantled carbonate and thinly mantled shale and carbonate occur in the example. This is nearly the terminology of Hack (1965) describing geomorphology of the region. Slopes do not differ in the two units. Instead, the degree of soil development is the most important factor. The deep well-drained soils of the thickly mantled carbonate support productive apple orchards, whereas in the thinly mantled shale and carbonate, the land is generally pasture. Carbonate outcrops occur at the surface in many fields. As the bedding is vertical to moderately dipping throughout the Great Valley, structure will often influence the definition of resource capability units.

A third humid temperate example occurs in northern Alabama near Birmingham (table 4). An important residential and commercial area of the city suffers catastrophic sinkhole formation (Newton and Hyde, 1971). A pinnacle solution-weathering process has developed and is reflected by rapid variation in the thickness of the residual soil. Lowering of the water table produces rapid collapse of inherently unstable natural formations. Building foundations settle, sinkholes appear overnight in parking lots and highways, and linear cracks intersect railroad and highway rights-of-way. If this resource capability unit had been mapped prior to man's development, he would have been forewarned to avoid occupying this unit. Similar carbonate resource capability units occur in Africa

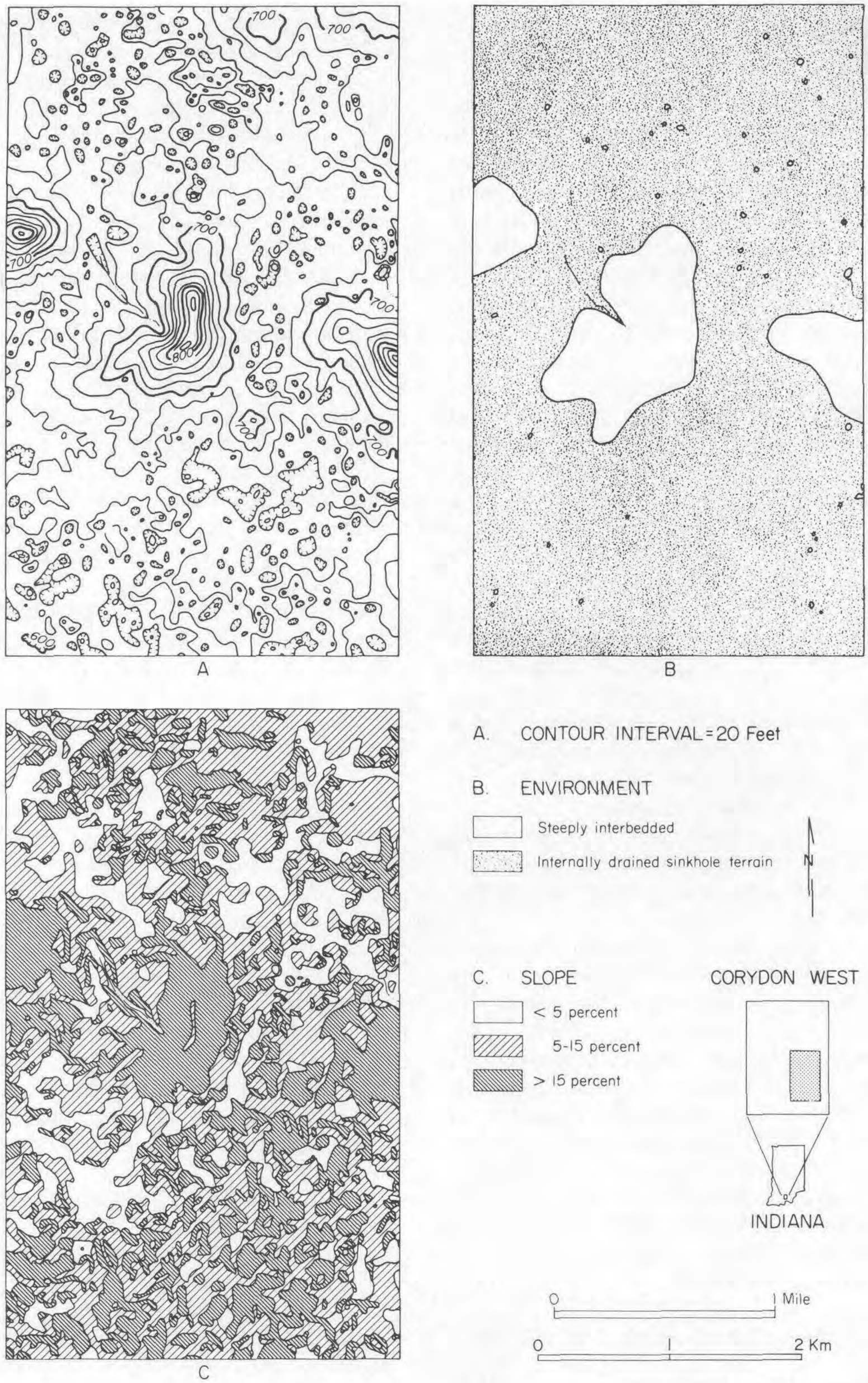

Figure 11. An internally drained sinkhole terrain in the West Corydon, Indiana quadrangle showing A, topography; B, environmental; and C, slope units.

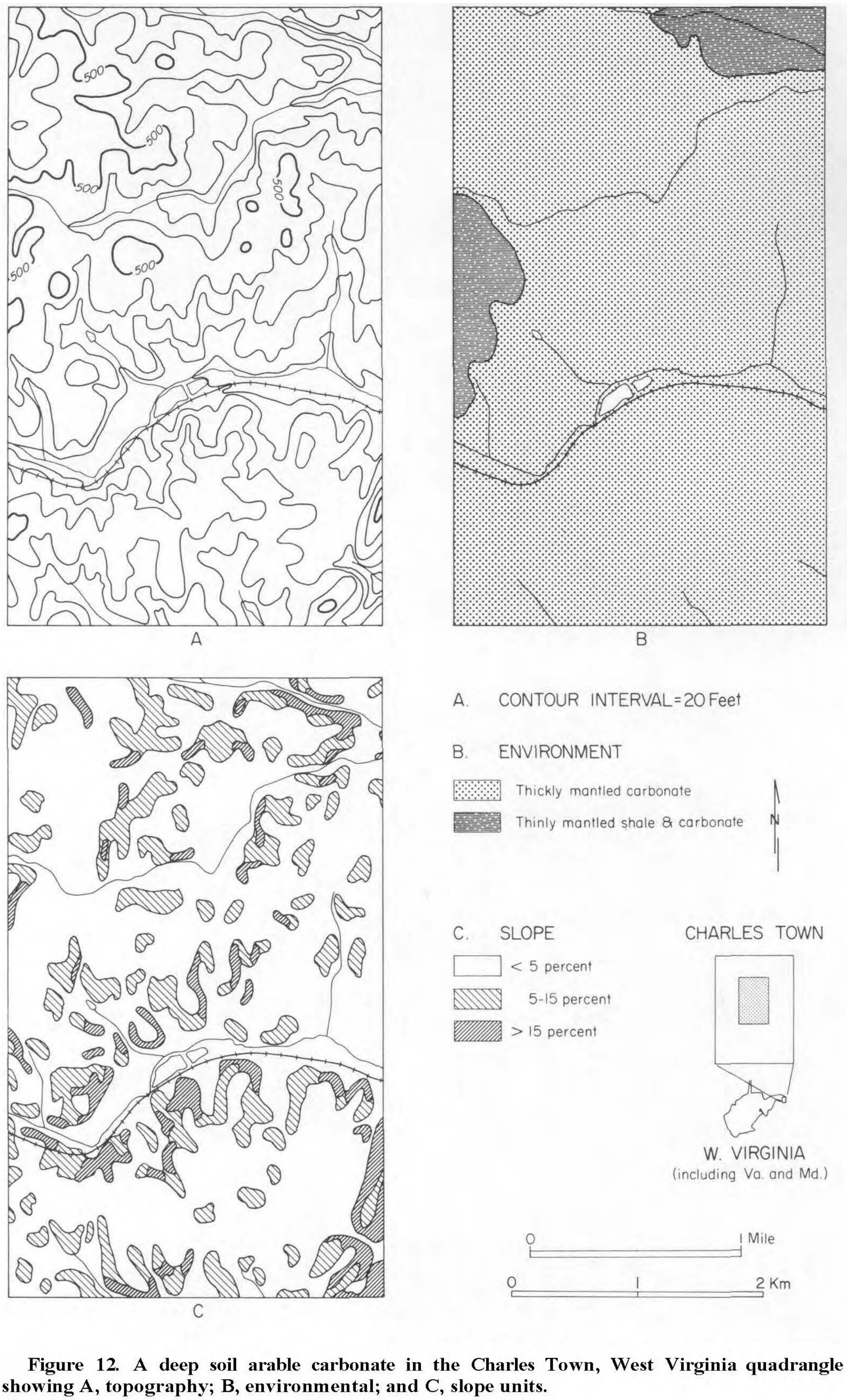

Figure 12. A deep soil arable carbonate in the Charles Town, West Virginia quadrangle showing A, topography; B, environmental; and C, slope units.

Table 4. Applications of case study-evolved concepts to other carbonate terranes—other environmental units.

Location	Southern Indiana	Great Valley, West Virginia	Northern Alabama	North-Central Texas	Central Yugoslavia	Northeastern Libya	Northern Puerto Rico
Formation	St. Louis Limestone St. Genevieve Limestone	Conococheague Limestone	Ketona Dolomite	Winchell Limestone	Mesozoic	Eocene	Aguada Limestone
Reference	Gray and others, 1970	Hack, 1965	Newton and Hyde, 1971	Wermund, 1966	Herak, 1972	Desio, 1968	Briggs & Akers, 1965
Climate	Humid Temperate	Humid Temperate	Humid Temperate	Subhumid	Mediterranean	Arid	Rain forest monsoon
Resource Capability Units	Internally drained Sinkhole Rangeland	Deep soiled Arable Carbonate	Catastrophic Sinkhole Carbonate Suburban	Limestone Pavement Rangeland	Rugged Karstic Carbonate Rangeland	Barren land Cliffs Hamadas	Cockpit karst Unused land
Bedrock	Cherty limestone interbedded with marl and dolomite in upper part	Limestone of impure limestone and dolomite with some cherty beds	Dolomite, coarsely crystalline	Limestone with rare thin shale interbeds	Dolomite, limestone breccias	Limestone and marl	Limestone Thick-bedded with chalky limestone and marl
Maximum relief (ft.)	60	70	35	25	600	80	300
Slopes	Generally >15%, <5% is rare	Mostly <5%	<5%	<5%	Mostly >15%	Mostly <5%, up to 15% on escarpments	>15%
Soil	Red clay	>40 feet, brown, silty and sandy loam	5-75 feet red clay	Black-brown acid clay	Thin terra rosa	Barren	Reddish silty loam
Vegetation	Scrubby	Cleared deciduous hardwood	Wooded where not habitated	Prairie	Brushy	Rare shrubs on hills	Rain forest
Structure	Nearly flat beds	Moderate to near vertical dips	Moderate to steep dips	Strongly jointed. Flat beds	Faulted, nearly flat beds	Nearly flat beds	Almost flat bedding
Man altered	Cleared pasture	Pasture and orchards	Suburban—commercial building	--------------	--------------	--------------	Any flat area is farmed
Remarks	Internal drainage	Rare sinks marked by residuum	Pinnacle weathering indicated by variable soil thickness	Dip-slope bare rocks; no workable soils; pasture in part	Classical rugged karst	Some residual karst of another climate and time	Can be developed as an aquifer

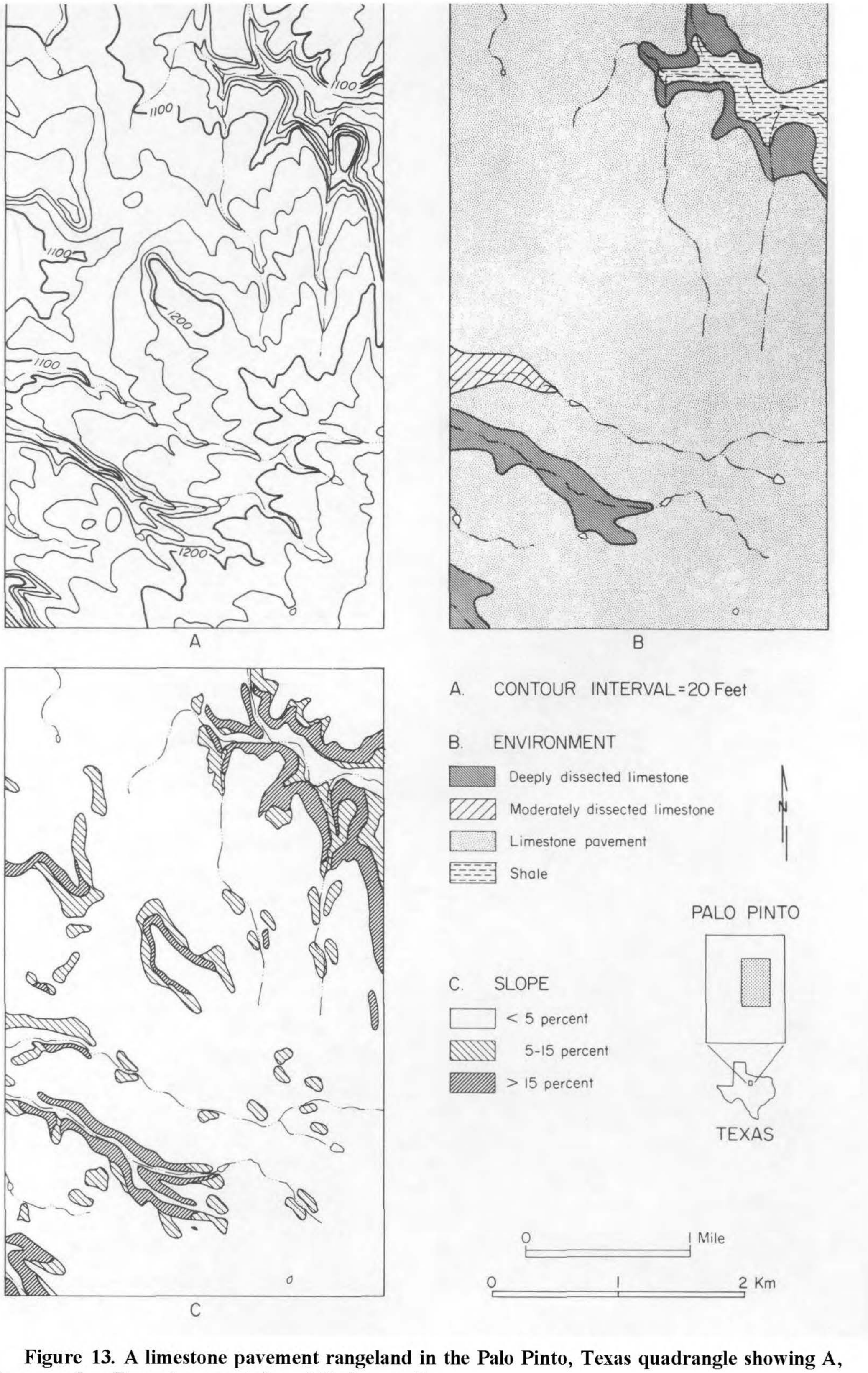

Figure 13. A limestone pavement rangeland in the Palo Pinto, Texas quadrangle showing A, topography; B, environmental; and C, slope units.

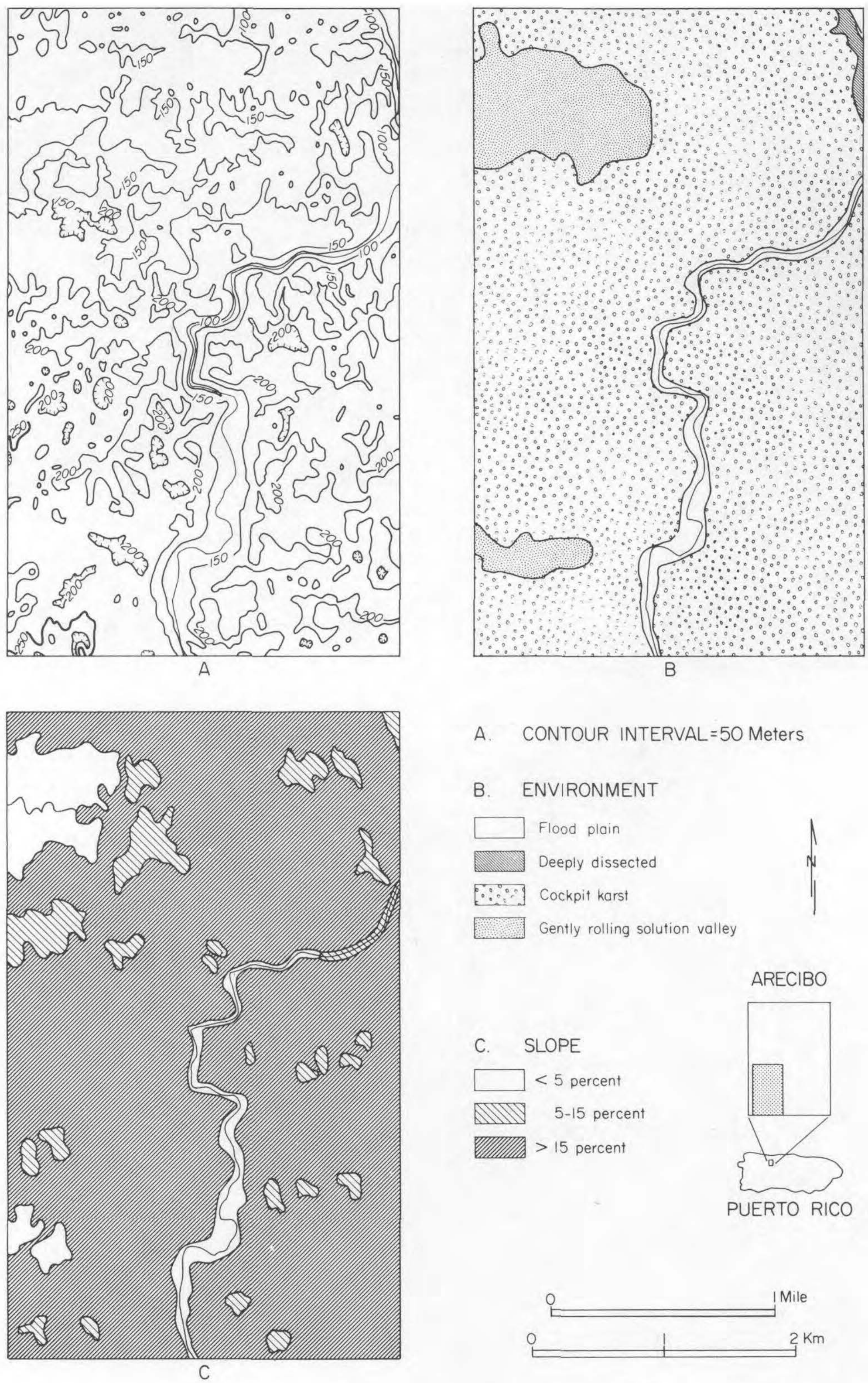

Figure 14. A cockpit karstic limestone in the Arecibo, Puerto Rico quadrangle showing A, topography; B, environmental; and C, slope units.

where catastrophic collapse has killed people (Foose, 1967).

A semiarid terrain north of the case-study area was selected for a particular feature—a limestone pavement. The example occurs in the Palo Pinto, Texas quadrangle (fig. 13). Most of the limestone pavement has slopes of less than 5 percent. The unit occurs on the Winchell Limestone which dips less than one-half degree to the northwest (Wermund, 1966). The limestone at the surface is strongly jointed and thin beds form a rough riding surface of micro-steplike topography. The limestone pavement resource capability unit can support no use other than grazing. Similar pavements occur the world over and in variable climates. In some places as in Yugoslavia (Herak, 1972, fig. 4), limestone pavements may be deeply fluted and grooved by karren and lapiaz tens of feet deep. Such pavements with corrosional relief may be barren and nearly impassable for man and animals.

Further corrosional effects along with doline (sinkhole) formation in semiarid or Mediterranean climates develop very rugged landscapes (Herak, 1972, fig. 5) as shown in table 4. The differences among the Yugoslavian terrain, the rugged-karstic-carbonate-rangeland resource capability unit, and the deeply dissected carbonate environmental unit in the case-study area (and fig. 13) are related to process. The rugged karstic terrain is altogether formed by solution-dominated processes, whereas the deeply dissected unit is dominated by headwardly-mechanically eroding streams. One of the most inhospitable terrains developed on carbonates is the solution-controlled cockpit karst formed in climates epitomized by tropical rain forests. The illustration shown near Arecibo, Puerto Rico, is an excellent example (fig. 14). Although the maximum relief is no more than 100 meters per kilometer, there are no slopes less than 15 percent, except on valley floors. The land is nearly uninhabitable, although rare flat valleys are farmed. In part this reflects a strong population pressure rather than a natural environment in equilibrium. However, for nearby large coastal cities, this cockpit karst terrane may be a significant recharge zone (Briggs and Akers, 1965).

Having shown the highest rainfall situation within a carbonate terrane, as in Puerto Rico, the opposite climate ought to be described. An arid climatic carbonate terrane is documented for Libya (table 4). To look at illustrations of this terrane (Desio, 1968, photos 1 and 2), it may seem facetious to describe barren land cliffs and hamadas as a resource capability unit. Nevertheless, as man gains some controls over climate and weather, part of managing such controls will relate to resource capability units. This terrain can be fertile given enough moisture.

SUMMARY AND CONCLUSIONS

It has been shown that the derivation of both environmental and resource capability units in a case-study area of carbonate terrane reflects both the geology and land use presently practiced by man. A significant complementary parameter is a decision toward future possible land use or resource capability in varied geologic terranes. Philosophies and practices generated while environmental geologic mapping a case-study area of carbonate terrane are readily applied to other worldwide carbonate terranes. It is also evident that climate is a major factor determining resource capability, as it largely affects the observable geology everywhere.

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PRELIMINARY ENVIRONMENTAL GEOLOGIC MAPPING ON THE INNER COASTAL PLAIN, SOUTHWEST TEXAS

Thomas C. Gustavson and P. Jan Cannon

INTRODUCTION

The inner Coastal Plain of southern Texas presents some interesting problems to the environmental geologist.

The area is predominantly rural, and its agriculture contributes large quantities of grains, cotton, and livestock to national markets. Furthermore, several major ground-water recharge areas are located within the inner Coastal Plain. Land use, consequently, is largely determined by its suitability for agriculture.

The study area is part of a larger mapping program undertaken by the Bureau of Economic Geology for the Texas Water Development Board to provide environmental geologic data for the Carrizo-Wilcox, Queen City, and Edwards aquifers and their recharge areas. The Carrizo-Wilcox and Queen City aquifers occur, in part, within the region discussed in this paper and supply most of the ground water used by municipalities, agricultural operations, industries, and individuals within the study area.

This paper will discuss and illustrate the means by which the environmental geologic units used to map the environmental geology of the study area were derived. The present land use and the potential resources of these units will also be discussed.

GEOLOGY

The area of study extends in a broad band from the eastern divide of the Guadalupe River drainage basin on the east to approximately the longitude of Eagle Pass on the west (fig. 1). The northern limit lies south of the Balcones Escarpment, but within the Balcones fault zone. Throughout most of the area, Tertiary clastic sediments are exposed (fig. 2). In the fault zone and at the western limit of the area, however, Cretaceous clastic and carbonate sediments are exposed. The Cretaceous units are predominately shallow water carbonates and shales. A widespread regional unconformity marks the base of the Tertiary sediments in the study area. Following a period of erosion, a Paleocene marine transgression resulted in the deposition of the shelf muds of the Midway Formation. Sedimentation continued into the Eocene with deposition of Wilcox sand and mud facies which are thought to have originated as extensive barrier bar and lagoon-bar systems (Fisher and McGowen, 1967). The overlying Carrizo Sand is predominantly a fluvial deposit and represents a return to nonmarine deposition. The sediments of the Reklaw Formation lie stratigraphically above the Carrizo Sand and consist of heavily iron-stained marine sands and shales. The youngest Tertiary units exposed in the study area are the Queen City and Reklaw Formations. The Reklaw Formation is the shelf and prodelta facies of the episode of deltation in which the Queen City Formation represents the sandy deltaic and strandplain facies (Guevara and Garcia, 1972). Outcropping Tertiary units contain progressively lower percentages of sand toward the west.

Extensive gravel units derived mostly from the Edwards Plateau in the eastern portion of the area and from the Big Bend area in the west lie unconformably above the coastward-dipping Cretaceous and Tertiary units. These gravels occur both as dissected alluvial plains where the gravel thickness may exceed 40 feet, and as gravel veneers or drapes across other coastal-plain units. These veneers or drapes are the residual gravels that are the basal part of, or are colluviated material derived from older, much dissected gravel deposits. The age of both gravels is somewhat problematical.

The large outcrop areas of sands within the northern part of the inner Coastal Plain have provided excellent sources of eolian material resulting in numerous localized areas of eolian sand sheets and dunes. The broad, flat dunes reach 15 feet in height and 100 feet in width. The sand sheets are commonly less than 5 feet thick and spread over several acres. Both are stabilized by vegetation.

Caliche is present throughout the entire area. Units which were originally highly permeable, such as gravels and some terrace deposits, may be heavily calichified in the eastern part of the area, whereas units of low original permeability contain only disseminated $CaCO_3$ nodules. Westward, however, calichification becomes increasingly pervasive, apparently irrespective of substrate composition.

The environmental geologic units described in this paper are generally underlain by slightly dipping, dissected, unindurated clastic sediments

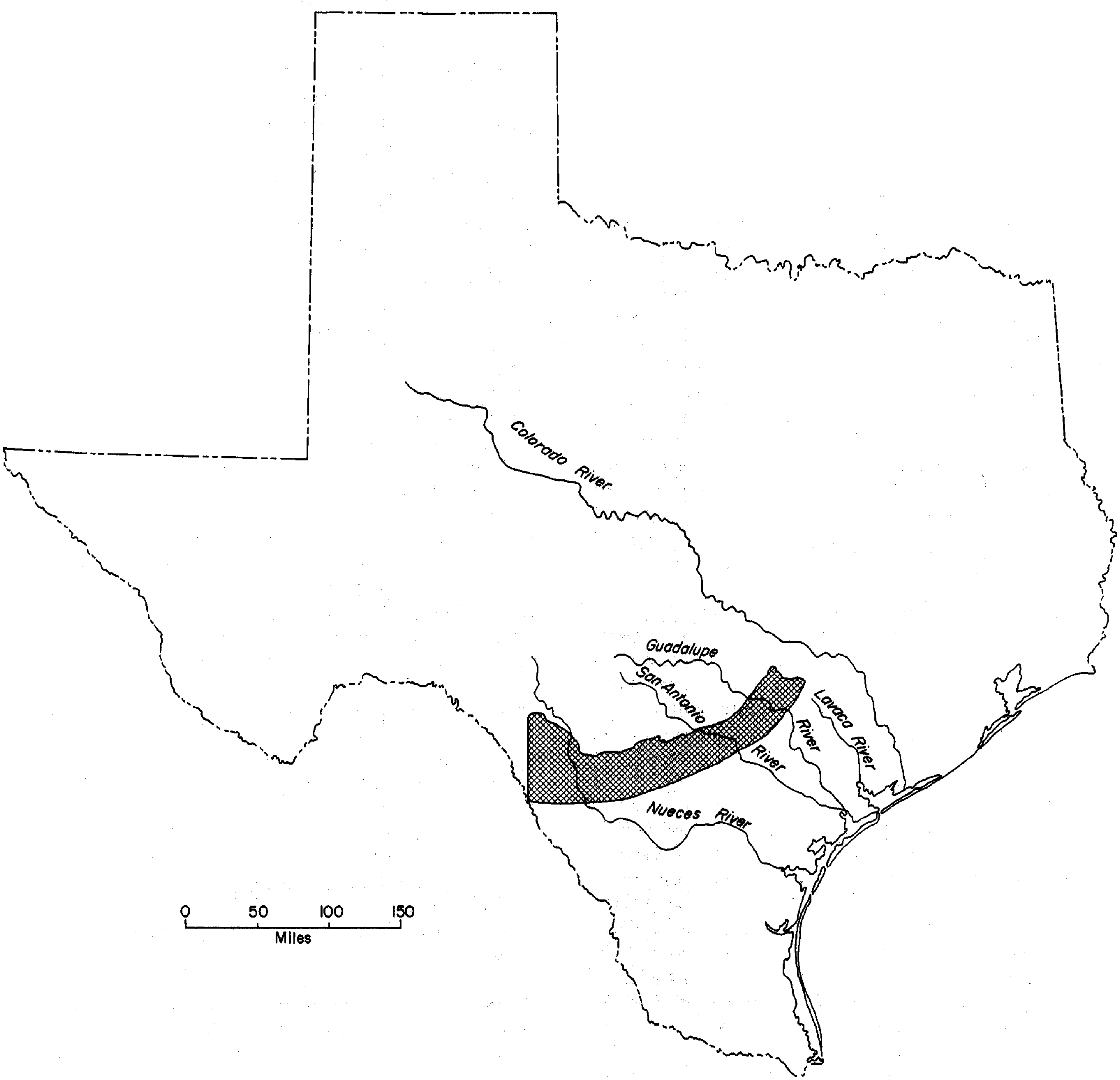


Figure 1. Location of environmental geologic mapping, discussed in this report, on the inner Gulf Coastal Plain of Southwest Texas.

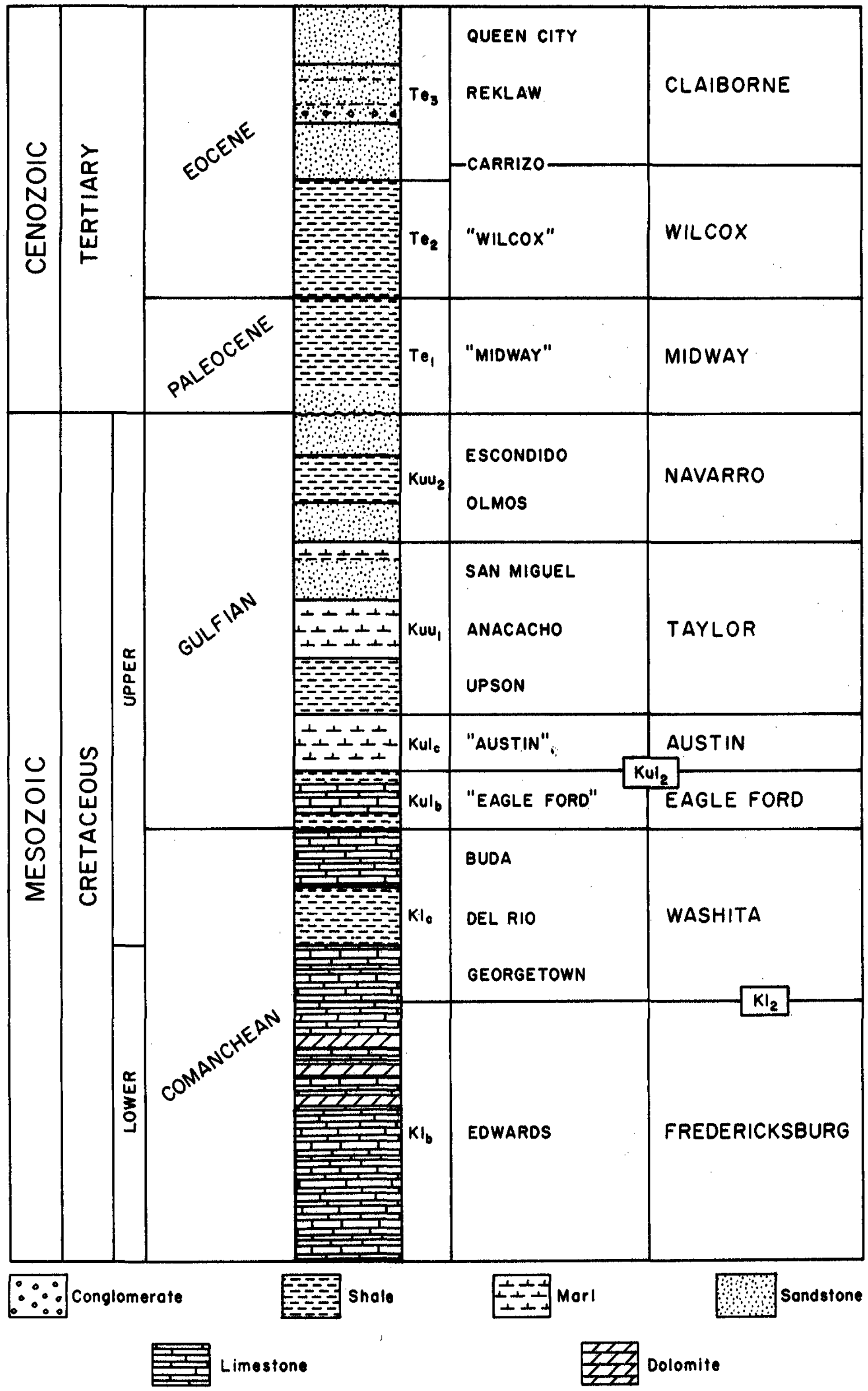


Figure 2. Stratigraphic column, Southwest Texas inner Coastal Plain. Adapted from the Geological Highway Map of Texas (Renfro and others, 1973).

and differ substantially from the flat-lying, largely undissected sediments of the outer Coastal Plain (Fisher and others, 1972), and from the predominately well-indurated carbonate units of the Edwards Plateau (Wermund, 1974).

PHYSIOGRAPHY

The area lies within the western Gulf Coastal Plain physiographic province (Fenneman, 1938). The topography east of the Nueces River consists of a series of alternating cuestas developed on gently dipping, resistant Cretaceous and Tertiary units with intervening lowlands developed on more easily erodible sediments. The major drainage systems—the Nueces, San Antonio, Guadalupe, and Lavaca Rivers—lie nearly transverse to the northeast-to-southwest regional topographic trend. Typically these streams lie within wide flood plains and are associated with numerous terraces. High-level, dissected gravel alluvial plains are commonly associated with the major drainage lines and also transect the regional topographic trend.

Within the drainage basin of the Nueces River and westward, the physiography and geology of the study area change markedly. The absence of an escarpment along the Balcones fault zone is reflected in the gradual southward change from the rugged topography of the Hill Country to the moderately rolling topography of the limestone terrane. Farther south, the moderately rolling limestone terrane is replaced by low rolling terrane of the Cretaceous and Tertiary clastic sediments of the inner Coastal Plain. The Balcones fault zone, which nearly bisects the study area west of the Nueces River, is marked by faulting along the north side of the Anacacho Mountains and by numerous Cretaceous-Tertiary basalt plugs. Westward of the Anacacho Mountains the Balcones fault zone is obscured beneath a flat gravel plain. The gravel plain, lying along the western margin of the study area, is largely undissected, but contains several large deflation basins.

CLIMATE AND VEGETATION

Climate, in addition to the physiography and substrate composition of an area, is a major factor in land capability. The dominant climatic factors within the study region are shown in figure 3. All of these factors illustrate an increase in aridity to the west reflected both by an increase in temperature and by a decrease in available moisture. Vegetation and soils reflect the subhumid environment of the eastern portion of the study area and are closely controlled by physiography and substrate composition. A great variety of trees, shrubs, and grasses are extant, and in general are closely tied to a particular substrate composition. Westward, particularly west of the Nueces River, vegetation and soils reflect the increasing aridity and become much less dependent on substrate composition and slope. In the east, deciduous oaks, for example, occur on sandy substrates, live oaks occur over calcareous substrates, and mesquites occur over muddy substrates. Westward the deciduous oaks and live oaks decline in importance and are not found in the western limits of the study area although the sandy, muddy and calcareous substrates persist. Here the heavily calichified, rocky, arid and subarid soils show little substrate or slope control and are vegetated with mesquite, cacti, thorny shrubs, and short and mid-length grasses.

Precipitation throughout the area is episodic and consequently becomes an increasingly effective geologic process towards the southwest as vegetative cover decreases.

ENVIRONMENTAL GEOLOGIC UNITS—CRITERIA AND MAPPING METHODS

The environmental geologic units (table 1) used in this report are similar in definition to the resource capability units of Brown and others (1971). Environmental geologic units were established in order to define and catalog areas where similar activities and similar amounts of activity could be carried out without losing acceptable levels of environmental quality. The elements which define environmental geologic units include: (1) geologic substrate and soil, (2) topography and landform morphology, (3) geologic process, (4) biota, and (5) human activity. In certain cases an environmental unit is comprised of several elements. For example, the sand hills unit used in this report is defined in terms of both geologic substrate and topography, while the black soil alluvial plain is defined in terms of geologic substrate, soil, and landform morphology. The black soil alluvial plain unit is an alluvial plain composed of sand and gravel on which a thick black or dark-brown clay loam has developed. On the other hand, some units are defined on the basis of a single element. The gravel cap unit is defined by its composition, and oil fields are the result of human activity.

Environmental geologic map units were determined from stereographic aerial black-and-white

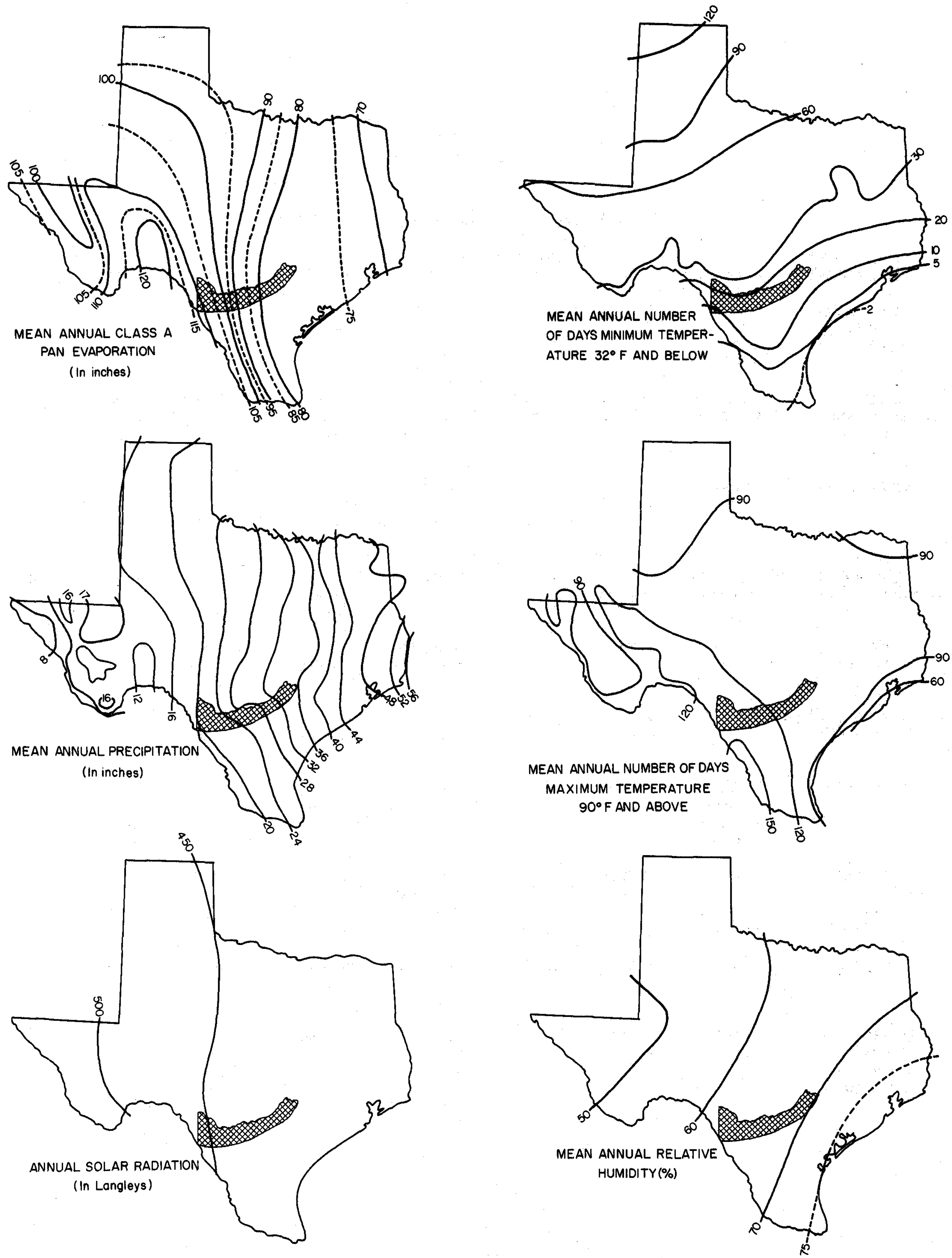


Figure 3. Texas climatic factors. From the Climatic Atlas of the United States (1968).

Table 1. Characteristics of Environmental Geologic Units

ENVIRONMENTAL GEOLOGIC UNIT	SUBSTRATE	RELIEF	MAXIMUM SLOPE (%)	SOIL	VEGETATION	PROCESS	RESOURCE CAPABILITY
BLACK SOIL ALLUVIAL PLAIN	Heavily calichified sand and gravel	Nearly flat	2	Silty or clay loam, may be gravelly	Grasses, mesquite	Runoff, infiltration, recharge	Arable, aquifer, rangeland
DISSECTED BLACK SOIL ALLUVIAL PLAIN	Calichified gravel and sand	Moderate to gentle	12, rarely to 20	Clay loam, gravelly clay loam	Grasses, scattered live oak, mesquite	Recharge, infiltration, runoff	Rangeland, gravel aquifer
GRAVEL CAP	Gravel	Moderate to gentle	5	Gravelly sand, gravel, or gravelly sandy loam	Post oak, blackjack oak	Infiltration, runoff	Rangeland, gravel
MODERATE-RELIEF SANDY MUD	Interbedded sands and mud	Moderate to gentle	6	Sandy clay loam	Grasses, mesquite, acacia	Runoff, infiltration	Rangeland, aquifer
LOW-RELIEF SANDY MUD	Interbedded sands and mud	Gentle	3	Sandy clay loam	Grasses, mesquite, acacia	Runoff, infiltration	Rangeland, arable, aquifer
MODERATE-RELIEF CLAYEY MUD	Mud	Moderate to gentle	5	Silty and clay loam, clay	Grasses, mesquite, acacia	Runoff, gilgai formation	Rangeland
SAND HILLS	Friable and loose, locally iron-cemented sand	Moderate	5	Sand and sandy loam	Post oak, blackjack oak	Recharge	Aquifer, rangeland, wildlife, forest
HIGH-RELIEF IRON-CEMENTED UPLANDS	Heavily iron-cemented clastics	Moderate to steep	10	Erosional thin rocky soils	Oak forest	Runoff	Rangeland
OIL FIELDS	Variable	Variable	Variable	Variable	Variable	Runoff, infiltration	Production of crude oil
MODERATELY DIPPING, DISSECTED CARBONATE	Limestone, marl	50 - 250 feet	20 - 100	None to loose thin lithosol	Mesquite, grasses	Slumping, debris slides and flows, rainwash	Grazing

HIGH GRAVEL PLAIN	Caliche, calichified gravel, gravel	20 feet	1 - 2	Very thin caliche soil	Mesquite, grasses	Eolian, runoff	Grazing
DISSECTED HIGH GRAVEL-PLAIN MARGIN	Gravel	10 - 20 feet	20 - 60	None	Sparse mesquite, grasses	Gullying mass wasting	Grazing
BEDROCK AND TALUS	Shale, limestone, basalt, talus debris	Variable	Variable	None, loose rock, or thin lithosol	Mesquite, sage, thorny brush, grasses	Mass wasting	Grazing
CALCIUM CARBONATE CEMENTED SANDSTONE	Sandstone	40 - 120 feet	Variable	None, loose sand, or thin lithosol	Mesquite, sage, live oak, grasses, brush	Mass wasting, deflation, infiltration	Grazing
INTERBEDDED SANDSTONE AND SHALE	Sandstone and shale	30 - 70 feet	Variable	None, or loose rocky soil	Mesquite, sage, grasses	Mass wasting, runoff	Grazing
ALLUVIAL APRON	Caliche, cemented limestone, gravels	5 - 20 feet	5 - 60	None to thin lithosols	Juniper, cactus, mesquite, grasses	Mass wasting, sheetwash, flooding, runoff	Grazing
FLOOD PLAIN	Sand, silt, and clay, alluvium, gravel rare	Nearly flat	2	Fine sandy, silty, or clay loam	Pecan, grasses	Flooding, infiltration, runoff	Arable, rangeland, aquifer
TERRACE	Sand, silt, and clay, alluvium, gravel infrequent	Nearly flat to gentle	3 - 5	Fine sandy, silty, or clay loam	Grasses, scattered pecan	Infiltration, runoff, very rare flooding	Arable, rangeland, aquifer
MIXED FLUVIAL AND COLLUVIAL	Variable, but mostly sand and silt	Variable	Variable, generally concave up	Sandy, silty, or clay loam, clay	Variable	Infiltration, runoff	Rangeland, arable
MODERATELY DISSECTED CARBONATE TOPOGRAPHY	Limestone	50 - 300 feet	6 - 10	None to thin lithosol	Juniper, cactus, mesquite, grasses	Debris slides, sheetwash, rilling	Grazing
GENTLY ROLLING LIMESTONE TOPOGRAPHY	Limestone	20 feet	3 - 5	None to thin lithosol	Juniper, cactus, mesquite, grasses	Sheetwash, rilling	Grazing

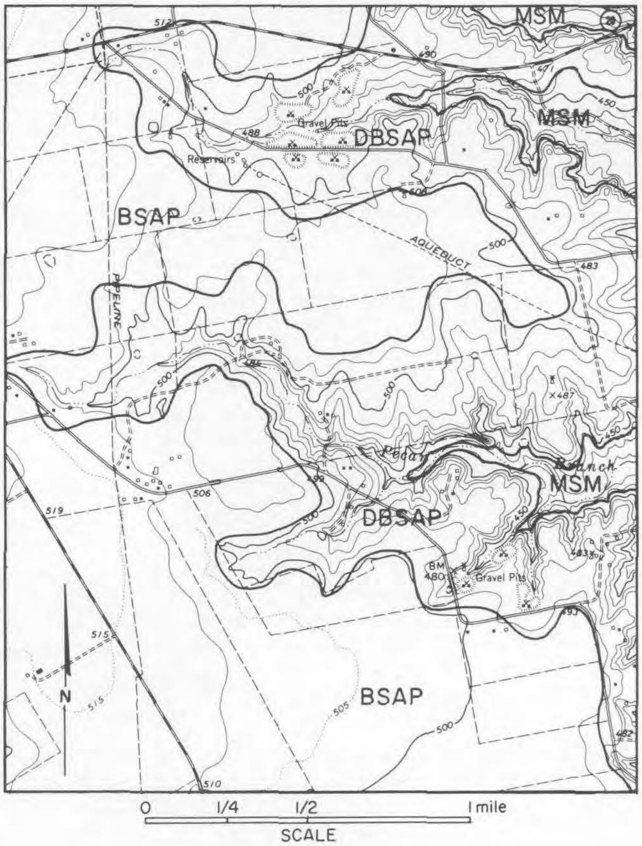


Figure 4. Environmental geologic units: BSAP, black soil alluvial plain; DBSAP, dissected black soil alluvial plain; MSM, moderate-relief sandy mud. On an aerial photograph and topographic map of a portion of the Lockhart South quadrangle. (U.S.G.S. topographic map, Lockhart South Quad., Tx.; aerial photograph reproduced with permission of Tobin Surveys, Inc.)

photographs, scale 1:40,000 and 1:80,000. Units were delineated in terms of color tone, tonal patterns, vegetation patterns, relief, and landform morphology. Units delineated on aerial photographs were carefully field checked to confirm or ascertain the composition of substrate materials. Environmental geologic units observed on aerial photographs were generally found to be consistent with limits observed on the ground surface. After field checking, the units were transferred to 1:24,000-scale topographic maps, eventually to be reduced to a scale of 1:125,000.

Using this method, 21 environmental geologic units were recognized: (1) black soil alluvial plain, (2) dissected black soil alluvial plain, (3) gravel cap, (4) moderate-relief sandy mud, (5) low-relief sandy mud, (6) moderate-relief clayey mud, (7) sand hills, (8) high-relief iron-cemented uplands, (9) oil fields, (10) moderately dipping, dissected carbonate unit, (11) high gravel-plain unit, (12) dissected high gravel-plain margin, (13) bedrock and talus units, (14) calcium carbonate cemented sandstone, (15) interbedded sandstone and shale, (16) alluvial apron, (17) flood plain, (18) terrace, (19) mixed fluvial and colluvial material, (20) moderately dissected carbonate topography, and (21) low rolling limestone topography.

Flood plains, terraces, mixed fluvial and colluvial material, alluvial apron, and moderately dissected and low rolling limestone topography have been described by Wermund (p. 52). The remaining units are described below.

Black soil alluvial plain.—Numerous large alluvial surfaces were developed as extensive gravel deposits built outward from the escarpments along Balcones fault zone. The alluvial surfaces are generally underlain by thick sequences of gravel and sand composed predominantly of carbonate material and a smaller amount of admixed siliceous clasts. The sands and gravels are calichified to various depths and form the calcareous base on which thick black clayey, organic-rich soil—a Chernozem—occurs. These surfaces, probably originally grasslands, are 95 percent cultivated, producing mostly cotton and maize. On aerial photographs of the eastern part of the area, they are recognized as flat cultivated areas that are usually topographically high and surrounded by moderate to steep slopes (fig. 4). West of the Sabinal River, black soil alluvial plains are no longer topographically high. Heavy calichification, a thick soil profile, and frequent reworking of surface materials by plowing and root growth preclude recognition on aerial photographs of the paleochannels and bars of the braided stream system that deposited the gravels in the eastern portion of the area. Westward channels can be recognized perhaps because of less frequent plowing and less vegetation growth. Since the land is seldom used for livestock grazing, there are few stock ponds. Gravels generally are not exposed at the surface nor are they commonly incorporated into the soil. When precipitation exceeds the infiltration capacity of the soils, surface drainage is via sheetwash into ill-defined swales near the periphery of the alluvial surface. During heavy precipitation, serious flooding can occur on alluvial surfaces such as these.

These gravels are important aquifers in many areas south of the Balcones Escarpment, providing water for domestic and livestock use and, infrequently, for irrigation.

Dissected black soil alluvial plain.—The dissected black soil alluvial plain is easily recognized as the dissected slopes bordering the black soil alluvial plains (fig. 4). Here erosion has removed some of the thick soils and caliche that cap the gravels. On this unit, steep slopes and gravel-rich soils generally preclude cultivation. Cleared land is usually used for pasturage. Gravel-quarrying operations are very common, and both active and abandoned pits scar large areas of this unit.

Gravel cap.—In many areas the dissection of gravel deposits has proceeded to the extent that no remnants of the original depositional surface remain. The soft, unindurated, underlying Tertiary and Cretaceous sediments are easily erodible, while the gravels originally deposited in valley bottoms are often heavily calichified in their upper sections and resistant to erosion. Consequently, an inversion in topography has occurred where the gravels now cap many hills, and the older sediments form the valley bottoms and sides. Where the original depositional surface has been lost to erosion, no distinctive landform can be recognized or associated with the gravel lithology.

On aerial photographs the gravel cap environmental geologic unit (fig. 5) appears as heavily wooded with oaks predominating and is only about 20 percent cleared of trees. The exposed ground surface is neither mottled nor gullied and its tone is medium gray. Gravel pits occur in some areas, and the unit appears to be limited to the higher elevations. Distinguishing between gravel cap units, with relatively thick gravel sequences underlying them, and other Tertiary sediments, overlain by thin gravel sequences, is difficult and sometimes impossible on aerial photographs.

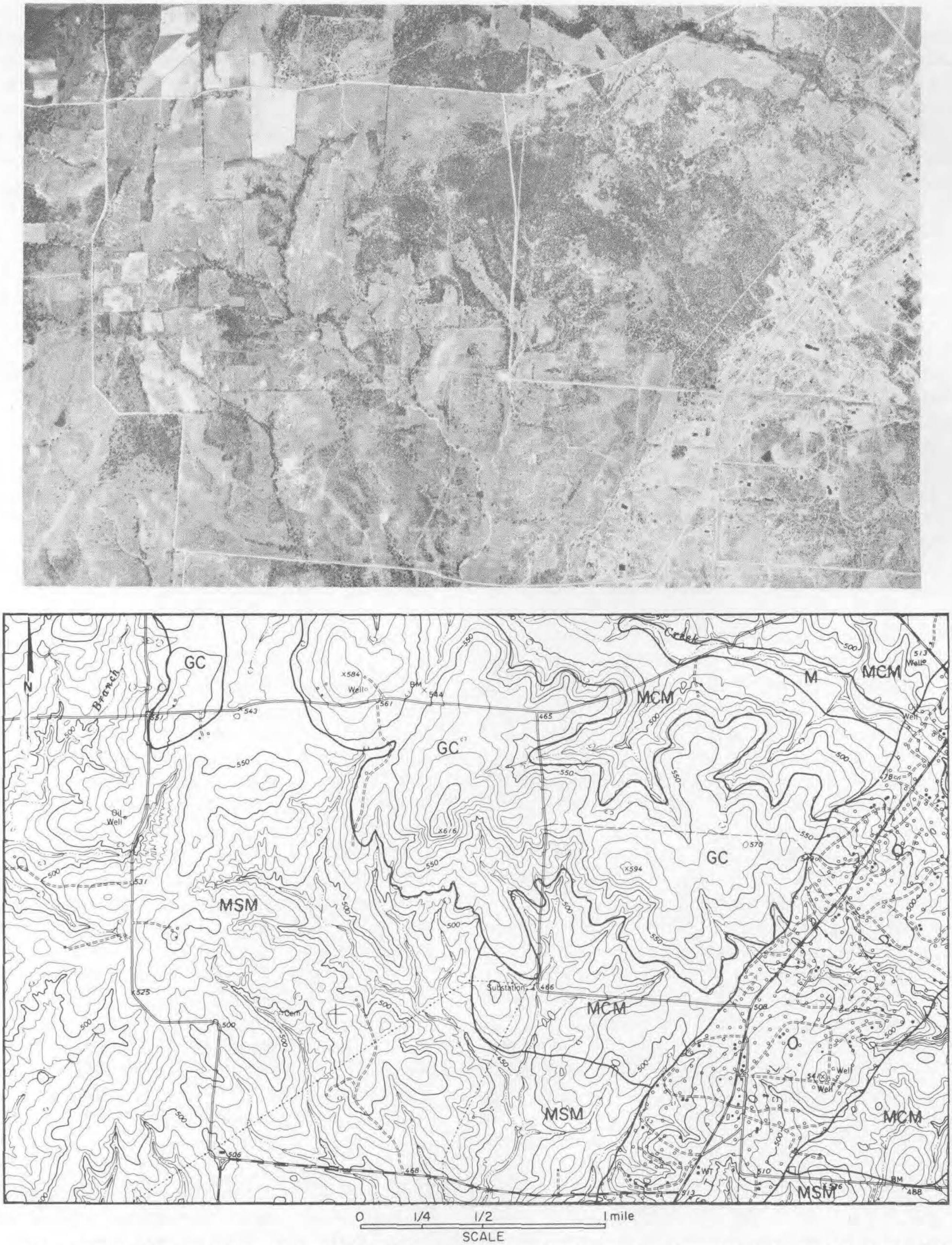


Figure 5. Environmental geologic units: GC, gravel cap; M, mixed fluvial and colluvial material; MCM, moderate-relief clayey mud; MSM, moderate-relief sandy mud; O, oil fields. On an aerial photograph and topographic map of a portion of the Darst Creek quadrangle. (U.S.G.S. topographic map, Darst Creek Quad., Tx.; aerial photograph reproduced with permission of Tobin Surveys, Inc.)

Low- and moderate-relief sandy mud units.—Topographic relief of these units ranges from moderate to low and gently rolling. Areas with slopes of less than two percent are called low-relief and areas with steeper slopes are called moderate-relief units. About 90 percent of the low-relief sandy mud unit has been cleared for cattle grazing and, to a lesser extent, for cultivation. On the other hand only about 60 percent of the moderate-relief sandy mud has been cleared. The dominant vegetation on the wooded portions of the sandy mud units is mesquite. Stock tanks—small excavations or dams used to hold water for livestock—are common, attesting to both the slow percolation rates of the clayey soil and to the major land use, livestock grazing. The soil of this unit is a pedocal with a slightly calichified B horizon and is developed on interbedded thin sands and muds.

On aerial photographs, the surfaces of the low- and moderate-relief sandy mud environmental geologic units are characterized by a mottled appearance ranging from dark-gray to nearly white (fig. 6). The tops of some knolls appear white between trees, looking as though grass and underbrush are at a minimum and exposing a sandy soil. Some animal trails, fence lines, roads, and dry stream channels also appear white in part, further suggesting a sandy soil only partly protected by vegetation. Many hillsides are scarred by gullies which generally appear white, steep sided, narrow, and relatively deep. The gullies suggest an easily erodible sandy mud which is cohesive enough to support steep gully walls. The gullies appear as areas of heavily crinkled contour lines on topographic maps.

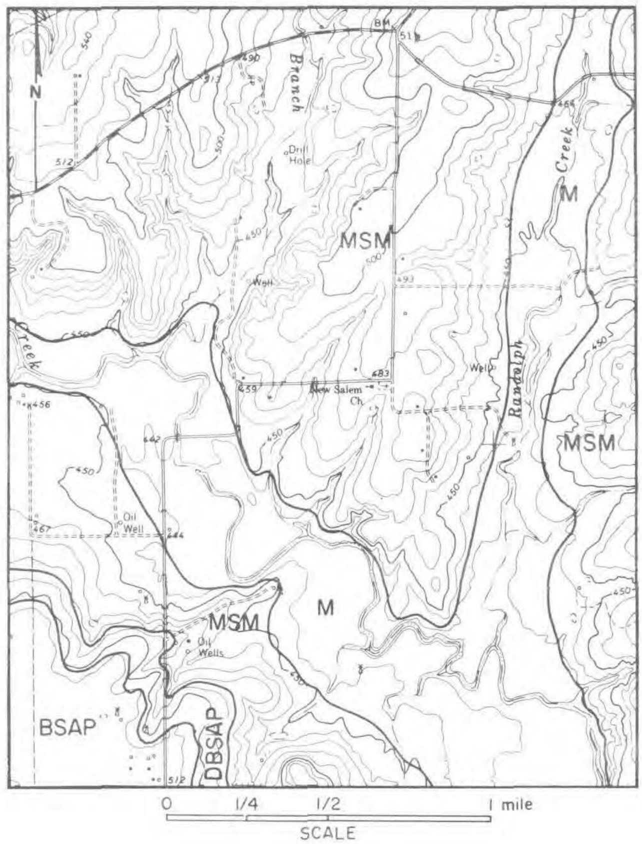


Figure 6. Environmental geologic units: BSAP, black soil alluvial plain; DBSAP, dissected black soil alluvial plain; M, mixed fluvial and colluvial material; MSM, moderate-relief sandy mud. On an aerial photograph and topographic map of a portion of the Darst Creek quadrangle. (U.S.G.S. topographic map, Darst Creek Quad., Tx.; aerial photograph reproduced with permission of Tobin Surveys, Inc.)

The formation of gullies in these units seems to be a major land use problem. Gullying probably results both from the clearing of trees from steep slopes and from deep cultivation of more moderate slopes, including root plowing. The unfortunate result is the reduction or total loss of use of large land areas. Furthermore, the increase in channel area within the gullied portions of streams results in rapid runoff and increased discharge downstream. Thus, the potential for flooding is increased.

Moderate-relief clayey mud.—Topography is of moderate relief and gently rolling. Approximately 75 percent of the moderate-relief clayey mud environmental geologic unit has been cleared, mostly for pasture land. Stock ponds are common and the dominant vegetation in the wooded areas is mesquite. On aerial photographs, areas vegetated predominantly with mesquite appear medium gray, rather than the dark gray of sandy areas vegetated predominantly by oaks (fig. 5). The land surface is broadly mottled but generally slightly darker than the surfaces underlain primarily by sandy muds. Gully scars are not common; where they do occur they are dark toned, broad, and shallow, perhaps suggesting that the gullies were formed in a cohesive material, that is, in sediment with a relatively high proportion of silt and clay. Soil developed on this unit is a pedocal with small amounts of caliche in the B horizon. Gilgai structures are observed in some areas.

Sand hills.—The sand hills environmental geologic unit consists predominantly of pink to orange-red or white, moderately well-sorted, fluvial quartz sand. Locally thin mud units are present. Throughout this unit aluminum, iron, and clay minerals have been removed from the A horizon and have accumulated in the B horizon to form a thick Podsol. The thick, easily friable or loose sand that makes up the surface of the sand hills is an excellent source for eolian material. Dunes stabilized by vegetation have been recognized at many places on the surface. The dunes are composed of a distinctive white, well-sorted sand. Unfortunately, their morphology is masked by vegetation and the moderately well-sorted, light-gray sand that was their source cannot be readily distinguished from dune sands on black-and-white aerial stereo photographic pairs. The moderately steep slopes and the thin sandy soils preclude most cultivation, and for the most part even limit clearing for pasturage. The dominant vegetation is post oak and blackjack oak, both of which appear dark gray to nearly black on aerial photographs (fig. 7). The sand hills support only a thin growth of grass and brush so that, on aerial photographs, the light-gray to white tone of the surface materials appears very light gray between trees. Roads, trails, fence lines, and stream bottoms appear almost white, suggesting a sandy substrate. Stock ponds and reservoirs are small and uncommon. Gullys are very uncommon.

High-relief iron-cemented uplands.—The highest relief unit in the study area consists of moderately well-indurated, red, iron-cemented muds, sands, and gravels. Slopes surrounding these areas commonly reach 15 to 25 percent, far steeper than slopes developed on any of the other units. With the exception of caliche-cemented sediments, which occur below black soil alluvial plains and in some terrace deposits, this is the only environmental geologic unit within the study area east of the Nueces River that is moderately well indurated; consequently it supports the steepest slopes in the eastern part of the study area. This unit is rarely cleared for pasturage, but remains covered with the dominant vegetation of blackjack oak and post oak. In addition to its relief and vegetation, this unit is recognized on aerial photographs by the dark-gray tone of surface materials—iron-cemented or iron-stained mudstone and sandstone exposed between trees (fig. 7).

Oil fields.—Several of the older oil fields within the map area should be considered as environmental geologic units. Areas such as the Darst Creek field have been systematically disturbed to the point that the land surface is of little value for use other than petroleum production. Several hundred oil wells have been drilled, mostly with derricks built on concrete piers. The derricks have been removed, but the pilings remain, along with various other discarded machinery. Mud pits from early wells remain open and unfilled, and are lined with a heavy, asphalt-like substance. Salt water, produced with the crude oil, has been collected in some of these pits. Loss of salt water from some operations has contributed to the depletion and destruction of the natural vegetation in many areas. Service roads to well sites have further destroyed or depleted vegetation. Finally a heavy, pervasive odor of hydrocarbon gases and H_2S, recognizable even in small aircraft several miles downwind and at an altitude of 1,500 feet, blankets the area making habitation unpleasant and difficult.

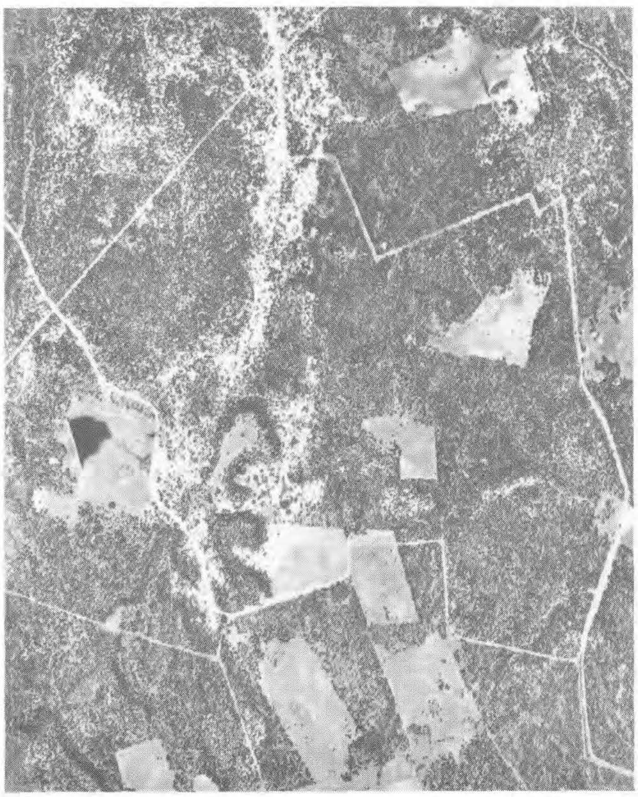
These areas, usually several miles long and less than a mile wide, are easily recognized on aerial photographs (fig. 5). Mud pits appear as roughly rectangular depressions, often partly filled with water. Oil storage tanks abound and are easily recognized by their cylindrical shape. Unpaved access and service roads form a complex network interconnecting well sites and oil storage and workshop areas with the public road system. The oil field pattern cuts across topography, and may cross environmental geologic map units.

Environmental Geologic Units Limited to the Nueces River Basin

In the Nueces River Basin, many of the environmental geologic units undergo a marked change in response to both facies changes and climatic changes. In addition Cretaceous limestones and shales crop out. Westward the coastal plain sediments are more lithified either due to stronger cementation, calichification, or case hardening.

In the Nueces River Basin, the subarid climate and thin soils preclude cultivation on most surfaces. Only on portions of black soil alluvial plains and along some of the lower stream terraces is cultivation attempted, usually with the aid of irrigation. For all environmental units in the region, the primary agricultural land use is grazing of cattle, sheep, goats, and deer. The sale of deer leases—the right to hunt deer over specific tracts of land—provides an important secondary source of income for many land owners in the area. The thickness of vegetative cover is highly variable and dependent both on substrate and on the length of time since the land was cleared. Thorny brush may be dense (termed chaparral) on one side of a fence and widely scattered on the other side.

Moderately dipping, dissected carbonate.—The Anacacho Mountains are an isolated group of



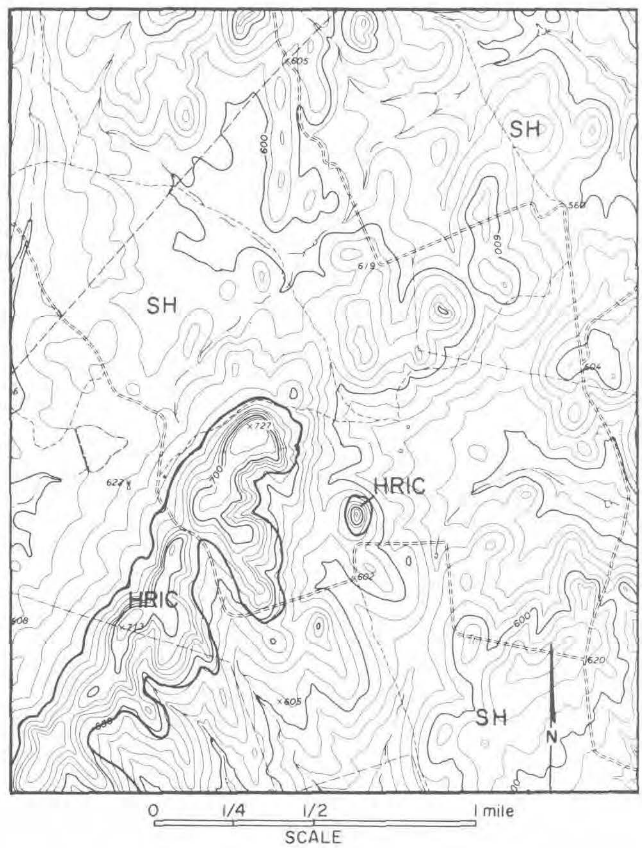


Figure 7. Environmental geologic units: HRIC, high-relief iron-cemented uplands; SH, sand hills. On an aerial photograph and topographic map of a portion of the Thomas Springs quadrangle. (U.S.G.S. topographic map, Thomas Springs Quad., Tx.; aerial photograph reproduced with permission of Tobin Surveys, Inc.)

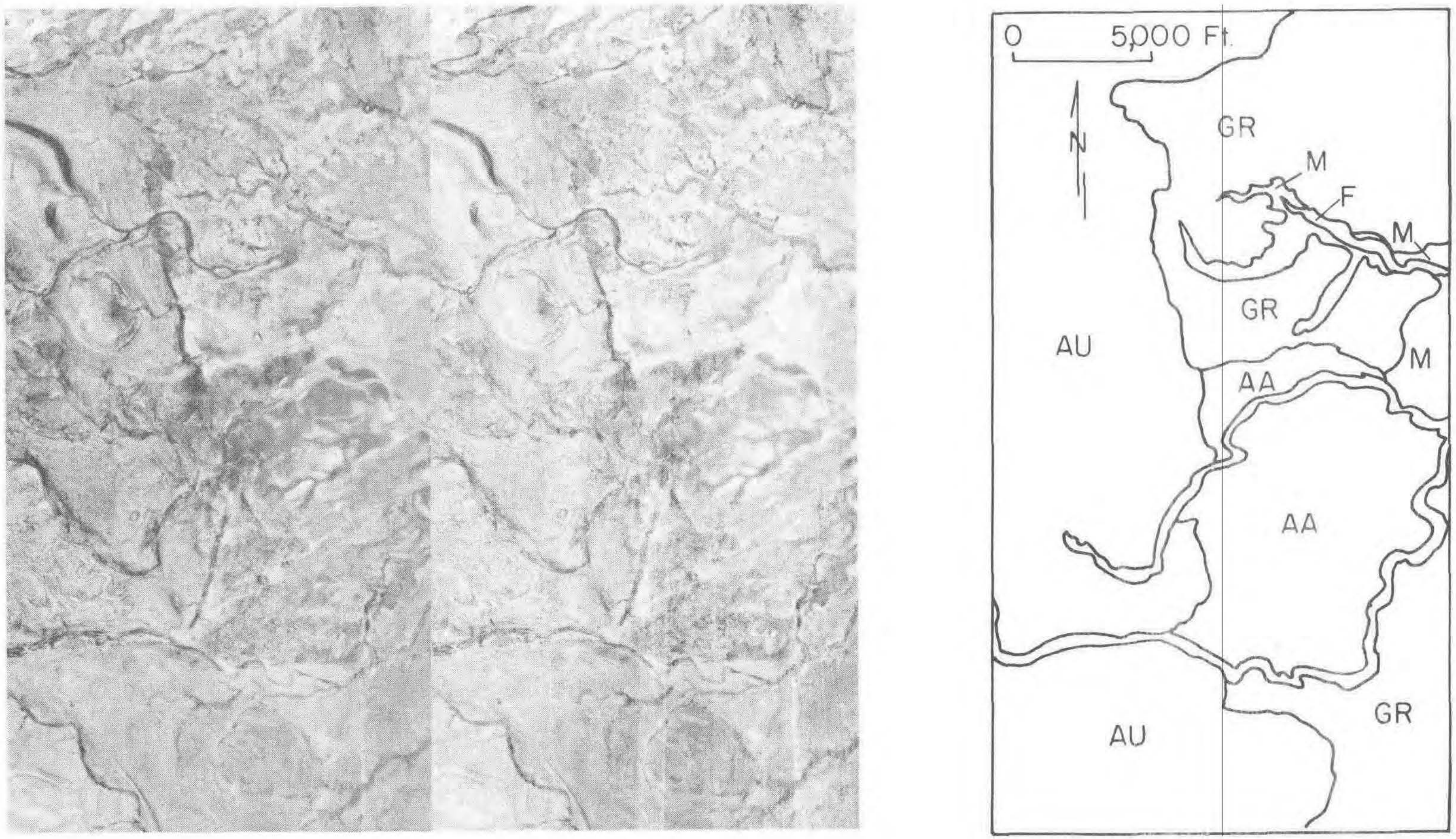


Figure 8. Stereo aerial photographs and environmental geologic map of an area illustrating the following environmental geologic units: AU, moderately dipping, dissected carbonate; GR, gently rolling limestone topography; M, mixed fluvial and colluvial material; F, flood plain; AA, alluvial apron. (Aerial photographs reproduced with permission of Tobin Surveys, Inc.)

limestone hills that rise above the low rolling terrane of the upper Gulf Coastal Plain (fig. 8). These limestone hills are mapped as the moderately dipping, dissected carbonate unit. Although the overall relief of this unit is moderate, reaching only 250 feet, the slopes are very steep, in places forming cliffs. Dip of the beds range from five to seven degrees. Specific karst features such as sinkholes were not observed, although solution activity along bedding and joint planes has occurred. In response to steep slopes and subarid climate, soils are poorly developed ranging from none over bedrock exposures to thin lithosols. Vegetation is thin and consists predominantly of short grasses, mesquite, and thorny shrubs.

High gravel plain.—A high gravel plain occurs along the western divide of the Nueces River (fig. 9). It contains clasts of rhyolite, basalt, and vein quartz that have been transported from the Big Bend area lying to the west. The gravel is composed predominantly of limestone and chert, and is heavily calichified. Soils are thin or gravelly or composed of weathered caliche fragments; they are commonly capped by a thin veneer (up to three inches) of eolian silt. Eolian activity has modified approximately 15 percent of the surfaces of these alluvial plains by creating large, shallow, elliptical deflation basins with internal drainage. Both relief and slopes are very low, and vegetation consists mostly of short grasses and mesquite. Aside from deflation basins, the surface relief is minimal and relict channels are not visible, perhaps being obscured in part by eolian material.

Dissected high gravel-plain margin.—The dissected edge of the high gravel-plain unit consists of loose gravel and does not support the formation of soils (fig. 9). While relief ranges from 10 to 20 feet, slopes are generally steep and narrow in areal extent. Vegetation is sparse and consists mostly of grasses and mesquite. There are no gravel pits,

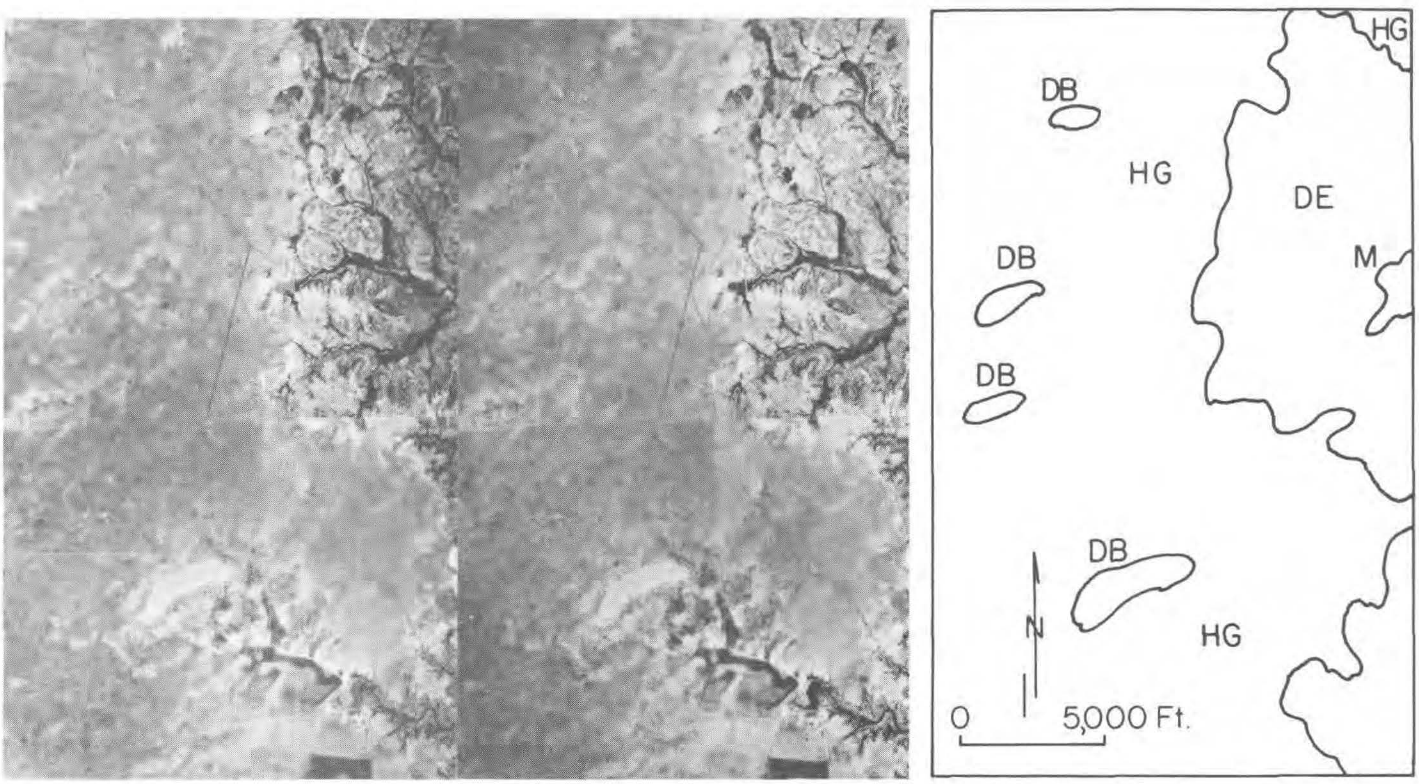


Figure 9. Stereo aerial photographs and an environmental geologic map of an area illustrating the following environmental geologic units: DB, deflation basin; HG, high gravel plain; DE, dissected high gravel plain margin; M, mixed fluvial and colluvial material. (Aerial photographs reproduced with permission of Tobin Surveys, Inc.)

probably because there is little nearby demand for gravel.

Bedrock and talus units.—The following units are predominantly bedrock exposures and associated talus (fig. 10). They include outcrops of basalt, talus derived from the basalt, limestone (Buda Limestone), and clay (Del Rio Clay). The basalt occurs as small, dissected volcanic plugs of Tertiary-Cretaceous age. The talus consists of debris derived from the volcanic plugs. The Buda Limestone is moderately dissected and contributes large float blocks which mantle the upper portions of the slopes of the Del Rio Clay. In most areas the Del Rio Clay is light toned. The clay is not expansive because of its high calcium content, but does form unstable slopes that are concave upward. Vegetation is relatively thin. In general, soils of these units range from nonexistent, to loose rock, to thin lithosols; and vegetation consists predominately of sage and thorny shrubs with some short grasses.

Calcium carbonate cemented sandstone.—In the Nueces River Basin, the sand hills unit becomes relatively strongly cemented with $CaCO_3$. The unit is further characterized by both low relief and gentle slopes (fig. 11). Solution features modified by eolian activity occur on the surface of the sandstone. The calcium carbonate cement has been dissolved by water and the sand residue has been removed by wind action to form wide, shallow depressions. At lower elevations in the eastern part of the Nueces River Basin, there appears to be

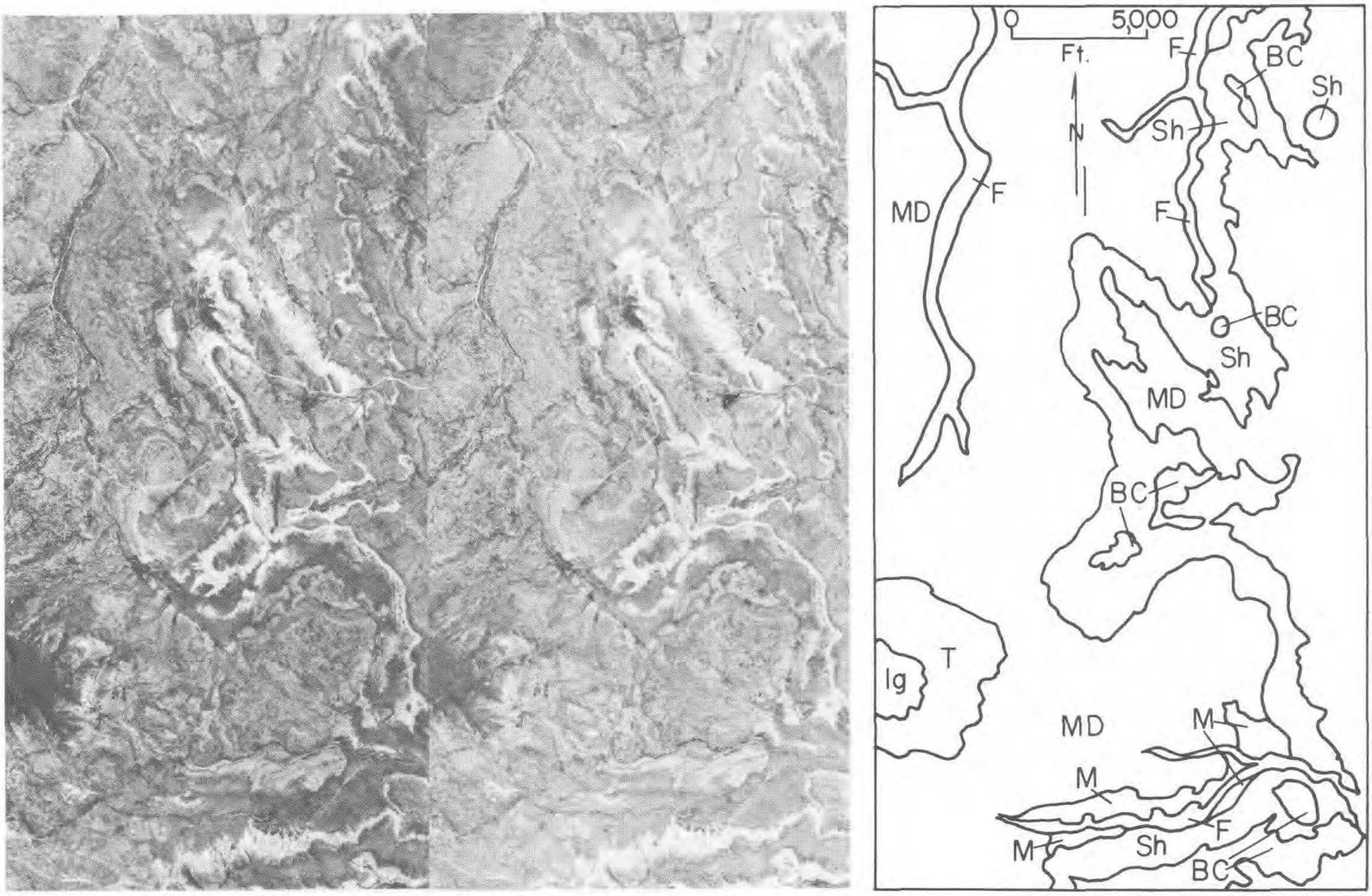


Figure 10. Stereo aerial photographs and environmental geologic map of an area illustrating the following environmental geologic units: MD, moderately dissected carbonate topography; F, flood plain; Ig, basalt; T, talus; M, mixed fluvial and colluvial material; Sh, Del Rio Clay; BC, Buda Limestone. (Aerial photographs reproduced with permission of Tobin Surveys, Inc.)

sufficient ground water present to support large live oak trees and good pasture grasses.

Interbedded sandstone and shale.—Lithification of the low- and moderate-relief sandy and clayey muds of the eastern part of the study area occurs west of the Nueces River. The sandstones and shales are moderately to poorly indurated and friable and are complexly interfingered. Thin rocky soils support growths of grass, cactus, mesquite, and low thorny brush. The topography of this unit is low and gently rolling, except where gravel capped and where dissection by small streams has produced badlands topography (fig. 12).

LAND USE

The land use units (table 2) are predominantly agricultural and, to a large extent, have been identified by their present use. Both the type of agricultural use and the intensity of land use is a function of local relief, slope, and climate, and to a lesser extent substrate composition. The three to five percent slopes and the very poor soils of the forested sand hills will not support either cultivation or heavy grazing, and consequently this land is generally left uncleared. This unit is the least intensively used in the study area. The pasture

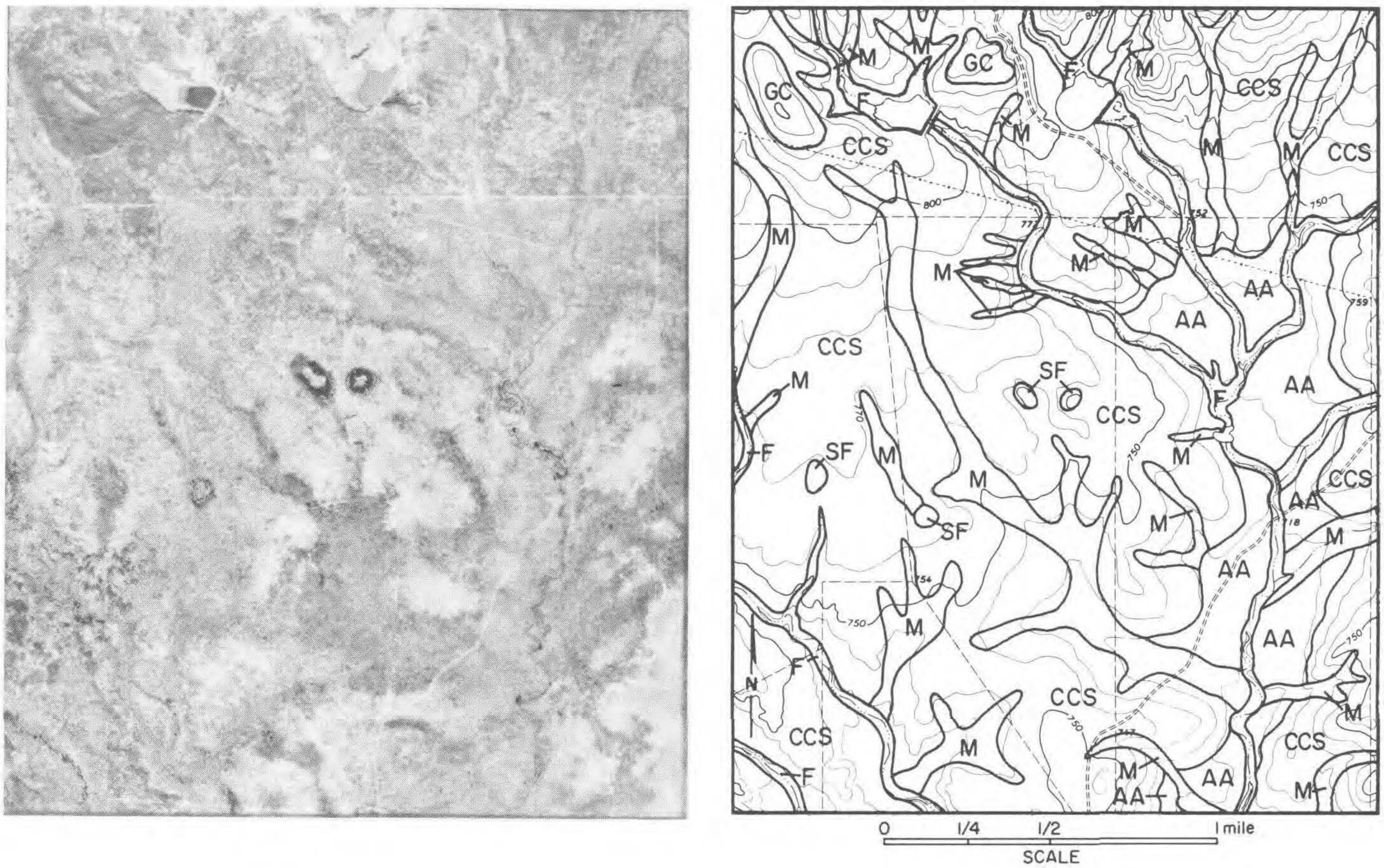


Figure 11. Environmental geologic units: AA, alluvial apron; CCS, carbonate-cemented sandstone; F, flood plain; GC, gravel cap; M, mixed fluvial and colluvial material; SF, solution feature in carbonate-cemented sandstone. On an aerial photograph and topographic map of a portion of the Irishman Hill Quadrangle. (U.S.G.S. topographic map, Irishman Hill Quad., Tx.; aerial photograph reproduced with permission of Tobin Surveys, Inc.)

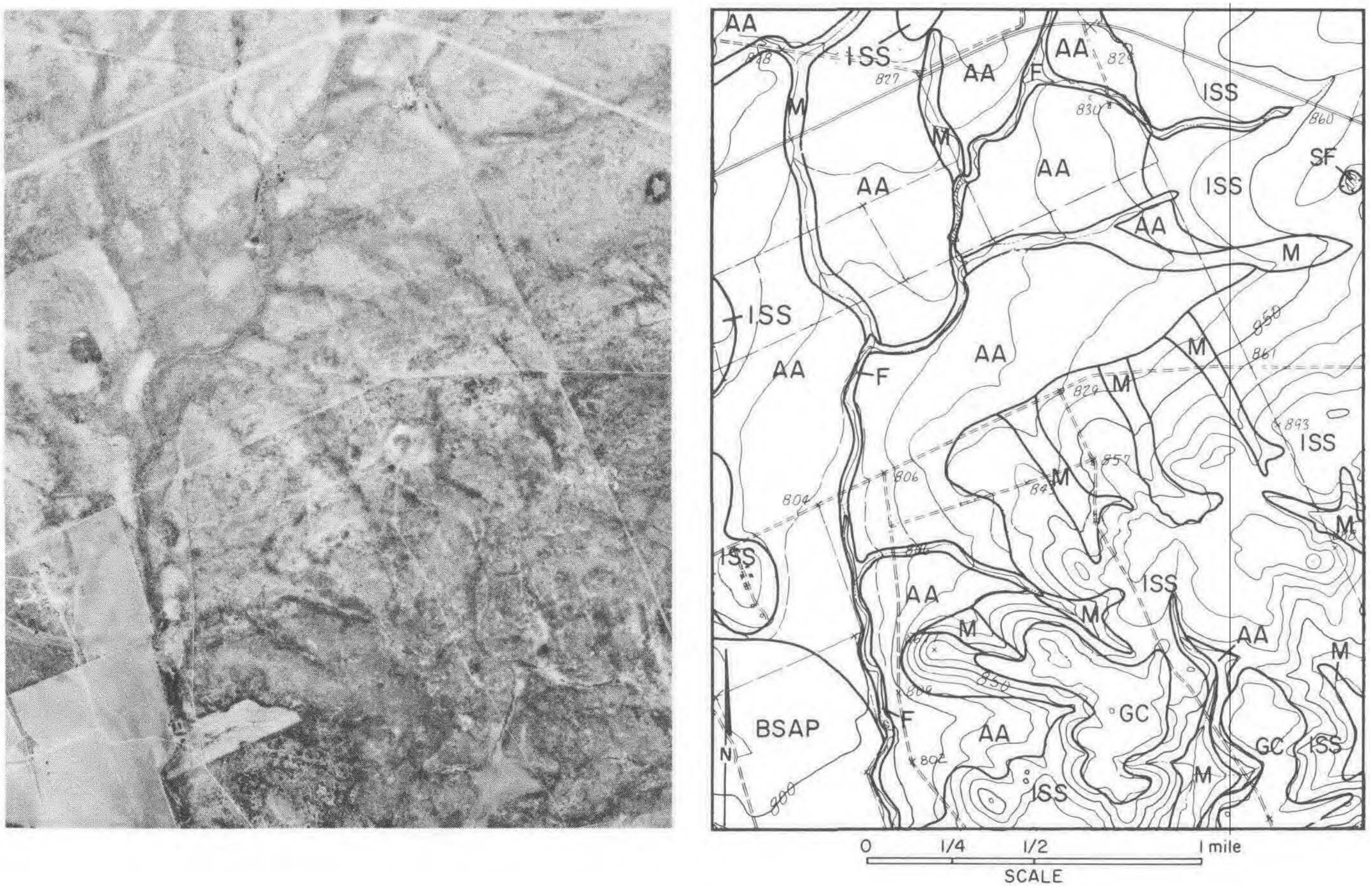


Figure 12. Environmental geologic units: AA, alluvial apron; BSAP, black soil alluvial plain; F, flood plain; GC, gravel cap; ISS, interbedded sandstone and shale; M, mixed fluvial and colluvial material; SF, solution feature. On an aerial photograph and topographic map of a portion of the Uvalde 4 SW quadrangle. (U.S.G.S. topographic map, Uvalde 4 SW Quad., Tx.; aerial photograph reproduced with permission of Tobin Surveys, Inc.)

Table 2. Land Use Units

UNIT	LAND USE	MAXIMUM RELIEF	SLOPES	BEDROCK	SOIL	VEGETATION	REMARKS
FORESTED LAND	Light grazing, hunting	200 feet	Gentle 3-5%	Sand	Sand	Post oak, blackjack oak	Sandy surface, very unstable
PASTURE LAND	Grazing, hunting	100 feet	Gentle 2-5%	Variable	Sandy, silty or clay loam, often with admixed gravel	Grasses with scattered oaks and/or mesquite	Gullying is common
MIXED PASTURE, CULTIVATED LAND	Grazing, agriculture, hunting	50 feet	Gentle to flat 2-3%	Muds; interbedded sands & muds	Sandy, silty, or clay loam, with admixed gravel	Grasses with scattered oaks and/or mesquite	Gullying is common
CULTIVATED LAND	Agriculture	20 feet	Flat 1-2%	Flood plain and terrace sands, silt, and clays, calichified gravels and sand	Clay loam, silty loam, gravelly clay loam	Grasses	Thick soil and caliche cause slow infiltration
RECREATION, NON-URBAN AREAS	Camping, picnicking, golf, motorcross, swimming	300 feet	Variable 1-10%	Variable	Variable	Variable	Almost any land will sustain some type of recreational use
CITY-VILLAGE	Communal living	50 feet	Gentle 1-3%	Variable	Variable	Variable	
OIL FIELDS	Production and temporary storage of crude oil	Variable	Variable 1-10%	Variable	Variable	Variable	H_2S odor commonly very strong, numerous interconnecting roads, much active and abandoned oil field equipment
QUARRIED LAND	Substrate is quarried	30 feet	Steep	Gravel, sand, caliche, clay	None	None in active pits	Unreclaimed quarries are generally unsuitable for most uses

Increasing intensity of activity

Use not controlled by surface characteristics

Environment severely disturbed

Table 3. Resource Capabilities for Construction (derived, in part, from several established soil series reports, U. S. Dept. Agriculture, Soil Conservation Service)

	Construction	Reservoirs	Roads	Sanitary Landfills	Septic Tanks	Sewage Lagoons
Black Soil Alluvial Plain	M	M-S	M	S	S	S
Dissected Black Soil Alluvial Plain	L	M-S	L	S	L	M
Gravel Cap	L	S	L	S	S	S
Moderate-Relief Sandy Mud	S	L-M	M	M	S	S
Low-Relief Sandy Mud	S	L-M	M	M	S	S
Moderate-Relief Clayey Mud	S	L-M	M	M	S	S
Sand Hills	L	M-S	L	S	S	S
High-Relief Iron-Cemented Uplands	S	S	—	—	—	—
Oil Fields	V	V	V	V	V	V
Moderately Dipping, Dissected Carbonate	M	L	M	S	S	S
High Gravel Plain	L	M	L	S	S	S
Dissected High Gravel-Plain Margin	S	S	M	S	S	S
Bedrock and Talus	S	S	S	S	S	S
Calcium Carbonate Cemented Sandstone	L	S	L	S	S	S
Interbedded Sandstone and Shale	L-M	L-M	L	L-M	L-M	L-M
Alluvial Apron	L	M	L	M	M	S
Flood Plain	S	S	S	S	S	S
Terrace—noncalichified	L	M-S	M	L	L-M	M-S
Mixed Fluvial and Colluvial	L-M	M-S	M	L	L-M	M-S
Moderately Dissected Carbonate Topography	L	L	L	S	S	S
Gently Rolling Limestone Topography	L	L	L	S	S	S

Degree of Limitations on Construction

S — Severe limitations
M — Moderate limitations
L — Low limitations

V — Variable limitations
— No information

unit, mixed pasture and cultivated unit, and cultivated unit form a series of units which show an increase in agricultural activity with a corresponding decrease in slope and relief.

Quarried land is of necessity controlled by substrate composition. However, a secondary control is an economic consideration. Since it is in general more profitable to derive income from cultivated lands than to quarry gravel, sand, or clay, cultivated areas usually are not quarried, whereas areas used predominantly for grazing may be. An additional consideration in determining if sand, gravel, or clay production is feasible is proximity to market, whether it is an urban area or a road or dam construction site.

Economic considerations control land use adjacent to population centers and overlying petroleum reservoirs. If there is the opportunity of a choice of land uses, it is simply more profitable to develop land adjacent to populated areas than it is to farm it; certainly it is more profitable to use land for the production of crude oil or natural gas than it is to limit use to any other purpose.

Land used for recreation is of minor extent and apparently not controlled by either physical, agricultural, or economic considerations.

The major aquifer in the study area is the Carrizo Sand, a part of the sand hills environmental geologic unit. Also mapped in the sand hills unit is the Queen City Formation which locally yields a moderate amount of ground water. In order to preserve the quality and production capability of the Carrizo aquifer, that portion of the sand hills unit should probably be retained as an uncleared unit suitable for light grazing. The Wilcox Formation also yields small amounts of ground water locally, especially from sandy facies in the upper portion of the formation.

Alluvium, which comprises the terrace and black soil alluvial plain environmental geologic units, has also yielded moderate amounts of ground water to communities and individuals. These shallow aquifers, especially material below the black soil alluvial plains, are beginning to show the effects of man's activities in the form of abnormally high NO_3 content in the waters. Here, too, adequate planning is needed to insure the continued availability of potable water.

Tables 3 and 4 list the environmental geologic units that have been described in this report and indicate the limitations of each unit with respect to nonagricultural human activities, flooding, and soil characteristics. Although most of the units have variable limitations for man's activities, the flood plain represents the most severe.

Table 4. Processes Limiting Construction (derived, in part, from several established soil series reports, U. S. Dept. Agriculture, Soil Conservation Service)

	Corrosivity	Flooding	Shrink-Swell
Black Soil Alluvial Plain	L-H	M	L-M
Dissected Black Soil Alluvial Plain	L	O	L-M
Gravel Cap	L	O	O
Moderate-Relief Sandy Mud	L-H	O	M-H
Low-Relief Sandy Mud	L-H	L	M-H
Moderate-Relief Clayey Mud	L-H	L	M-H
Sand Hills	M	O	L
High-Relief Iron-Cemented Uplands	–	O	–
Oil Fields	V	V	V
Moderately Dipping, Dissected Carbonate	L	L	O
High Gravel Plain	L	M	O
Dissected High Gravel-Plain Margin	H	H	O
Bedrock and Talus	H	L	O
Calcium Carbonate Cemented Sandstone	L	L-M	–
Interbedded Sandstone and Shale	L-H	L-H	L-M
Alluvial Apron	L	H	O
Flood Plain	L-M	H	L-H
Terrace-noncalichified	L-M	L	M-L
Mixed Fluvial and Colluvial	L-M	M-H	L-M
Moderately Dissected Carbonate Topography	L	L	O
Gently Rolling Limestone Topography	L	L	O

Degree of Process Activity

H – High
M – Moderate
L – Low

O – None
V – Variable
– No information

RESOURCE CAPABILITY

Each environmental geologic unit has resource potential which is limited by the characteristics that pertain to it—substrate, relief, slope, soil, vegetation, and geologic process. What these units may be used for, their resource capability, is in large part determined by man's needs. These units are in an area that, except for a few locales, is not likely to be urbanized or industrialized. The resources that are presently developed here are thus almost exclusively agricultural. Nevertheless, some urban and industrial expansion is likely to occur in the future; in this event certain of the environmental geologic units will have a more limited development capability than others (table 3).

Several environmental geologic units are recharge zones for ground-water aquifers supplying water to many moderate-sized communities to the south. The presence of ground water may enhance these units' agricultural potential as well as the agricultural potential of units that lie above the aquifers. On the other hand, four of the units—dissected black soil alluvial plain, gravel cap, flood plain, and terrace—are sometimes quarried for sand and gravel or clay, a land use practice which, without reclamation, destroys an area's potential as an agricultural resource. However, with urban expansion in this area and with depletion of gravel sources near urban areas to the east, gravel within the study area may become an increasingly valuable resource.

SUMMARY AND CONCLUSIONS

Twenty-one environmental geologic units have been recognized within the study area of this report. The units were defined by recognition from aerial photographs of one or more of these elements: (1) geologic substrate and soil, (2) topography and landform morphology, (3) geologic process, (4) biota, and (5) human activity.

As a consequence of increasing aridity to the southwest, the character of some of the environmental geologic units changes toward the southwest. Calichification increases to the southwest and soils and vegetation become less characteristic of the substrate materials.

Each of the environmental geologic units has a resource capability, limited by the characteristics which define it—substrate, relief, slope, soil, vegetation, and geologic process. Land use in this area has been predominantly agricultural, and to a large extent its specific use is controlled by slope and relief. Flat lands have been cleared for cultivation and have been irrigated in the more arid areas. Areas of intermediate relief and slope have been cleared for grazing, while the higher relief areas have been left uncleared. In general, the intensity of land use seems to increase with potential economic return.

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ENVIRONMENTAL GEOLOGY—AN AID TO URBAN PLANNING: Austin Area, Texas

L. E. Garner

INTRODUCTION

The problem of resolving the need for urban growth and a desire to preserve natural features and systems has prompted much concern about future development of metropolitan areas. Among the many problems which must be solved are proper distribution of residential, commercial, and park areas and adequate solid and liquid waste disposal. Solutions to these problems must be compatible with existing natural systems for optimum economic and aesthetic benefits. Planning based on sound land resource data can detect potential problem areas and, before actual development, can provide adequate adjustments based on ultimate use and capability.

Evaluation of ultimate land use should be based on an inventory of the natural components of our environment and the reaction of these components to the impact of development. The natural components are (1) geologic, (2) physiographic, (3) biologic, and (4) hydrologic; variables include (a) rock types, (b) topography, (c) vegetation, (d) streamflow, (e) soils, and (f) mineral resources. Examination of the physical properties associated with various rock units and of the relationship of rock units to other physical features and to each other is one basis for judging the impact of development on the environment.

The purpose of this paper is to contribute toward a solution of problems arising during development of an urban complex. Austin (fig. 1) is a model for concepts which can be used in metropolitan areas. The diversity of rock types and their complex relationships in a major fault zone present many problems which are shared with other urban areas. The model lies in a rapidly developing region (figs. 2, 3) between two major cities and along an Interstate Highway. It is predicted to be one of Texas' two future giant metropolitan areas.

The approach here is to describe the basic elements of the environment which affect and are affected by development and to indicate how these elements can be used to evaluate areas of potential growth. The reasoning behind this approach is not to tell individuals what is best for them but to acquaint them with potential problems and urge them to think of development and environmental resources as a unit.

GEOLOGIC SETTINGS

Rock units exposed in the model area include limestone, dolomite, clay, sand and gravel, alluvium, basalt, and tuff (table 1, fig. 4). Cretaceous rock units generally strike northeast and dip gently eastward (fig. 5), except in the fault zone where the magnitude and direction of dips are irregular. The total accumulated thickness of sediments is about 2,500 feet. Alluvial deposits which locally overlie bedrock units vary from about 5 to 50 feet in thickness.

Gently dipping bedrock units are broken and displaced down to the southeast by the northeast-trending fault zone. Units on the upthrown side dip at about 20 feet per mile toward the northeast; dips near the fault zone are about 50 feet per mile to the east; and the dip on the downthrown side increases to about 100 feet per mile.

Most faults in the Balcones system strike about N 40° E and are normal faults (fig. 5). Maximum displacement of the largest fault is about 600 feet. Most have displacements of less than 50 feet and dip between 55° and 75°. Total displacement across the fault zone is about 1,200 feet. No movement has been detected during modern times (Weeks, 1945).

TOPOGRAPHY

A highly dissected plateau occupies approximately a third of the model area. It is in the northwestern section, bounded on its eastern margin by the major fault zone. Slopes are generally greater than 5 percent, with those in excess of 15 percent common along stream courses.

A broad northeast-trending belt, across a major portion of the city, has topography which is moderately dissected. Its slopes are commonly less than 5 percent, except in a few local areas.

A slightly to moderately dissected prairie occurs east of the Balcones fault zone. Slopes range from 2 to 5 percent, with a few broad areas having slopes less than 2 percent.

Slopes were determined from the spacing of contour lines on a topographic map, providing a slope-intensity map (fig. 6). Slope-intensity units important in land use planning are: (1) slopes that

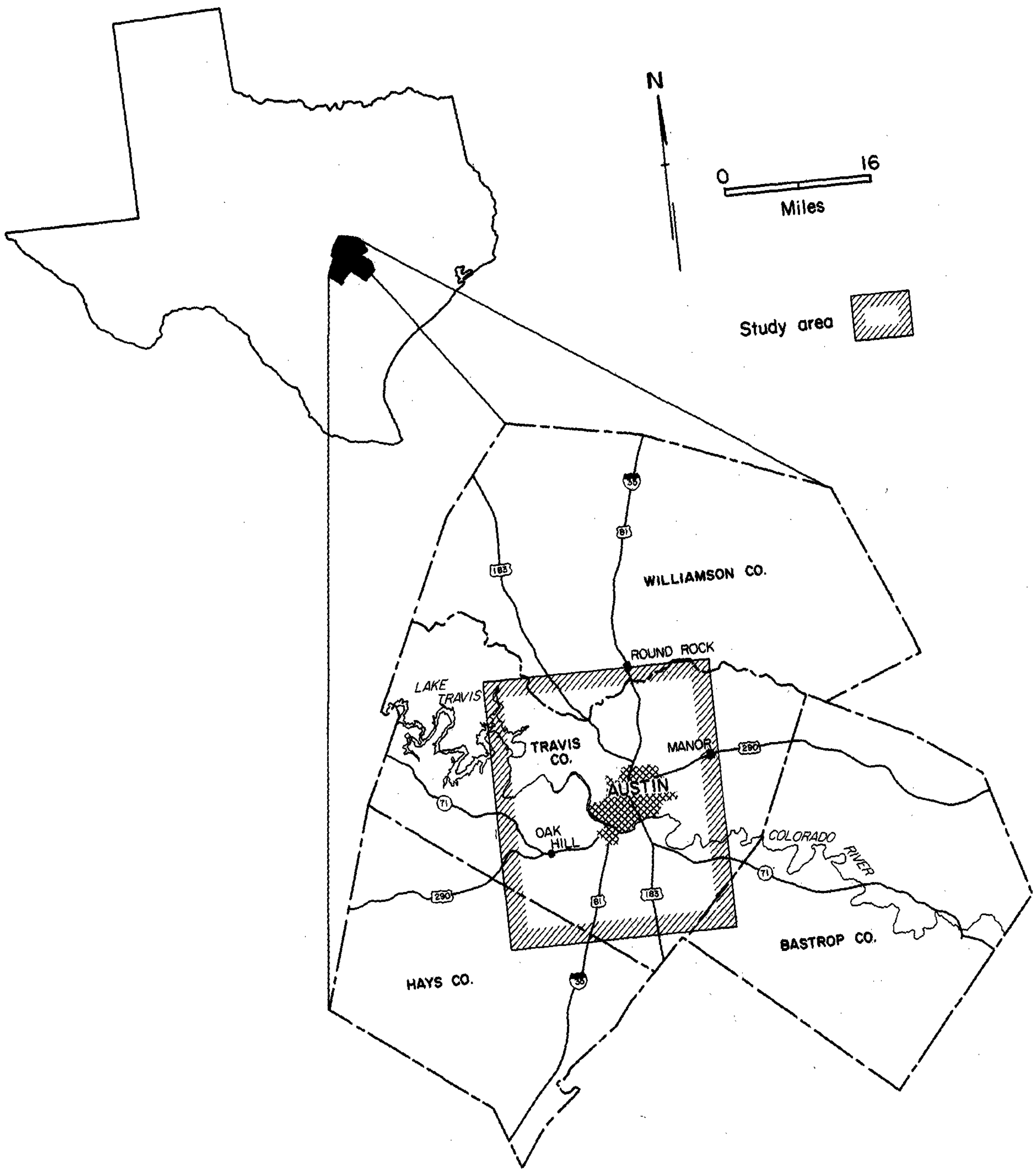


Figure 1. Index map, Travis, Williamson, Hays, and Bastrop Counties, Texas.

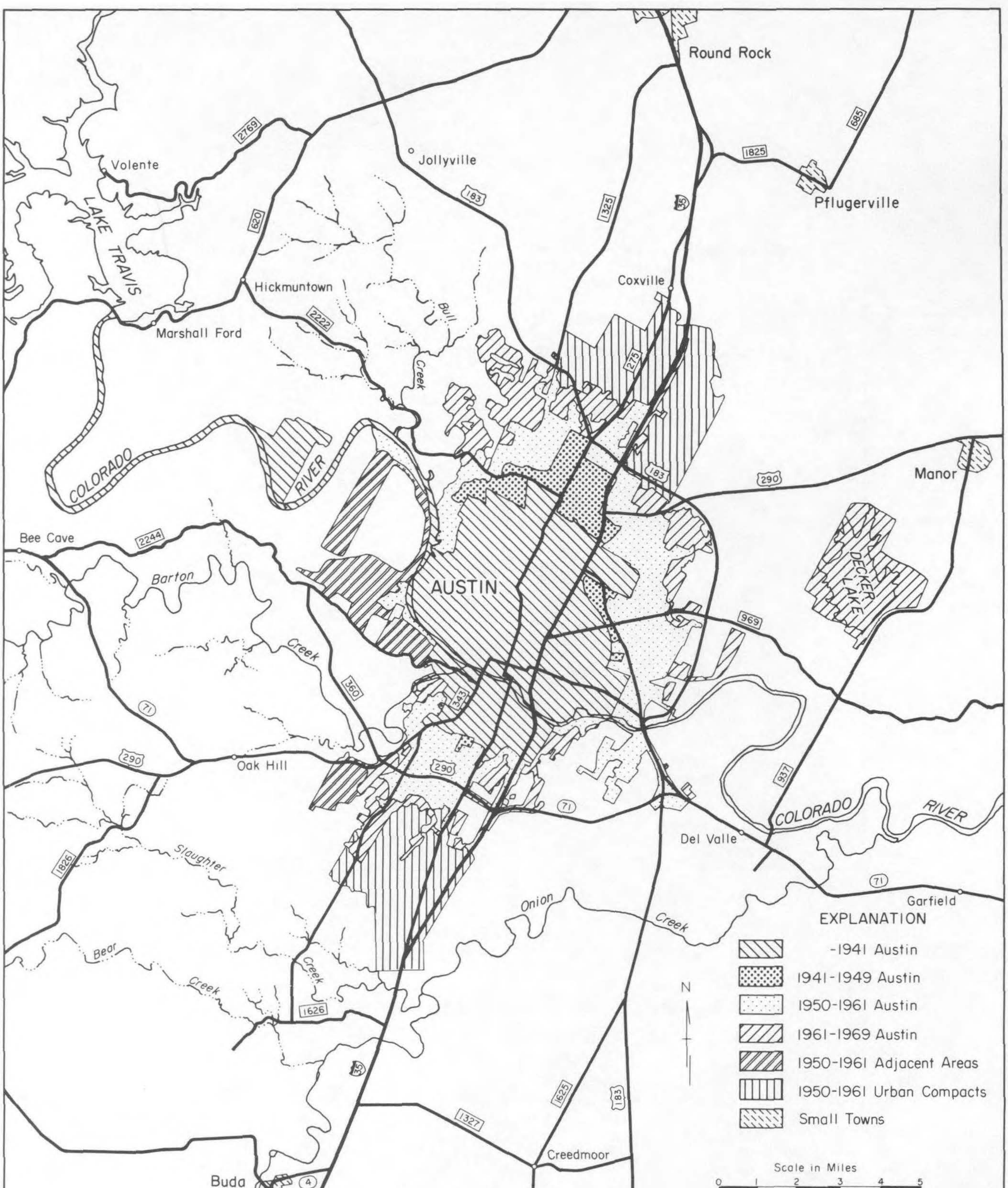


Figure 2. Urban growth of the Austin area, 1940 to 1970.

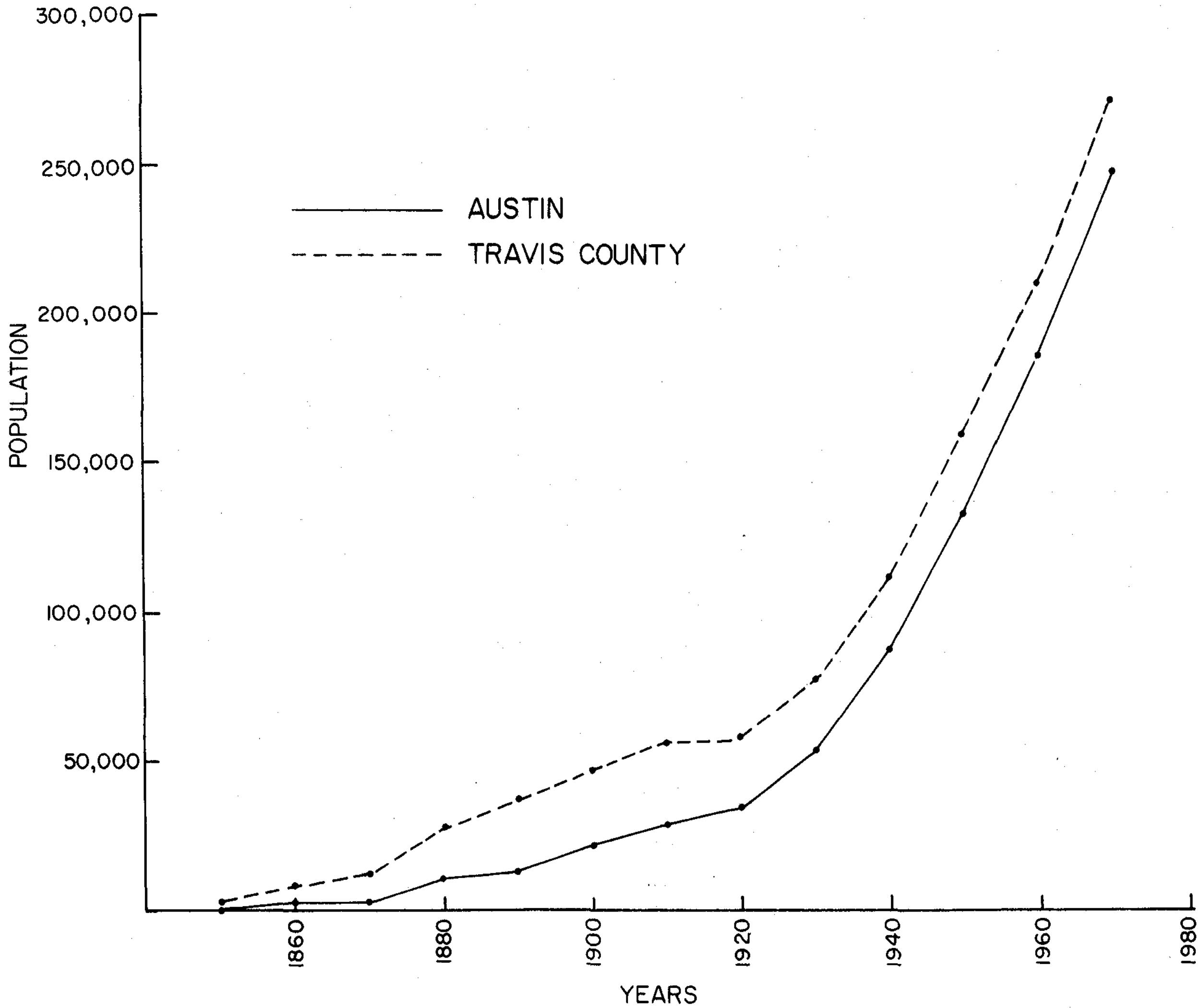


Figure 3. Population growth of Austin and Travis County, 1850 to 1970.

average less than 2 percent—inadequate drainage may be a problem; (2) slopes that average 2 to 5 percent—commonly preferred for commercial and industrial development; (3) slopes that average 5 to 15 percent—acceptable for general urban and residential development, such development commonly limited to slopes of less than 15 percent; and (4) slopes that average greater than 15 percent—require supplemental engineering design for most structures (Hilpman and others, 1968).

An inventory of the slope-intensity units in the model area shows that (1) slopes of 15 percent or greater occupy 7 percent of the land area, (2) slopes between 5 and 15 percent occupy 22 percent of the land area, (3) slopes between 2 and 5 percent occupy 48 percent of the land area, and (4) slopes of 2 percent or less occupy 23 percent of the total land area.

SOILS AND VEGETATION

Soil and vegetation development is closely related to underlying rock types and climatic conditions. Soils associated with the various rock types are in some cases similar to the underlying rock materials, such as those in clay bedrock areas or in some sand and gravel units. Other units may have poorly developed or thin soils, such as those over parts of the mixed limestone units, or they may have soils which contrast with underlying rock materials, such as the plastic black-clay soils that overlie some of the soft limestone units. These basic areas can also be characterized by vegetation assemblages.

Soils in the eastern part of the model area (over clay units) are dark-gray to gray-brown and black clays, 12 to 36 inches deep. Gravelly clays are developed on some hilltops in this area. Vegetation consists primarily of grasslands with scattered mesquites. Fluvial deposits commonly have brown to tan sands and silty clay soils, 4 to 20 inches deep. Terrace deposits are commonly vegetated by post oak, blackjack oak, and elm woodlands, whereas alluvium is covered by cottonwood, sycamore, willow, pecan, and grasses. The northeast-southwest zone across the central part of the area (soft limestones) has gray-brown to dark-brown and black, calcareous clay and silty clay soils, 7 to 65 inches thick. Gray-brown to tan, calcareous, silty clay soils, 4 to 20 inches thick, cover most of the western part of the model area, where soil thickness commonly varies with the topography. Thick soils occur in relatively flat areas below steep slopes, whereas thin soils occur on slopes and hilltops. Characteristic vegetation in limestone areas is comprised of live oak, Spanish oak, scrub oak, and juniper with broad grassland areas.

Soil character and vegetation types are essential elements to many phases of development. In many cases, small building foundations or roadbeds are based entirely within the soil zone. Areas where soils are thin or absent can present severe limitation for septic tank installation. Vegetation preservation aids in the prevention of erosion and promotes infiltration of surface runoff. Devegetation of broad areas contributes to increased runoff and flooding.

DRAINAGE BASINS AND FLOODING

The primary drainage basin (fig. 7) within the model area has nine major tributaries. Three dams have been constructed on the main stream. The upstream dam within the model area, and other dams upstream from the model area, provide flood control protection. High water on the main stream is not a problem unless reservoir capacity is exceeded. However, tributaries of the major stream are subject to flooding caused by local rainstorms.

Drainage basins which lie totally or mostly within developed areas are more flood prone because of the increased runoff caused by paving and construction. Leopold (1968) has shown that the number of floods increases with increased urbanization. Development of an area decreases the exposed ground surface which can absorb rainwater and decreases the vegetation which can retard the flow of water. These two conditions act together to increase the total amount of water which must be drained from an area during a specific time interval; in many cases, this amount of water exceeds the amount that a stream can carry within its banks, and flooding results. Urbanization also decreases the lag time (time required for surface runoff to reach a given point) of peak runoff which results in an increase of the flood peak (Leopold, 1968). The four largest tributaries which lie totally within developed areas of the model can be expected to have flooding problems during heavy rainstorms. Other streams may produce similar hazards as a result of future development. Construction of check dams and storm-water storage can help prevent flooding in currently developed areas. Elimination or restriction of construction within the flood zones can also reduce or eliminate property loss and damage.

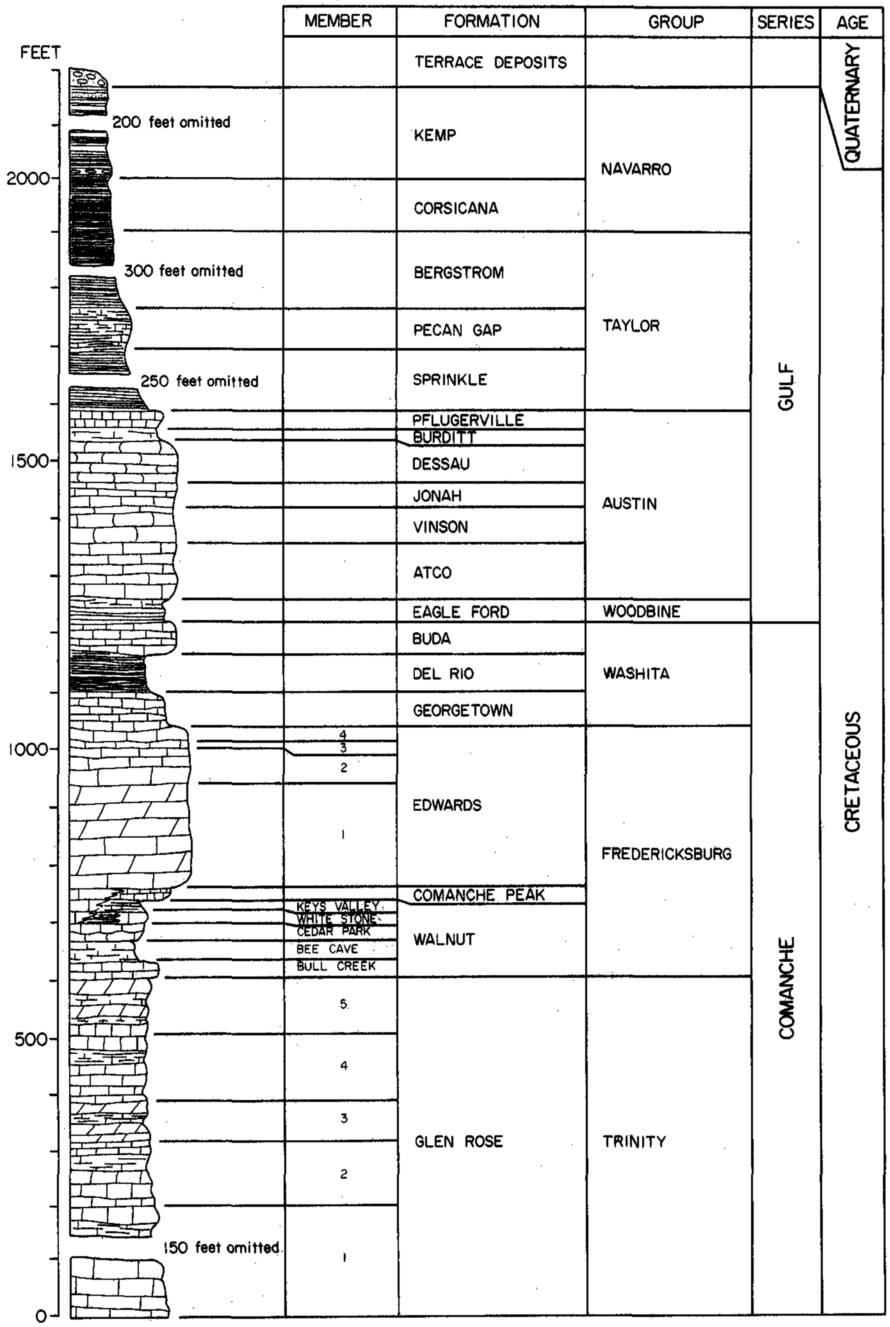


Figure 4. Columnar section of geologic units exposed in the Austin area.

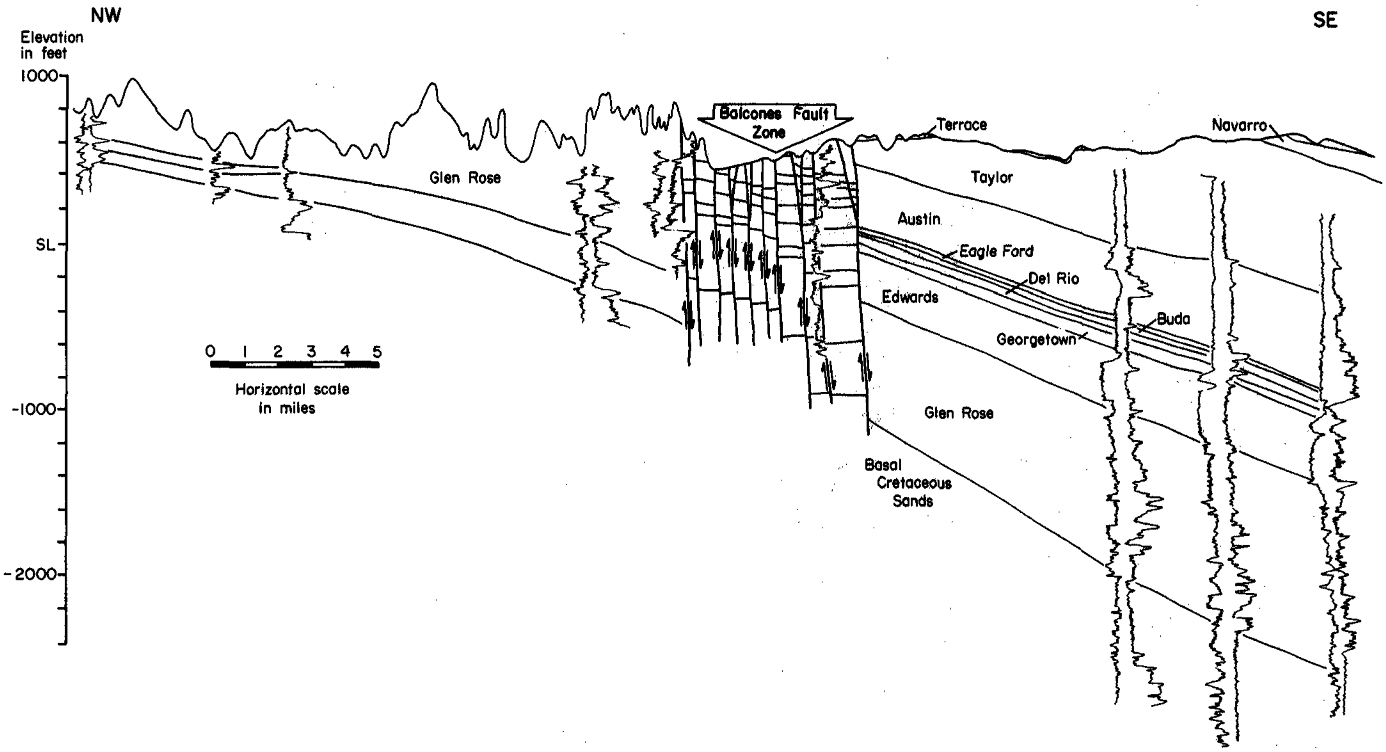


Figure 5. Dip-oriented cross section of geologic units exposed in the Austin area.

ROCK TYPES

Twenty-three bedrock units (formations and members) and eight alluvial units (terraces and alluvium) have been recognized in the model area. Examination of the rocks and comparison of their physical properties have resulted in the delineation of nine basic rock types (fig. 8). Table 1 shows the stratigraphic units which are combined to make up the various rock units and includes a generalized description of each formation in Austin—the model city.

Rock types (table 1) include hard limestone, soft limestone, mixed limestone, dolomite and dolomitic limestone, clay, basalt, altered volcanic material, sand and gravel, sandy alluvium, and clayey alluvium. These rock units are discussed in the following sections; associations between rock types and characteristic soils, vegetation, topography, and physical properties are included in table 2.

Rock Unit Variability

Hard limestone and dolomite, as described in table 1, account for about 17 percent of the total map area (fig. 8). Variations of the typical lithology include some slightly nodular limestones, thin marly limestones (too thin to be delineated at the map scale), and a solution collapse zone. This zone results in local development of sinkholes and caverns.

Soft limestones (table 1) are composed mostly of chalks, marls, and marly limestones and comprise about 14 percent of the total map area (fig. 8). Chalk occurs in a broad belt within the fault zone. Thin marl and marly limestone units (15 to 30 feet thick) crop out in the dissected plateau area in northwestern Austin. Members of the soft limestone unit, exposed adjacent to a volcanic plug, are shelly limestone and coquina, interbedded locally with altered tuff.

Figure 6. Slope-intensity map.

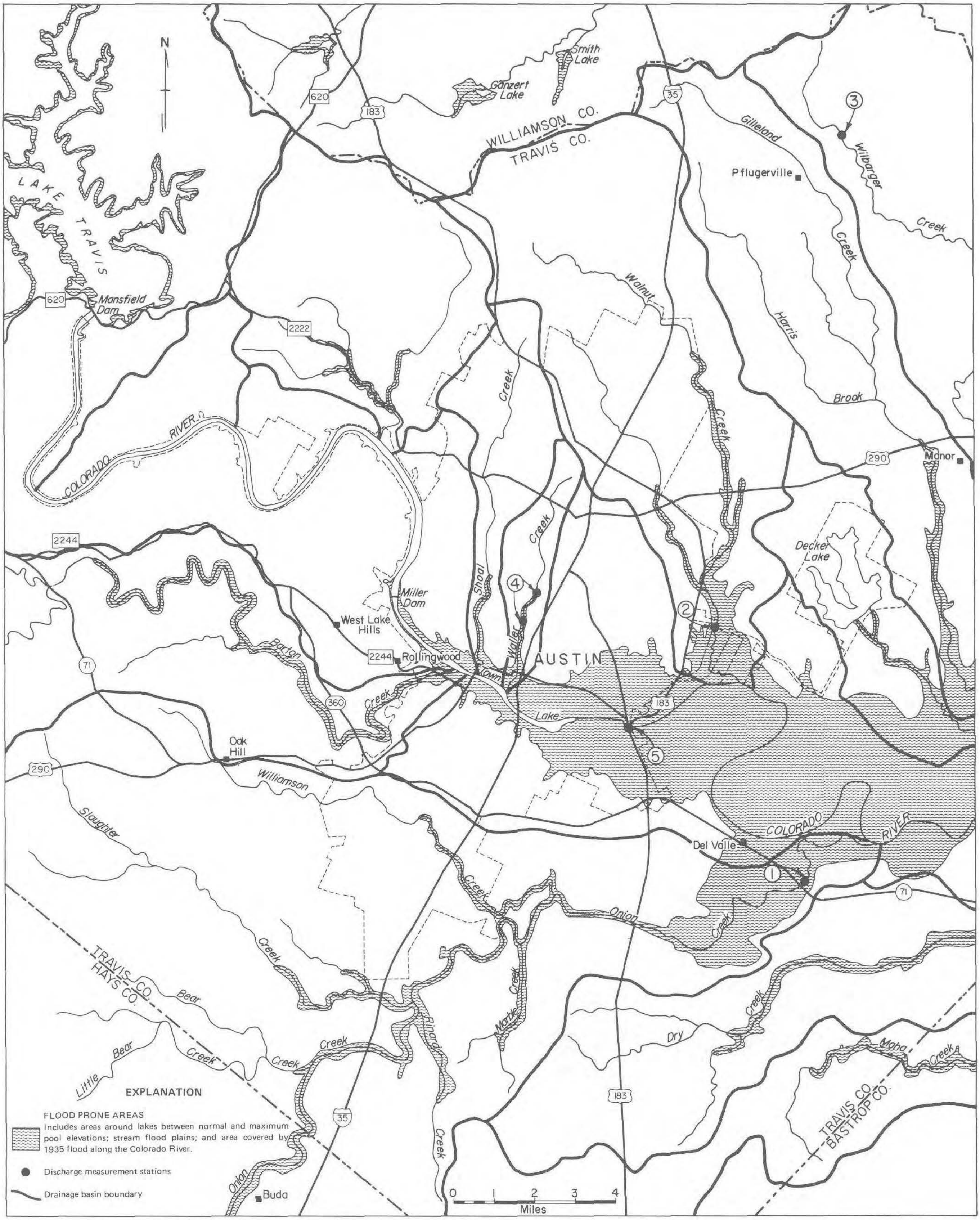


Figure 7. Drainage basin and flood-plain map.

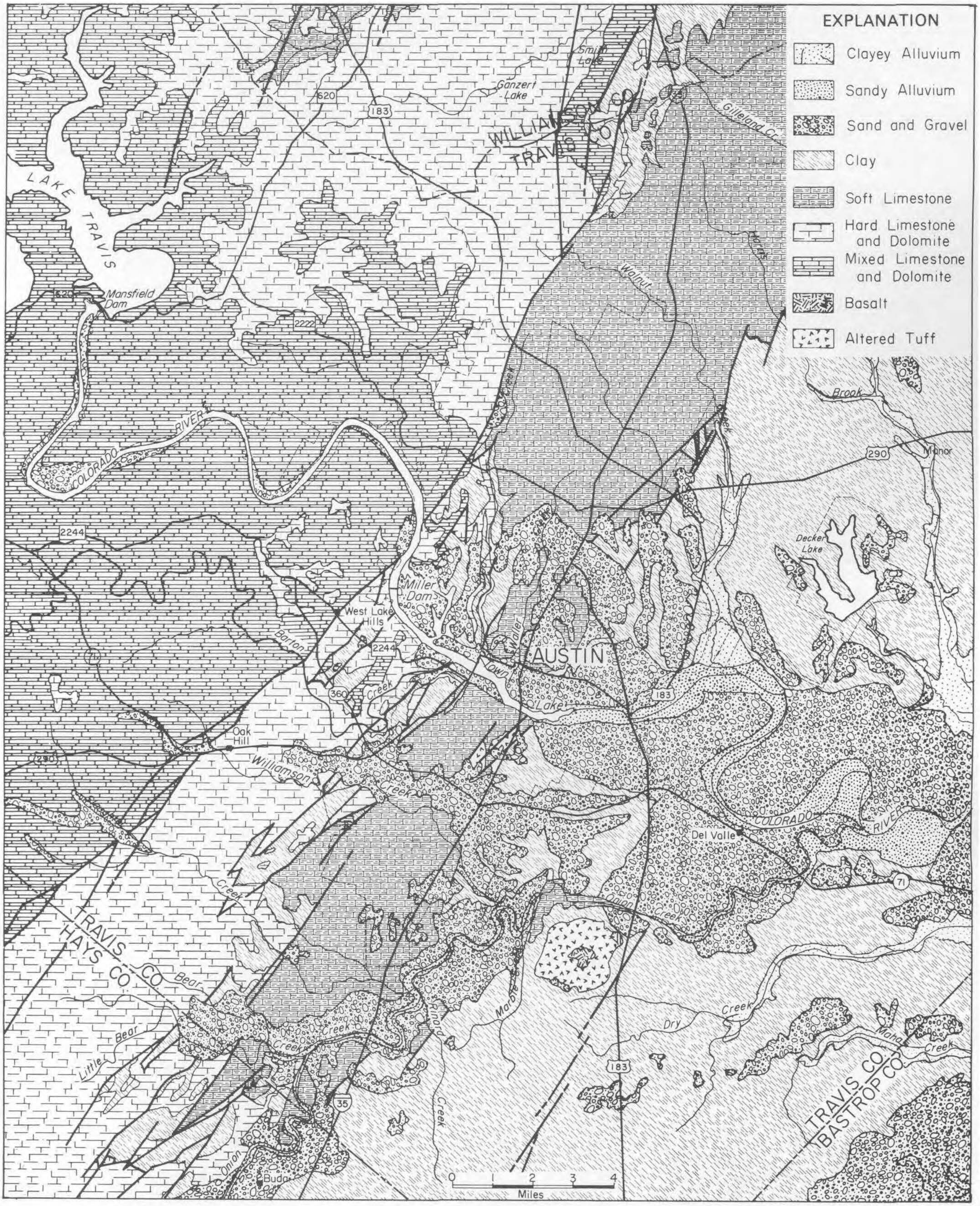


Figure 8. Rock type map.

Table 1. Characterization of rock units, Austin area.

Rock Unit	Geologic Unit	Thickness (feet)	General Geologic Description
Sandy Alluvium	Alluvium	2-20	Unconsolidated gravel, sand, silt, and clay of the Colorado River and tributary streams.
Clayey Alluvium		2-20	Unconsolidated clay, silt, and sand of tributary streams.
Sand and Gravel	Colorado River terrace deposits	2-40	Mostly unconsolidated, yellow- to orange-brown gravel, sand, silt, and clay; consists mostly of Cretaceous limestone and chert fragments with minor amounts of older igneous, sedimentary, and metamorphic rocks. Gravel more common in higher (older) units, and more abundant near base of each unit. Upper surface of First Street terrace is level of maximum recorded flood (1869, 1935). Lower three units partly or completely flooded above Tom Miller Dam. Lower two units were frequently flooded prior to regulation of flow by Colorado River dams.
	Tributary terrace deposits	2-20	Mostly unconsolidated, light-gray to tan, gravel, sand, silt, and clay; consists of locally derived limestone and chert gravel and calcareous silt and clay. Forms terraces along Barton Creek, Bull Creek, Shoal Creek, and other smaller creeks; includes minor, topographically high, alluvial deposits not directly related to modern streams.
Clay	Navarro Group	400	Dark-gray to greenish-gray clays with local sandy layers. Total thickness not present within map area, poorly exposed.
	Taylor Group	700-800	Dark-gray unctuous calcareous clay, generally more calcareous in the mid-portion of the unit. Poorly exposed, fails by slump and creep on moderate and severe slopes.
	Eagle Ford Fm.	40	Upper part is dark-gray clay; middle part consists of thin interbeds of sandy and flaggy limestone, chalk clay, and bentonite; lower part is mostly dark gray calcareous clay. Includes Pepper Shale at base—soft, laminated, noncalcareous, three feet thick.
	Del Rio Clay	75	Dark-gray to olive-brown, pyritic, gypsiferous, calcareous clay containing abundant *Exogyra arietina* (ram's horn oyster). Poorly exposed in steep to shallow slopes below Buda Formation. Del Rio slopes readily fail by slide and creep. Slopes commonly covered with a thin layer of Buda Formation rubble.
Soft Limestone	Austin Chalk	375	Gray to white, thin- to thick-bedded, massive to slightly nodular, fine-grained limestone, marly limestone, and chalk.
	Walnut Fm. Bee Cave Member	30	Soft, gray to tan, nodular weathering, fine-grained limestone, marly limestone, and marl with abundant fossil shells.
	Comanche Peak	20	Gray to tan, fine-grained, nodular limestone, marly limestone, and marl. Forms gentle slope.
Hard Limestone and Dolomite	Edwards Fm. Upper	90-100	Mostly hard, light-gray to tan, fine- to medium-grained, thin- to thick-bedded limestone; thin beds mostly fine grained, flaggy; thicker beds coarser grained with abundant rudist fragments and miliolid foraminifers; soft, nodular weathering, gray to tan, marly limestone near middle. Chert nodules in lower 15 feet.
	Edwards Fm. Lower	200	Mostly thin- to medium-bedded, gray-brown, porous dolomite and dolomitic limestone, and gray to tan, fine- to medium-grained rudist limestone. Nodular chert common. Top of unit is a 20-foot cavernous, solution-collapse zone. Total thickness estimated; complete section not exposed.
	Walnut Fm. Bull Creek Member	35	Hard, dense, gray to tan, fine- to medium-grained, thin- to thick-bedded limestone; shell fragments and miliolid foraminifers common. Forms prominent bench on high topography west of main fault.
	Buda Fm.	35	Gray to tan, hard, fine-grained, glauconitic, shell fragment limestone. Lower part less resistant and slightly nodular weathering. In outcrop fresh surfaces yellowish to pink. Commonly forms steep slopes above the Del Rio Clay.
Mixed Limestone and Dolomite	Glen Rose Fm. Member 5	100	Mostly thin-bedded, gray-brown, fine-grained, porous dolomite; upper 10 to 20 feet pulverulent.
	Glen Rose Fm. Member 4	120	Gray to tan, mostly thin- to thick-bedded, fine- to medium-grained limestone, marly limestone, and marl. Many beds with fossil shells.
	Glen Rose Fm. Member 3	70	Gray-brown to tan, thin interbeds of dolomite, dolomitic limestone, limestone, and marly limestone.
	Glen Rose Fm. Member 2	120	Gray to tan, thin- to thick-bedded, fine- to medium-grained limestone, marly limestone, and marl. Many beds with fossil shells.
	Glen Rose Fm. Member 1	30	Gray to tan, thin- to thick-bedded limestone, marly limestone, and marl. At top is thin, orange-brown limestone ledge with abundant small fossil clams (*Corbula harveyi*); underlying marly limestone abundantly fossiliferous. Thickness is minimum; lower contact not exposed.
	Georgetown	55	Thin interbeds of gray to tan, nodular weathering, fine-grained limestone, marly limestone, and marl; contains abundant fossil shells. Forms moderate to shallow slope above Edwards Limestone.
Basalt	Pilot Knob Basalt	?	Black to dark greenish-gray, hard, fine-grained basalt, exposed in the vicinity of Pilot Knob.
Altered Tuff	Altered Tuff	5-60	Green-brown to tan altered volcanic material and green clays. Thickness is highly variable due to the lenticular nature of deposits. Unit is interbedded with members of the Austin Chalk.

Table 2. Physical properties and general characteristics of rock units, Austin area.

Rock Unit	Slope Stability	Excavation Potential	Foundation Characteristic	Infiltration Capacity	Rock and Mineral Resources	Corrosion Potential	Soils	Characteristic Vegetation	Topography
Sandy Alluvium	Moderate to Low	Low	Moderate	High	Sources of sand and gravel	Moderate to High	Red-brown to gray sandy loam and gravelly sand	Cottonwood, sycamore, willow, ash, pecan, bois d'arc	Broad, flat flood plain
Clayey Alluvium	Low	Low	Moderate	High	Sources of sand and gravel	Moderate to High	Gray clay and clay loam, calcareous		
Sand and Gravel	Moderate	Low	Moderate	High	Sources of sand and gravel	Moderate to High	Red-brown and brown sandy loam and gravelly sand less than 20 inches deep	Post oak and blackjack oak, elm dominant on many tributary deposits	Broad, flat terraces, upper levels are dissected
Clay	Low to Moderate	Low to Moderate (local thin limestones and sandstones may require ripping)	Low	Low	Cement raw material	High	Brown, dark-gray, and olive, calcareous clays and clay loams, 12 to 36 inches deep	Grasses and mesquite trees	Rolling prairies
Soft Limestone	High to Moderate	High (generally can be ripped with heavy equipment)	High	Low to Moderate	Cement raw material	High	Dark-brown to gray-brown, calcareous silty loams, 7 to 65 inches deep	Oak, juniper	Moderately dissected
Mixed Limestone and Dolomite	High to Moderate	Moderate to Very High (some beds may be ripped; some will require blasting)	High	Low to High	Minor source of road material Minor aquifers	Moderate to High	Dark-brown to gray-brown, calcareous silty clays; clay loams and stony clays less than 20 inches deep; locally absent	Juniper, oak	Moderately to deeply dissected, stairstep topography
Hard Limestone and Dolomite	High to Moderate	High to Moderate (blasting commonly required)	High	Low to High	Aquifer Dimension stone Crushed stone	Moderate to High	Red-brown and brown, calcareous clays and stony clays, less than 20 inches deep; locally absent	Oak, juniper, hackberry, persimmon	Moderately to deeply dissected
Basalt	High	Very High (blasting required)	Very High	Low	Crushed aggregate Soil conditioner	Moderate	Dark-brown, non-calcareous clay with basalt rock fragments	Grasses	Too local for characterization
Altered Volcanic Rocks	Moderate to Low	Moderate	Low	Low	None	High	Dark-brown, non-calcareous clay, 12 to 30 inches deep	Grasses and mesquite trees	Too local for characterization

Mixed limestones and dolomite (table 1) are composed mostly of alternating beds of hard limestone, soft marly limestone, and marl, and cover about 21 percent of the map area (fig. 8). They are too thin to be mapped separately and are exposed in the dissected area west of the fault zone. Within the fault zone, members of this unit consist of interbedded nodular limestone, marl, and marly limestone.

Clay units (table 1) are mostly calcareous montmorillonitic clays and occupy about 28 percent of the map area (fig. 8). East of the fault zone, clay marls occur locally within the clay unit. Clays exposed within the fault zone contain thin calcareous sandstones and marl beds.

Surficial deposits include clayey alluvium, sandy alluvium, and sand and gravel units (table 1) which are associated with the fluvial system; they comprise about 20 percent of the map area (fig. 8). Sand and gravel deposits are composed primarily of limestone, flint, and quartz materials. Alluvium is delineated as a separate unit to indicate areas which are dominated by river processes. Alluvium units underlie modern stream channels and areas subject to flooding.

Basalt (table 1) is an extremely local unit and occupies less than 0.1 percent of the total area (fig. 8). Altered tuff (table 1) comprises about 0.3 percent of the map area (fig. 8).

PHYSICAL PROPERTY UNITS

Physical properties which characterize each of the rock types include slope stability, excavation potential, foundation characteristics, infiltration capacity, and corrosion potential. Evaluation of each rock unit (table 2) is based on laboratory tests, field tests, and field observations. Table 3 lists the physical properties and shows how they are related to land use categories, while table 4 shows the ranges of data for engineering tests performed on rock units. Evaluations of units presented in this report should be used as background for land use planning. These evaluations, however, do not eliminate the need for detailed site studies.

Slope Stability

Slope stability (table 2) indicates the resistance of materials to slope failure. Landslides are the result of slope failure and may occur rapidly or slowly. Slides are commonly caused by undercutting the toe of an existing slope, but also may be caused by a gradual disintegration of the material or an increase in the pore-water pressure in rock units which are susceptible to changes in moisture content.

Excavation Potential

The relative ease with which a rock unit may be excavated is termed excavation potential (table 2). This factor is determined primarily by the nature of consolidation or cementation. Excavation potential should be considered in planning large buildings with basements or in designing routes of pipelines.

A rippability chart, developed by the Caterpillar Tractor Company, shows the relative ease of excavation (rippable, marginal, and non-rippable) for various types of rock units based on the velocity transmission of seismic waves. The chart was developed using a Soil Test, MD-1 Refraction Seismograph and a Caterpillar D9 with mounted hydraulic No. 9 ripper (Wylie, 1969). Figure 9 is a modified form of this chart; it shows rock types which occur in the model area.

Foundation Characteristics

Units classed as having high foundation strength (table 2) have high bearing capacities and require only conventional foundation design for large structures. Unconfined compression tests on these units commonly show support strengths greater than 50 tons per square foot (table 4). Units classed as having moderate foundation strength have moderate bearing capacities, can support between 10 and 50 tons per square foot, and may require special designs for large structures. Units with low foundation strength have low bearing capacities, generally require special foundation design for large structures, and may require special design for smaller structures.

Shrink-swell ratios of predominantly clay units should be considered in all types of construction. Pressures in excess of 7,000 pounds per square foot may result from the swelling of some clays. Construction design of structures in units with moderate and high shrink-swell ratios should provide for adequate drainage to prevent the accumulation of excess water. Proper drainage can be obtained in new structures by placing compacted fill below foundations. In older structures, a trench placed adjacent to a foundation, filled with porous material and drained to a lower elevation, can prevent accumulation of excess water.

Table 3. Physical requirements for land use categories, Austin area.

LAND USE		Light Construction	Heavy Construction	Parks and Recreation	Waste Disposal Solid	Waste Disposal Liquid Untreated	Street and Highway Construction	Reservoir Construction
PHYSICAL REQUIREMENTS	Slope Stability	High	High	No Limit	No Limit	No Limit	High	Moderate to High
	Slope Intensity	2-15%	2-5%	No Limit	2-5%	2-5%	2-15%	No Limit
	Flooding Potential	Low	Low	No Limit	None	None	Low	Not Applicable
	Excavation Potential	No Limit	No Limit	No Limit	Low to Moderate	No Limit	No Limit	Low to Moderate
	Foundation Characteristic	Moderate to High	High	No Limit	No Limit	No Limit	Moderate to High	Moderate to High
	Infiltration Capacity	Moderate	Moderate	No Limit	Low	Moderate	No Limit	Low
	Corrosion Potential	Low to Moderate	Low to Moderate	No Limit	No Limit	No Limit	No Limit	No Limit

Table 4. Ranges of engineering data for rock units, Austin area.

Rock Unit	Unit Weight (lb/cu.ft.)	Moisture (% by volume)	Seismic Velocity (ft/sec.)	Triaxial Compression (tons/sq.ft.)	Unconfined Compression (tons/sq.ft.)	Plasticity Index	Absorption Swell (%)	Absorption Pressure (lb/sq.ft.)
Alluvium	81 to 123	3 to 70	1000 to 2500	.1 to 5	.1 to 7	4 to 60	0 to 7	2 to 6000
Sand and Gravel	81 to 123	3 to 70	1000 to 2500	.1 to 5	.1 to 7	4 to 40	0 to 5	2 to 4500
Clay	80 to 123	7 to 45	2000 to 6000	.1 to 8	.9 to 25	10 to 70	.1 to 9	800 to 6600
Soft Limestone	87 to 123	10 to 30	3 to 8000	x	25 to 250	10 to 40	.1 to 8	400 to 1400
Hard Limestone and Dolomite	x	x	4000 to 11000	x	60 to 420	x	x	x
Mixed Limestone and Dolomite	x	x	3000 to 11000	x	50 to 255	x	x	x
Basalt	x	x	8000 to 12000	x	65 to 152	x	x	x
Altered Volcanic Rock	73 to 100	19 to 45	2000 to 5000	x	1 to 3	11 to 43	0 to 5	400

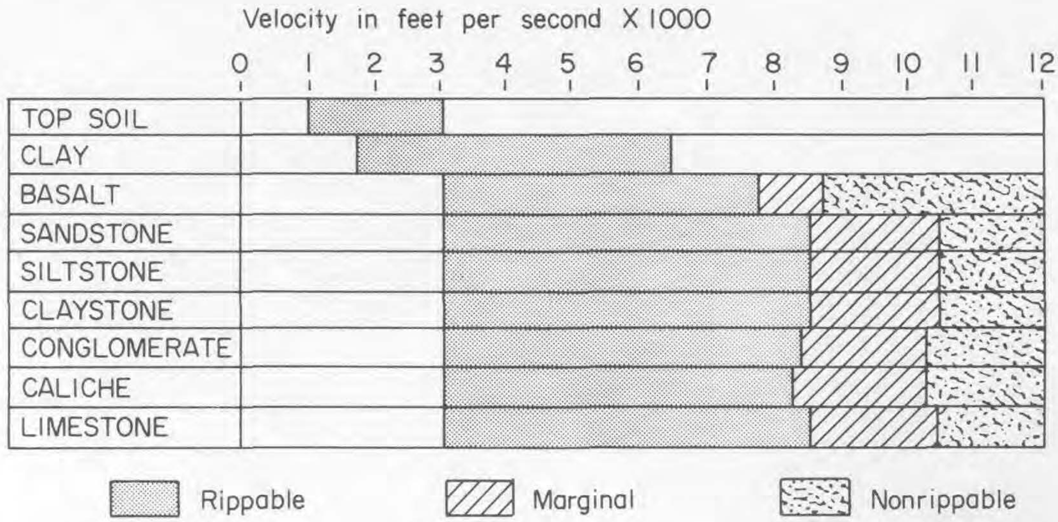


Figure 9. Chart of relationship between seismic velocity and rippability (modified from Wylie, 1969).

Infiltration Capacity

Units with high infiltration capacity provide adequate drainage of fluids at all times. Units which have moderate infiltration capacities generally yield adequate drainage except during extended wet periods when the unit may become saturated. Units with low infiltration capacities generally block fluid access.

Corrosion Potential

Corrosion of buried metals, such as pipelines, is the result of an electrochemical reaction. Electrochemical corrosion occurs when a chemically induced electric current exists between two points that are electrically connected. A corroded pipeline is a negative pole of a corrosion cell (Romanoff, 1957).

Rock and soil units in which pipelines are buried provide the electrical connection for points that have electrical potential differences. Factors which determine the nature of the electrical connection, and therefore the corrosivity of rock and soil units, are composition, permeability, moisture content, oxygen concentration (aeration), acidity (pH), and bacterial content.

The resistivity (resistance to the flow of electric current) of a rock or soil depends on many of the same factors which are related to corrosion. Corrosion potential of various units may be estimated from resistivity measurements. A modification of corrosivity groupings according to resistivity measurements (Romanoff, 1957) is used in this report. Table 5 shows the corrosion categories and their respective resistivity ranges.

Table 5. Arbitrary ranges of corrosivity with respect to resistivity (modified from Romanoff, 1957).

Corrosion Potential		Resistivity
This Report	**Romanoff**	**Ohm-cm**
Low	Very Low	> 10,000
	Low	5000 to 9999
Moderate	Moderate	2000 to 4999
High	High	1000 to 1999
	Very High	<1000

RESOURCES

Geographic Resources

Urban planning should include maximum utilization of the total resources which occur within an area. Resources include not only the natural rocks and minerals but also the geographic situation, vegetation, and climate, all of which are important to the development of industry, residences, and recreation.

Approximately 42 percent of the total land area and 68 percent of the population of Texas lie within a 200-mile radius of the model city. Major highways and railways connect it with other population and industrial (metropolitan) areas.

The moderate climate permits outdoor activities throughout most of the year; the mean high temperature for July is about 95 degrees and the mean low temperature for January is about 41 degrees. Rainfall is about 32 inches annually and the growing season is 270 days.

Rock and Mineral Resources

Mineral resources should be included in the overall plan for growth so that development and expansion do not preclude future extraction of the materials. Proper zoning and encouragement of dual land use will be helpful in insuring maximum benefit from local resources. Materials suitable for development as mineral resources occur in certain areas; if these deposits are covered by urban areas, potential economic benefits are lost.

Several types of mineral raw materials available in the model should be considered in urban planning. About $5 million annually is earned from crushed stone, dimension stone, lime, sand and gravel, and oil. Raw materials for cement and brick clays have been produced in the past and are potential future resources. Knowledge of the distribution of these mineral deposits is essential to the development of an area.

Several sites within the area are examples of what has been done in the past, both with and without regard to the conflict between urbanization and resource extraction. Some of these sites show good practices and others stand as examples of what should be avoided in the future. For example, portions of the area are underlain by sand and gravel deposits suitable for commercial production; however, development of residential and commercial areas (fig. 8) has now precluded the extraction of the deposits. Proper land use practices could have saved this resource.

Limestones.—Limestones provide large reserves of dimension stone and crushed stone for construction uses, and high-purity limestone for chemical and industrial uses.

The Edwards Limestone is exposed extensively on the Jollyville Plateau and in the southwest section of the Austin area. This hard limestone and dolomite unit (fig. 8) is a source of high-purity limestone used in producing lime, fluxstone, agricultural limestone, and crushed stone (Rodda and others, 1966). Purity of many limestones in this formation exceeds 97 percent $CaCO_3$.

Hard limestones just north of the area are quarried for dimension stone and occur in the northwest part of the map area.

Soft limestones (fig. 8) are potential sources of cement raw materials. Lime materials from this formation are used for the production of cement in other parts of the State. Where these rocks are coarse grained, they also have good characteristics for use as road base material.

Sand and gravel.—Stream deposits are currently mined as sources of aggregate. Although many sand and gravel deposits have been covered by the urban area, significant reserves of these materials still remain in undeveloped areas. The general distribution of sand and gravel deposits is shown in figure 8; pit symbols indicate areas where extraction of materials is currently active and areas where materials have been extracted in the past.

Ground water.—Principal sources of water for rural areas, communities, industrial uses, and small towns in this area are from two major aquifers. Ground-water withdrawal from all aquifers in the county in 1970, for municipal and industrial use, was 293,430,002 (294×10^6) gallons.

Sands not exposed in the model area have been penetrated by many wells (Arnow, 1957) at about 1,000±100 feet (fig. 10). The quality of water is generally good.

Subsurface dolomites and dolomitic limestones provide a source of ground water at depths ranging from about 100 to 1,000 feet within the fault zone, and greater than 1,000 feet east of the fault zone (fig. 11). Major springs in the vicinity flow from fractures which intersect the water-bearing strata of the lower part of the hard limestone and dolomite unit. Dissolved-solids content ranges from a few hundred to more than five thousand parts per million (Mount and others, 1967).

Minor aquifers of the mixed limestone and dolomite unit supply small quantities of water in the area west of the main fault. Water-bearing units in this interval occur within the dolomitic units and are laterally discontinuous.

Low-level alluvial deposits of the main stream are commonly saturated with water at relatively shallow depths, and can provide large quantities of water. Recharge is primarily from the river. Water quality is about 276 mg/1 dissolved solids. Local surface contamination is easily transmitted to this shallow aquifer. These alluvial units are capable of producing large quantities of water in many local areas.

Petroleum.—One small oil field is within the area. The field includes four wells which have

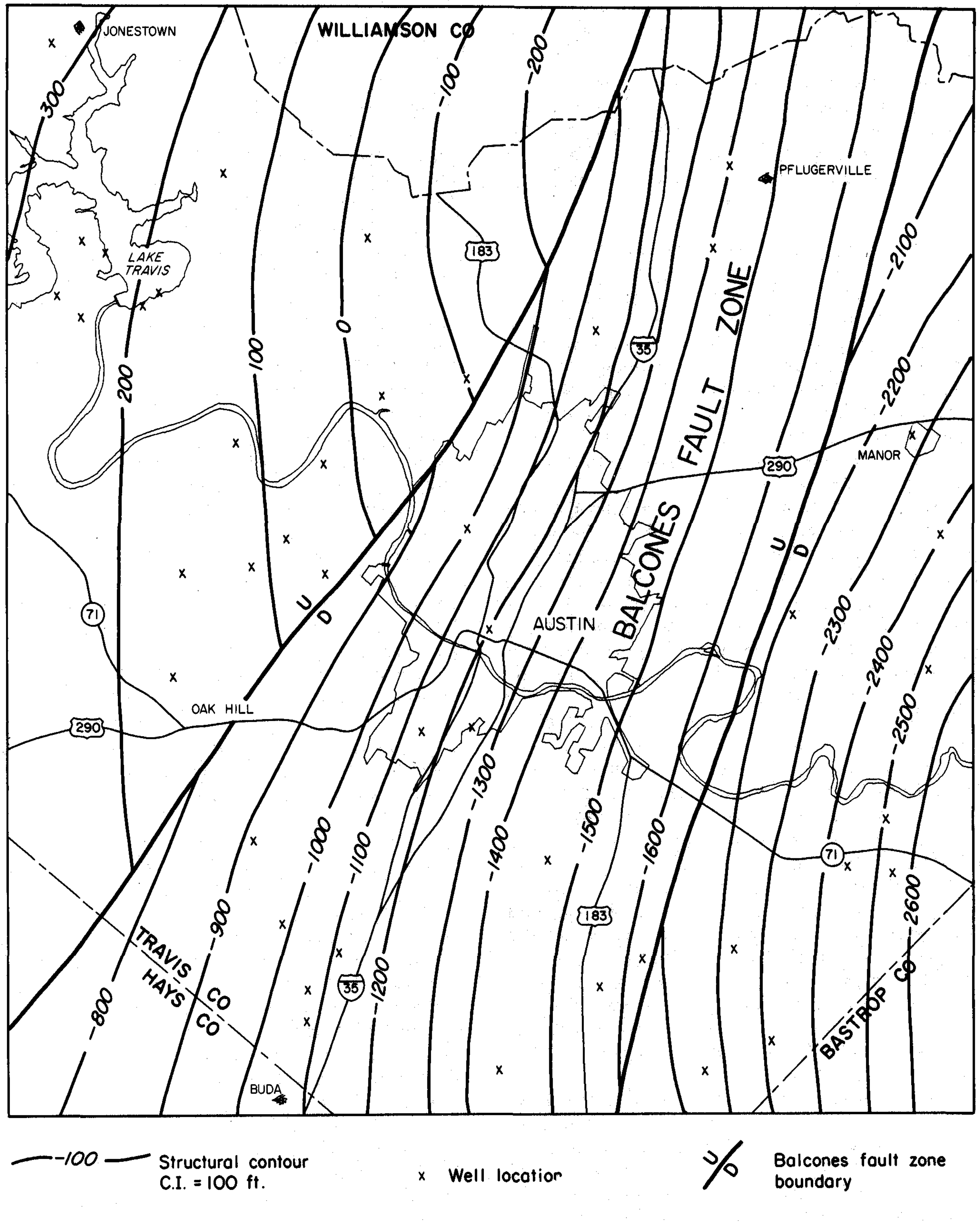
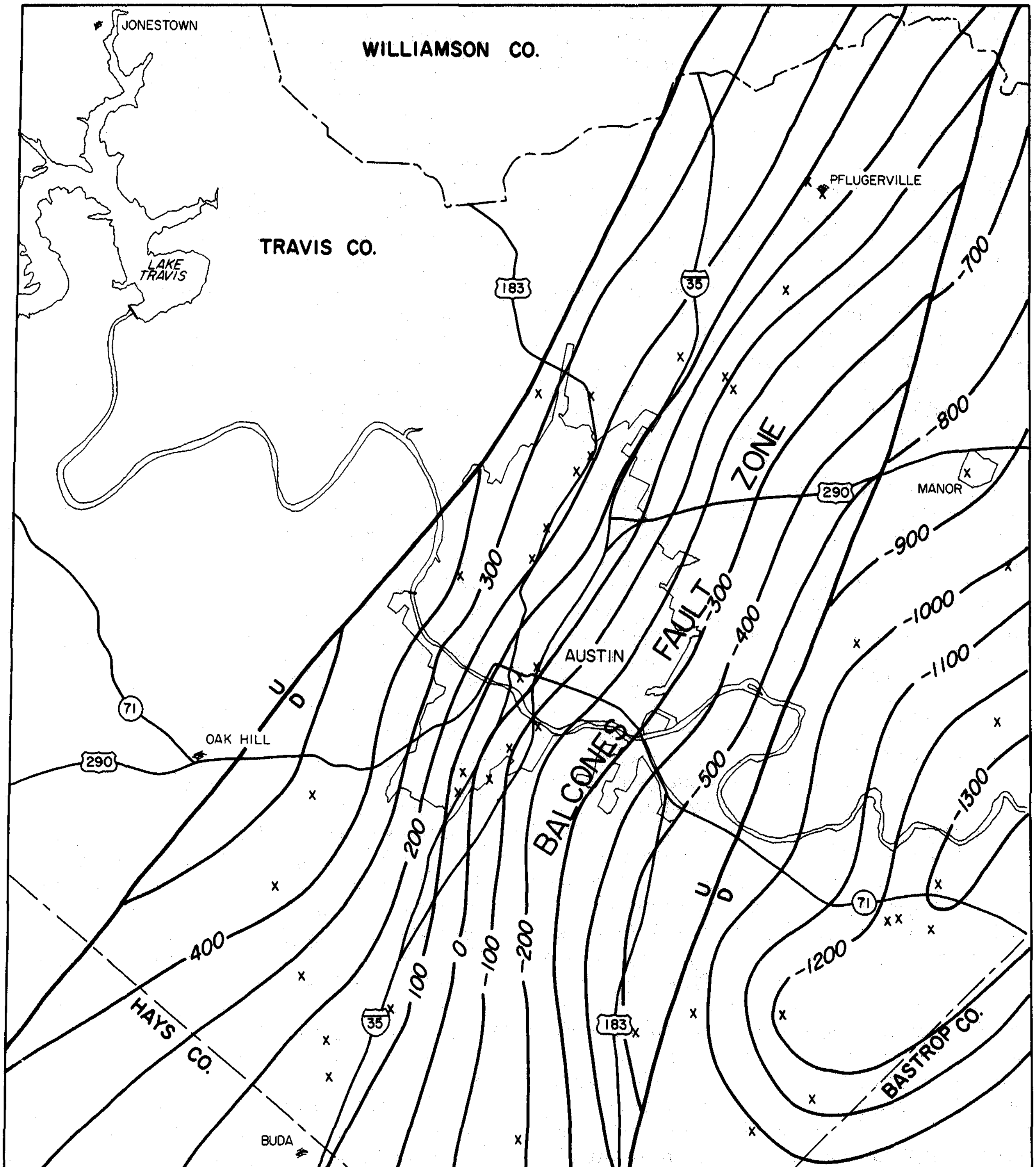


Figure 10. Structural contour map on the top of the Trinity aquifer, Austin area, Texas.



—-100— Structural contour C. I. = 100 ft.

x Well location

U/D Balcones fault zone boundary

Figure 11. Structural contour map on the top of the Edwards aquifer, Austin area, Texas.

cumulative production of approximately 400,000 barrels. Oil is produced from faulted zones associated with serpentine plugs in the Late Cretaceous strata.

APPLICATION OF ENVIRONMENTAL GEOLOGY

The complexity and number of problems associated with planning urban growth can be reduced significantly when land resource data are available. There are many physical conditions which impose limiting factors on development. Limiting factors do not necessarily rule out a particular area for certain types of construction; they do, however, point out the problems which are present. If a choice of locations is available, the area with the least number of limiting factors can be selected without extensive investigation. For example, a firm seeking a site for an industrial complex needs an area of low relief and high foundation-support strength, and access to railroads. Topographic and slope-intensity maps may indicate several suitable locations near railroads; the environmental geologic map and physical properties map can be used to eliminate those areas which are unfavorable because of poor foundation materials or prohibitive construction costs. Site evaluation by engineers is therefore necessary for only a few sites, rather than several, where environmental mapping is complete; this fact alone can save the firm a substantial amount of money and time.

Urban development can be considered in five basic categories: (1) light construction, (2) heavy construction, (3) recreational areas, (4) waste disposal, and (5) road construction. Properties of the available land resources outlined in this paper are: (1) slope stability, (2) slope intensity, (3) flooding, (4) excavation potential, (5) foundation requirements and limitations, (6) infiltration-capacity requirements and limitations, and (7) corrosion potential. The physical properties are used to evaluate each rock type for the development categories, and land resource properties can be used to outline areas which are best suited for some types of development or have severe limitations for others (table 3). A particular advantage to this kind of evaluation is the recognition of problem areas prior to development, rather than the attempt to solve problems after development is completed.

Factors considered for the advanced planning of an urban complex are outlined below according to the categories mentioned. Parameters other than the ones noted may be of significance in some areas or for specific uses, but are not always necessary for general consideration.

Light construction.—Single-family residential and small (single-story) commercial structures are included in the light construction category. Primary considerations are slope stability and foundation characteristics. Slope stability is especially important in areas where natural slopes are steep. The degree of slopes is also an important factor in residential developments; building costs disproportionately increase in areas with slopes in excess of 15 percent, and surface drainage problems may exist in areas with slopes of less than 2 percent. Infiltration capacity should be considered in areas where septic tanks and filter fields are used, and corrosion potential should be considered if metal plumbing or electrical conduits are used.

Heavy construction.—Industrial and institutional complexes, multistory commercial buildings, and apartment buildings are included in the heavy construction category. Slope stability and foundation characteristics are the major parameters. Slope-intensity values ranging from 2 to 5 percent are generally most desirable; and foundation strength and excavation potential are important in estimating construction costs, especially when one or more basement levels are used. Corrosion potential should be considered when pipelines or metal structures are placed in direct contact with the soil or bedrock. High shrink-swell materials are capable of cracking and removing protective coatings, therefore cathodic protection devices are commonly more effective and durable.

Recreational areas.—Parks and greenbelt zones do not require special engineering properties and consequently can be placed in areas where limitations are too severe for other uses. Flood plains, for example, can provide attractive and desirable areas for recreation, whereas they present flooding problems to housing developments or businesses. High-relief areas may present construction problems, but they provide attractive recreational sites.

Waste disposal—Infiltration capacity or permeability is the controlling factor in the selection of sites for solid waste disposal and sewage lagoons, and for determining the suitability of potential residential-suburban areas for individual sewage systems.

Relatively impermeable materials are desirable for solid waste disposal and sewage lagoons, whereas septic tank systems require moderate to high permeabilities. Areas which have a high density of fractures (faults and joints), cavernous rock formations near the surface, or a shallow water table (such as associated with a river flood plain) should not be considered as potential areas for waste disposal because of the possible contamination of aquifers and streams.

Road construction.—Bearing capacity, shrink-swell potential, and slope stability are important properties which should be considered in road construction. Bearing capacity is of primary importance in areas where bridges or overpasses are to be constructed; whether the material is a clay, limestone, or sandstone is important in determining the type of foundation and the amount of site exploration which will be required. Shrink-swell potential and slope-stability data are necessary to determine the type of base and grades of embankments that are required.

SUMMARY AND CONCLUSIONS

Geologists can contribute to environmental planning and to the presentation of physical data consistent with the requirements of planners and individuals. Physical data and planning criteria presented here are not unique; only the emphasis and mode of presentation are different from traditional geologic studies. This type of study can be generated from most detailed geologic maps, engineering test data for individual rock types, and standard topographic maps. The amount of detail depends on the nature of initial basic data and the project duration. The model presented here shows the data and the types of presentation which can be most effective in environmental geologic studies of similar urban areas.

Areas with high population densities and rapid growth rates are the most critical areas for environmental planning. This critical need exists because man's impact on the natural environment is magnified by population concentration. Except by expensive urban renewal, existing cities can do little to change previously developed areas. Land use planning can make valuable contributions toward environmental compatibility of areas which will be developed. Environmental abuse by an individual or small group of individuals may go undetected, but environmental abuse by a city of several hundred thousand individuals can upset the natural balance of several systems. Some improper development practices and resulting adverse effects are: (1) improper placement of solid and/or liquid waste disposal that may result in aquifer and/or surface water pollution; (2) alteration of natural vegetation and drainage patterns that may result in excess erosion and flooding; and (3) urbanization of mineral resource areas (particularly construction materials) that may result in longer hauling distances and higher consumer prices.

In addition to polluting and disrupting natural systems, individuals may impose costly and unnecessary regulations upon themselves. A typical unnecessary cost factor is the design of foundations which will withstand stresses much greater than those which are anticipated. This method of insuring adequate foundation design is always expensive and is only rarely justified. In many areas where building and foundation conditions are highly variable, building codes impose uniform requirements for all areas. This practice can lead to inadequate building design in some areas and overcompensated building design in other areas. In both cases the result is an unwarranted expense, either for secondary foundation repair or for unnecessary materials.

A city which foresees growth into surrounding areas should look into development problems which might occur in different zones. It should try to avoid types of development that would conflict with these problems. Building codes can be made more flexible so that construction practices are not required to be uniform, but are dependent upon the types of materials in which foundations are placed. Park areas can be selected in advance and located in areas which are less satisfactory for construction purposes (acquisition of park property in advance of development can be less costly than purchasing after development is completed). If mineral resources such as sand and gravel are available within adjacent areas, plans for extraction prior to development would prevent extensive construction over valuable resource material and possible loss of a large portion of the deposit. Potential sites for sanitary landfills and sewage lagoons can be selected so that their conflict with the natural environment and developed areas is minimal.

Not all of the detrimental effects of more intensive land use can be avoided. However, they can be reduced significantly in most cases where adequate data is available.

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ENVIRONMENTAL GEOLOGY OF THE GREATER HOUSTON AREA

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INTRODUCTION

The Greater Houston area represents one of the most rapidly developing areas of the State of Texas. In order to provide rational and prudent management programs for this accelerated growth area, an inventory of natural resources and their capability to support certain activities is requisite. Toward this goal the Bureau of Economic Geology, The University of Texas at Austin, in conjunction with the Earth Observations Applications Office of National Aeronautics and Space Administration, initiated in 1972, an environmental geologic evaluation of 10,000 square miles encompassing the Greater Houston area. Results of this project were a set of maps depicting the distribution of geologic, physical process, biologic, and man-made units and a report which described and evaluated the map units. The purpose of this paper is to describe the methodology used in the development of this Atlas and to present salient results of the project.

Physiography of the project area (fig. 1) includes a flat, prairie coastal plain near the City of Houston and heavily forested uplands and upland savannas north of Houston. Elevations range from less than 50 feet on the coastal plain to over 500 feet in the northern forested areas.

The project area is bounded by the Colorado and Brazos Rivers on the west, the Trinity River on the east, low-lying marsh and prairie areas to the south, and upland forest belts to the north. Geologic evaluation of the southern marsh and prairies of the Greater Houston area are included in another Bureau report, "Environmental Geologic Atlas of the Texas Coastal Zone—Galveston-Houston area" (Fisher and others, 1972). Herein, discussion of environmental geology in the Greater Houston area is restricted to the area bounded by the Brazos and Trinity Rivers and extending northward from the Galveston-Houston Coastal Atlas map area for approximately 75 miles. Representative examples of land resource features common to the entire area are utilized to present a regional overview of the project.

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Five maps were constructed to depict the environmental geology of the Greater Houston area. These include maps of (1) environmental geology delineating and defining basic geologic, physical process, and biologic features; (2) linear features observed on aerial photographs, which may represent fracture zones or active and potentially active fault zones based on mapping; (3) biologic assemblages and environments based on vegetation; (4) man-made features and water systems; and (5) mineral and energy resources.

In addition, a Resource Capability Map was based on a synthesis and evaluation of mapped environmental geologic units in terms of first-order environmental significance, whether physical, biological, hydrological or chemical.

Methodology

The basic data source utilized in the mapping was photo imagery supplied by NASA. It included NASA/MSC 191 NOV. 1971 color infrared photography, NASA/MSC 197 APR. 1972 black-and-white photography, and NASA/MSC 145 NOV. 1970 color photography, all at a scale of approximately 1:120,000. All environmental units were mapped using stereo pairs of photographs and mapped units were than transferred from individual photos to a 1:125,000 photomosaic base. Changes in color, tone, and fabric were the bases for defining environmental units; field checking verified the validity of the units. Models of alluvial and deltaic systems developed in mapping the Environmental Geologic Atlas of the Texas Coastal Zone and basin analysis studies at the Bureau of Economic Geology strongly influenced the interpretation. Sedimentary facies and planar or aerial patterns were stressed in deriving environmental units because the low topographic relief prohibited the use of morphological modifiers.

Special-use maps were derived from the environmental geologic units utilizing interpretive and compilation methods. Although certain data, such as pipeline distribution and waste-disposal sites, were compiled from other sources, most data were obtained either directly from NASA photography or interpreted from the environmental geologic units. General sources and flow of data used in preparation of the unpublished environmental geologic atlas of the Greater Houston area are shown in figure 2.

ENVIRONMENTAL GEOLOGY UNITS

A total of 51 discrete environmental geologic units were defined and mapped within the Greater Houston area. These units range from extensive, broad sand belts continuous for tens of miles to small, isolated mud and marsh units only a few tens of feet in width. Fundamental environmental geologic units mapped include: (1) physical units, composed of geologic substrates and soils where composition and physical properties are of first-order importance; (2) biologic units, such as fresh-water marsh and swamp, where biologic activity and productivity are dominant features; and (3) active process units, such as alluvial fans and steep slope units, where specific activity or potentially active processes are first-order considerations.

Scheme of Classification

Three broad classes of environmental geologic units exist within the project area. These are designated according to a temporal scheme and include (1) relict natural units formed during the Tertiary period within environments no longer active, (2) relict natural units formed during the Pleistocene epoch in previously active but currently inactive environments, and (3) Holocene-Modern units that are the product of

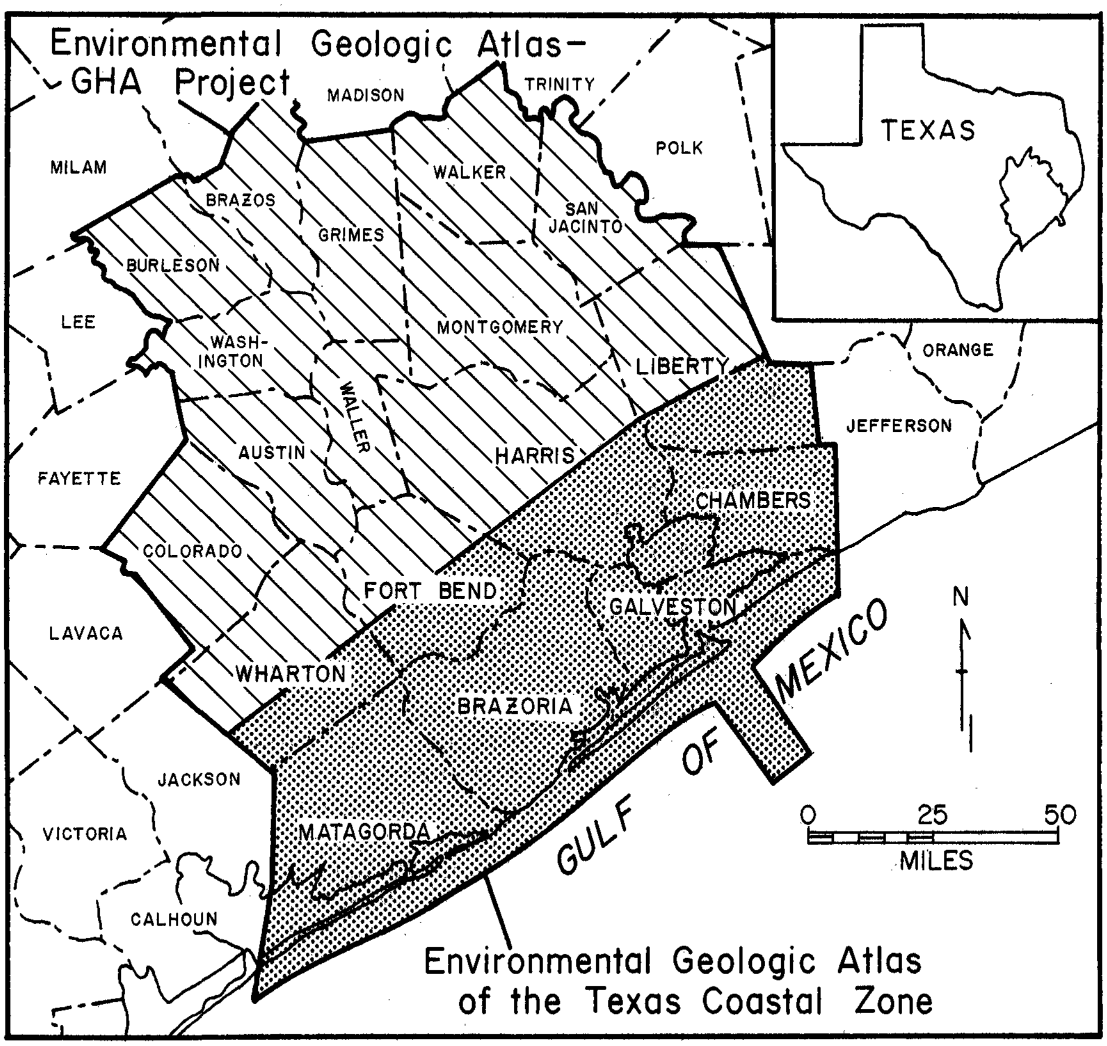


Figure 1. Location of Greater Houston area. Greater Houston area is shown by diagonal lines, whereas the region covered by maps of the Environmental Geologic Atlas of the Texas Coastal Zone is stippled.

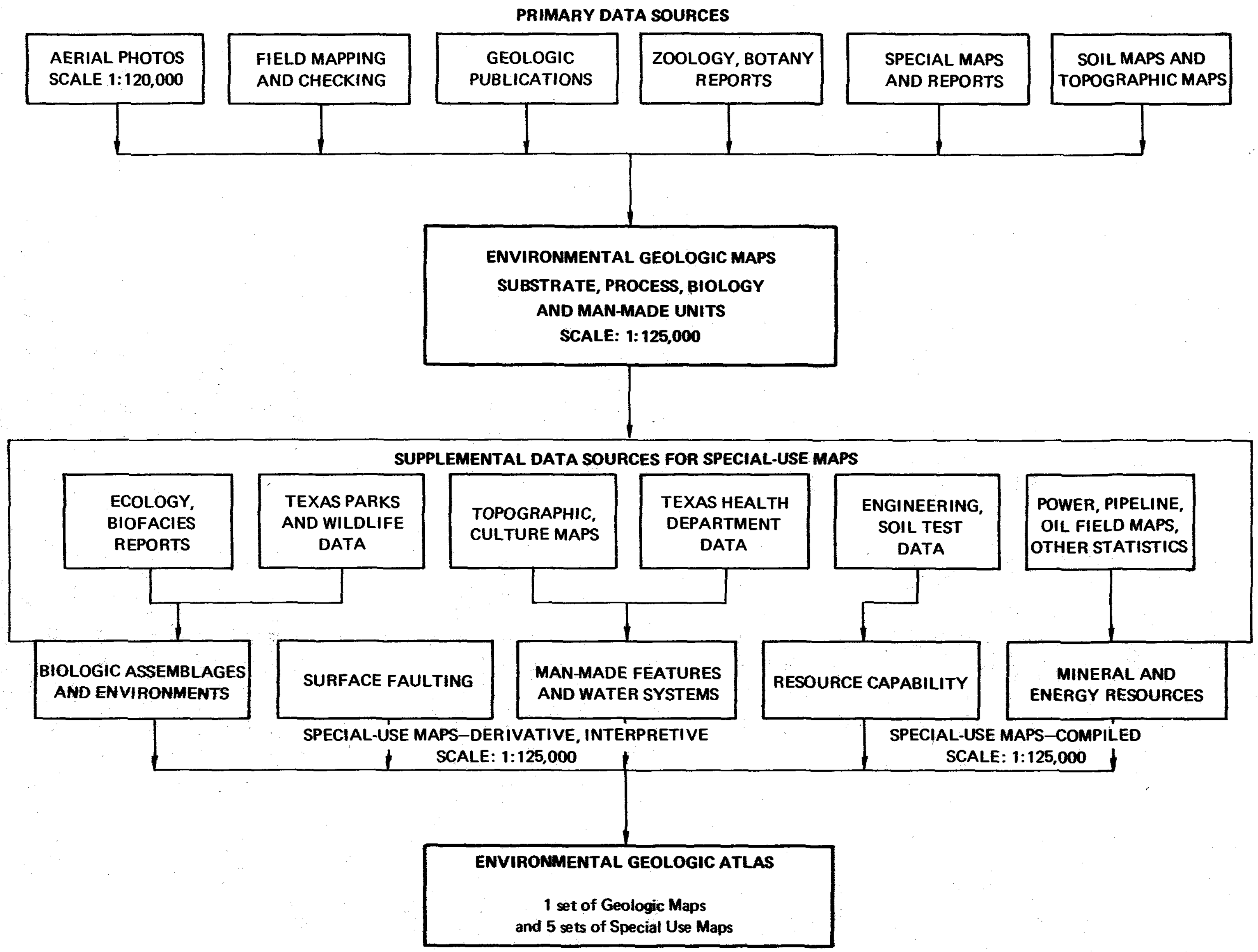


Figure 2. Sources and flow of data used in Greater Houston area project.

currently active processes and environments originating less than about 20,000 years B.P.

In the classification scheme, the mapped environmental geologic units are further grouped into large-scale natural systems. Such grouping reflects the natural association and origin of specific units and helps to predict their important characteristics—composition, physical and chemical properties, and hydrologic features. Natural systems include: (1) deltaic-marine systems, a series of relict Tertiary and Pleistocene substrates formed by ancient deltas and marine processes; (2) fluvial systems, a suite of relict Tertiary and Pleistocene substrates and currently active Modern environments and substrates formed by ancient and present-day rivers, respectively; (3) alluvial fan system of relict Pleistocene substrate; and (4) marsh-swamp system in which flora actively grows today.

Certain minor units are not included in the above systems. For example, small alluvial fans, steep slopes, and soil units are included in an independent category.

An Example—Environmental Geology Units of the Greater Houston Area

An example of the distribution and general setting of environmental geologic units is illustrated in figure 3. This map is schematic and, because of scale, depicts only the principal framework units within the area. However, sufficient detail is given to illustrate adequately the classification scheme and to show the diversity of environmental geologic units.

Tertiary Systems

The two depositional systems that constitute the Tertiary include a fluvial-deltaic system and a fluvial system (fig. 3). The Tertiary fluvial-deltaic system occurs in the most northern parts of the area and is composed of a band of sands which are covered by dense tree growth and expanses of delta-plain muds forming prairies covered by grass (Unit I, fig. 3).

The Tertiary fluvial system is distributed across a north-central belt and consists of east- to west-trending tuffaceous fluvial sands which are tree covered, and overbank mud which supports prairies (Unit II, fig. 3). Locally within the areas of overbank mud, there are narrow bands of fluvial sands which trend north to south.

Pleistocene Systems

Two natural Pleistocene systems—an alluvial fan system and a fluvial-deltaic system—dominate the southern half of the mapped area. The alluvial fan system occurs as a wedge-shaped belt of tree-covered sands and gravels in the south-central part of the area (Unit III, fig. 3). Interspersed within the coarse-grained alluvial fan deposits are isolated prairie areas composed of overbank mud deposits (fig. 3).

The Pleistocene fluvial-deltaic system is further subdivided into two basic units—fluvial sands and delta-plain muds. The fluvial sand deposits occur as a continuous blanket of meanderbelt sand deposits across the southwestern and southeastern parts of the Greater Houston area (Unit IV, fig. 3). Pleistocene delta-plain deposits of the fluvial-deltaic system occur in the southern parts of the area as flat mud and clay substrates covered with prairie grasses. These fine-grained clayey sediments bound isolated narrow, elongate distributary sands trending in a north-south direction (fig. 3). Mapping of these distributary sands dramatically emphasizes the utility of color infrared photography over other types of imagery in mapping environmental geologic units. Using black-and-white photography to map a high-mud system, the distributary channels are delineated as discontinuous sand segments. In contrast, color infrared photography permits a more complete definition of the surface trend of the channel bodies (fig. 4).

Holocene-Modern Systems

Two major systems compose the Holocene-Modern deposits: (1) fluvial systems, and (2) marsh-swamp systems. The through-flowing major fluvial systems of the Brazos, San Jacinto, and Trinity Rivers (fig. 3) are fine-grained meanderbelt streams characterized by highly sinuous courses, relatively high mud load, and broad flood plains. Dominant sediment types of these systems include meanderbelt sands, flood-plain muds, and isolated terrace deposits. Terrace deposits are composed of meanderbelt sands and normally occur approximately 20 to 40 feet above the present river level. Marsh-swamp units are located mainly within the valleys of the major rivers (Unit VI, fig. 3). Substrates associated with marsh-swamp units are predominantly mud derived from overbank flooding of through-flowing streams.

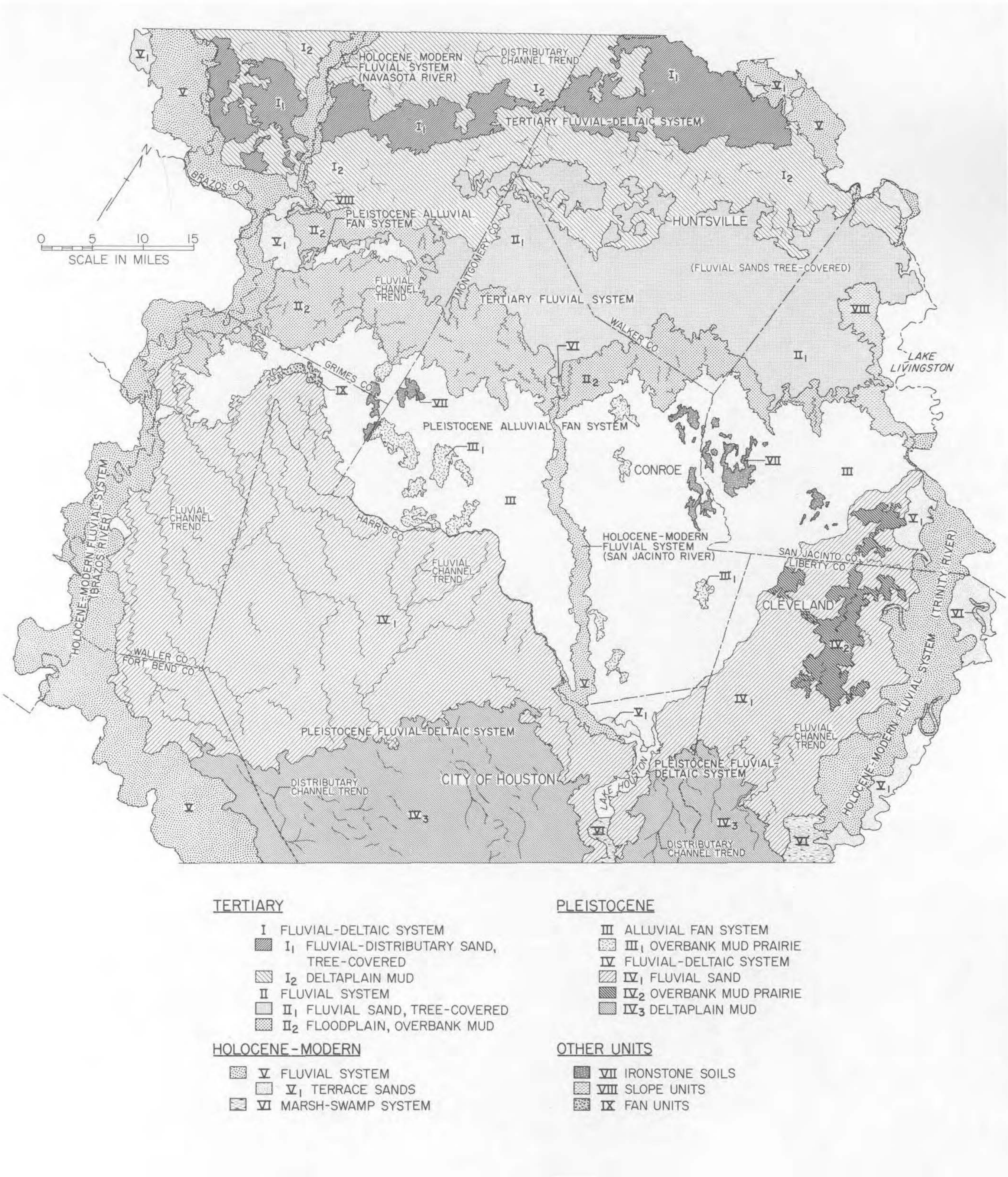
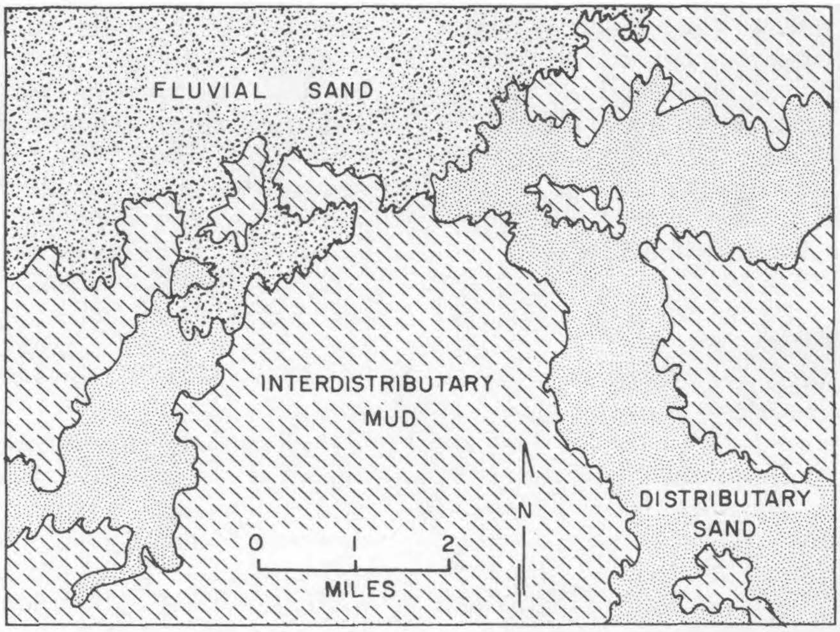
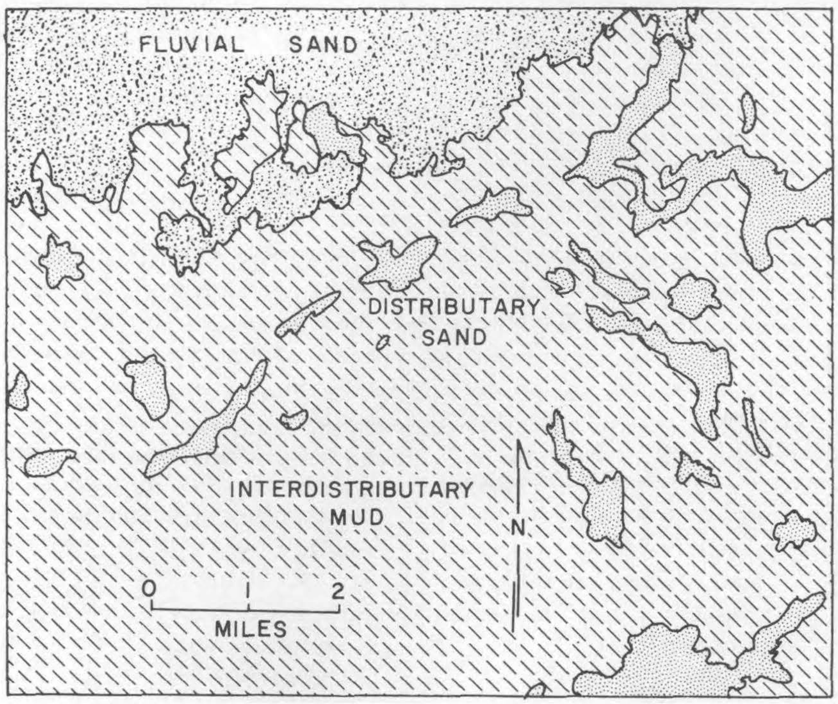


Figure 3. Natural systems defined by environmental geologic mapping in the Greater Houston area.



A.



B.

Figure 4. Sand trends in a high-mud deltaic system in the Greater Houston area.

Other Units

Additional units mapped within the area include: (1) ironstone soils which are developed on the Pleistocene alluvial fan deposits north and northwest of the City of Houston (Unit VII, fig. 3); (2) steep slope units which occur adjacent to the valleys of the Brazos and Trinity Rivers (Unit VIII, fig. 3); and (3) fan units composed of sands developed marginal to the upland Pleistocene fluvial sands and fan deposits (Unit IX, fig. 3).

SURFACE FRACTURES

Structural lineaments are observed on aerial photographs to characterize extensive portions of the Greater Houston area. A number of these are active faults which have resulted in breakage of pipelines, pavements, structural foundations, and other types of surface or buried structures. Most of the structural lineaments are probably fracture zones with the potential for fault activation. There is some evidence to suggest a relationship between lineaments and deep faults mapped by petroleum geologists. The Houston area has a higher incidence of known surface faults than any other area along the Texas Coastal Plain.

Activation of Structural Lineaments

Faults within the Greater Houston area exist because of natural geologic processes. However, an apparent cause and effect relationship exists between certain of man's activities and increased frequency of movement along surface faults. Most of the known currently active faults are located in areas of extensive withdrawal of ground water (Fisher and others, 1972).

Within the aquifers, the dewatering of the clays results in subsidence and may activate movement along faults. Accordingly, areas of large ground-water and hydrocarbon withdrawal are areas in which surface faulting is most acute. Most fractures mapped are inactive at present; however, many of them occur in ground-water withdrawal areas and should therefore be considered as potential problems in any development program.

Recognition of Structural Lineaments

Several types of evidence indicate the active and potentially active nature of lineaments on aerial photographs. These include: (1) topographic scarps as shown by abrupt changes in relief along the coastal-plain surface; (2) anomalies in drainage, vegetation, and geologic facies patterns; and (3) photographic tonal and textural linear trends (lineaments). All these lines of evidence were utilized in mapping active and potentially active faults in the Greater Houston area. These features are designated structural lineaments in this paper.

Structural lineaments were mapped on NASA black-and-white (1:125,000) photomosaics and color infrared (1:120,000) aerial photographs. Three techniques were utilized:

(1) A set of photomosaics of the entire area was joined together to delineate regional lineaments. This synoptic overview provides good definition of linear features which are continuous for many tens of miles.

(2) Individual photomosaics were utilized to map short, discontinuous linear segments.

(3) Color infrared photographs were employed in stereo to map local, relatively obscure linear segments. Many short linear features which are locally mappable on color infrared photographs are not visible on black-and-white photography. This utility of color infrared photographs is probably a function of the inherent quality of the photographic technique resulting in better interpretation of soil, moisture, and vegetation contrasts. By using this approach, the complete spectrum of structural lineaments—visible on 1:125,000 scale aerial photography—was defined in the Greater Houston area.

Distribution

Mapping identified approximately 6,750 linear miles of structural lineaments. Distribution of these lineations shows two distinct trends—a northeast to southwest orientation comprised of regional, continuous lineations and a northwest to southeast lineation set of short, discontinuous lineations (fig. 5). The linear miles of structural lineaments for individual counties within the Greater Houston area include:

Austin County	570
Brazos County	280
Burleson County	220
Colorado County	650
Fort Bend County	474
Grimes County	570
Harris County	978
Liberty County	274
Montgomery County	362
San Jacinto County	234
Walker County	600

Waller County	346
Washington County	310
Wharton County	884

These data show that greatest concentrations of lineations are within counties of the southwestern and northern parts of the Greater Houston area. The relative paucity of lineaments in the central part of the mapped area possibly results from the difficulty in interpreting geologic data from photo imagery in this heavily tree-covered area.

BIOLOGIC ASSEMBLAGES

Biologic assemblages defined in the Greater Houston area are based primarily on the occurrence of land vegetation. The distribution of plant groups within the area was mapped on color infrared photography and categorized according to compiled information supplied by the Texas Parks and Wildlife Department.

Color infrared photography proved superior to other available imagery (color and black-and-white photography) in mapping the distribution of plant groups. Color infrared prints display, in general, the contrasts of dominant assemblages and are particularly sensitive to the occurrence of marsh-swamp vegetation and hardwood forest. In addition, color infrared photography distinctly defines tree-covered flood plains. This permits easy delineation of stream valleys from tree-covered uplands—the requisite data in any flood-plain management program.

A total of 15 biologic units were delineated. These units are grouped broadly into: (1) upland forest and savanna assemblages; (2) coastal-plain assemblages; (3) a variety of bottomlands within stream valleys and low-lying areas; and (4) lakes and ponds.

Upland Forest and Savanna Assemblages

Upland forests and savannas dominate the northern half of the area. This area is comprised of three major vegetation assemblages; (1) a forested upland; (2) a post oak savanna; and (3) a tall-grass prairie upland.

Upland forests.—The upland forest represents one of the major biologic units. This unit occurs

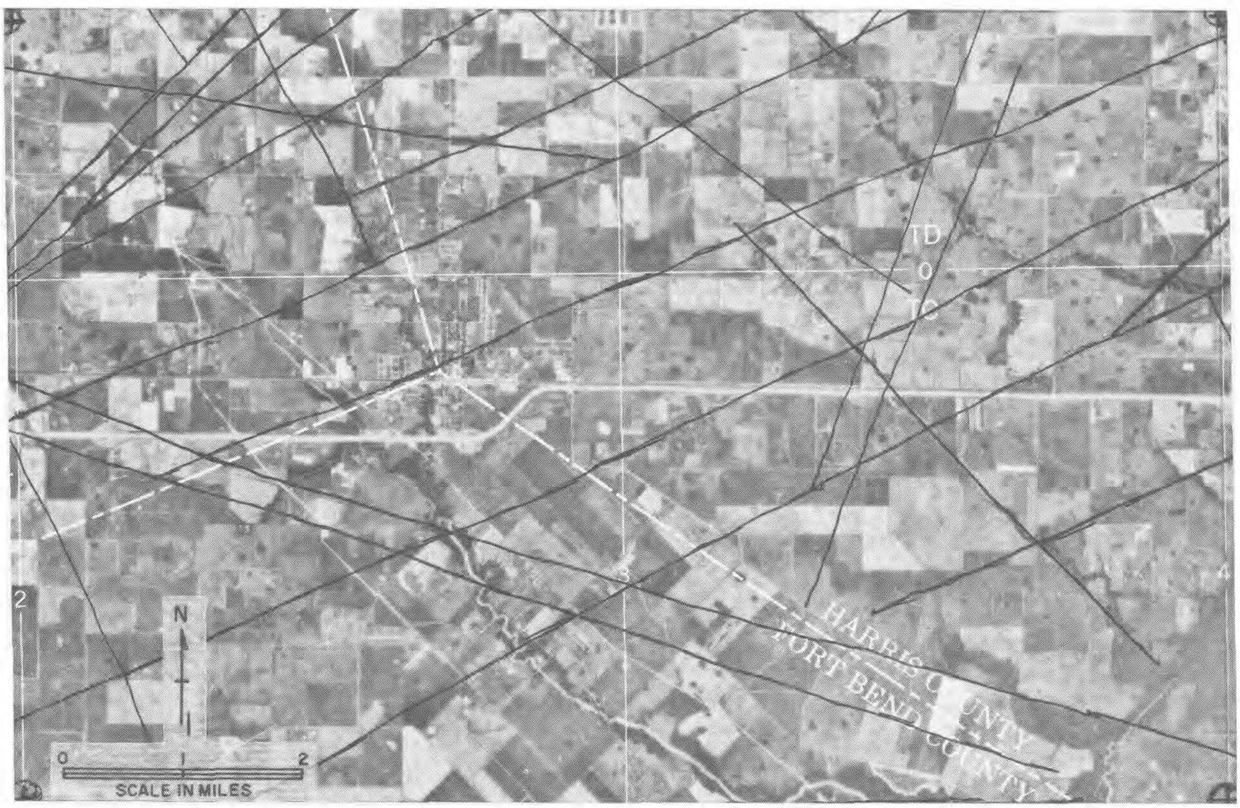


Figure 5. Structural lineaments delineated in the Greater Houston area—an example from an area west of the City of Houston.

throughout the central part of the area and extends from the Trinity River on the east to the Brazos River on the west (Units I_1, I_2, and I_3, fig. 6). The upland forest is dominated by pine trees to the east and varieties of oak to the west. The boundary between the two types of forest is transitional and occurs near the Navasota River (fig. 6).

Post oak savanna.—The post oak savanna in the northern parts of the area separates hardwood forest belts on the northwest from pine forest on the northeast (fig. 6). The post oak savanna is characterized by scattered, open stands of post and blackjack oaks, accompanied by a ground cover of tall grasses.

Tall-grass prairie upland.—The prairie upland covers a broad area in the west-central portion of the area and extends eastward in a band which narrows toward the Trinity River (fig. 6). This unit represents a transition from the savanna upland to the short-grass coastal prairie and consists of cultivated fields, improved pasture, or native tall-grass rangeland.

Coastal-Plain Assemblages

The coastal plain extends from the forest and prairie uplands to the southern boundary of the mapped region (fig. 6). The coastal prairie grasslands, one of the dominant vegetation assemblages of the Texas Coastal Plain, are flat to slightly rolling surfaces covered with thick stands of short grasses—primarily little bluestem, Texas grama grass, buffalograss, and common bermudagrass. The grassland prairies are broken locally by isolated, small groves of pine and oak. In addition, many of the small drainage courses of the area support a distinct assemblage of water-tolerant hardwoods; however, locally the streams have been stripped of their tree cover by man.

Bottomland Environments

Bottomland assemblages are concentrated dominantly within the valleys of the Brazos, Navasota, San Jacinto, and Trinity Rivers and the smaller drainage courses (fig. 6). All these areas are characterized by permanently high water tables. The bottomlands of the Brazos River have been largely cleared for agriculture and only local, small stands of native vegetation are present. Units comprising the bottomland consist of swamp and marsh vegetation, hardwood-covered flood plain, grass-covered flood plain, grass-covered terrace deposits, and grass- and tree-covered steep slopes.

RESOURCE CAPABILITY UNITS

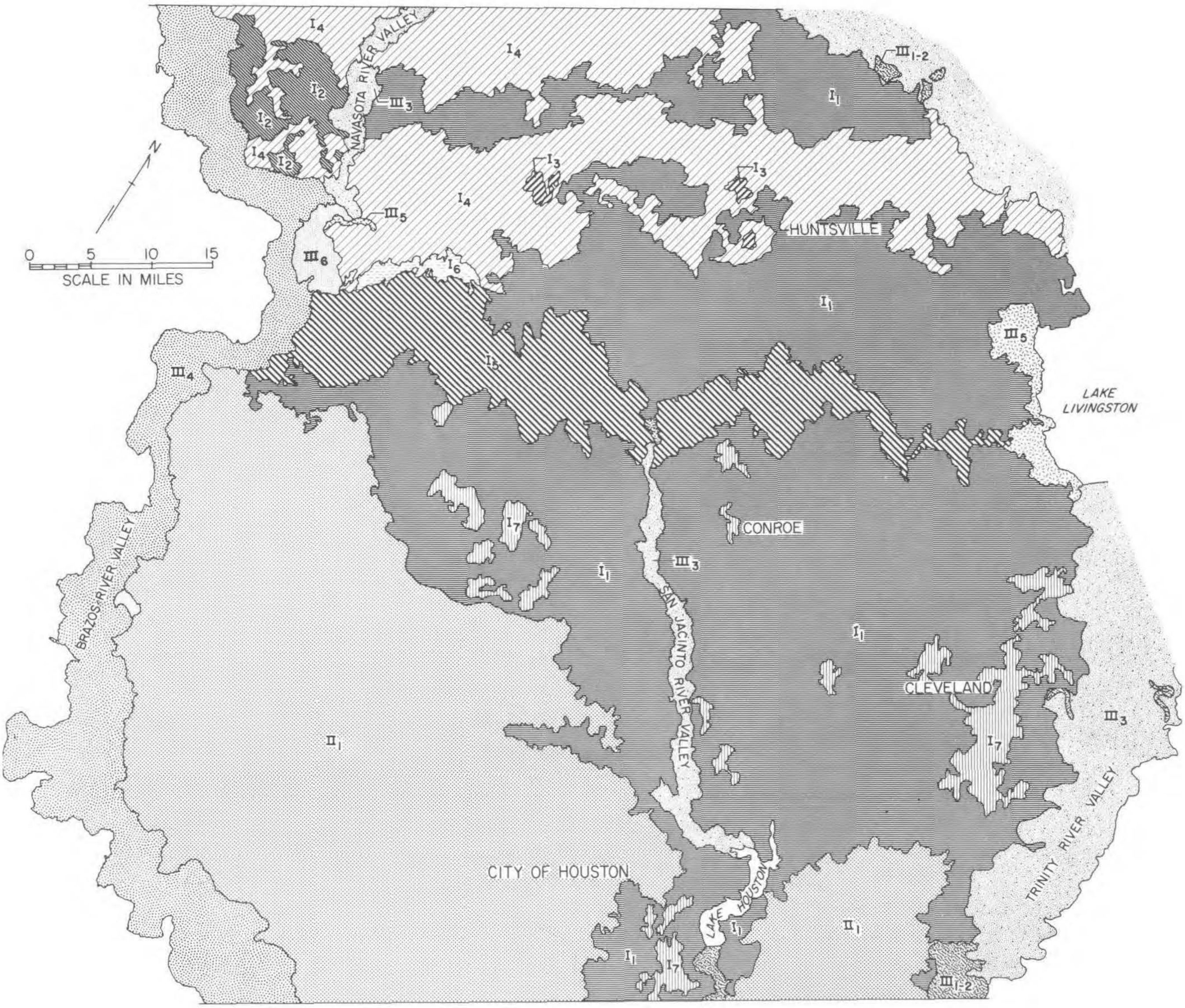
Environmental geologic units display diverse physical, chemical, process, and biologic properties. As these properties basically dictate the response of a particular unit to environmental stresses, their wide range often makes them cumbersome to translate into resource management guidelines. However, individual environmental geologic units can be synthesized and grouped into a system which may be a useful management tool. This system is based on the concept of resource capability.

"A resource capability unit is an environmental entity—land, water, area of active process, or biota—defined in terms of the nature, degree of activity, or use it can sustain without losing an acceptable level of environmental quality" (Brown and others, 1971). Units may be dominantly physical, chemical, hydrologic, or biologic in character—such as (1) physical units where the geologic substrate and soil properties are of primary importance; (2) hydrologic units where recharge and ground-water characteristics are dominant factors; (3) biologic units, such as marsh and swamp, where biologic activity is dominant; (4) water units where water chemistry and turbidity are the significant factors; and (5) man-made units, such as canals, levees, dams, and made land, where man's activities have significantly modified the environment.

Within the Greater Houston area, 18 basic land and water resource capability units are recognized. These units are defined chiefly by negative constraints based on factors that locally limit one or more of the principal human activities as shown in table 1. Generally the clays, grouped as IV, have fewest constraints for man's utilization of these units. Most constraints on the sands, grouped as III, relate to their permeable nature and contain ground water. It is paradoxical that the flood-plain units, grouped as I, are utilized to the largest degree by man and yet by nature produce many negative reactions.

SUMMARY AND CONCLUSIONS

Environmental geologic mapping in the Greater Houston area illustrates a diverse suite of natural resources. Although diverse in character the distribution of these resources follows a systematic pattern with large-scale natural systems of deposited mud and sand. This technique of grouping resources into natural (depositional)



UPLAND FOREST AND SAVANNA ASSEMBLAGES

I_1 PINE HARDWOOD FOREST
I_2 HARDWOOD PINE FOREST
I_3 ISOLATED PINE HARDWOOD GROVE
I_4 POST OAK SAVANNA
I_5 UPLAND TALL-GRASS PRAIRIE
I_6 HARDWOOD FOREST
I_7 ISOLATED PRAIRIE WITHIN FOREST

COASTAL PLAIN ASSEMBLAGES

II_1 COASTAL SHORT-GRASS PRAIRIE

BOTTOMLAND ENVIRONMENTS

III_1 FRESH MARSH
III_2 SWAMP
III_3 FLUVIAL WOODLAND
III_4 GRASS-COVERED FLOODPLAIN
III_5 GRASS- AND TREE-COVERED DISSECTED, STEEP SLOPE
III_6 GRASS-COVER TERRACE DEPOSIT

Figure 6. Biologic assemblages defined in the Greater Houston area.

Table 1. <u>Resource capability units—use and capability.</u> Evaluations are based on natural capability which can be improved by engineering. Blank areas represent either no problem or the use is not applicable on the particular resource capability unit. x = undesirable; will require special planning and engineering. o = possible problem(s).

RESOURCE CAPABILITY UNITS		ACTIVITIES: Liquid Waste Disposal			Solid Waste Disposal	Inland Construction											
		Surface Disposal of Untreated Liquid Wastes	Disposal of Untreated Liquid Wastes, Subsurface, Shallow	Maintenance of Feed Lots	Disposal of Solid Waste Materials	Placement of Pipelines and/or Subsurface Cables	Light Construction	Construction of Highways	Heavy Construction	Flooding (through dam construction	Dredging of Canals and Channels, and Spoil Disposal	Excavation (includes extraction of natural materials)	Filling for Development	Draining of Wetlands	Well Development	Devegetation	Use of Herbicides, Pesticides, Insecticides
FLOOD-PLAIN UNITS	I_1 Active, headward-eroding stream valleys	x	x	x	x	o	x	o	o		o	o	x		o	x	x
	I_2 Meanderbelt sands	x	x	x	x		x		o	o	o		o		o	x	x
	I_3 Overbank mud and silt	x	x	x	x	o	x	o	o	o			o		o		o
	I_4 Meanderbelt sand and overbank mud, undifferentiated	x	x	x	x	o	x	o	o	o	o		o		o	x	x
	I_5 Terrace sands	x	x	x	x					o	o				o	x	x
WETLANDS	II_1 Marsh, swamp, and local abandoned channels within major flood-plain systems	x		x	x	o	x	x	x	x	x	x	x	x	o	x	x
GEOHYDROLOGIC UNITS	III_1 Highly permeable recharge sands	x	x	x	x					o	o				o	x	x
	III_2 Elongate recharge sands	x	x	x	x						o				o	x	x
	III_3 Moderately permeable recharge sands and clayey sands	x	x	x	x						o				o	x	x
PHYSICAL UNITS	IV_1 Unstable sandy clay, marginal croplands	x	o			o	o	o	o								o
	IV_2 Unstable clay, good cropland	o				o	o	o	o						o		o
	IV_3 Unstable clay, poor cropland	o				o	o	o	o						o	x	o
SUBSTRATE UNITS	V_1 Siliceous gravel and sand	x	x	x	x		o		o	o	o				o	x	x
	V_2 Glauconite-ironstone sandy clay	x				o	o		o							o	
	V_3 Mixed sandy clay and lignite	o				o	o	o	o	o						o	o
	V_4 Tuffaceous sand and sandy clay	x	x	x	x	o	o	o		o					o		x
OTHER UNITS	VI_1 Steep slopes and alluvial fans	x	o	x	x		o	o	o			x				x	x
	VI_2 Water bodies	x			x						x						x

systems furnishes a powerful tool in predicting important properties and distribution of specific units. This method is gainfully employed in both flat coastal-plain terranes and upland clastic terranes of moderate relief with forestation. Although exceptions may exist, this approach should be applicable for environmental mapping in any sand and mud terrane of relatively low relief.

The product of the above technique is enhanced by improved aerial photography. That is, interpretations are improved by utilizing color and color infrared photography compared to using only black-and-white photography. Recognition of the variability of vegetation which reflects substrate is especially upgraded interpreting color infrared photography. Furthermore, sands are better separated from muds on both color and color infrared photography than they are on black-and-white photography. This is especially true where strong surficial oxidation of sandy soils and substrates has occurred.

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ENVIRONMENTAL GEOLOGY AND LAKESHORE DEVELOPMENT

C. M. Woodruff, Jr.

INTRODUCTION

Lakeshore areas have become increasingly popular as sites for residential development. This popularity is derived mainly from aesthetic factors and recreational appeal, and indeed, many surface reservoirs have been justified for recreational potential as well as for water supply and flood control. However, lakeshore areas are not universally suited to sustain increased human population. In some areas, intensive lakeside development has resulted in water quality declines. Less commonly, threats to the personal safety or property of inhabitants have occurred. Knowledge of the natural carrying capacity of the land is especially valuable in preventing these environmental abuses.

The Highland Lakes of Central Texas (fig. 1) provide examples of many problems attendant to lakeshore residential development. Among these examples are problems associated with waste-water treatment, solid waste disposal, erosion control, storm runoff, and ground stability. Second home and recreational development of these lakes is occurring at a rapid pace with projection of continued rapid growth in the future. This area, then, represents a timely model for applying geologic expertise to determine land capability. This paper (1) discusses fundamentals of land capability evaluation in terms of environmental geologic mapping, (2) presents specific case examples of environmental geologic mapping along two of the Highland Lakes, and (3) evaluates the case-study areas in terms of the degrees to which various human activities can be sustained without environmental harm or human hazard.

FUNDAMENTALS OF ENVIRONMENTAL GEOLOGIC MAPPING

General

Applying geologic input to problems of land use requires the construction of at least two maps, one depicting physical-engineering properties of materials, and the other showing the interaction of active processes, materials, and terrain features. These are termed physical properties and environmental geologic maps, respectively. The two displays are largely complementary.

Physical Properties Map

A physical properties map shows the areal distribution of materials in terms of rock types, weathering characteristics, presence of fractures and solution features, and rock geometry. The physical properties map gives information on construction feasibility. It also is a predictive tool regarding long-term structural-engineering stability of the finished products (houses, roads, and utilities).

Physical properties units are best described in terms of quantitative tests of materials as determined by the conventions of applied soil and rock mechanics. Where such data are unavailable, realistic approximations of engineering parameters can be made. Examples of parameters that should be evaluated include: shrink-swell potential, foundation strength, slope stability, rippability, permeability, and corrosion potential. Judgments as to values of these engineering factors may be made inferentially by comparison to an area of similar substrate in which the quantitative data exist. Especially noteworthy clues regarding substrate properties are observations of rocks and soils in the field and of problems associated with existing man-made features.

Physical properties maps can be generated using the same techniques as those used in constructing traditional geologic maps—that is, by aerial photographic reconnaissance and field work. Also information regarding physical properties can be derived from a traditional geologic map insofar as geologic formations are representative of their material (rock) constituents. However, physical properties units are generally defined without regard to age or mode of origin.

Soil may constitute a physical properties unit; however, confusion might stem from the multiplicity of definitions of the term "soil." Soil defined by civil engineers is earth material that can be excavated without blasting. Soil defined as such by engineers may exist as a mere surface veneer, or it may extend to great depths (as it can correspond to geologic bedrock). Surficial soil as defined by the geologist is the rind (commonly less than a few feet thick) of bacterially active, biologically fecund (biogenic) material derived by weathering from a parent substance. This "biogenic" soil is important beyond its characteristics as an agronomic medium

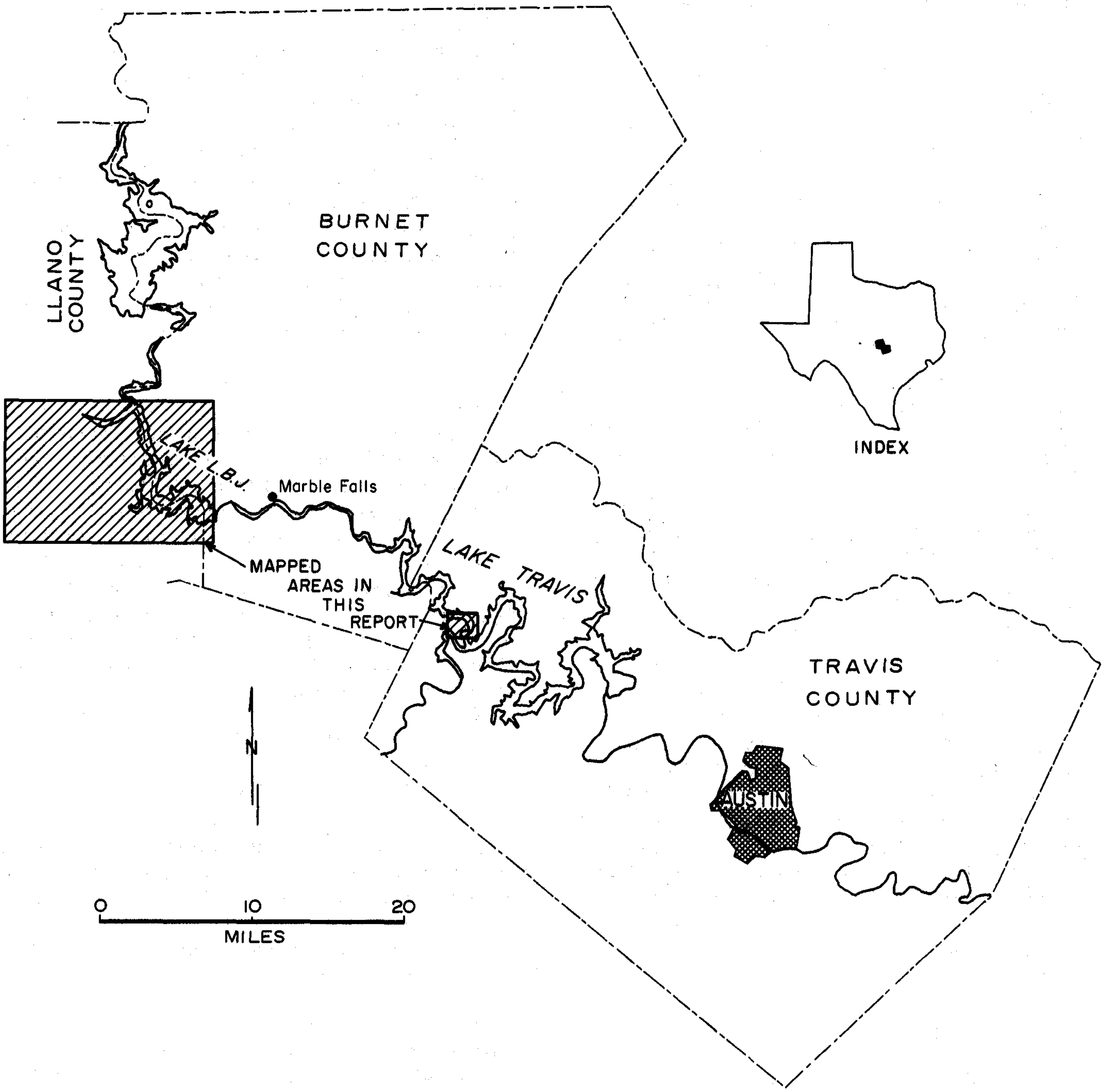

Figure 1. Location of Highland Lakes in Central Texas showing case-study areas along Lake Travis and Lake Lyndon Baines Johnson (Lake L. B. J.).

and, in some cases, foundation host; it is material that beneficiates the quality of waste water by physical-chemical and biological activities. The geologic and engineering definitions are mutually compatible only where residual soil overlies well-indurated substrate.

Environmental Geologic Map

The environmental geologic map is an interpretive display of interactions between processes, landforms, and substrate materials; the corresponding units are process, material-landform, and material units. Environmental geologic maps based on similar units as described herein have been constructed on a diversity of geologic settings (Wermund and others, 1974; Woodruff, 1973; Woodruff and Lentz, 1973). Such a map can be applied to a spectrum of environmental problems ranging from health and safety of inhabitants of a particular terrain to suitability of extracting minerals or growing certain crops. The underlying premise of this map is that the earth is not uniformly suited to sustain various uses. The premise is basic to the concept of resource capability as defined by Brown and others (1971). A resource capability map is readily derived from an environmental geologic map.

Process Units

Process units depict areas subject to ongoing natural activities that warrant special attention of the user of the land. Examples include flood-prone areas, land subject to mass movements, areas subject to land subsidence, and earthquake-prone areas, to mention a few. Other areas of processes that are not so dire in consequences include aquifer recharge zones, and areas subject to intensive erosion. Any of these processes or a myriad of others might be active along a man-made lake.

Activation of processes near reservoirs may have catastrophic results as seen in numerous historical cases. For example, the Vaiont (Italy) disaster of 1963 resulted from landsliding into the reservoir and *not* from dam failure (Kiersch, 1964). The Baldwin Hills Reservoir incident of 1963 was a case of dam failure resulting from ground subsidence due to fault movement (Hamilton and Meehan, 1971). However, the effects of processes might also be subtle and observable only over a considerable period of time. Examples are the siltation of a reservoir or pollution by waste water introduced to the lake by surface runoff or subsurface infiltration (Rickert and Spieker, 1971).

Material-Landform Units

Material-landform units represent areas where terrain and substrate interact to impose restrictions on land use. Many of the material-landform restrictions result from the activity of a subtle long-term (noncatastrophic) process. For instance, a high-slope, high-relief terrane on a poorly indurated substrate indicates the presence of an erosive regime. This compounds the land use problems related to steep slopes or engineering characteristics of a “soft-rock” substrate, as sediment derived from eroding highlands can fill a body of water. This reservoir infilling is accompanied by a concomitant decline in water quality.

Material Units

Material units are mapped in areas where substrate properties dictate the most amenable land use. These units may be defined in terms of certain engineering properties, such as low permeability of a clay deposit, allowing its use as a sanitary landfill host. Also, a material unit might be defined because of the presence of extractable minerals. Thus, areas of sand and gravel deposits, localities containing certain types of clay, or areas containing strippable coal or lignite might all be mapped in this category.

CASE EXAMPLES

General

A diversity of geologic substrates, landforms, and processes occurs within a relatively small area along the Highland Lakes of Central Texas (fig. 1). This affords an opportunity to apply the previously mentioned environmental geologic concepts and techniques to an evaluation of residential land use along lakes. Two locales within the Highland Lakes are presented herein as case studies. These case examples include a part of Lake Travis, which lies mainly within a carbonate rock terrane, and Lake Lyndon B. Johnson (Lake L.B.J.), which is in a predominantly igneous-metamorphic rock terrane.

Lake Travis Vicinity

Physical Properties Map

Two types of physical properties units are discriminated for the Lake Travis vicinity—bedrock

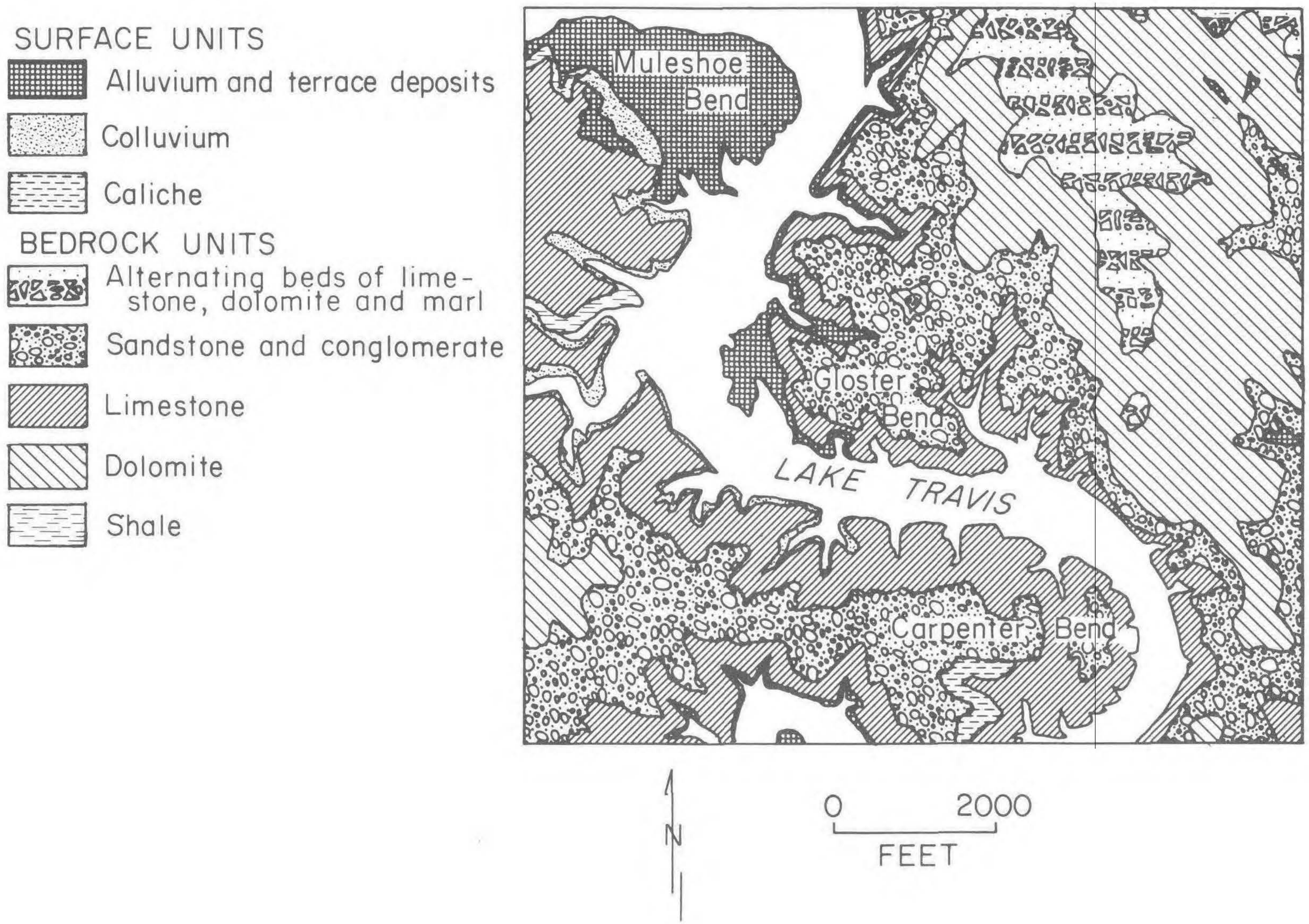

Figure 2. Physical properties map of the Lake Travis vicinity.

Table 1. Description of physical properties units, Lake Travis vicinity.

UNIT	DESCRIPTION	TOPOGRAPHIC-PHYSIOGRAPHIC EXPRESSION	SOIL
BEDROCK UNITS			
Limestone	Hard, dense, with fractures and solution features	Areas of low to moderate relief; forms escarpments at contacts with less resistant rocks	Loam, clay (<2')
Dolomite	Porous, surficially friable dolomite; also siltstone, limestone, and marl	Stairstep topography	Loam (<2')
Alternating beds	Interbeds of hard to soft limestone, marl, and dolomite	Stairstep topography	Clay loam (<2')
Shale	Claystone; minor hard sandstone	Steeply cut stream banks	Clay (<2')
Sandstone and conglomerate	Poorly indurated silty clay, and sand and gravel	Gently rolling lowlands	Fine sandy loam; sandy clay (>2'<6')
SURFACE UNITS			
Alluvium and terrace	Silty clay--sand and gravel; admixed blocky "float"	Low relief; low slope (2-5%); localized along stream courses and high terrace levels.	Silty loam (>2' <6' locally >6')
Colluvium	Clay matrix with blocky limestone or gravel-cobble debris	Slump blocks or debris veneers on steep slopes (>15%)	Stony clay (<2')
Caliche	Caliche without admixed detritus; caliche-welded residuum	Very low slopes (<2%), commonly near limestone-sandstone contact	"Calcisol" (<2')

Table 2. Qualitative engineering characteristics of physical properties units, Lake Travis vicinity.

	SLOPE STABILITY	PERMEABILITY	EXCAVATION POTENTIAL	FOUNDATION STRENGTH	SHRINK-SWELL	CORROSION POTENTIAL
BEDROCK UNITS						
Limestone	High	Low-high	Low	High	*	Low
Dolomite	High	Moderate-high	Low-moderate	High	*	Low
Alternating beds	Moderate-high	Low-moderate	Moderate-low	High-moderate	Low	Moderate-low
Shale	Low	Low	High	Moderate-low	Moderate-high	High
Sandstone and conglomerate	Moderate	Moderate-high	High	Moderate	Low	Moderate
SURFACE UNITS						
Alluvium and terrace	Moderate-low	Moderate-high	High	Moderate	Moderate-low	Moderate-high
Colluvium	Low	Low	Low	Low	High	High
Caliche	High	Low-moderate	Moderate-low	High	Low	Low

* Not applicable.

and surface deposits (fig. 2). The main criterion for distinguishing the two types of units is that they differ markedly in geometry and areal extent. Surface deposits occur in response to relatively recent and localized processes such as stream deposition, soil formation, and colluviation. These deposits may be up to 50 feet thick in the Lake Travis vicinity, but they are not through-going strata as is most bedrock in this area.

Surface units include alluvium and terrace deposits, colluvium, and caliche (table 1). Bedrock units consist of limestone; dolomite; alternating beds of limestone, dolomite, and marl; sand and conglomerate; and shale.

Table 1 presents generalized descriptions, physiographic expression, and biogenic soil characteristics of each of the physical properties units in the Lake Travis vicinity. Table 2 presents qualitative statements of characteristics of these physical properties units. The qualitative approximation of properties in this area is based on work by Woodruff (1973). Included in these tabulations are extrapolations from adjacent areas where engineering tests have been run, and the estimation of properties by observing materials in the field. The qualitative nature of the tabulated information represents valid approximations when mapping is done at a scale of 1:24,000 or smaller. If more detailed information is needed, on-site investigations and testing of materials are necessary.

Environmental Geologic Map

The environmental geologic map of part of the Lake Travis vicinity (fig. 3) shows the area dominated by the activity of processes—flooding, mass wasting, and aquifer recharge. One material-landform unit occurs—nonkarstic carbonate terrane. The only material unit shown in figure 3 is a local occurrence of fluvial sand and gravel.

Flood-prone areas within the part of the Lake Travis vicinity shown are determined using the maximum spillway elevation of the lake. Elsewhere, flood-hazard zones are determined by previous records of gaged streams, and by geomorphic evidence on ungaged streams (for example, the presence of low terraces or stream incisement into bedrock or terrace).

Areas mapped as being susceptible to slope failure are determined mainly by the occurrence and extent of colluvium. The unstable slope areas are extended beyond actual colluvial occurrences to include similar geologic and topographic settings in which slumping has not yet occurred (for example, steep slopes near the contact where limestone overlies shale).

Aquifer recharge zones are delimited based on the occurrence in outcrop of the so-called "Trinity sands" aquifer. This unit consists of parts of all four bedrock units on the physical properties map. In detail, localized permeability and slope variations are important in determining where recharge is most probable within the aquifer unit. Most recharge occurs on gently sloping ground underlain by sandstone.

The only material-landform unit in the Lake Travis vicinity, nonkarstic carbonate terrane, is an area of steep slopes (generally greater than 8 percent), high relief (total relief generally greater than 200 feet), and relatively high stream density. It consists of parts of the dolomite and alternating bed units from the physical properties map. In this setting, runoff of water predominates with attendant erosion, and thin or absent soils. There is little ground-water infiltration.

Limitations of the one material unit (fluvial sand and gravel) are derived from the descriptive information accompanying the physical properties map. Alluvium is an erodable material under conditions of steep slope, whereas on low slopes, a thick (up to 6 feet) soil may form. Fluvial sand and gravel may serve as a local small-yield aquifer and might be a local source of construction aggregate.

Lake Lyndon B. Johnson Vicinity

Physical Properties Map

Surface deposits and bedrock in the Lake L.B.J. vicinity (fig. 4) are discriminated as distinct sets of physical properties units as in the Lake Travis example. Bedrock units include resistant granite, mixed granite-gneiss, schist, limestone, mixed limestone and sandstone, and shale. Surface units include alluvium and terrace deposits and grus.

Characteristics of these units are summarized on tables 3 and 4, following the same format as the descriptions of units in the Lake Travis vicinity. The map of the Lake L.B.J. vicinity is presented at a much smaller scale than that of Lake Travis, and even more latitude is implied in the discussion of properties. Thus, on-site study is all the more important where specific information is needed.

Environmental Geologic Map

The environmental geologic map of the Lake L.B.J. vicinity (fig. 5) includes process units,

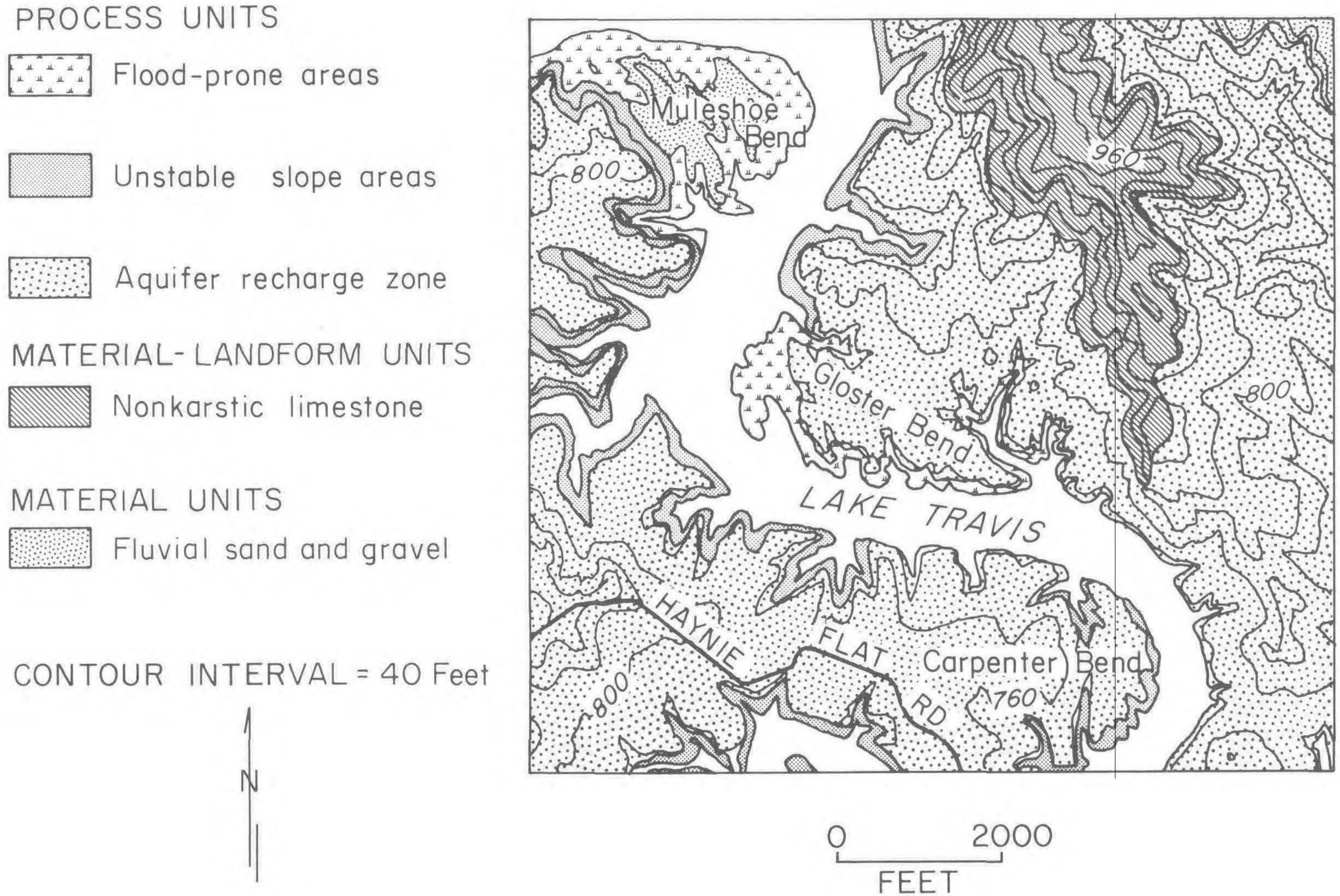

Figure 3. Environmental geologic map of the Lake Travis vicinity.

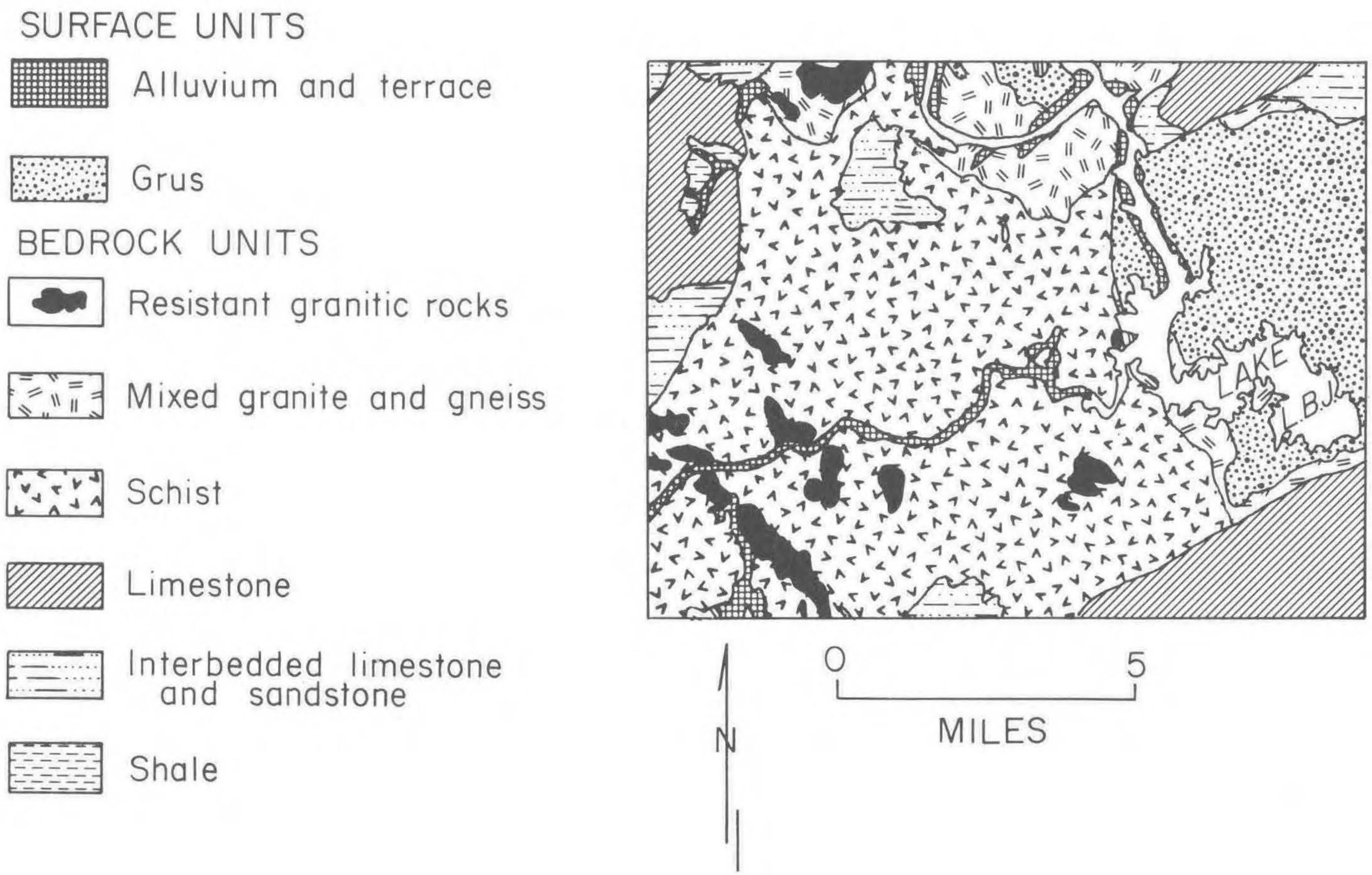

Figure 4. Physical properties map of the Lake L. B. J. vicinity.

Table 3. Description of physical properties units, Lake L.B.J. vicinity.

UNIT	DESCRIPTION	TOPOGRAPHIC-PHYSIOGRAPHIC EXPRESSION	SOIL
BEDROCK UNITS			
Resistant granitic rock	Hard, coarsely crystalline igneous-metamorphic rocks; locally fractured	Rugged, high-relief, high-slope (>8%) areas; exfoliation domes	Stony clay (0-1')
Mixed granite-gneiss	Hard, granite-gneiss substrate; generally covered by thin regolith; locally fractured	Moderate-high relief; variable slope	Stony clay; Sandy loam (0-4')
Schist	Schist, gneiss, marble and associated rocks; covered by regolith	Moderately hilly to low rolling terrain; variable slope	Stony clay (0-2')
Limestone	Hard, dense, with fractures and solution features	Gently rolling; local steep slopes (8-15%); karst features	Loam, clay (<2')
Interbedded limestone and sandstone	Interbedded sandy limestone and limy sandstone; coarse-grained sandstone; siltstone; minor shale	Escarpments above lower relief granite terrace; slopes generally 8-15%	Stony ground (<2')
Shale	Claystone; minor hard sandstone	Low rolling terrain; local steep slopes along stream banks; colluvium cover	Clay (<2')
SURFACE UNITS			
Alluvium and terrace	Silty clay; sand and gravel; locally calichified	Gently sloping (2-5%) areas adjacent to stream course; high terraces (locally dissected)	Silty loam; gravelly loam (>2' <6' locally >6')
Grus	Weathered granite <u>in situ</u>; regolith of quartz and feldspar grains; locally hard bedrock	Broad low-relief areas, gently sloping terrain (<5%)	Gravelly, sandy loam (>2' <6')

Table 4. Qualitative engineering characteristics of physical properties units, Lake L. B. J. vicinity.

	SLOPE STABILITY	PERMEABILITY	EXCAVATION POTENTIAL	FOUNDATION STRENGTH	SHRINK-SWELL	CORROSION POTENTIAL
BEDROCK UNITS						
Resistant granitic rock	High	Low (high in fracture zones)	Low	High	*	Low
Mixed granite-gneiss	High	Low (locally high)	Low	High	*	Low
Schist	High	Low	Moderate	High	Low	Low-moderate
Limestone	High	Low-high	Low	High	*	Low
Interbedded limestone and sandstone	High	Low-high	Low-moderate	High	Low	Low-moderate
Shale	Low	Low	High	Moderate-low	Moderate-high	High
SURFACE UNITS						
Alluvium and terrace	Moderate-low	Moderate-high	High	Moderate	Moderate-low	Moderate-high
Grus	Moderate	High	High	Moderate-high	Low	Moderate-high

* Not applicable

material-landform units, and material units. Figure 6 is a topographic map of the Lake L.B.J. area, an aid in understanding terrain modifiers on material-landform units.

Process units include flood-prone areas and both limestone and sandstone aquifer recharge units. Material-landform units include high-relief igneous-metamorphic rock areas, low-moderate relief, igneous-metamorphic rock terrane, low-relief residuum, karstic limestone, and high-relief mixed-limestone terrane. Material units include shale and fluvial sand and gravel.

Flood-prone areas are determined by extrapolation of gage heights along major stream valleys. Other land adjacent to streams too small to be presentable at this scale might also be subject to floods, however.

Limestone aquifer areas are distinguished from sandstone aquifers because differences in terrain, soil cover, and permeability between the two aquifer types lead to differences in recharge characteristics. In limestone aquifers, the porosity development is extremely localized (associated with fractures, caverns, and sinkholes). In sandstone aquifers, permeability and thus potential for recharge is more uniformly distributed because of intergranular porosity, rather than fracture or solutional openings.

Of the material-landform units, the high-relief igneous-metamorphic rock areas include land where granite or gneiss bedrock is at the ground surface. Slopes are generally steep (greater than 8 percent), and soils are thin or absent. Runoff and sheetwash are the dominant processes.

Low-moderate relief, igneous-metamorphic rock terrane is the most areally extensive unit in the Lake L.B.J. vicinity. It consists of granitic, gneissic, and schistose bedrock of generally low to moderate slope (generally less than 8 percent). It excludes those steep-sloped areas where bedrock lies at the surface and the low-relief, low-slope areas which are covered mostly by granite residuum. Generally some regolith and thin soil covers bedrock in this area. Some ground-water infiltration occurs in highly fractured areas. Erosion is a locally important process along stream courses.

Low-relief residuum occurs in granitic terrane where a mantle of grus up to 20 feet thick covers bedrock. Slopes are generally low (commonly less than 5 percent) and soil may be thickly developed (up to 5 feet over the regolith). Because of low slopes and high permeability, this area may be a recharge zone for a shallow grus aquifer above less permeable bedrock. Erosion is only locally important as a process in such a terrane (for example, along stream banks).

Karstic limestone includes extensions of the limestone aquifer unit onto a terrain of moderate to steep slope (greater than 8 percent). Also, it includes outcrop areas of karstic limestone that are not part of an aquifer of importance. This unit is characterized by solution features; so rapid infiltration of water can occur. Erosion is not an important process because of resistant bedrock. Thin soils (commonly *terra rosa*) cover bedrock.

Mixed limestone-sandstone is hard-rock terrane and generally forms escarpments. A high amount of runoff and erosion may occur on this terrane. Soils are thin or absent.

Material units include shale and fluvial sand and gravel. Both are exposed only locally. Physical properties such as low permeability and low foundation strength of the shale, and high permeability of the fluvial deposits determine constraints to land use. Both types of materials may be easily eroded, so that low rolling terrain develops.

ANALYSIS OF LAND CAPABILITY

Tables 5 and 6 present environmental geologic units from maps of both the Lake Travis and Lake L.B.J. vicinities in terms of selected uses that can be sustained without environmental harm. These matrices synthesize the interpretations of physical-engineering constraints shown in tables 2 and 4, along with factors derived from the environmental geologic map, such as erosional regime, surface water and ground-water interactions, and soil variations.

Categories of land use presented on tables 5 and 6 are: high-density residential development (two houses per acre or more), low-density residential development, commercial development, septic tank use, sanitary landfill, and parkland-greenbelt (minimal use).

Important generalities derived from the matrix can be made. Process units sustain the fewest uses without deleterious environmental effects. Also, there is a hierarchy among the process units according to immediacy or severity of process effects. Flood-prone areas are most critical, and unstable-slope terrains are only slightly less so. Aquifer recharge is also a process, but not actually a hazard. Thus, aquifer recharge areas have fewer constraints to use than the areas subject to catastrophic processes.

Subtle processes associated with material-landform units (erosion and nonerosive runoff)

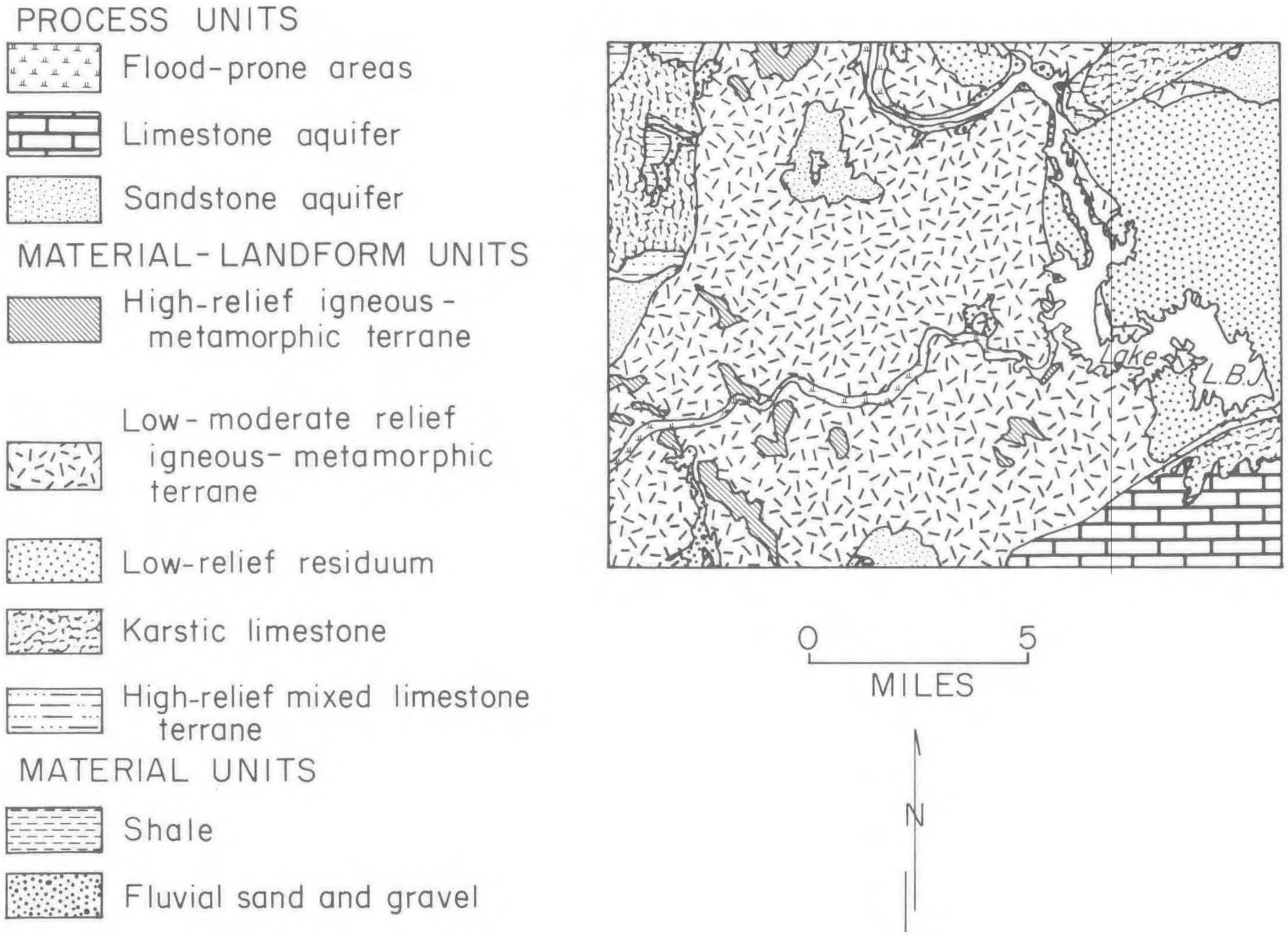

Figure 5. Environmental geologic map of the Lake L. B. J. vicinity.

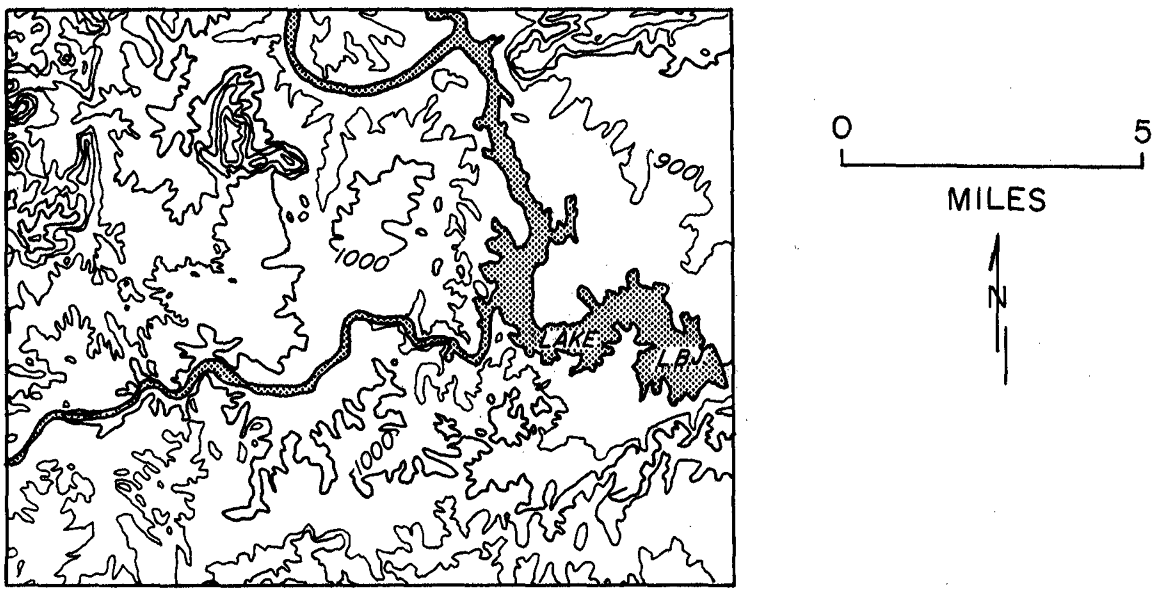

Figure 6. Topographic map of the Lake L. B. J. vicinity (contour interval = 100 feet).

affect surface water and ground-water quality. Terrain features, substrate, and soil characteristics determine the amenability of the land for various waste-disposal methods, which in turn also affect water quality.

Aquifer recharge areas probably will structurally support intensive residential development (tables 2 and 4), but the expanse of roofs and pavement cover reduces the amount of water that can be recharged. Fertilizer and biocide applied on lawns, and inadequate domestic sewage systems (septic tanks or leaky sewers) may pollute surface or subsurface water. Commercial development is an undesirable land use in aquifer recharge areas because of pavement cover that acts as sluiceways along which detritus, chemicals, and biological pollutants are washed during rain. This low-quality water can then infiltrate into an aquifer, or depending on local topographic features, can enter the lake as a slug of polluted runoff.

High-relief, high-slope, material-landform units (nonkarstic limestone, high-relief crystalline rock, high-relief mixed limestone) pose constraints to use because they are potential zones of intensive erosion. This is especially critical when the ground is laid bare during construction. Sediment influx derived by erosion of uplands has deleterious effects on water quality (decreases dissolved oxygen). Also, sediment input results in ultimate siltation of the reservoir. As in aquifer recharge zones, pavement wash from these terrains results in polluted runoff.

Moderately sloping, moderate- to low-relief terrain (low-moderate relief, igneous-metamorphic rock terrane, low-relief residuum, karstic limestone) and material units present constraints to use mainly by the nature of substrate (*see* physical properties map). Constraints are also imposed based on composition and thickness of soil cover. These areas are not as easily categorized and thus, must depend upon on-site investigations. Some characteristics are noteworthy, however. Karstic limestone is closely kin to a limestone aquifer unit. Because of a paucity of soil and the presence of underground conduits for waterflow, many of the same land use limitations are imposed as are imposed in recharge zones. The grus of the low-relief residuum unit also may be a local aquifer. Although the terrane is well suited materially for construction, waste-disposal methods should be implemented with care because of high substrate permeability.

The material unit, fluvial sand and gravel, is suited for perhaps the greatest variety of uses. It has physical properties suitable for construction, it occupies a low-slope terrain and generally has a moderately thick, permeable soil cover.

Shale presents problems with construction because of its engineering properties (table 2). However, it is suitable as a host for sanitary landfill because of its low permeability.

Table 5. Land capability--Lake Travis vicinity.

	Intensive Residential Development	Low-Density Residential Development	Commercial Development	Septic Tank Use	Sanitary Landfill	Parkland-Greenbelt
(PROCESS UNITS)						
Flood-prone areas	-	-	-	-	-	+
Unstable slope areas	-	-	-	-	-	+
Aquifer recharge zones	-	+	-	-	-	+
(MATERIAL-LANDFORM UNIT)						
Nonkarstic limestone	0	+	-	-	-	+
(MATERIAL UNIT)						
Fluvial sand and gravel	+	+	+	+/-	-	+

+ = NO APPRECIABLE CONSTRAINTS
0 = MODERATE CONSTRAINTS
- = SEVERE CONSTRAINTS

Table 6. Land capability--Lake L.B.J. vicinity.

	Intensive Residential Development	Low-Density Residential Development	Commercial Development	Septic Tank Use	Sanitary Landfill	Parkland-Greenbelt
(PROCESS UNITS)						
Flood-prone areas	-	-	-	-	-	+
Limestone aquifer recharge areas	-	-	-	-	-	+
Sandstone aquifer recharge areas	-	+	-	-	-	+
(MATERIAL-LANDFORM UNITS)						
High-relief crystalline rock terrane	-	-	-	-	-	+
Low-moderate relief crystalline rock terrane	+	+	+	-/0	-	+
Low-relief residuum	+	+	+	-/0	-	+
Karstic limestone	0	0	0	-	-	+
High-relief mixed limestone	-	-	-	-	-	+
(MATERIAL UNITS)						
Fluvial sand and gravel	+	+	+	+/-	-	+
Shale	0	+	0	-	+	+

+ = NO APPRECIABLE CONSTRAINTS
0 = MODERATE CONSTRAINTS
- = SEVERE CONSTRAINTS

CONCLUSIONS

Physical properties and environmental geologic maps describe the salient features of the land necessary for enlightened land use planning. The complementary maps present interpretations regarding relative impact of processes, terrain, and substrate materials on human uses of the land. In terms of specific uses, the environmental geologic map is also a resource (land) capability map.

Lakeshore residential land use demands that special consideration be given to processes active or potentially active, in order to insure the safety of inhabitants. Also important are factors that affect public health, such as providing long-term potable water supply and proper disposal of wastes. These considerations are essential in maintaining environmental quality for human habitation.

Basic to the planning process is the realization that the land is not uniformly suited to sustain various uses. Armed with information regarding the variables of the land (obtainable from physical properties and environmental geologic maps), the planner can conceptualize orderly and environmentally sound development of the land. Likewise, the engineer and builder can effect this orderly development.

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QUANTIFICATION OF RESOURCE CAPABILITY UNITS, Corpus Christi Area

Robert S. Kier and Dennis L. Bell

INTRODUCTION

Basic data requirements for land use evaluation include more than qualitative interpretation of surface and near-surface environments and general statements about their physical properties. Among the additional data needed is quantification of the physical parameters of land units, particularly those affecting construction and waste disposal. Quantification of the physically defined units provides information to planners and engineers in a familiar format, permits direct comparison of engineering properties between possible development sites, and should aid in identifying areas naturally suitable for particular types of construction or areas which with proper engineering enhancement would be suitable.

Consulting engineering firms, soils testing firms, and many public agencies involved in construction have extensive files of site-specific soils test data pertinent to construction and waste disposal. Rarely are these soils test results extrapolated to untested areas, for sound reasons. The test values are valid only for the immediate test site, and few existing geologic or soils maps provide a reliable basis for extension of such data. By considering all soils test values available for a given kind of land unit, however, quantitative characterization can be extended to untested areas. The representative test value or range of values provides a measure of quantification short of adopting an expensive systematic testing program.

Physically defined units have been investigated quantitatively by Fisher and others (1973) in a pilot study of Nueces, San Patricio, Aransas, and Refugio Counties of the Corpus Christi area (fig. 1, table 1) as part of a broad interdisciplinary study of environmental and economic carrying capacity of the area encompassed by the Coastal Bend Regional Council of Governments (Fruh and others, 1972a, 1972b, 1972c, 1973a, and 1973b). These units were defined through analysis of resource capability (Brown and others, 1971), a basis for delineating areas with similar natural ability to withstand given kinds and rates of use without deteriorating beyond an acceptable level of environmental quality. A generalized example of a resource capability map of Nueces County is contained in figure 2.

Presentation of the approach used to quantify capability units in the Corpus Christi area, some results of data compilation, uses and interpretive limitations of the data, and methods for refinement of the quantification procedure is the purpose of this paper.

QUANTITATIVE CHARACTERIZATION

Basic Data

Abundant soils test data available from public agencies and private firms provided the basic information necessary to quantify physical parameters of land resource units. More than 8,000 engineering test values were obtained from tests of more than 2,000 core samples (fig. 3) representing nearly all the major, physically defined land capability units (table 1) that occur in developed areas in the Coastal Zone.

Types of test data collected are listed in table 2. These tests are the kinds most commonly performed by engineering testing laboratories to assess site suitability and foundation requirements for most commercial buildings, large single and multi-family developments, and industrial plants. Descriptions of these tests are contained in the Appendix.

Methodology

Arithmetic means and standard deviations of engineering test results were calculated from samples of each capability unit. Test values were recorded for the different types of engineering tests as a function of 5-foot increments of depth extending to 50 feet below the ground surface. For example, the value for a given engineering test, e.g., unit dry weight, performed on a sample of soil taken at a depth of 12 feet is considered in the calculations with other results from the same kind of soils test performed on samples of the same capability unit taken from the depth interval greater than 10 feet but less than or equal to 15 feet. Arithmetic means of test results characterize given depth intervals within each capability unit by a single number. Standard deviations (normal distribution assumed) show probable ranges and variability of test results, and to some extent allow

Table 1. Resource capability units—Corpus Christi area.*

COASTAL PLAIN	
A1	Sand, recharge, highly permeable: thin, shallow aquifer, maximum thickness approximately 50 feet, high water table, low moisture-retention capacity, poor waste-disposal capability, excavation easy, low shrink-swell potential, high foundation strength, very high corrosion potential, locally tree-covered
A3	Sand and silt, moderately permeable: shallow aquifer, thickness up to 100 feet, low to moderate water-retention capacity, excavation easy, low shrink-swell potential, high foundation strength, high corrosion potential, moderately susceptible to erosion, mostly cropland
A6	Sandy mud, low to moderate permeability, moderately permeable sand veneer: veneer highly variable in thickness, moderate water-retention capacity, moderate to good waste-disposal capability, excavation moderate, moderate to high shrink-swell potential, low to moderate foundation strength, very high corrosion potential, mixed range and cropland
A8	Mud, low permeability: moderate to high water-retention capacity, cracks extensively when dry, good waste-disposal capability, excavation difficult to moderate, high shrink-swell potential, low foundation strength, very high corrosion potential, commonly cropland
A11	Sand, calichified: low to moderate permeability, moderate to low water-retention capacity, poor to moderate waste-disposal capability, excavation moderate, low shrink-swell potential, high foundation strength, low corrosion potential, commonly rangeland
ACTIVE FLOOD PLAINS	
B1	Sand and gravel, highly permeable: point bar deposits, highly susceptible to flooding, high water table, poor waste-disposal capability, excavation easy, low shrink-swell potential, generally high foundation strength, high to very high corrosion potential, locally tree-covered, some unmapped mud lenses
B2	Mud and silt, low to moderate permeability: overbank deposits, high susceptibility to flooding, high water table, generally occurs in topographic lows that pond water easily, poor waste-disposal capability, excavation difficult to moderate, high shrink-swell potential, low foundation strength, very high corrosion potential, locally good cropland
B3	Natural levee, elevated: mixed mud and sand, susceptible to flooding during extreme floods, essential for flood protection during lesser floods, poor waste-disposal capability, excavation moderate, variable shrink-swell potential, low to moderate foundation strength, very high corrosion potential, locally tree-covered
B4	Alluvium, small active streams: sand, silt, and mud, highly susceptible to flooding and bank erosion, poor waste-disposal capability, low foundation strength and bank stability, locally tree-covered
BARRIER ISLANDS	
C2	Fore-island dunes and vegetation-stabilized barrier flats: sand and shell, highly permeable, perched brackish- to fresh-water aquifer, highly susceptible to flooding and erosion by storm tides, salt-tolerant grasses dominant vegetation, maintenance of vegetation critical in preventing wind and water erosion and providing natural barrier to storm surge, very poor waste-disposal capability, very high corrosion potential, poor to fair construction site, detrimental sand excavation
C4	Storm washover areas, washover channels and fans: loose sand and shell, subject to extensive flooding by storm tides with scour and fill and significant transport of sediment during hurricanes and other storms, subject to extensive modification by wind between major floods, very poor waste-disposal capability, very high corrosion potential, extremely poor construction site
C5	Tidal flats: mixed mud, sand, and shell, subject to rapid and sudden inundation by astronomical, storm, and wind-driven tides, moderate wind erosion between floods, poor waste-disposal capability, very high corrosion potential, poor construction site
MAN-MADE FEATURES	
E1	Made land and subaerial spoil: mixed mud, silt, sand, and shell, composition and physical properties highly variable, locally steep relief, locally subject to extensive erosion, poor solid waste-disposal capability, very high corrosion potential, construction should be undertaken with caution
BAYS, LAGOONS, ESTUARIES, AND OPEN GULF	
F 1-5	Bay and estuarine bottom material: mostly mud and sandy mud, local concentrations of sand and shell, high organic content, high water content, overlying water mass varies from restricted or enclosed to tidally influenced, brackish to normal marine salinities, poor waste-disposal capability, low foundation strength

*Capability units described in this table are only those for which quantitative data are reported here. Units were not renumbered for this report. F 1-5 equals F on the graphs (figs. 4–17). For more complete descriptions of these capability units, see Fisher and others, 1973.

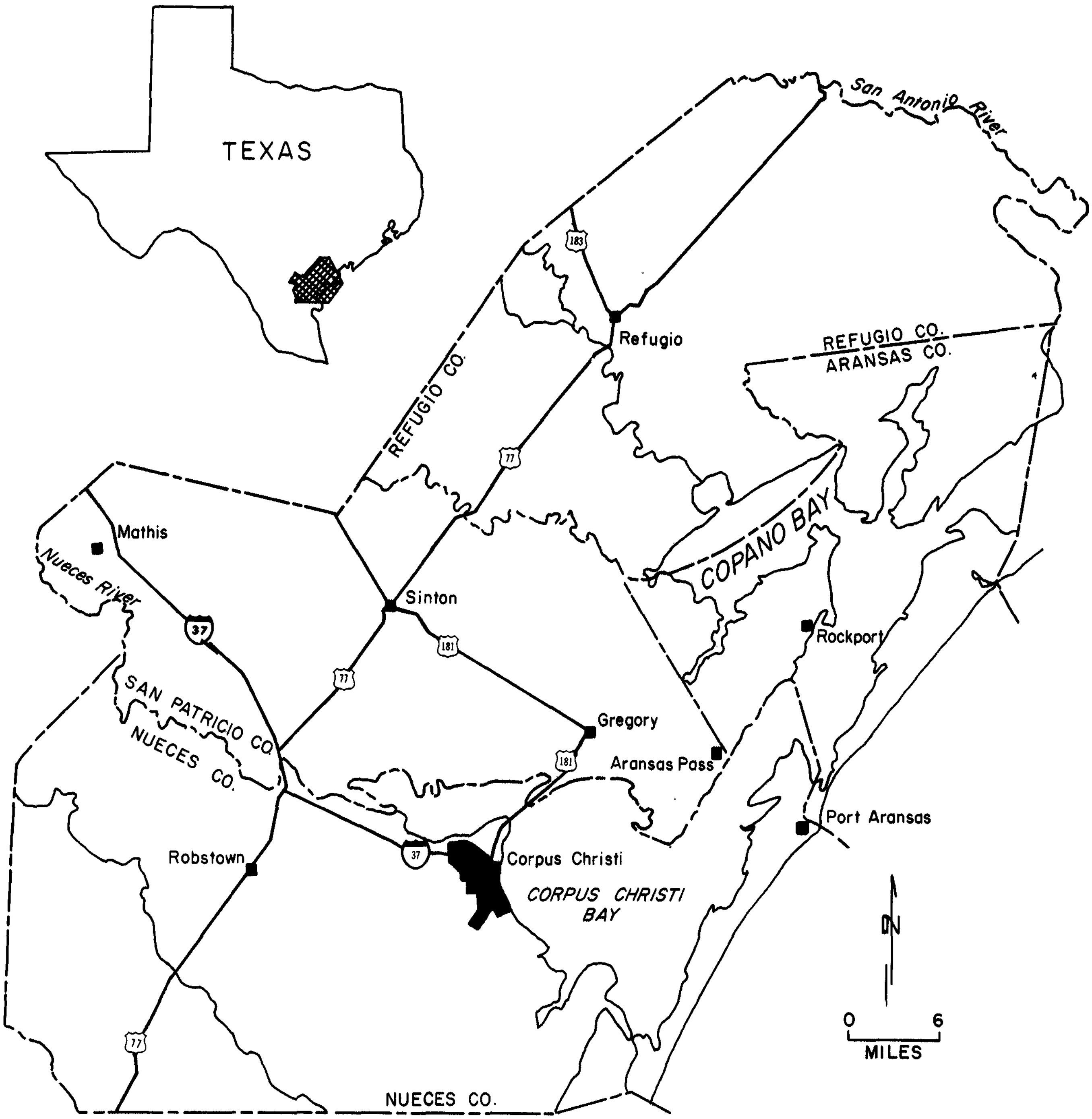

Figure 1. Index map to study area, Nueces, San Patricio, Aransas, and Refugio Counties, Texas.

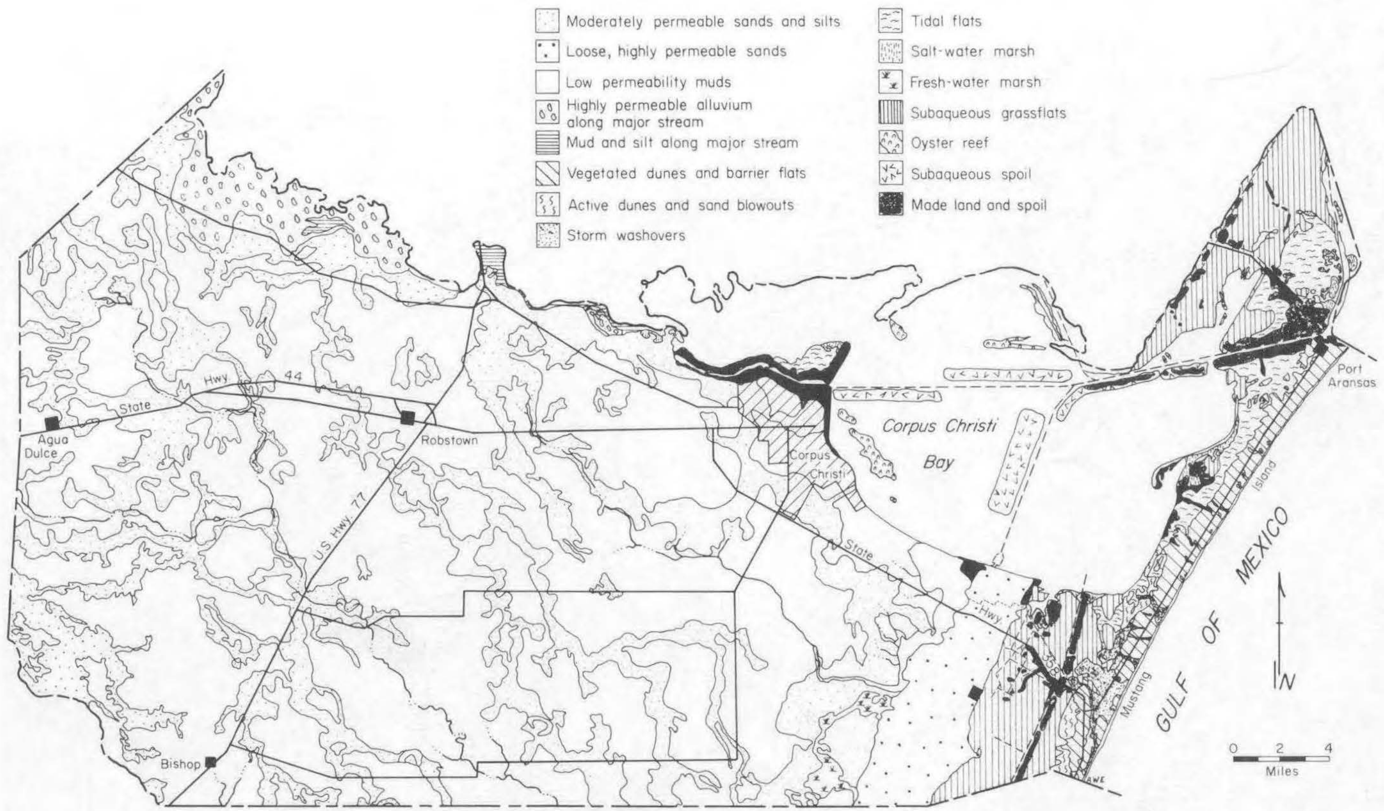

Figure 2. Generalized resource capability map, Nueces County, Texas.

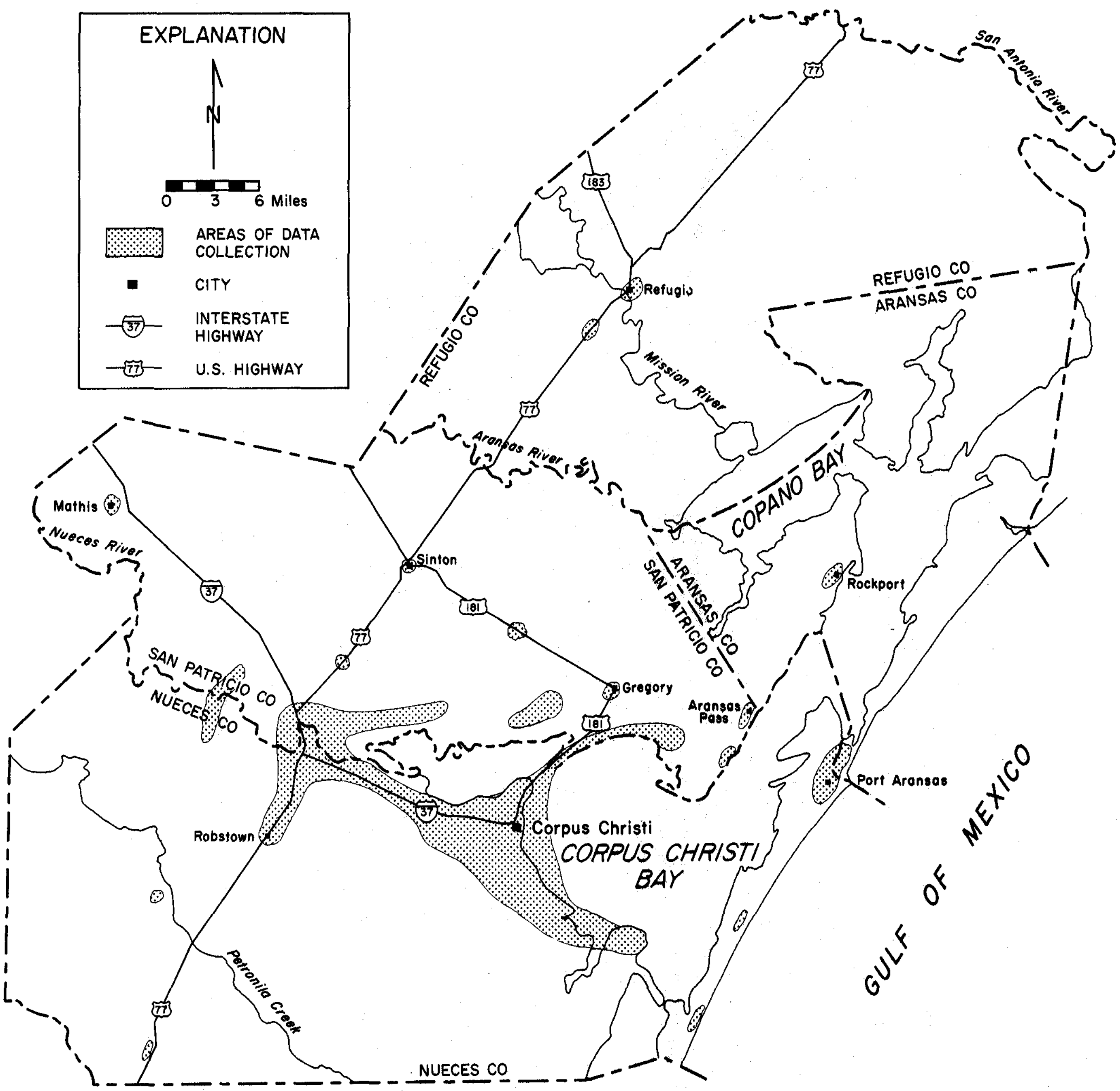

Figure 3. Distribution of engineering test data from the Corpus Christi area.

Table 2. Physical test data.

1. Unit dry weight (lbs/ft^3)
2. Natural moisture content (% of dry weight)
3. Foundation strength
   a. Standard penetrometer (blows/foot)
   b. Texas Highway Department (THD) cone penetrometer (blows/foot)
   c. Unconfined compressive strength ($tons/ft^2$)
   d. Triaxial shear strength ($tons/ft^2$ or ø)
   e. Hand penetrometer ($tons/ft^2$)
4. Linear drying shrinkage (% distance)
5. Atterburg limits
   a. Liquid limit (% of dry weight)
   b. Plastic limit (% of dry weight)
   c. Plasticity index (% of dry weight)
6. Grain size distribution—passing 200 mesh (% of sample)
7. Void ratio (vol. of voids/vol. of solids)

prediction of future test values. Numerous other kinds of statistical parameters are available—e.g., mode, median, mean deviation, and range—each with its own meaning and use. It was felt, however, that nearly everyone is familiar with the definitions of arithmetic mean and standard deviation, and that these statistical values were sufficient for the purposes of the pilot study.

Assignment of test data to individual capability units was based on core locality in relation to land capability at the surface, boring log descriptions, and prediction of sediment type at depth considering the interpreted environment of deposition. All core localities were plotted on 7.5- or 15-minute topographic maps and the Universal Transverse Mercater (UTM) coordinates were determined to facilitate input into a data storage bank. Data sources and actual core localities must be kept confidential, however, to protect proprietary information.

The 5-foot class interval for depth calculations was chosen as a compromise between: (1) the desire to show changes, if any, in results of tests with depth in individual capability units, and (2) the statistical validity of the mean and standard deviation calculations based on the anticipated amount of data to be collected from any one class interval; too few data in each class would lead to fallacious means and standard deviations.

Fifty feet was chosen as the maximum average depth for confident prediction of the kinds of depositional systems in which the sediments accumulated.

All calculations and construction of tables and graphs (tables 3–16, figs. 4–17) were performed by automatic data processing techniques; all data are presently stored on magnetic tape. In this first attempt to quantify physical properties of resource capability units, only basic statistical procedures were employed. No adjustments were made for difference in the number of samples used in the calculations nor for skewness of data distribution. In future work, further statistical treatment of the engineering test values will undoubtedly provide additional information. In plotting the graphs, mean values were arbitrarily assigned to the base of each 5-foot interval and the curves were not smoothed.

Interpretation of Data

Tables 3 through 16 contain mean and standard deviation values of the 14 types of engineering tests for which sufficient data were available to justify performing calculations. Nearly 1,300 statistical calculations were made for the ten 5-foot-depth intervals in each of the 15 capability units for which data were collected. For visual comparison, mean values of the engineering tests are displayed graphically in figures 4 through 17 and, for quick reference, mean values have been retabulated for the 0- to 5-foot depth interval in table 17.

Means of the various engineering parameters correlate well with certain expected characteristics of the capability units. Units that are dominantly mud, e.g., A8 in table 1, have low unit dry weights (97.2 to 101.2 lbs/ft^3), high natural moisture contents (23.1 to 27.3% of unit dry weight), high shrink-swell potentials (linear drying shrinkage of 17.8 to 26% of distance; plasticity index, an indicator of shrink-swell potential, of 37.0 to 40.0% of unit dry weight), and low foundation strengths (standard penetrometer test values of 19 to approximately 40 blows/ft; unconfined compression test values of 2.1 to 3.5 $tons/ft^2$). Units that are dominantly sand, e.g., A1 and A3, have higher unit dry weights (approximately 106 to 111 lbs/ft^3), lower natural moisture contents (13.1 to 20.5% of unit dry weight), lower shrink-swell potentials (linear drying shrinkage of approximately 0 to 14% of distance; plasticity index of approximately 8 to 25% of dry weight), and higher

Table 3. Unit dry weight (pounds/cubic foot). In this table and the subsequent tables, letter-number symbols correspond to unit symbols in table 1; blank areas indicate no data.

		Land and Water Capability Units													
Depth		A1	A3	A6	A8	A11	B1	B2	B3	B4	C2	C4	C5	E1	F1-5
	mean		107.3	106.9	97.2	112.0				101.0				104.5	98.0
0-5	s.d.		8.0	8.0	8.3	2.8				0.0				6.7	3.5
	# samp		38	165	228	3				1				27	5
	mean		110.9	108.3	97.7					112.0				96.9	102.2
5-10	s.d.		4.7	7.4	6.7					0.0				7.3	4.9
	# samp		36	216	256					1				11	5
	mean	106.0	107.6	108.3	101.2									104.5	99.8
10-15	s.d.	3.0	6.2	6.4	6.6									11.7	8.0
	# samp	2	36	197	212									6	11
	mean		109.8	108.8	100.2									94.0	94.4
15-20	s.d.		6.6	6.1	6.1									0.0	9.8
	# samp		37	138	187									1	8
	mean		106.8	108.5	99.8										92.4
20-25	s.d.		5.1	6.1	6.3										6.0
	# samp		16	56	122										7
	mean		105.8	107.4	97.9										103.8
25-30	s.d.		4.6	4.7	6.8										7.4
	# samp		9	22	56										4
	mean		109.0	104.8	98.4								96.0		94.5
30-35	s.d.		7.5	4.9	6.3								0.0		4.8
	# samp		3	8	42								1		4
	mean		109.5	107.2	99.1								95.3		96.8
35-40	s.d.		2.5	3.5	6.3								16.5		1.5
	# samp		2	4	35								3		5
	mean			105.1	100.4								118.5		93.6
40-45	s.d.			14.8	7.8								1.5		10.7
	# samp			8	25								2		5
	mean		116.0	110.3	99.0								109.5		97.8
45-50	s.d.		0.0	4.2	4.8								2.5		7.5
	# samp		1	6	23								2		7

Table 4. Natural moisture content (percent dry weight).

		Land and Water Capability Units													
Depth		A1	A3	A6	A8	A11	B1	B2	B3	B4	C2	C4	C5	E1	F1-5
	mean	13.8	16.2	14.8	23.7	8.3				24.0				20.7	38.1
0-5	s.d.	4.0	6.0	5.5	6.4	0.5				0.0				6.2	12.5
	# samp	7	37	189	242	3				1				37	10
	mean	16.7	13.1	16.8	24.9					19.0				23.1	34.7
5-10	s.d.	0.9	4.4	5.6	4.9					0.0				5.8	10.2
	# samp	3	37	219	263					1				11	15
	mean	17.5	15.7	18.0	23.1									22.1	27.8
10-15	s.d.	1.5	5.8	6.5	4.8									10.4	8.1
	# samp	2	38	211	220									7	14
	mean		15.5	19.0	23.9									26.0	28.5
15-20	s.d.		5.1	4.0	4.4									1.0	5.1
	# samp		40	143	192									2	8
	mean		19.9	19.5	24.6										29.3
20-25	s.d.		6.8	5.1	4.9										4.0
	# samp		23	60	133										7
	mean		20.2	20.0	26.6									37.0	22.2
25-30	s.d.		4.1	4.1	5.4									0.0	3.8
	# samp		10	27	63									1	4
	mean		19.8	28.0	26.2								35.0		27.2
30-35	s.d.		2.6	11.0	4.8								0.0		4.3
	# samp		4	14	49								1		4
	mean		20.5	23.5	26.1								24.3		26.0
35-40	s.d.		2.7	10.3	5.3								8.6		2.4
	# samp		4	10	42								3		5
	mean		16.6	22.1	26.7								16.0		28.8
40-45	s.d.		5.7	11.8	7.2								1.0		6.5
	# samp		5	10	33								2		5
	mean		17.6	18.9	27.3								18.0		25.7
45-50	s.d.		4.1	3.8	4.1								2.0		4.5
	# samp		5	8	31								2		7

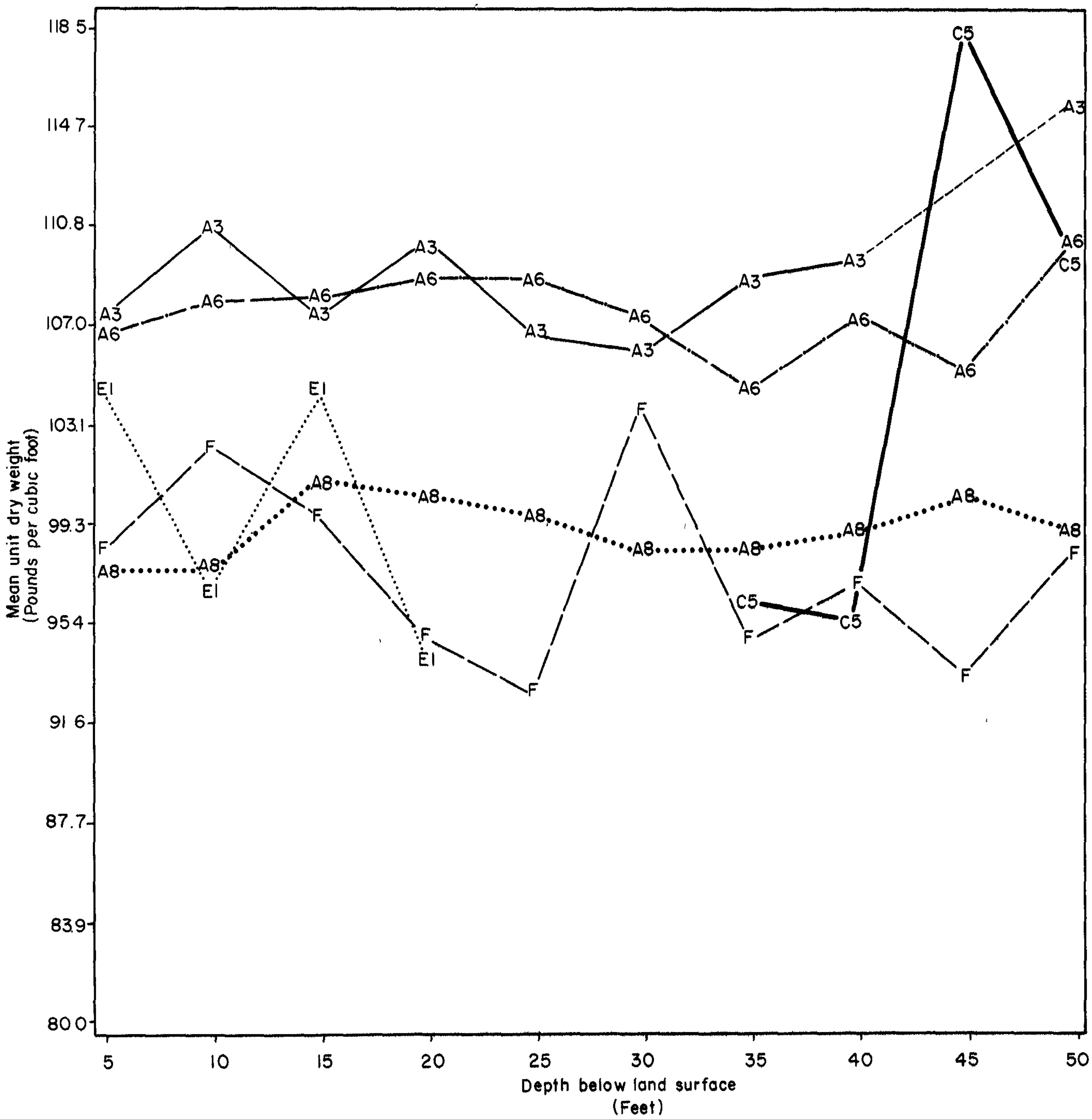

Figure 4. Curves showing variation of mean unit dry weight with depth. Dashed lines indicate incomplete data. Meaning of symbols: A3, Moderately permeable sand and silt; A6, Sandy mud; A8, Low permeability mud; C5, Tidal flats; E1, Made land and subaerial spoil; and F(F1-5), Bay and estuarine bottom sediment.

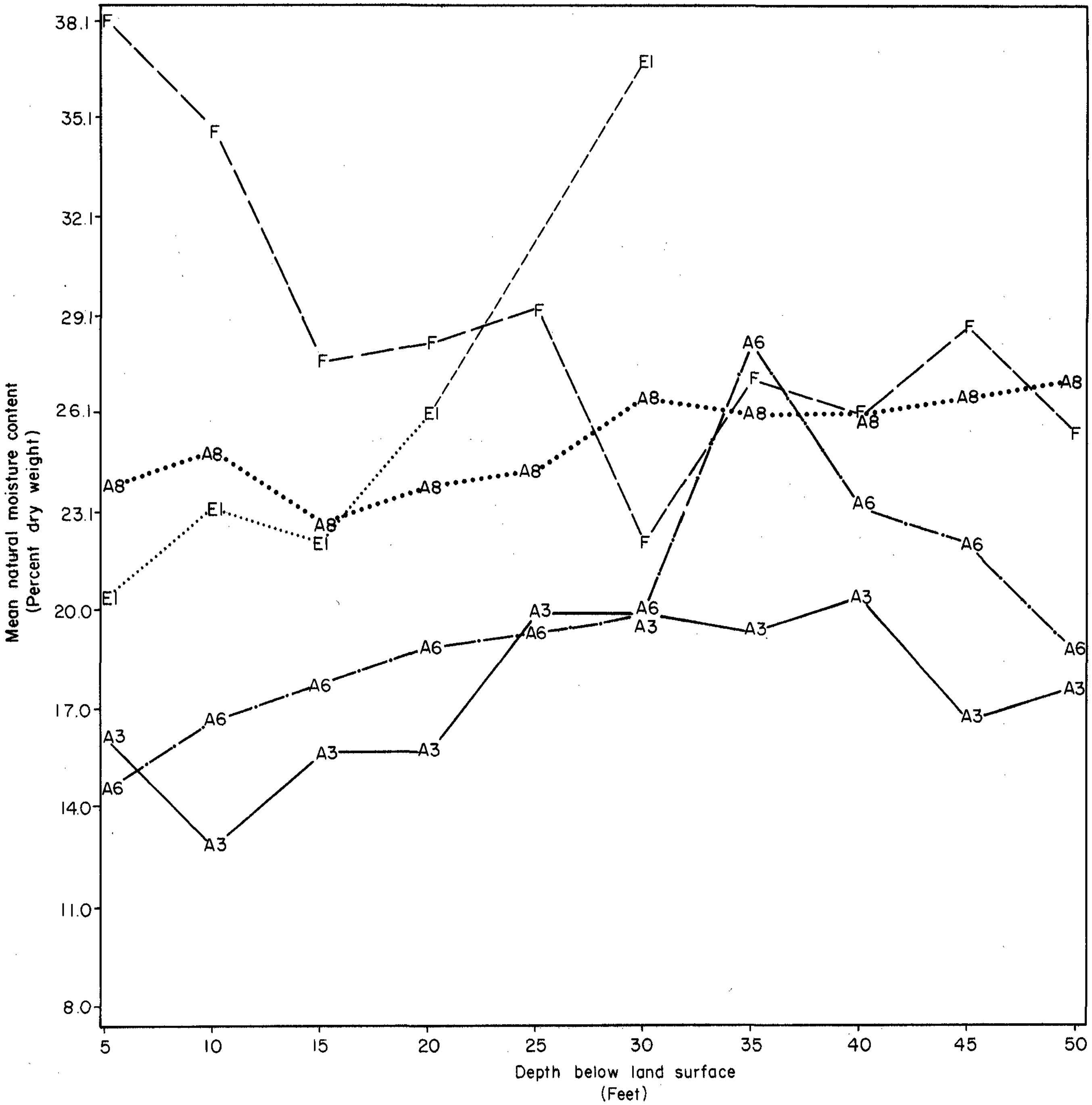

Figure 5. Curves showing variation of mean natural moisture content with depth. Meaning of symbols: A3, Moderately permeable sand and silt; A6, Sandy mud; A8, Low permeability mud; E1, Made land and subaerial spoil; and F(F1-5), Bay and estuarine bottom sediment.

Table 5. Standard penetrometer (blows/foot).

		Land and Water Capability Units													
Depth		A1	A3	A6	A8	A11	B1	B2	B3	B4	C2	C4	C5	E1	F1-5
0-5	mean	8.4	42.0	27.0							22.2	27.0	6.5	12.0	
	s.d.	5.5	25.0	0.0							7.1	3.0	2.5	7.8	
	# samp	18	2	2							24	2	2	5	
5-10	mean	12.4	22.8	12.0	18.6	26.0			2.0		27.9	18.8	22.8	17.8	27.0
	s.d.	5.6	16.6	8.6	10.2	15.0			0.0		8.2	3.9	22.6	14.7	0.0
	# samp	20	17	5	5	2			1		18	8	6	7	1
10-15	mean	23.4	27.6	18.3	20.0						25.8	24.8	13.0	20.5	
	s.d.	12.7	16.7	8.4	11.8						9.4	3.4	7.7	10.6	
	# samp	11	77	28	16						18	8	6	8	
15-20	mean	36.8	36.2	27.7	19.1						30.2	36.0	29.3	7.0	53.5
	s.d.	16.6	18.0	17.1	11.2						12.8	6.4	31.6	6.5	1.5
	# samp	9	136	28	10						11	7	6	6	2
20-25	mean	30.2	44.2	19.9	34.2						64.5	43.2	42.5		
	s.d.	4.5	19.4	13.6	13.6						16.2	10.7	25.5		
	# samp	4	99	17	13						10	8	4		
25-30	mean	42.3	52.7	34.7	34.5		2.0				52.3	45.9	27.7		30.7
	s.d.	5.8	21.4	16.5	17.0		0.0				12.6	9.6	8.2		12.5
	# samp	7	63	21	10		1				11	8	3		3
30-35	mean		42.0	24.8	39.6		3.0				39.1	44.8	12.5		32.6
	s.d.		22.6	20.4	15.8		0.0				12.3	9.3	9.5		11.7
	# samp		43	6	16		1				10	8	2		5
35-40	mean		49.7	18.2	33.8		7.0				38.1	48.7			41.7
	s.d.		19.3	15.4	21.4		0.0				13.9	4.1			11.9
	# samp		28	5	10		1				10	7			3
40-45	mean		44.0	54.4	26.8		9.0				59.9	54.1			52.0
	s.d.		18.0	13.6	23.0		0.0				19.7	4.8			15.0
	# samp		24	5	6		1				10	7			2
45-50	mean		51.3	40.5	44.5						49.7		46.0		27.0
	s.d.		24.1	2.5	10.5						18.2		0.0		0.0
	# samp		15	2	2						3		1		1

Table 6. THD cone penetrometer (blows/foot).

		Land and Water Capability Units													
Depth		A1	A3	A6	A8	A11	B1	B2	B3	B4	C2	C4	C5	E1	F1-5
0-5	mean			25.2	9.8									10.0	
	s.d.			14.8	5.5									0.0	
	# samp			6	4									1	
5-10	mean		39.2	36.7	22.1								76.0	6.0	
	s.d.		27.2	18.4	7.4								0.0	0.0	
	# samp		6	7	9								1	1	
10-15	mean		37.3	20.4	20.6								39.5		6.5
	s.d.		24.0	16.4	5.9								1.5		0.5
	# samp		17	9	5								2		2
15-20	mean		31.4	30.6	27.4								20.5		9.0
	s.d.		21.4	27.8	20.5								2.5		0.0
	# samp		9	9	11								2		1
20-25	mean		24.3	10.8	22.4								8.0		
	s.d.		20.3	6.3	10.7								0.8		
	# samp		13	6	11								3		
25-30	mean		25.4	47.5	23.6								7.7		5.5
	s.d.		22.3	42.5	12.8								3.7		2.5
	# samp		5	2	14								3		2
30-35	mean		39.5	10.2	20.5								7.3		
	s.d.		35.5	9.0	22.5								0.5		
	# samp		2	5	17								3		
35-40	mean		36.5	20.2	21.2								23.0		4.0
	s.d.		5.5	17.5	20.8								0.0		0.0
	# samp		2	5	14								1		1
40-45	mean		40.1	26.3	16.1										
	s.d.		9.8	30.6	15.7										
	# samp		7	6	16										
45-50	mean		36.0	70.5	25.8										
	s.d.		3.7	18.5	25.6										
	# samp		3	2	11										

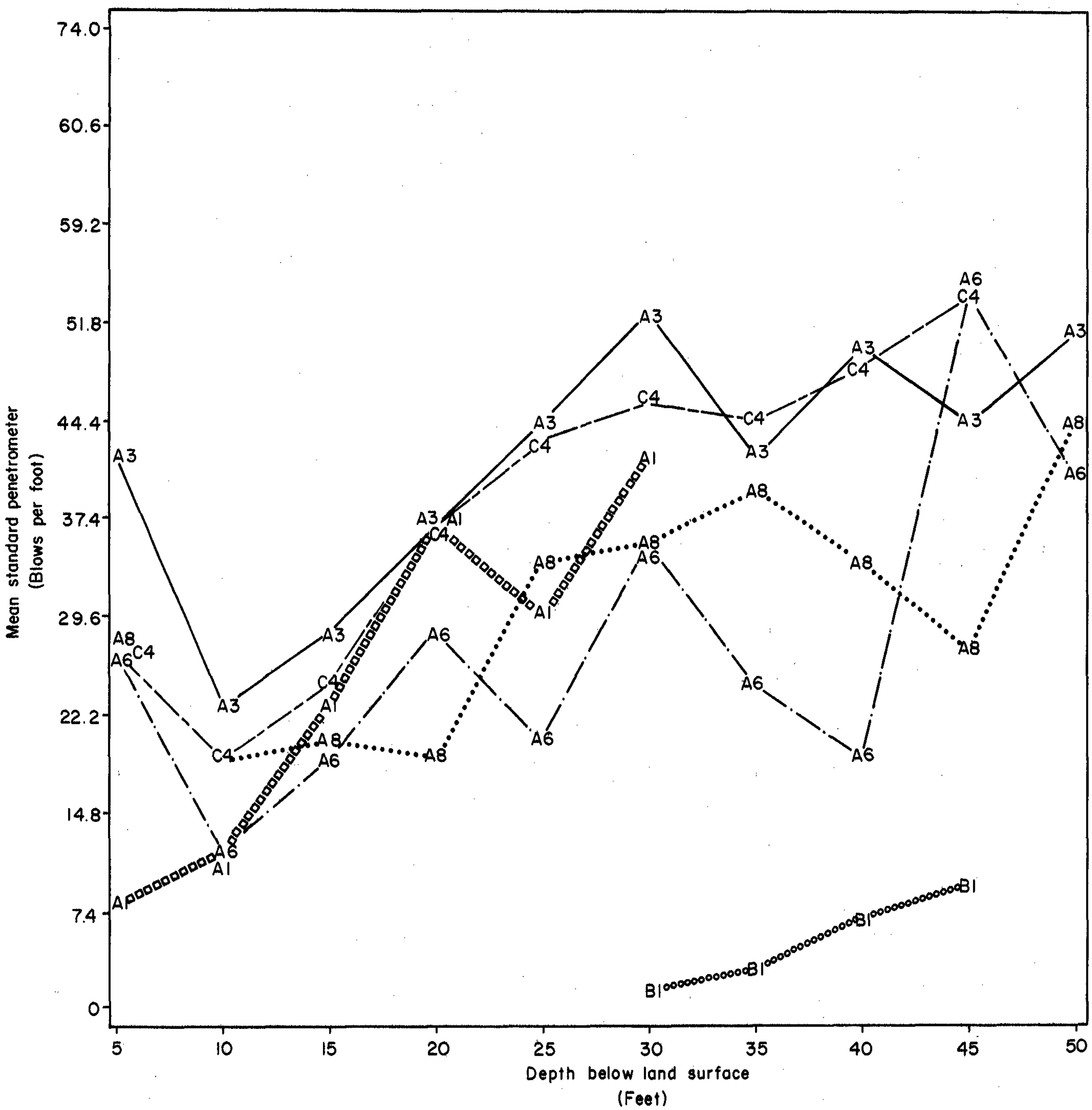

Figure 6. Curves showing variation of mean values of standard penetrometer measurements with depth. Meaning of symbols: A1, Highly permeable recharge sand; A3, Moderately permeable sand and silt; A6, Sandy mud; A8, Low permeability mud; B1, Highly permeable sand and gravel; and C4, Storm washover area. Curves for units C2, C5, E1, and F were omitted from this graph in order to maintain readability.

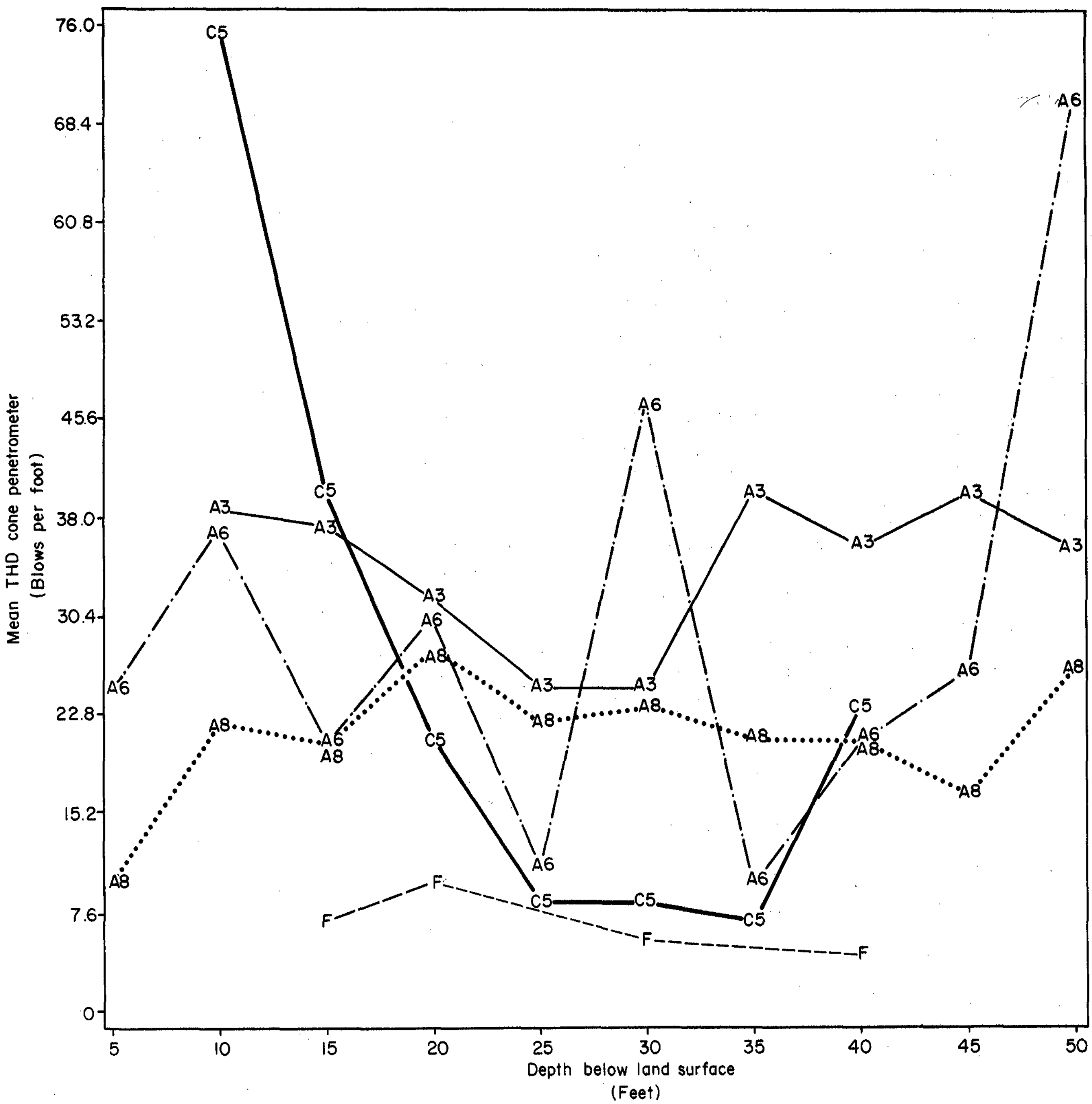

Figure 7. Curves showing variation of mean values of Texas Highway Department (THD) cone penetrometer measurements with depth. Meaning of symbols: A3, Moderately permeable sand and silt; A6, Sandy mud; A8, Low permeability mud; C5, Tidal flats; and F(F1-5), Bay and estuarine bottom sediment.

foundation strengths (standard penetrometer values generally above 30 blows/ft; unconfined compression values—A3 only—of approximately 2 to 4 tons/ft^2). Units that are highly variable (A6, F 1–5, E1) tend to have highly variable means and large standard deviations, e.g., mean natural moisture content of unit A6 is between 14.8 and 28.0% of dry weight; standard deviations are up to 11.0%.

These calculated means establish representative values for physical properties which strongly influence the ability of land areas to support man's use. The standard deviations show the most likely range over which these values might occur. Important differences in the characteristics of several of the units are clearly shown. For example, the plasticity index for low permeability mud (A8) in the Corpus Christi area is 37 to 40% of dry weight. This is commonly more than twice the plasticity index for moderately permeable sand and silt (A3) at 8 to 28%; future determinations of the plasticity indices for the two units should seldom overlap. Test values for unit dry weight average 100 lbs/ft^3 for mud units and 108 to 110 lbs/ft^3 for sandy units; value ranges for this test may overlap although standard deviations are 10% or less. Other units are, of course, more variable and several of their properties overlap with the properties of different units. Knowledge of the variability of the unit is itself informative.

Anomalies

Although most mean values for the engineering tests tend to correspond to expectations, a few anomalies in the results of tests for foundation strength can be noted. Mean values of standard penetrometer readings show an expected increase in foundation strength with depth; curves of mean values of hand and Texas Highway Department penetrometer test results, triaxial test results, and unconfined compression test results are flat or are too variable to indicate a trend. There are several possible explanations: (1) the number of samples tested was too small to give a good indication of average foundation strength; (2) unconfined compression strength values were recorded whether or not failure occurred on slickensided surfaces, giving a reading which may be too low; and (3) practicing soils engineers generally consider triaxial tests on materials from the Corpus Christi area to be unreliable because it is difficult to obtain undisturbed samples and return them to the laboratory for testing (Joe Stapp, personal communication).

In addition, fore-island dunes and vegetation-stabilized barrier flats (C2) were distinguished from washover areas (C4) at depth in calculating means and standard deviations of engineering test values. These two units can be distinguished geologically in the subsurface, but distinctions based on drilled core descriptions are probably unreliable and in any case unimportant in terms of natural capability. They should therefore be lumped; mean and standard deviation values contained in tables 3–16 for the two units show strong similarity.

LIMITATIONS OF QUANTITATIVE CHARACTERIZATION

It must be understood, of course, that mean values presented for engineering parameters of like-capability lands are only averages and may not represent actual values at any given locality. The values are a planning tool and should not be construed as actual site data. On-site testing will still be required to properly assess foundation requirements. In addition, test results that are outside the limits of the standard deviations may be obtained. Such readings can result from end-member compositions within a unit, normal unit variability, or scale factor where a land capability substrate penetrated by a test core is too small to show on a map at a scale of two miles to the inch (1:125,000).

Other limitations of the accuracy of the quantitative characterization of land resource units involve (1) imprecise logging and sample description by the testing laboratory, (2) errors in assigning test data to the proper capability unit, (3) possible differences in methods used by the various agencies and firms and their precision in performing essentially the same kind of test, and (4) lack of sufficient data for valid statistical calculations.

UTILITY AND APPLICATION

Despite limitations, quantitative knowledge of substrate parameters such as the data presented here can be a basic input in assessing engineering characteristics of land capability units and in estimating the less easily quantified substrate parameters of capability units, including (a) foundation strength, (b) plasticity, (c) compressibility, (d) slope stability, (e) shrink-swell potential, (f) ease of excavation, (g) fill potential, (h) internal drainage, (i) moisture-retention capacity, (j) waste-disposal capability, (k) ability to handle septic tank

Table 7. Unconfined compressive strength (q_u) (tons/square foot).

		Land and Water Capability Units													
Depth		A1	A3	A6	A8	A11	B1	B2	B3	B4	C2	C4	C5	E1	F1-5
0-5	mean		3.6	2.7	3.5									1.6	
	s.d.		2.3	1.9	2.3									0.6	
	# samp		2	13	18									8	
5-10	mean		4.0	3.3	2.1			1.0						2.5	1.8
	s.d.		2.1	2.7	1.2			0.0						0.0	0.7
	# samp		3	85	51			1						1	4
10-15	mean	0.9	2.8	3.0	2.4										1.9
	s.d.	0.6	2.5	1.9	1.6										1.2
	# samp	2	8	95	93										5
15-20	mean		3.5	3.2	2.3										0.9
	s.d.		1.5	1.5	1.3										0.0
	# samp		6	62	96										1
20-25	mean		1.3	2.7	2.5										2.3
	s.d.		0.6	1.2	1.1										1.3
	# samp		2	31	56										3
25-30	mean		1.7	2.0	2.6										2.7
	s.d.		0.4	0.8	1.4										0.0
	# samp		3	12	33										1
30-35	mean		2.6	2.7	2.6								0.7		1.0
	s.d.		0.0	0.7	1.3								0.0		0.0
	# samp		1	5	26								1		1
35-40	mean		2.0	4.0	2.8								2.1		2.4
	s.d.		0.0	0.0	2.0								2.0		0.0
	# samp		1	1	19								3		1
40-45	mean			2.6	2.5								2.1		2.0
	s.d.			0.8	2.4								0.0		0.6
	# samp			6	12								1		3
45-50	mean			2.4	3.4								1.6		2.6
	s.d.			1.1	3.1								0.5		0.2
	# samp			4	7								2		2

effluent, (l) corrosion potential, and (m) general suitability for construction purposes.

These kinds of quantitative and nonquantitative data allow better definition of natural environmental carrying capacity than nonquantitative maps can by themselves. Information provided by the data may reduce or eliminate the need for preliminary engineering investigations commonly undertaken to assess project feasibility and estimate costs, and may allow consideration of more sites than is now economically possible in preliminary studies. Quantitative information most certainly should aid planners in charting land utilization that maximizes resource use, yet does not significantly impair environmental quality, e.g., in the development of areas of known groundwater recharge and of areas where the land presents special engineering problems.

The approach presented above is applicable wherever there are good surface environmental maps and reasonable knowledge of the subsurface geology. Applicability is not necessarily limited by the scale of the investigation, although larger map scales and more detailed studies increase the likelihood that statistical values calculated for the engineering test results will reflect true average engineering properties of the capability units. Investigations using small-scale maps covering large areas will require a great amount of data to insure that means are statistically valid.

Once procedures and scales of investigations are established, a system can be set up so that new engineering data can be routinely collected and recorded until an acceptable confidence level for the sample population is achieved. Increasingly greater accuracy and reliability in the quantitative characterization will result, providing planning agencies with the best quantitative information available on land resources.

Furthermore, quantified and nonquantified engineering parameters can be easily entered into a comprehensive, computerized data management system. This data package can be designed to allow accessing numerous subjects in a variety of ways. For example, information desired could be retrieved (1) by geographic locality—giving the kinds and areal extent of land and water resource units in the locality, their physical, biologic, and hydrologic properties, and their current land use; (2) by site suitability—giving locations and properties of land areas meeting minimum performance standards for a given projected use; and (3)

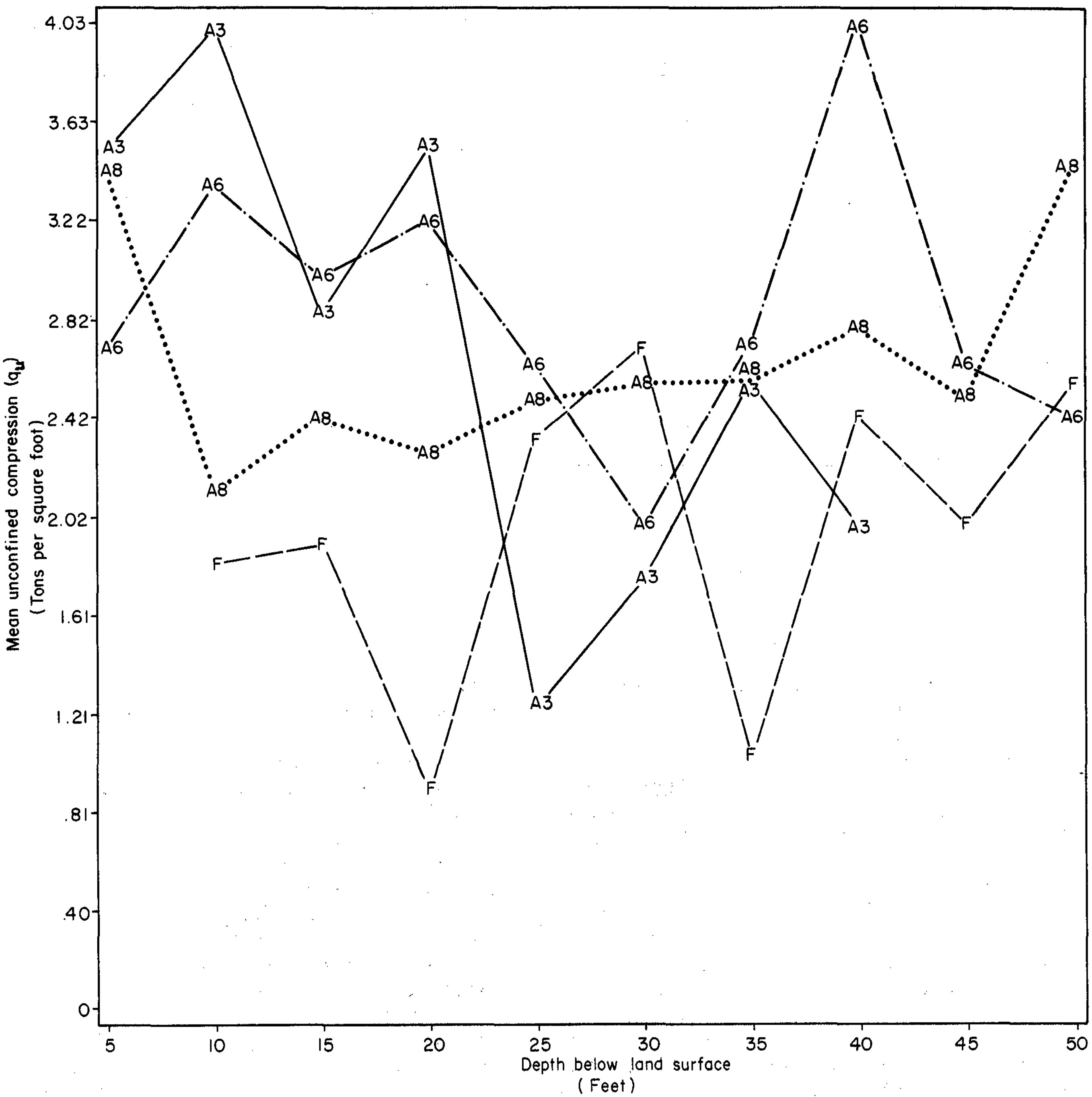

Figure 8. Curves showing variation of mean values of unconfined compression test measurements (q_u) with depth. Meaning of symbols: A3, Moderately permeable sand and silt; A6, Sandy mud; A8, Low permeability mud; and F(F1-5), Bay and estuarine bottom sediment.

Table 8. Triaxial shear strength (q_c) (tons/square foot).

		Land and Water Capability Units													
Depth		A1	A3	A6	A8	A11	B1	B2	B3	B3	C2	C4	C5	E1	F1-5
	mean			0.7	1.0										
0-5	s.d.			0.4	0.0										
	# samp			3	1										
	mean		0.2	0.8	0.6						0.0				
5-10	s.d.		0.2	0.1	0.1						0.0				
	# samp		3	2	2						1				
	mean	0.3	0.2	0.3	0.2			0.5							1.3
10-15	s.d.	0.1	0.1	0.0	0.0			0.1							0.7
	# samp	2	3	4	1			2							2
	mean		0.3		0.4			1.4			0.0				1.5
15-20	s.d.		0.0		0.0			0.1			0.0				0.8
	# samp		2		1			2			1				2
	mean		0.8		0.7										0.9
20-25	s.d.		0.0		0.4										0.0
	# samp		1		2										1
	mean			1.0							0.0				0.6
25-30	s.d.			0.5							0.0				0.0
	# samp			2							1				2
	mean			1.4				0.8			0.0				
30-35	s.d.			0.0				0.0			0.0				
	# samp			1				1			1				
	mean				0.6			1.2							
35-40	s.d.				0.0			0.0							
	# samp				1			1							
	mean		0.9		0.4										
40-45	s.d.		0.0		0.0										
	# samp		1		1										
	mean			1.4	1.1						1.1				0.6
45-50	s.d.			0.0	0.0						0.0				0.0
	# samp			1	1						1				1

by limiting factors—giving areas with one or more special limitations on use; or information could be retrieved by other aspects of land use such as areas of a given biologic assemblage, areas subject to known geologic hazards, or areas of certain kinds of present land use. A data management system of this kind will be described in a forthcoming report.

IMPROVEMENTS IN THE QUANTIFICATION OF LAND RESOURCE UNITS

We have continued to gather engineering test data from the Corpus Christi area and the region of the Coastal Bend Council of Governments in order to enlarge the data base and to achieve more uniform geographic distribution of test sites. Hopefully, with an increased amount of data, we will be able to employ more sophisticated statistical techniques to lessen the effects of anomalous readings, perform an analysis of variance, allow better prediction of engineering characteristics where data are sparse, and investigate possible geographical differences in engineering parameters of particular capability units. Improved subsurface control is desirable and will extend and enhance our ability to quantify capability units at depth. A subsurface mapping program of Pleistocene sediments of the Coastal Plain is presently underway.

SUMMARY

A method of quantifying engineering parameters of natural land resource units of the Corpus Christi area, Texas has been developed by combining soils engineering test data available from public agencies and private firms with resource capability analysis developed by Brown and others (1971). Means and standard deviations of values from 14 different kinds of engineering tests have been calculated as a function of depth in the physically defined units. In general, although there are limitations in the procedure, results from the calculations correlate well with expected characteristics of the natural capability units. Quantitative knowledge of substrate characteristics should aid planners in charting optimum use of land resources, particularly when placed in a comprehensive environmental data package providing a wide range of natural resource information.

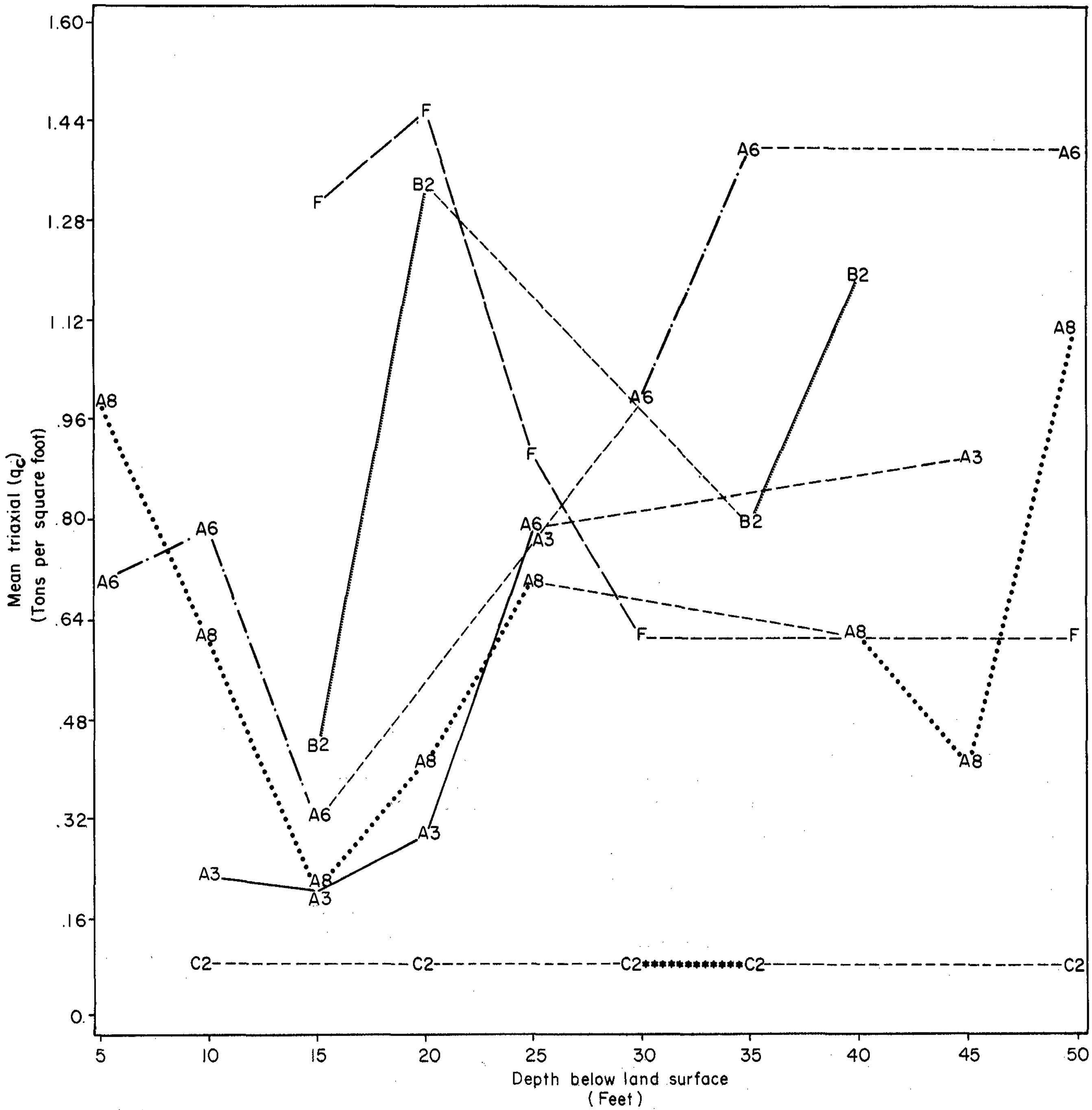

Figure 9. Curves showing variation of mean values of triaxial test measurements (q_c) with depth. Meaning of symbols: A3, Moderately permeable sand and silt; A6, Sandy mud; A8, Low permeability mud; B2, Low to moderate permeability mud and silt; C2, Fore-island dunes and vegetation-stabilized barrier flats; and F(F1-5), Bay and estuarine bottom sediment.

Table 9. Triaxial shear strength (ø) (degrees).

		Land and Water Capability Units													
Depth		A1	A3	A6	A8	A11	B1	B2	B3	B4	C2	C4	C5	E1	F1-5
	mean			29.4	29.0										
0-5	s.d.			0.6	0.0										
	# samp			3	1										
	mean		28.3	29.2	40.0						35.0				
5-10	s.d.		3.4	9.9	2.0						0.0				
	# samp		3	2	2						1				
	mean	21.8	28.4	28.1	23.7			13.1							15.3
10-15	s.d.	1.0	6.1	1.3	0.0			11.2							7.2
	# samp	2	3	5	1			2							2
	mean		34.3		35.0			8.0			29.0				10.6
15-20	s.d.		3.0		0.0			4.6			0.0				0.3
	# samp		3		1			2			1				2
	mean		11.3		26.0										17.5
20-25	s.d.		0.0		0.0										0.0
	# samp		1		2										1
	mean			15.9							36.0				25.0
25-30	s.d.			10.2							0.0				4.7
	# samp			2							1				2
	mean			7.1				12.5			31.0				
30-35	s.d.			0.0				0.0			0.0				
	# samp			1				1			1				
	mean				27.0			11.3							
35-40	s.d.				0.0			0.0							
	# samp				1			1							
	mean		31.0		29.0										
40-45	s.d.		0.0		0.0										
	# samp		1		1										
	mean			20.0	33.0						15.0				21.8
45-50	s.d.			0.0	0.0						0.0				0.0
	# samp			1	1						1				1

Table 10. Hand penetrometer (tons/square foot).

		Land and Water Capability Units													
Depth		A1	A3	A6	A8	A11	B1	B2	B3	B4	C2	C4	C5	E1	F1-5
	mean			4.0	2.3									3.9	2.4
0-5	s.d.			0.5	0.8									0.3	0.5
	# samp			2	7									2	4
	mean			3.5	2.7										2.7
5-10	s.d.			0.0	0.8										0.8
	# samp			1	16										5
	mean		1.3	3.8	2.3										2.6
10-15	s.d.		0.2	0.3	0.7										0.8
	# samp		2	3	21										7
	mean		1.5	2.9	2.5										2.6
15-20	s.d.		0.0	0.7	1.1										0.3
	# samp		1	6	12										5
	mean			3.4	3.1										2.7
20-25	s.d.			1.1	0.5										0.5
	# samp			2	7										4
	mean			3.5	3.2										3.2
25-30	s.d.			0.6	1.0										0.0
	# samp			6	3										1
	mean			2.3	3.2										3.2
30-35	s.d.			0.5	0.5										0.2
	# samp			3	6										2
	mean				3.4										3.2
35-40	s.d.				0.5										0.5
	# samp				7										3
	mean			2.6	2.8										3.2
40-45	s.d.			0.0	1.0										0.3
	# samp			1	4										4
	mean														3.1
45-50	s.d.														0.2
	# samp														4

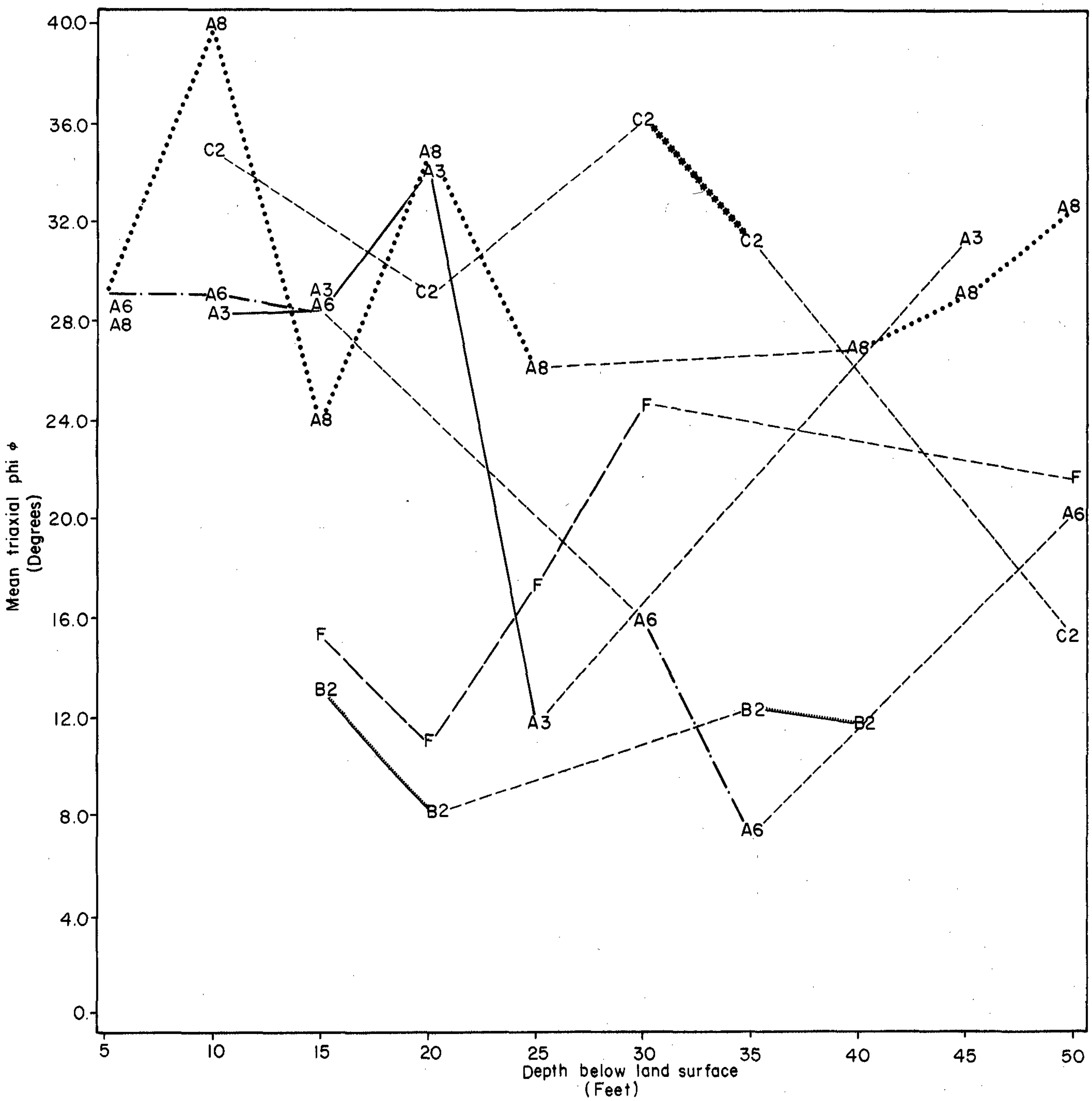

Figure 10. Curves showing variation in mean values of phi (ø) measured during triaxial tests with depth. Meaning of symbols: A3, Moderately permeable sand and silt; A6, Sandy mud; A8, Low permeability mud; B2, Low to moderate permeability mud and silt; C2, Fore-island dunes and vegetation-stabilized barrier flats; and F(F1-5), Bay and estuarine bottom sediment.

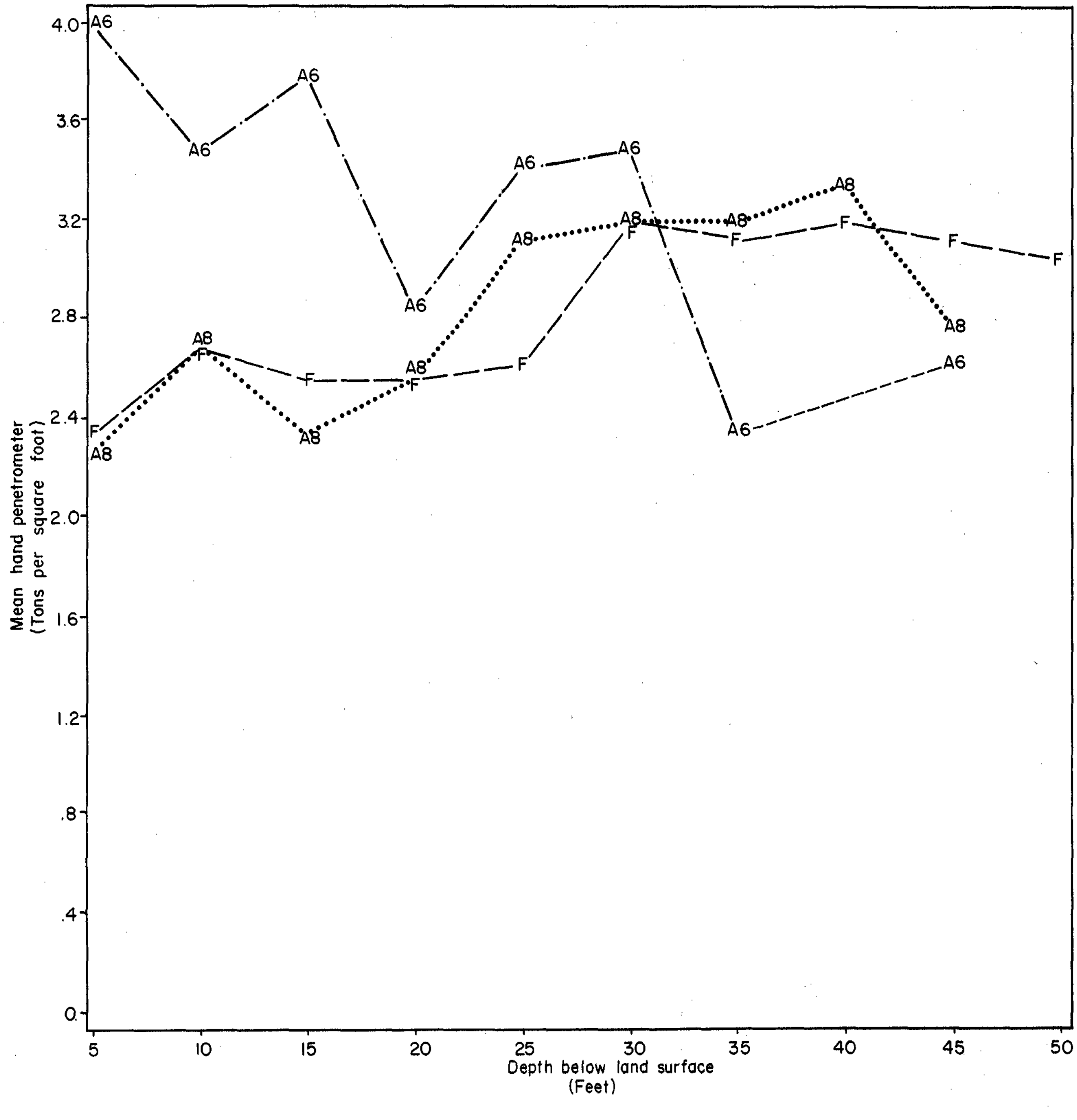

Figure 11. Curves showing variation of mean values of hand penetrometer measurements with depth. Meaning of symbols: A6, Sandy mud; A8, Low permeability mud; and F(F1-5), Bay and estuarine bottom sediment.

Table 11. Linear drying shrinkage (percent distance).

		Land and Water Capability Units													
Depth		A1	A3	A6	A8	A11	B1	B2	B3	B4	C2	C4	C5	E1	F1-5
0-5	mean		0.8	7.5	17.8									9.4	
	s.d.		0.0	3.3	3.6									1.8	
	# samp		1	5	4									7	
5-10	mean			8.7	20.0									5.0	
	s.d.			3.8	5.8									0.0	
	# samp			8	3									1	
10-15	mean		5.5	10.4	23.3										
	s.d.		3.9	3.6	7.4										
	# samp		3	5	3										
15-20	mean		6.5	5.3	25.2										
	s.d.		4.0	4.8	3.0										
	# samp		3	2	5										
20-25	mean		2.8	7.0	25.8										
	s.d.		2.1	0.0	3.4										
	# samp		3	1	8										
25-30	mean		9.3	21.0	26.0										
	s.d.		4.6	6.1	2.5										
	# samp		3	4	5										
30-35	mean		6.3	24.0	25.8										
	s.d.		1.8	0.0	2.7										
	# samp		2	1	5										
35-40	mean		9.0	15.1	25.8										
	s.d.		5.7	5.4	3.0										
	# samp		3	4	4										
40-45	mean		13.9		24.6										
	s.d.		9.4		6.2										
	# samp		6		5										
45-50	mean		13.7	15.0	24.3										
	s.d.		7.6	7.0	3.8										
	# samp		6	2	4										

Table 12, Liquid limit (percent dry weight).

		Land and Water Capability Units													
Depth		A1	A3	A6	A8	A11	B1	B2	B3	B4	C2	C4	C5	E1	F1-5
0-5	mean		32.0	40.1	60.5		18.5	61.0						41.5	54.9
	s.d.		6.6	6.0	9.1		2.5	3.0						10.1	14.7
	# samp		5	32	46		2	2						15	10
5-10	mean	28.0	29.8	39.9	59.7			36.5	25.0					48.3	45.9
	s.d.	3.7	7.3	7.8	12.2			15.5	0.0					26.8	9.5
	# samp	3	6	31	39			2	1					4	12
10-15	mean		25.5	41.7	62.6										61.9
	s.d.		4.2	13.1	12.8										11.4
	# samp		10	27	28										10
15-20	mean		31.0	40.3	64.4				29.0				40.0	31.0	85.0
	s.d.		9.3	10.0	13.9				0.0				0.0	0.0	0.0
	# samp		5	11	24				1				1	1	1
20-25	mean		30.6	41.5	74.9			54.0							
	s.d.		7.0	7.1	11.3			0.0							
	# samp		5	12	18			1							
25-30	mean		31.3	59.4	69.9									42.0	46.0
	s.d.		10.0	12.2	18.4									0.0	18.0
	# samp		6	5	15									1	2
30-35	mean		29.5	75.0	68.4								20.0		22.0
	s.d.		0.5	0.0	20.0								0.0		0.0
	# samp		2	1	15								1		1
35-40	mean		37.0	46.8	71.2								37.3		24.0
	s.d.		7.0	18.1	18.9								6.7		0.0
	# samp		4	6	13								3		1
40-45	mean		50.5	37.8	66.6								33.0		75.0
	s.d.		24.4	6.6	18.2								0.0		0.0
	# samp		6	4	16								1		1
45-50	mean		39.9	59.5	75.1								29.0		
	s.d.		18.1	15.5	13.8								0.0		
	# samp		7	2	10								1		

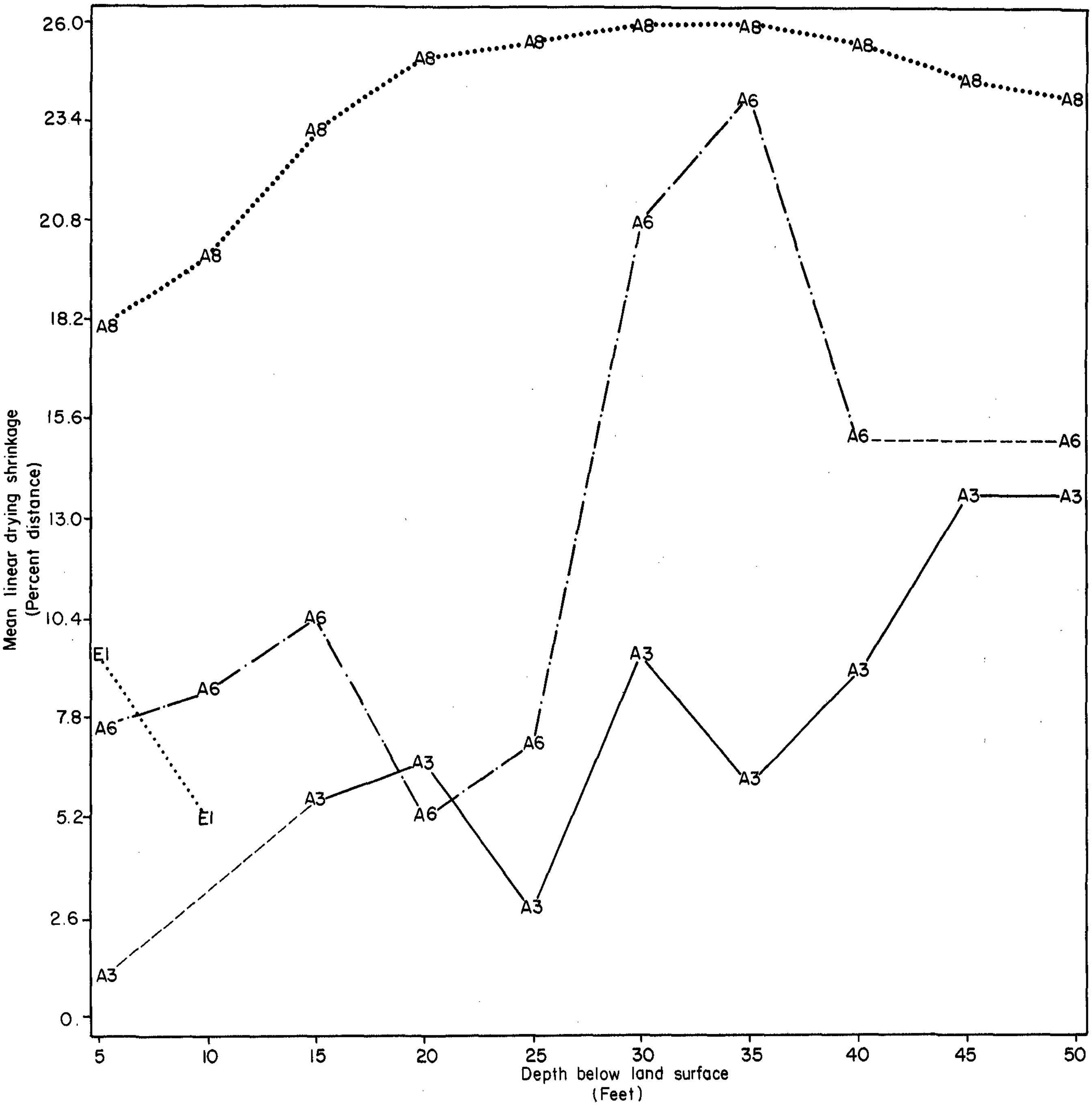

Figure 12. Curves showing variation of mean values of linear drying shrinkage tests with depth. Meaning of symbols: A3, Moderately permeable sand and silt; A6, Sandy mud; A8, Low permeability mud; and E1, Made land and subaerial spoil.

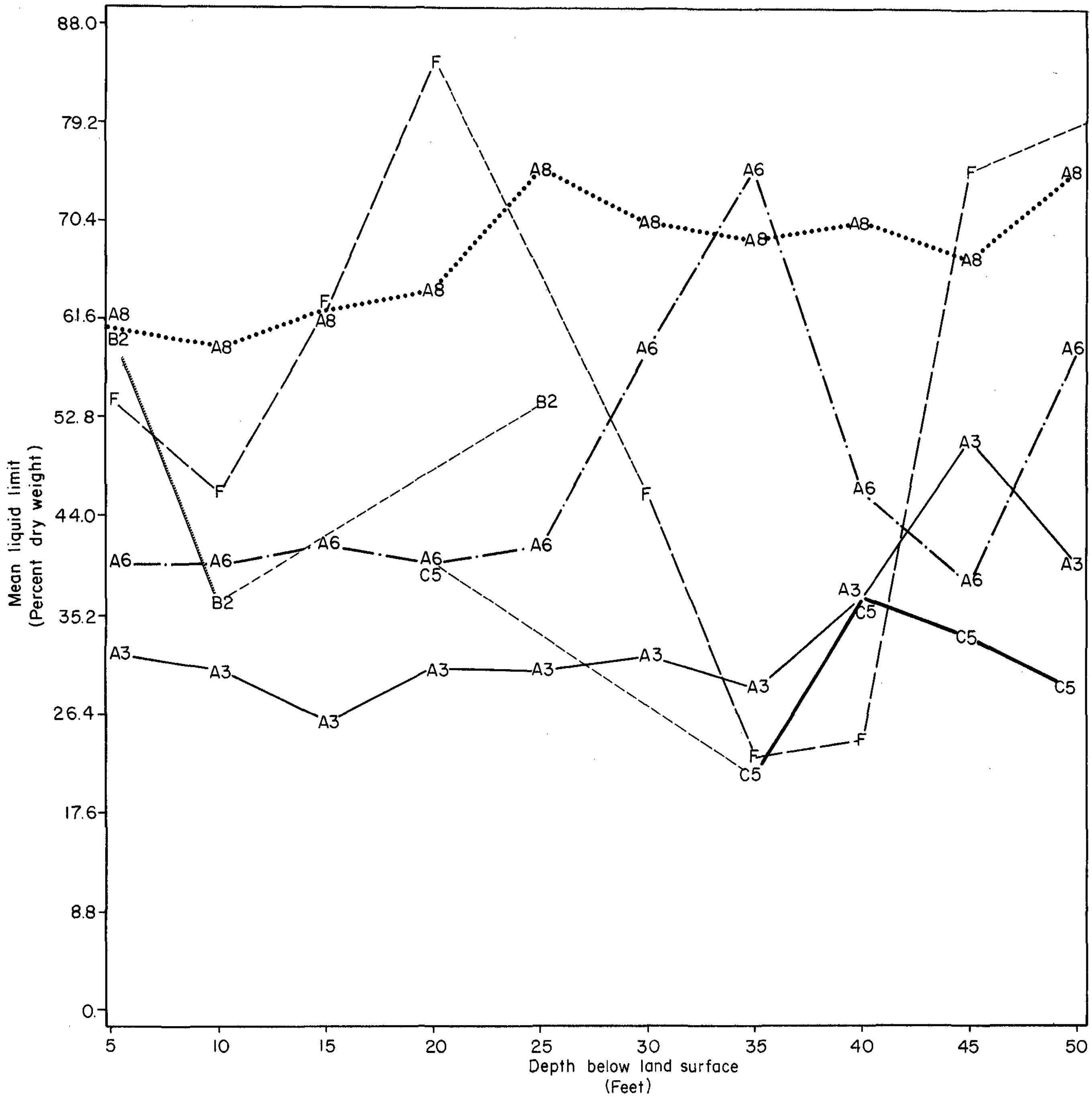

Figure 13. Curves showing variation of mean values of liquid limit tests with depth. Meaning of symbols: A3, Moderately permeable sand and silt; A6, Sandy mud; A8, Low permeability mud; B2, Low to moderate permeability mud and silt; C5, Tidal flats; and F(F1-5), Bay and estuarine bottom sediment.

Table 13. Plastic limit (percent dry weight).

		Land and Water Capability Units													
Depth		A1	A3	A6	A8	A11	B1	B2	B3	B4	C2	C4	C5	E1	F1-5
0-5	mean		16.0	18.3	23.2		17.5	27.5						19.5	26.4
	s.d.		1.4	3.0	4.6		2.5	0.5						3.1	5.4
	# samp		5	32	46		2	2						15	10
5-10	mean	22.3	17.0	18.3	22.7			18.0	23.0					18.8	24.4
	s.d.	0.9	2.5	2.3	5.8			1.0	0.0					6.0	3.0
	# samp	3	6	31	39			2	1					4	12
10-15	mean		19.0	18.3	22.5										27.6
	s.d.		2.4	4.8	4.2										3.3
	# samp		10	27	28										10
15-20	mean		20.6	18.4	24.3				23.0				21.0	15.0	29.0
	s.d.		2.7	2.7	5.3				0.0				0.0	0.0	0.0
	# samp		5	11	24				1				1	1	1
20-25	mean		18.4	18.3	26.7			21.0							
	s.d.		2.6	3.2	5.3			0.0							
	# samp		5	12	18			1							
25-30	mean		19.7	22.8	26.4									17.0	23.0
	s.d.		3.1	5.3	8.7									0.0	2.0
	# samp		6	5	15									1	2
30-35	mean		17.5	26.0	25.2								17.0		20.0
	s.d.		3.5	0.0	6.8								0.0		0.0
	# samp		2	1	15								1		1
35-40	mean		19.0	20.3	24.1								17.7		24.0
	s.d.		4.1	8.3	6.9								2.1		0.0
	# samp		4	6	13								3		1
40-45	mean		22.5	16.5	27.8								19.0		27.0
	s.d.		7.1	1.1	11.0								0.0		0.0
	# samp		6	4	16								1		1
45-50	mean		18.7	29.5	27.7								15.0		
	s.d.		5.6	1.5	5.5								0.0		
	# samp		7	2	10								1		

Table 14. Plasticity index (percent dry weight).

		Land and Water Capability Units													
Depth		A1	A3	A6	A8	A11	B1	B2	B3	B4	C2	C4	C5	E1	F1-5
0-5	mean		16.0	21.8	37.1		1.0	33.5						22.0	28.5
	s.d.		5.3	5.5	9.0		0.0	3.5						8.4	11.5
	# samp		5	32	46		2	2						15	10
5-10	mean	8.5	19.3	21.6	37.0			18.5	2.0					29.5	21.5
	s.d.	2.5	3.8	8.1	9.2			14.5	0.0					21.8	7.9
	# samp	2	4	31	39			2	1					4	12
10-15	mean		9.3	23.4	40.1										34.3
	s.d.		5.6	9.2	9.7										12.0
	# samp		7	27	28										10
15-20	mean		13.0	21.9	40.0				6.0				19.0	16.0	56.0
	s.d.		7.2	9.2	10.5				0.0				0.0	0.0	0.0
	# samp		4	11	24				1				1	1	1
20-25	mean		12.2	23.3	48.2			33.0							
	s.d.		8.0	5.8	8.7			0.0							
	# samp		5	12	18			1							
25-30	mean		11.7	38.6	43.5									25.0	23.0
	s.d.		9.9	13.7	11.3									0.0	16.0
	# samp		6	5	15									1	2
30-35	mean		12.0	49.0	43.2								3.0		2.0
	s.d.		3.0	0.0	16.0								0.0		0.0
	# samp		2	1	15								1		1
35-40	mean		18.0	26.5	47.1								19.7		0.0
	s.d.		10.4	10.3	15.7								7.4		0.0
	# samp		4	6	13								3		1
40-45	mean		28.0	21.3	38.8								14.0		48.0
	s.d.		19.0	6.5	10.8								0.0		0.0
	# samp		6	4	16								1		1
45-50	mean		21.1	30.0	46.0								14.0		
	s.d.		13.2	14.0	11.8								0.0		
	# samp		7	2	11								1		

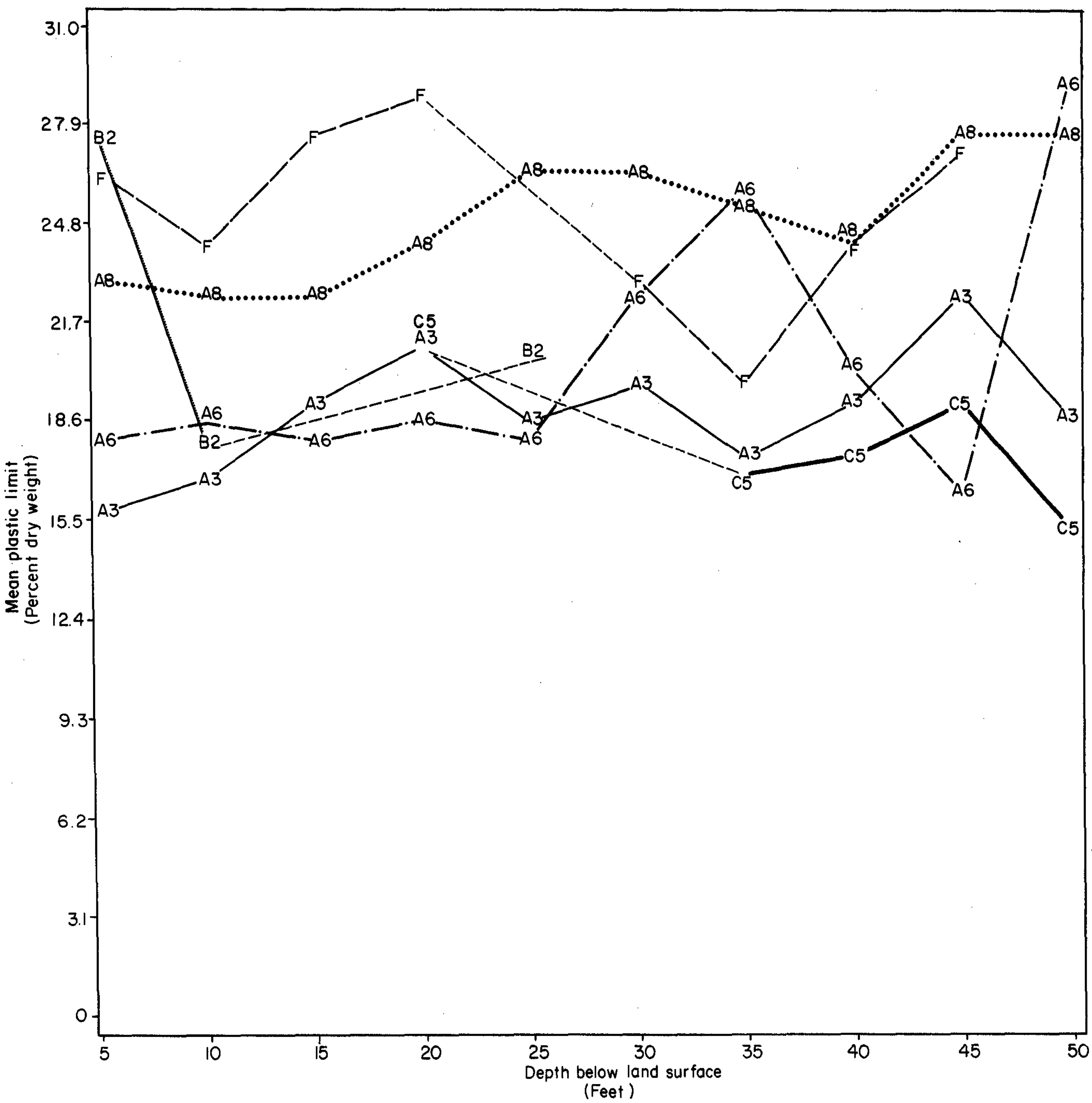

Figure 14. Curves showing variation of mean values of plastic limit tests with depth. Meaning of symbols: A3, Moderately permeable sand and silt; A6, Sandy mud; A8, Low permeability mud; B2, Low to moderate permeability mud and silt; C5, Tidal flats; and F(F1-5), Bay and estuarine bottom sediment.

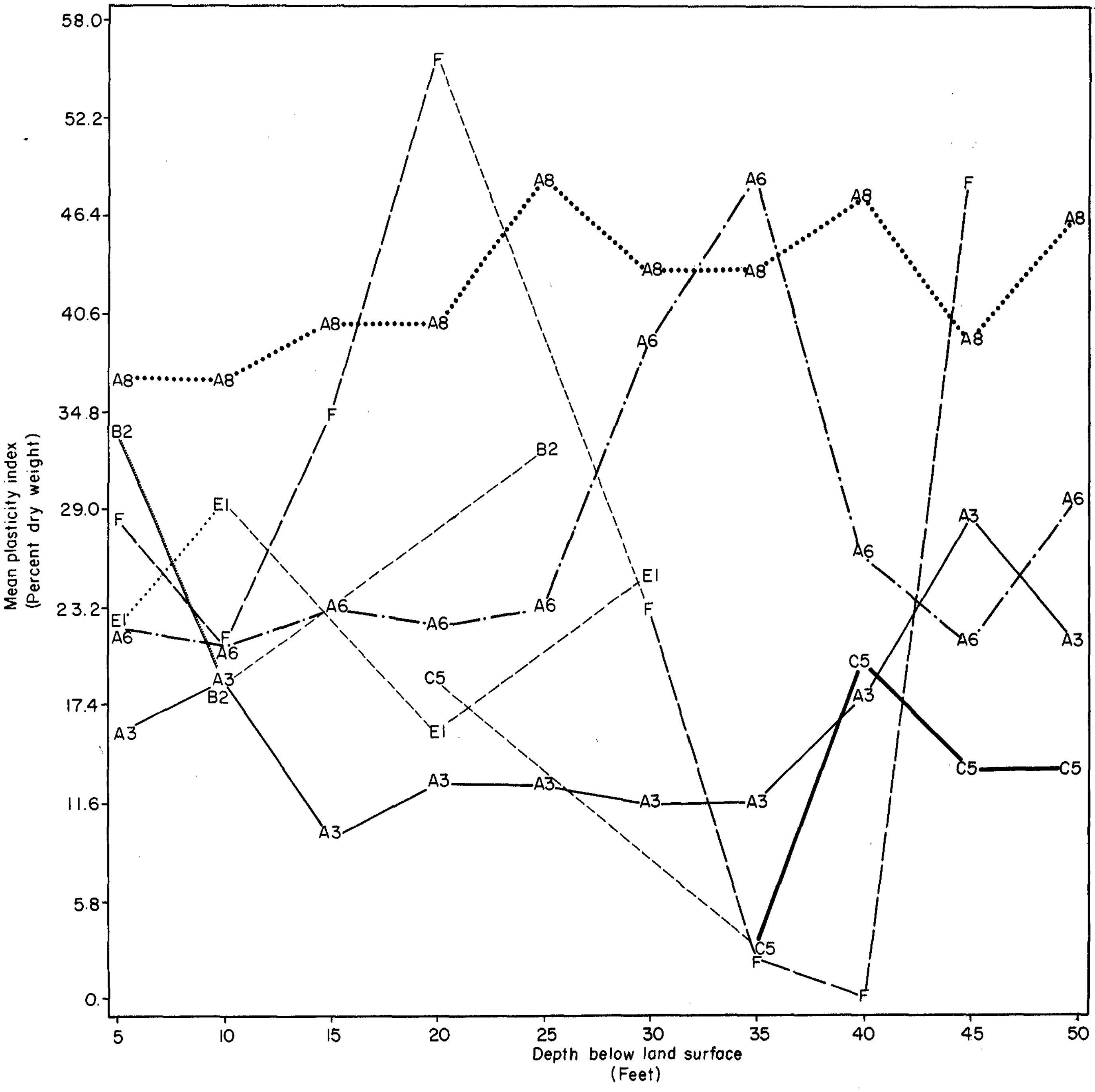

Figure 15. Curves showing variation of mean plasticity index with depth. Meaning of symbols: A3, Moderately permeable sand and silt; A6, Sandy mud; A8, Low permeability mud; B2, Low to moderate permeability mud and silt; C5, Tidal flats; E1, Made land and subaerial spoil; and F(F1-5), Bay and estuarine bottom sediment.

Table 15. Passing 200 mesh (percent of sample).

		Land and Water Capability Units													
Depth		A1	A3	A6	A8	A11	B1	B2	B3	B4	C2	C4	C5	E1	F1-5
0-5	mean	7.5	38.7	53.1	75.6	35.0	27.7						6.3	49.3	
	s.d.	1.5	12.7	9.4	4.8	5.0	12.2						3.3	23.4	
	# samp	4	11	27	8	2	10						6	8	
5-10	mean	18.0	33.5	55.8	76.1		28.0		23.0			4.0		18.0	75.0
	s.d.	8.8	15.1	14.1	9.5		11.0		0.0			0.0		0.0	0.0
	# samp	3	14	27	8		7		1			1		1	1
10-15	mean	11.7	30.1	60.6	74.4								17.0	36.7	63.8
	s.d.	2.9	18.0	21.7	11.6								9.0	23.1	14.7
	# samp	3	26	30	9								2	7	4
15-20	mean	6.0	19.8	54.9	74.2				42.0		2.0		57.0		
	s.d.	0.0	13.3	15.2	13.8				0.0		0.0		0.0		
	# samp	1	32	18	5				1		1		1		
20-25	mean	3.0	25.1	54.9	83.5							5.0			94.5
	s.d.	0.0	16.2	17.1	3.5							0.0			4.5
	# samp	1	22	8	2							1			2
25-30	mean	7.5	30.9	55.8	91.0		2.0				9.0				56.6
	s.d.	6.5	21.2	24.9	3.0		0.0				0.0				18.8
	# samp	4	12	9	2		1				1				5
30-35	mean		27.2	49.0											38.5
	s.d.		11.4	0.0											10.6
	# samp		6	1											4
35-40	mean		26.3	58.2	84.0						3.0		72.5		78.0
	s.d.		13.7	19.2	2.0						0.0		5.5		0.0
	# samp		8	5	2						1		2		1
40-45	mean		24.6	83.0	78.5							2.0	48.0		
	s.d.		13.2	0.0	2.5							0.0	1.0		
	# samp		5	1	2							1	2		
45-50	mean		13.0	36.0	72.5						40.0		44.0		67.0
	s.d.		4.9	0.0	19.5						0.0		0.0		13.4
	# samp		5	1	2						1		1		3

Table 16. Void ratio (volume of voids/volume of solids).

		Land and Water Capability Units													
Depth		A1	A3	A6	A8	A11	B1	B2	B3	B4	C2	C4	C5	E1	F1-5
0-5	mean														
	s.d.														
	# samp														
5-10	mean			0.6											
	s.d.			0.0											
	# samp			1											
10-15	mean			0.7	0.7										0.6
	s.d.			0.2	0.1										0.0
	# samp			2	3										1
15-20	mean		0.7	0.6	0.7										
	s.d.		0.0	0.2	0.1										
	# samp		1	2	3										
20-25	mean				0.8			0.7							
	s.d.				0.1			0.0							
	# samp				2			1							
25-30	mean				0.6										
	s.d.				0.0										
	# samp				2										
30-35	mean				0.8			0.8							
	s.d.				0.1			0.0							
	# samp				2			1							
35-40	mean			0.5	0.7										
	s.d.			0.0	0.0										
	# samp			1	1										
40-45	mean				0.7			0.7							
	s.d.				0.0			0.0							
	# samp				1			1							
45-50	mean				0.9										
	s.d.				0.0										
	# samp				1										

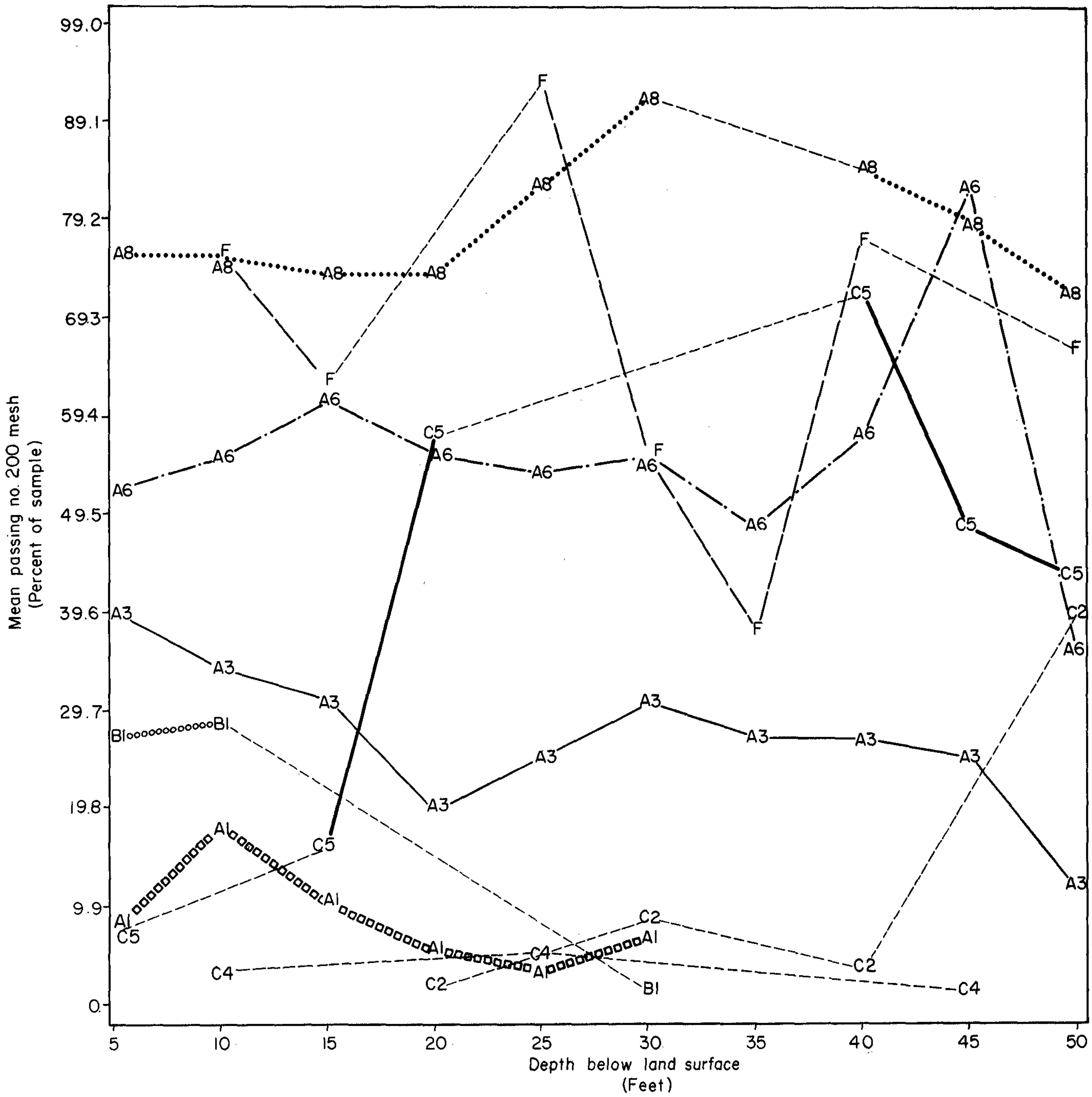

Figure 16. Curves showing the variation of mean values for the percentage of a sample passing through a 200 mesh screen with depth. Meaning of symbols: A1, Highly permeable recharge sand; A3, Moderately permeable sand and silt; A6, Sandy mud; A8, Low permeability mud; B1, Highly permeable sand and gravel; C2, Fore-island dunes and vegetation-stabilized barrier flats; C4, Storm washover area; C5, Tidal flats; and F(F1-5), Bay and estuarine bottom sediment.

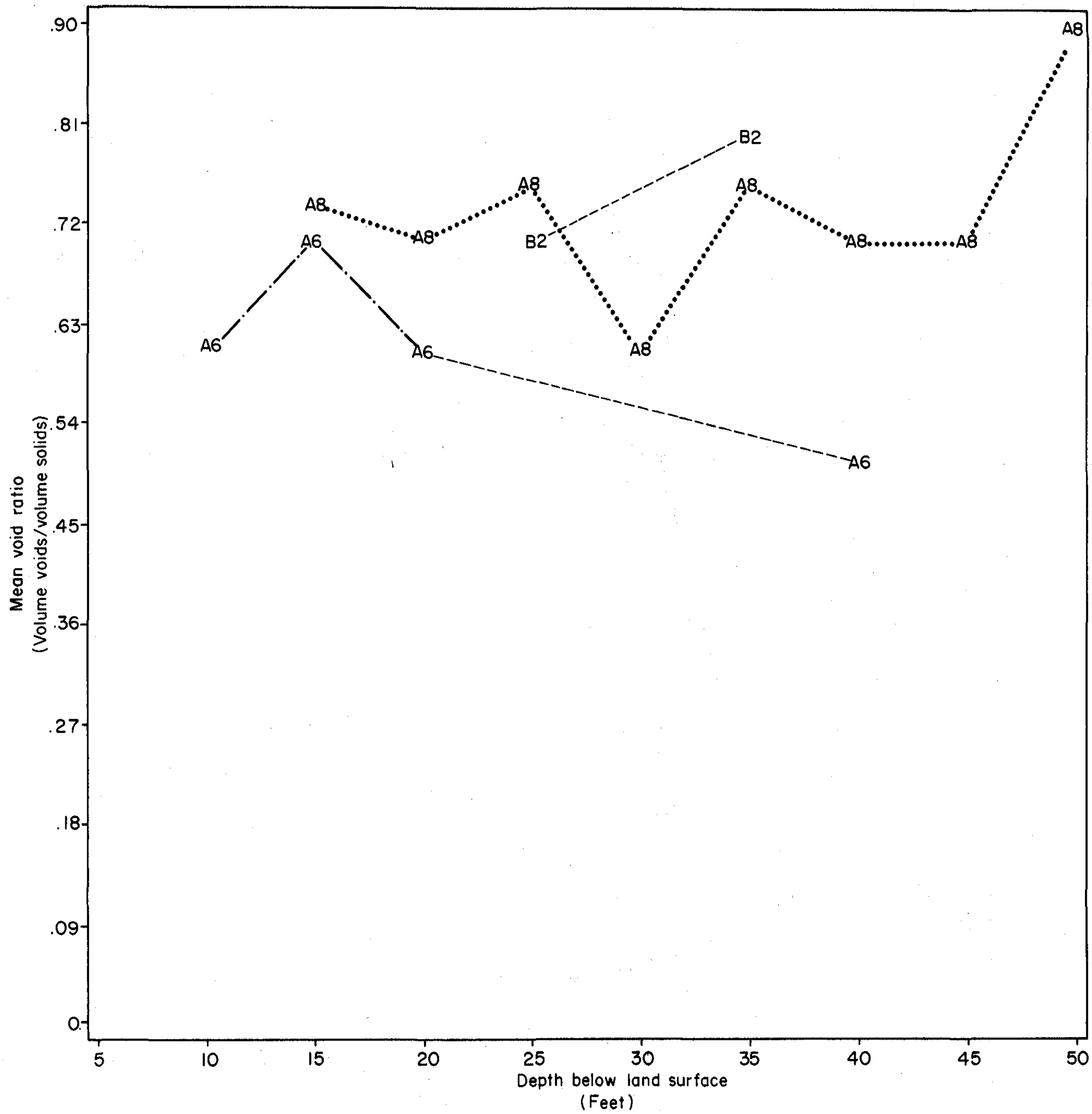

Figure 17. Curves showing the variation in mean void ratio with depth. Meaning of symbols: A6, Sandy mud; A8, Low permeability mud; and B2, Low to moderate permeability mud and silt.

Table 17. Mean values of all engineering test results for each capability unit from 0–5 feet of depth. Letter-number symbols correspond to unit symbols in table 1. Where blank, there are no data. Similar tables can easily be generated for the remaining 9 depth intervals.

	Capability units														
	A1	A2	A3	A6	A8	A11	B1	B2	B3	B4	C2	C4	C5	E1	F1-5
Unit dry weight (lb/cu ft)			107.3	106.9	97.2	112.0				101.0				104.5	98.0
Natural moisture content (% dry weight)	13.9		16.2	14.8	23.7	8.3				24.0				20.7	38.1
Standard penetrometer (blows/ft)	8.4		38.5	27.0							22.2	27.0	6.5	12.0	
THD cone penetrometer (blows/ft)				25.2	9.8									10.0	
Unconfined compression (q_u) (tons/sq ft)			3.5	2.7	3.5									1.6	
Triaxial shear (q_c) (tons/sq ft)				.7	1.0										
Triaxial phi (degrees)				29.4	29.0										
Hand penetrometer (tons/sq ft)				4.0	2.3									3.8	2.3
Linear dry shrinkage (% distance).			.8	7.5	17.7									9.4	
Liquid limit (% dry wt)			32.0	40.1	60.5		18.5	61.0						41.5	54.9
Plastic limit (% dry wt)			16.0	18.3	23.4		17.5	27.5						19.5	26.4
Plasticity index (% dry wt)			16.0	21.7	37.1		1.0	33.5						22.0	28.5
% sample passing 200 sieve	7.6	36.0	39.5	53.1	75.6	35.0	27.7				1.0		6.3	49.2	26.0

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APPENDIX

DESCRIPTION OF ENGINEERING TESTS*

Unit Dry Weight

The unit dry weight is the ratio of the oven-dried sample weight to the volume of the sample, expressed in pounds per cubic foot.

$$\text{U. D. W.} = \frac{\text{Dry weight of sample in pounds}}{\text{Volume of sample in cubic feet}}$$

Natural Moisture Content

The natural moisture content is the ratio of the weight of the water in the sample at the time it was removed from the ground to the oven-dried weight of the sample. The result is expressed as a percentage and is given by the following formula:

$$\text{N. M. C.} = \frac{\text{Weight of sample wet} - \text{Weight of sample dry}}{\text{Weight of sample dry}} \times 100$$

The natural moisture content will, of course, vary from place to place even in similar soils, and from time to time even where the same area is sampled repeatedly.

Atterberg Limits

Liquid Limit

The liquid limit (LL) is the maximum water content of a soil before it changes from the plastic to the liquid state; it is expressed as a percentage of the dry weight of the sample. The liquid limit is given by:

$$\text{LL} = \frac{\text{Weight of water in sample at liquid state}}{\text{Weight of oven-dried sample}} \times 100$$

Plastic Limit

The plastic limit (PL) is the minimum water content necessary for a soil to change from the solid to the plastic state. Soil is considered to be in the plastic state when it will rapidly and permanently deform without cracking. The plastic limit is expressed as a percentage of the dry weight of the sample.

$$\text{PL} = \frac{\text{Weight of water in sample at plastic state}}{\text{Weight of oven-dried sample}} \times 100$$

Plasticity Index

The plasticity index is a method of expressing the relative range of water content through which the soil will possess plasticity (being in a plastic state). The larger the value of the plasticity index of the soil, the smaller the range of resistance of that soil to remolding, and thus the greater the probability that the soil will be less desirable for construction. The plasticity index (PI) is stated as the numerical difference between the liquid limit and the plastic limit of a soil. The plasticity index is calculated by:

$$\text{PI} = \text{LL} - \text{PL}$$

Linear Drying Shrinkage

Linear drying shrinkage (LS) is the decrease in one dimension of the soil mass when the water content is reduced from the liquid limit to the shrinkage limit of the soil. The shrinkage limit is the maximum calculated water content at which further loss of water will not cause a decrease in the volume of the soil sample. Linear shrinkage is expressed as the percentage of shrinkage and is calculated by:

$$\text{LS} = \frac{\text{Length of wet soil bar} - \text{Length of dry soil bar}}{\text{Length of wet soil bar}} \times 100$$

OR

$$\text{LS} = \left[1 - \sqrt[3]{1 - \frac{\text{Volumetric shrinkage}}{100}}\right] \times 100$$

Triaxial Shear Test

A triaxial shear test is performed to determine the shear strength of material having a significant

*For additional information on these tests, refer to Terzaghi and Peck (1948).

sand content or lacking cohesion. The sample is subjected to confining pressure on all sides in addition to an axial load until the sample fails. The shearing strength is found by using Coulomb's equation:

$$s = c + p \tan \phi$$

where

s = Shearing strength expressed as either tons per square foot or pounds per square inch

c = Cohesion constant

p = Normal stress on the surface of sliding

ø =Angle of internal friction

and Mohr's diagram.

The values reported in this study are c, expressed in tons per square foot, and phi (ø), expressed in degrees.

Unconfined Compression Test

An unconfined compression test is used to determine the shear strength of materials with significant clay content. The test is performed by increasing the axial load to failure and is run sufficiently fast to prevent significant drainage or consolidation. The axial stress at failure is the unconfined compressive strength (q_u). The shear strength (C_q) is found by:

$$C_q = \tfrac{1}{2} q_u$$

Results are reported in tons per square foot.

Pocket or Hand Penetrometer

The pocket penetrometer is a direct-reading, hand-held, calibrated spring-loaded penetrometer. It is pushed with steady vertical pressure into the soil surface until the piston needle reaches the calibration groove (approximately ¼ inch). The readings are unconfined compression strength values and are accurate to approximately ±20% of the reading, up to a maximum of 4.5 tons per square foot.

Standard Penetrometer

The standard penetrometer test is the total number of blows a 140-pound hammer falling 30 inches takes to drive a split-spoon sampler one foot or to refusal. Refusal is defined as either penetration of less than one foot per 100 blows or penetration of less than six inches per 50 blows. The values are expressed as blows per foot for values less than refusal and inches per 50 or 100 blows for values greater than refusal.

THD Cone Penetrometer

The THD (Texas Highway Department) cone penetrometer test consists of driving a 3-inch diameter cone with a 170-pound hammer dropped from a height of two feet. Values are expressed either as blows per foot (up to 100 blows) or as inches per 100 blows for the same reasons as described above.

Passing 200 Mesh

The passing 200 mesh test is a grain size determination of the amount of clay and silt present in the sample. For particles to pass the no. 200 sieve, two dimensions of the grain must be smaller than 0.074 millimeters. The value is expressed as the percentage of the total sample and is given by:

$$\text{Pass 200} = 100 - \frac{\text{Dry weight of sample wash}}{\text{Dry weight before sample washing}}$$

Void Ratio

The void ratio is the ratio of the volume of voids (nonsolid material) to the volume of solid material. It is a dimensionless number.

$$e = \frac{\text{Total volume of voids}}{\text{Total volume of the sample - Total volume of the voids}}$$

COASTAL ZONE SHORELINE CHANGES: A FUNCTION OF NATURAL PROCESSES AND MAN'S ACTIVITIES

J. H. McGowen

INTRODUCTION

In recent years the Texas Gulf shoreline has become the site of increasingly rapid development. The main thrust has been the construction of second homes, condominiums and hotels. Not fully appreciated is the fact that 60 percent of the Texas Gulf shoreline is erosional, with rates up to 80 feet per year locally. The principal cause of erosion is natural, and certain of man's activities, although not the cause, have served to accelerate erosion. Such natural conditions as sand deficit and subsidence pose problems not easily rectified by artificial construction. Therefore, it is imperative that rates and directions of shoreline change be quantified and that man's developments proceed in concert with the effects of these natural changes.

The Matagorda Bay area was selected as a model for developing techniques of historical shoreline monitoring. A program was developed which permitted quantification of shoreline change. This area was selected because it is a segment of the Texas Coast that has been least affected by man's activities.

GEOLOGIC SETTING AND MODEL

The model area is low lying (fig. 1). Maximum elevations along mainland shoreline are erosional escarpments (wave-cut cliffs) cut into fluvial-deltaic deposits. Along Gulf shorelines, dunes form the highest points. Dunes are generally low and discontinuous from A to B, but fore-island dunes can attain heights up to 25 feet above mean sea level (fig. 1, B–C). Width of the barrier island and peninsula ranges from about 0.5 mile at the east to about 1.5 miles at the west of the area. The eastern bay is elongate parallel to the Gulf shoreline, and is shallow with maximum depth of about 4 feet. Between B and D, the bay is elongate parallel to the shoreline; here depths are up to 12 feet. The remaining bay system is elongate to the northeast. Water depth decreases generally toward the northwest from 13 feet to 1 or 2 feet.

Three principal streams (fig. 1, E, F, G) discharge into the bay system, the largest of which has constructed a delta dividing the bay into two segments. Discharge from this river is divided between the western bay and the Gulf of Mexico.

Marshes occupy low-lying areas along the mainland shoreline and the bayside of barrier islands and peninsulas. Major marsh areas of the mainland shore are directly related to major fluvial systems that discharge into the bay system. Delta plains are inhabited by marshes (fig. 1, D, H, I).

Grassflats occur in many areas but are best developed west of the Colorado Delta. Here, water depths are a few inches to about four feet, and the substrate is characteristically sand and muddy sand. Oyster reefs once flourished in several areas of this bay complex. Some reefs have been overrun by the Colorado Delta, covered with spoil, and removed by shell dredgers. There are also numerous oyster clumps in shallow water; most are dead.

Water exchange between the Gulf and bay system takes place through three natural passes and two man-made passes (fig. 1, A, J, B, K, L). Tidal exchange in the western part of the bay has been modified considerably by dredging within the bay system and by the dredging of a ship channel in 1965 (Harwood, 1973).

The model lies in the climatic division having precipitation that is greatest in the summer (Carr, 1967). Average annual rainfall ranges from 38 to 43 inches (fig. 2). Drainage basins of two major rivers, which affect sediment-water budgets in the model, have average annual rainfall ranging from about 44 inches at the Gulf to about 33 inches inland and 40 inches at the coast to about 32 inches inland, respectively.

HISTORICAL MONITORING

Evidence for migration of Gulf and mainland shorelines results from historical monitoring for the period 1856 through 1957. The procedure for historical monitoring is to collect and compare maps and charts of the area which have been compiled on a controlled base. These maps and charts, to be usable, must cover the entire study area. Materials used in the Matagorda Bay study are: (1) coastal charts (1856–1859); (2) photomosaics (1934–1937); (3) topographic maps (1946–1947); (4) stereo pairs of aerial photographs (1952); and (5) photomosaics (1956–1957).

The photomosaics and topographic maps were at a scale of 1:24,000; coastal charts were adjusted

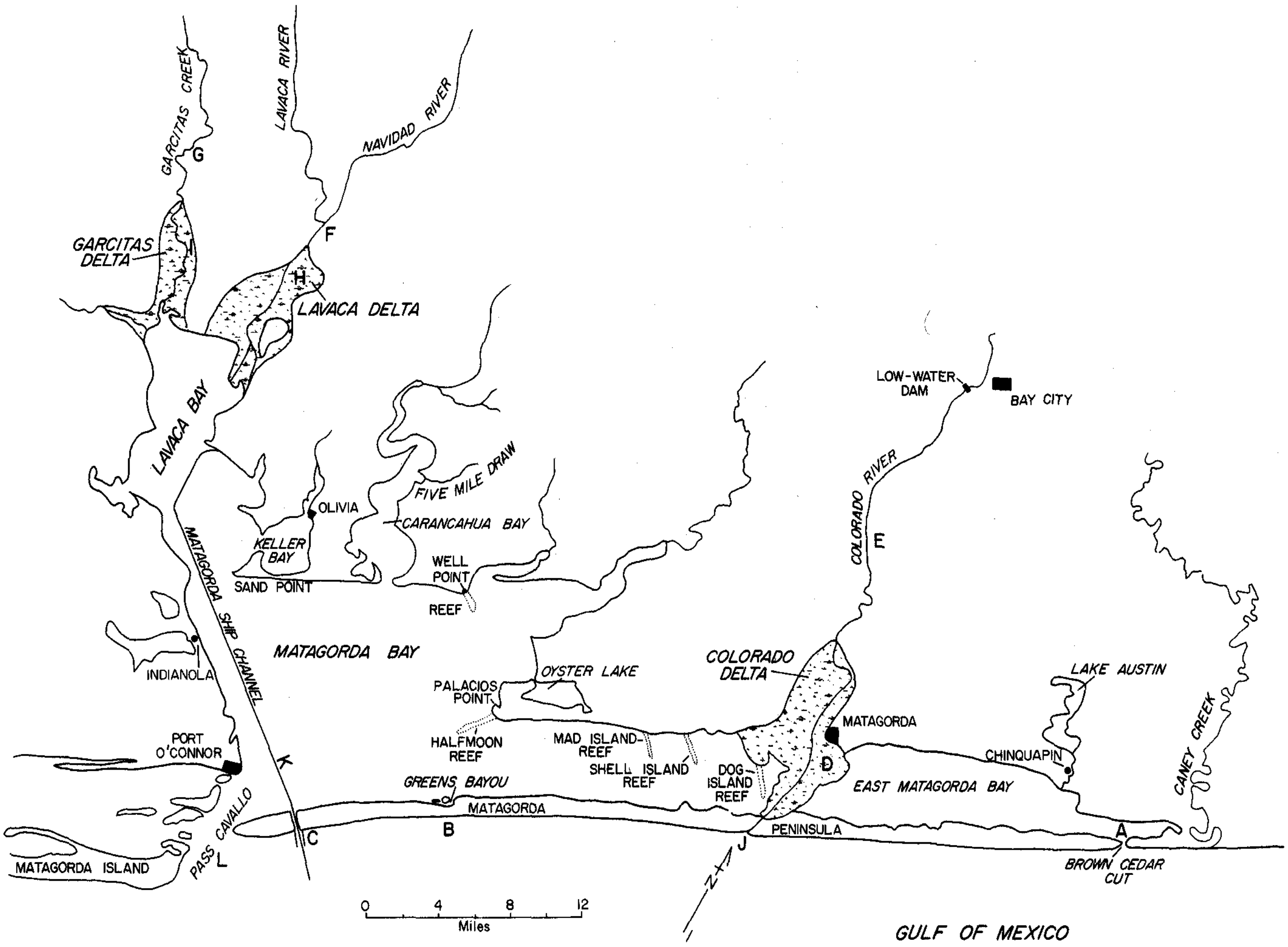

Figure 1. Locality map of the Matagorda Bay area. Some geographic areas and specific man-made and natural depositional features are referred to in the text by letter designation: (A) Brown Cedar Cut, (B) Greens Bayou, (C) Matagorda Ship Channel Jetties, (D) Colorado Delta, (E) Colorado River, (F) Lavaca-Navidad River, (G) Garcitas Creek, (H) Lavaca Delta, (I) Garcitas Delta, (J) Mouth of Colorado River, (K) Matagorda Ship Channel, and (L) Pass Cavallo.

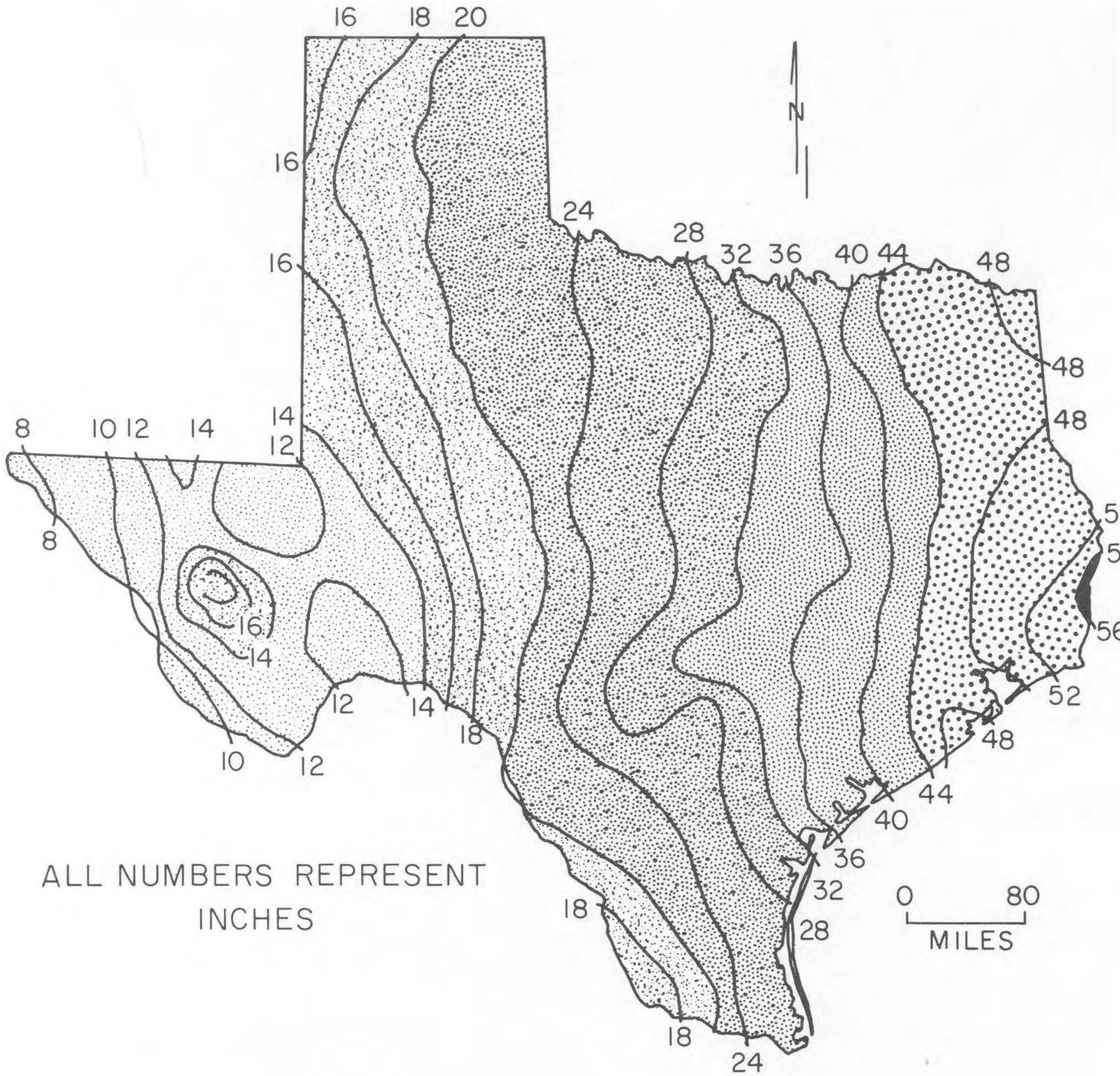

Figure 2. Regional distribution of precipitation in Texas (after Carr, 1967).

photographically to the same scale. Stereo pairs were at a scale of 1:10,000 and were not reduced. Shorelines were mapped for the years 1856 through 1957 on each vintage chart and photograph. These shorelines were then transferred, cartographically, onto a common base at a scale of 1:24,000. The shoreline on the coastal charts and topographic maps were already mapped and shorelines on photos were mapped in the office.

There are inherent errors in the historical shoreline monitoring procedure. It is not always possible to determine exactly the time of day when the aerial photos were flown, and therefore tidal stage (rising or falling) is not known. If the time of the flight were known precisely, water height along the beach could be calculated from the Tide Tables. However, the calculated water height and observed water height may be different, because astronomical tides alone do not determine water height. Barometric pressure and wind direction, speed, and duration often produce changes in water height that exceed the effect of astronomical tide. Another possible source of error results from improper mapping of the beach. Photomapping is based on judgment of the mapper. It is necessary that the person who does the mapping be familiar with the area, that he has seen it on the ground, that he be familiar with coastal processes and environments, and that he be aware of man's activities in the area.

Judgment errors are most likely to occur along mainland shorelines. For example, submerged spoil outwash has been interpreted (from aerial photographs) and mapped as emergent areas. Northers lower water level along northern shorelines and often extensive sandflats become exposed; these have been interpreted (from aerial photographs) and mapped as broad sand beaches. Such errors can be avoided.

Recorded shoreline erosions for the period 1856–1957 in the Brown Cedar Cut (A) area and eastern Matagorda Island were 1,600 and 2,100 feet, respectively (figs. 3, 4). These changes cannot be discounted on the grounds that tidal waters could have been at ebb during the 1856 measurement and at flood during the 1957 measurement. Admittedly, such fluctuations have a bearing on shoreline measurements, but not of the magnitude just mentioned.

Profiles were run along both Gulf and mainland shorelines (winter 1970 through spring 1972), and slopes of the forebeach were measured. Minimum slope of the forebeach was 1 degree, and maximum slope was 7 degrees. Slopes of 2, 3, and 4.5 degrees are the dominant slopes, and 55 percent of all beaches measured fall within this range (fig. 5). To demonstrate that tidal fluctuations cannot possibly be mistaken for legitimate shoreline changes in the time interval 1856–1957, the following short table is presented (table 1). This table shows (1) slope in degrees of the beaches between Caney Creek and Pass Cavallo (L) (fig. 1), (2) horizontal distance of tide movement across these beaches (tidal range of 2.0 feet), and (3) maximum and minimum beach slopes, and dominant slopes (2, 3, and 4.5 degrees). On beaches with a slope of 1 degree, the tide has the greatest inundation. The steepest beaches are not noticeably affected. Beaches having slopes between 2 and 4.5 degrees have a band from 60 to 25 feet wide which is bathed by 2-foot tides. All of these distances are considerably less than the 100-year change in the Gulf shoreline.

Table 1. Matagorda Peninsula forebeach slopes, and the horizontal distance affected by astronomical tide.

Beach Slope (degrees)	Horizontal Distance Between High and Low Tide, (feet)
1 (minimum slope)	130
7 (maximum slope)	17
2	60
3	42
4.5	25

Historical monitoring indicates that most of the Gulf and mainland shorelines in the Matagorda Bay area are in an erosional condition, and that erosion had been the trend for the time interval 1856–1957. In order to make the shoreline study current, data were needed for the interval 1957–1972. These data were provided by making field measurements. Measurements were made, using alidade and stadia rod, from water level (along both Gulf and mainland shorelines) to known geographic points. This distance was then compared with those same distances as they existed in 1957. Differences between the 1957 and 1972 distances revealed the magnitude and direction of shoreline change since 1956.

The five vintages of Gulf and mainland shorelines were compiled on a 1:24,000 base because it was found that at this scale changes as small as 40 feet could be measured. Each shoreline was coded in order to distinguish it from the other shorelines. Measurement of distances between the oldest and

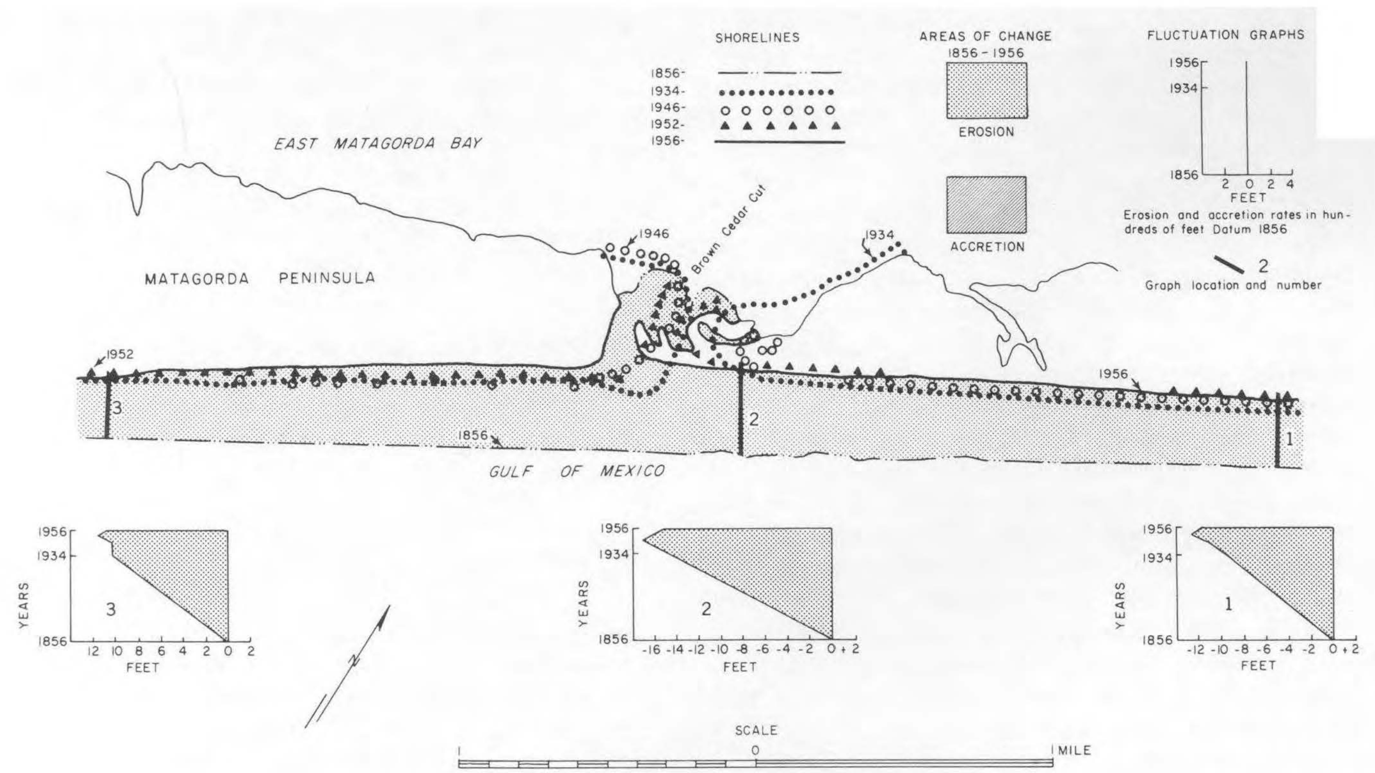

Figure 3. Historical change in the Gulf shoreline of Matagorda Peninsula in the area of Brown Cedar Cut. This shoreline segment was chiefly erosional during the interval 1856–1956. At station 1, the shoreline eroded approximately 1,200 feet, at station 2 about 1,600 feet, and at station 3 about 1,100 feet. This shoreline segment retreated approximately 1,300 feet over the 100-year time span. Yearly average erosional rate is 13 feet.

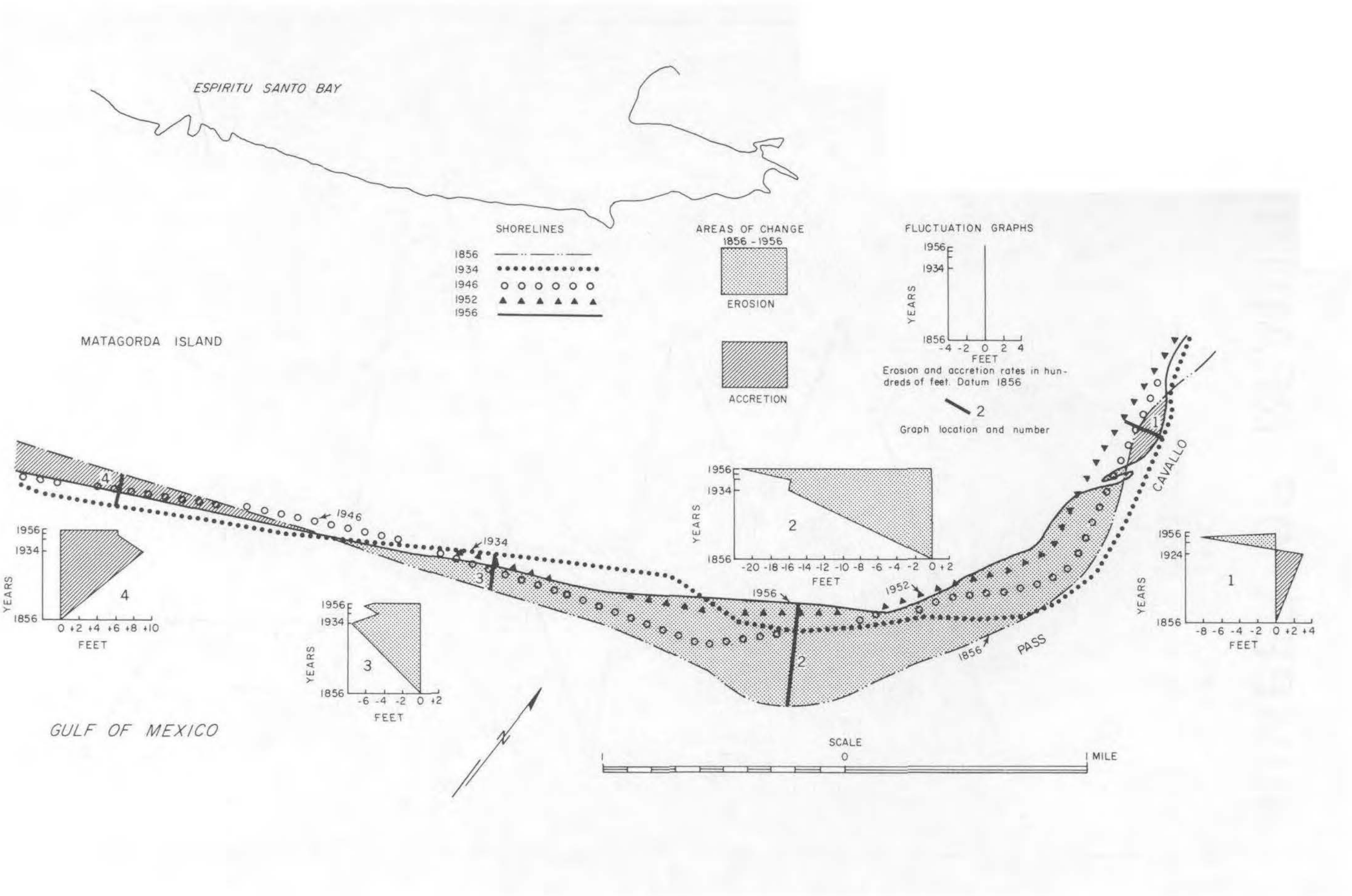

Figure 4. Historical change in the Gulf shoreline of Matagorda Island in the area of Pass Cavallo. The segment shown here was primarily erosional for the time interval 1856–1956. Station 1 was accretionary from 1856–1934, erosional from 1934–1952, and accretionary from 1952–1956. Stations 2 and 3 were erosional with maximum shoreline retreat of 2,200 feet at station 2. Net accretion occurred at station 4 since 1856, although the trend was erosional from 1934–1952, and equilibratory from 1952–1956.

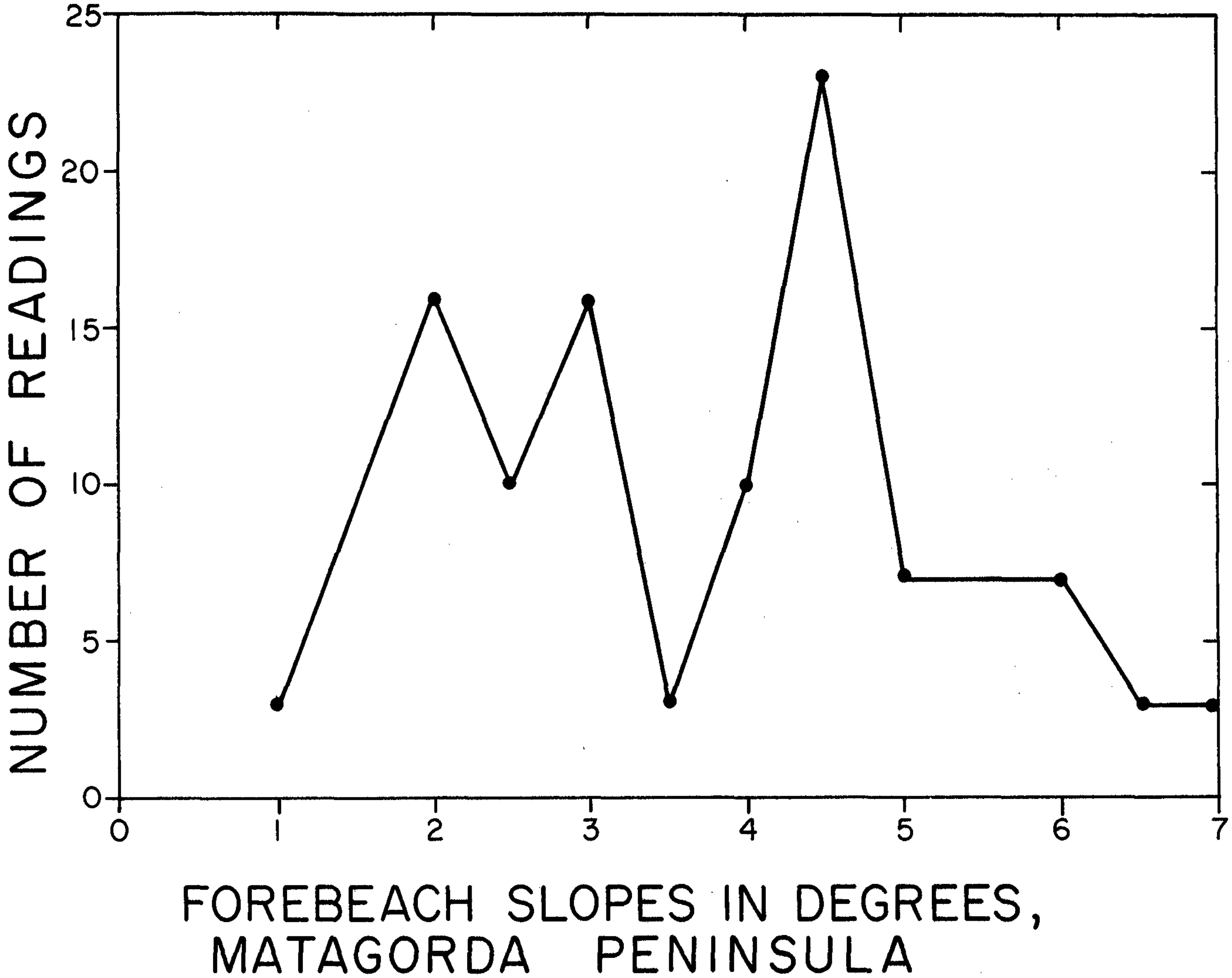

Figure 5. Slope, in degrees, of forebeaches of Matagorda Peninsula. Measurements were made in the area between Caney Creek and Pass Cavallo. Fore-beach slopes are greatest where shell is dominant and least where terrigenous sand is dominant.

youngest shorelines is adequate to show long-term shoreline trends. Intermediate shorelines may not all show the same trend (erosion or accretion). To aid in reading the shoreline map, graphs were made at selected intervals along the shoreline (see figs. 3 and 4). The 1856 shoreline serves as the base line for these graphs. Even though a shoreline segment may have an overall erosional trend, it may display short-term accretionary trends; these trends will be depicted by the graphs.

Long-term erosional and accretionary shorelines are highlighted on the maps by patterns, stippled for erosional shorelines and lined for accretionary shorelines (fig. 3). Width of the patterns is indicative of the amount of erosion or accretion that a particular shoreline segment has experienced. Changes can be determined by measuring distances between the coded, vintage shorelines. Rate and direction of shoreline change should be carefully considered in planning man's developments.

COASTAL PROCESSES

In addition to long-term changes, many short-term changes in shoreline position related to ongoing coastal processes are relevant. Processes that construct and modify shorelines include astronomical and wind tides, longshore currents, normal wind and waves, storms and hurricanes, river transport of sediment and water, gravity sliding along cliff faces, and biological activity. Wind-regime effects, raising or lowering water level along both Gulf and mainland shorelines, and the generation of waves and longshore currents are described by Price (1954), Hayes (1965, 1967), Watson (1968), Watson and Behrens (1970), McGowen (1971, 1974), and Scott and others (1969). McGowen and others (1970) have shown the importance of hurricanes as geological agents. Rivers make significant contributions to the coastal-sand budget. Animals and plants make deposits, trap or bind sediment, and mix or stir sediments. Only a few processes are emphasized in the following discussion to illustrate the interaction of coastal processes and land use.

Short-term shoreline changes, those occurring in days, weeks, or months, may require constant monitoring. In a brief time frame it is not economical to collect repetitive aerial photography, and standard topographic maps are updated infrequently. Therefore, measurements of accelerated progradation or accretion and retrogradation or erosion become field operations. At intervals of either equal timespread or during irregular climatic events, areas of deposition or erosion are measured and located on a map. Profiles transverse to the shoreline are measured. Boreholes are dug and logged in critical areas. Surface and bottom samples are collected and examined. Aspects of active processes are observed and related to field measurements. All these data and interpretations can be related to the historical monitoring. Results of the investigations of short-term phenomena are important in view of man's development, which may be short-lived also.

Wind

Wind effects are obvious along barrier islands and peninsulas that have a plentiful supply of sand-sized material. Prevailing wind is from the southeast quadrant ten months of the year in a general landward direction (fig. 6). In winter, as many as 16 to 20 storms occur with strong north winds (Hayes, 1965). Wind effect is expressed by low coppice mounds and small wind-shadow dunes on the back-beach and fore-island dunes behind the Gulf beach. The wind also creates waves whose dominant direction of movement is onshore; it causes a change in water level along both Gulf and bay shorelines.

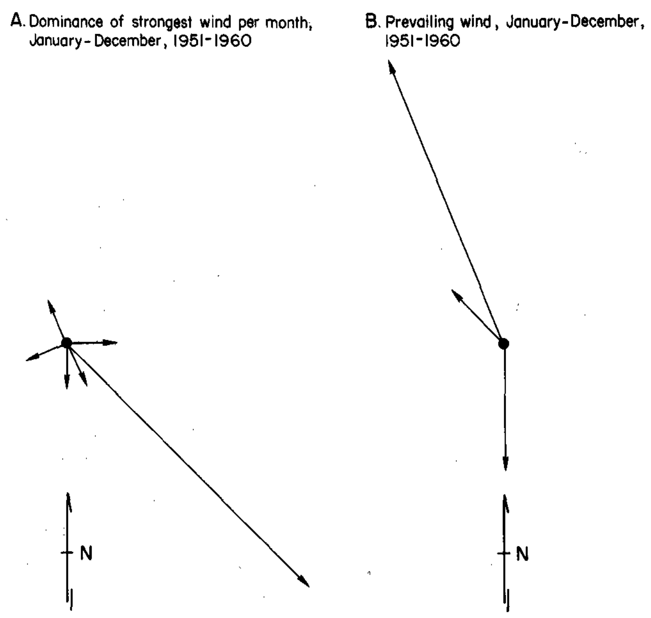

Figure 6. Strongest winds and prevailing winds, Victoria, Texas (data from Orton, 1969).

Waves

Waves that most affect the Gulf shoreline are directed onshore by prevailing southeast winds. Sediment movement in the area from Mean High Water offshore to a water depth of about 40 feet bears directly on the stability of Gulf shorelines. Onshore waves generate currents that move sand landward and waves moving at a high angle to, or parallel with, the shoreline transport sand away from a particular shoreline segment.

East and southeast waves create longshore currents that move sand to the southwest, and south and southwest waves generate longshore currents that move sand to the northeast. When east and southwest waves are compared (fig. 7) for any given water depth and wave height, waves approaching from the east occur more frequently than those from the southwest. When southeast and south waves are compared, the frequency of occurrence of southeast waves exceeds the frequency of those from the south (fig. 8). Waves which produce westward-moving longshore currents exceed by two months those which produce eastward longshore drift. Wave data and direction of spit accretion closely agree. Waves produced by north winds move away from the Gulf shoreline, consequently their effect on shoreline stability or sediment transport is of little importance. However, northers generate waves that erode bay shorelines and generate currents that transport sediment along bay margins.

Wind Tides

Meteorological conditions superimpose fluctuations of water level upon astronomical tides. Wind blowing across the Gulf of Mexico and the bay system not only creates waves but it also causes a change in water level along both the Gulf and the bay shoreline. Change in water level produced by the wind is known as wind tide. Since astronomical tides are low in the bays, maximum inundation is provided by wind tides.

Northers lower water level along the mainland shoreline and raise it on the back side of barrier islands and peninsulas. Raising of water level on the bayside of barriers generally coincides with the relatively inactive season for marsh plants. Marsh distribution is not affected as much by northers as by wind tides produced by prevailing southeast wind. A large part of the area on the bayside of barrier islands and peninsulas that is affected by wind tides is virtually barren. These barren areas are termed wind-tidal flats and they lie between the salt marsh (on the bayside) and the vegetated barrier flat toward the Gulf of Mexico (fig. 9).

Astronomical Tides

Tides in the Gulf of Mexico are chiefly diurnal (one high water and one low water tide per day). Along the Texas Gulf Coast they range from about 1.5 to 2.0 feet (U. S. Dept. Commerce, 1973a). Tidal effects are most pronounced in tidal-pass areas. Here currents attain velocities up to four knots in 8 to 30 feet of water as a consequence of tidal exchange between bays, lagoons, and the Gulf of Mexico (U. S. Dept. Commerce, 1973b). Sediment, in suspension and as bedload, moves through these passes. Part of the sediment load is deposited in the bays and lagoons as flood-tidal deltas (fig. 10).

Hurricanes and Tropical Storms

A spectacular geologic agent in the Gulf Coast is a hurricane which initiates a complex of processes. During hurricane approach, landfall, and inland movement, conditions along the coast are drastically changed and rather violent conditions may exist for a few hours to a few days. Associated with hurricanes are (1) a barometric low that causes a rise in water level along the Gulf and mainland shorelines, (2) a strong wind that changes direction as the storm approaches, makes landfall, and passes inland, (3) large waves that break higher on Gulf and mainland shorelines than waves associated with normal sea conditions, and (4) heavy rainfall (McGowen and others, 1970).

Storm approach is marked by rising tides and increased wind velocities (fig. 11). When the storm strikes the coast, it (1) erodes beaches and dunes, (2) transports sediment from offshore toward barriers and peninsulas, and (3) locally breaches barriers and peninsulas. Sediment eroded from the shoreface, beaches, and dunes is transported through storm channels and spread over vegetated flats and into the bays as washover deposits. Cliffed shorelines of the bays are eroded and storm berms develop locally atop these cliffs. At *landfall* (fig. 11) current and wave direction change, and water and sediment are flushed from the bays.

Highest intensity winds are felt as the storm comes ashore. Heavy rains that accompany hurricanes may produce floods which inundate low-lying areas along stream courses and bay margins. After the storm passes from the coastal

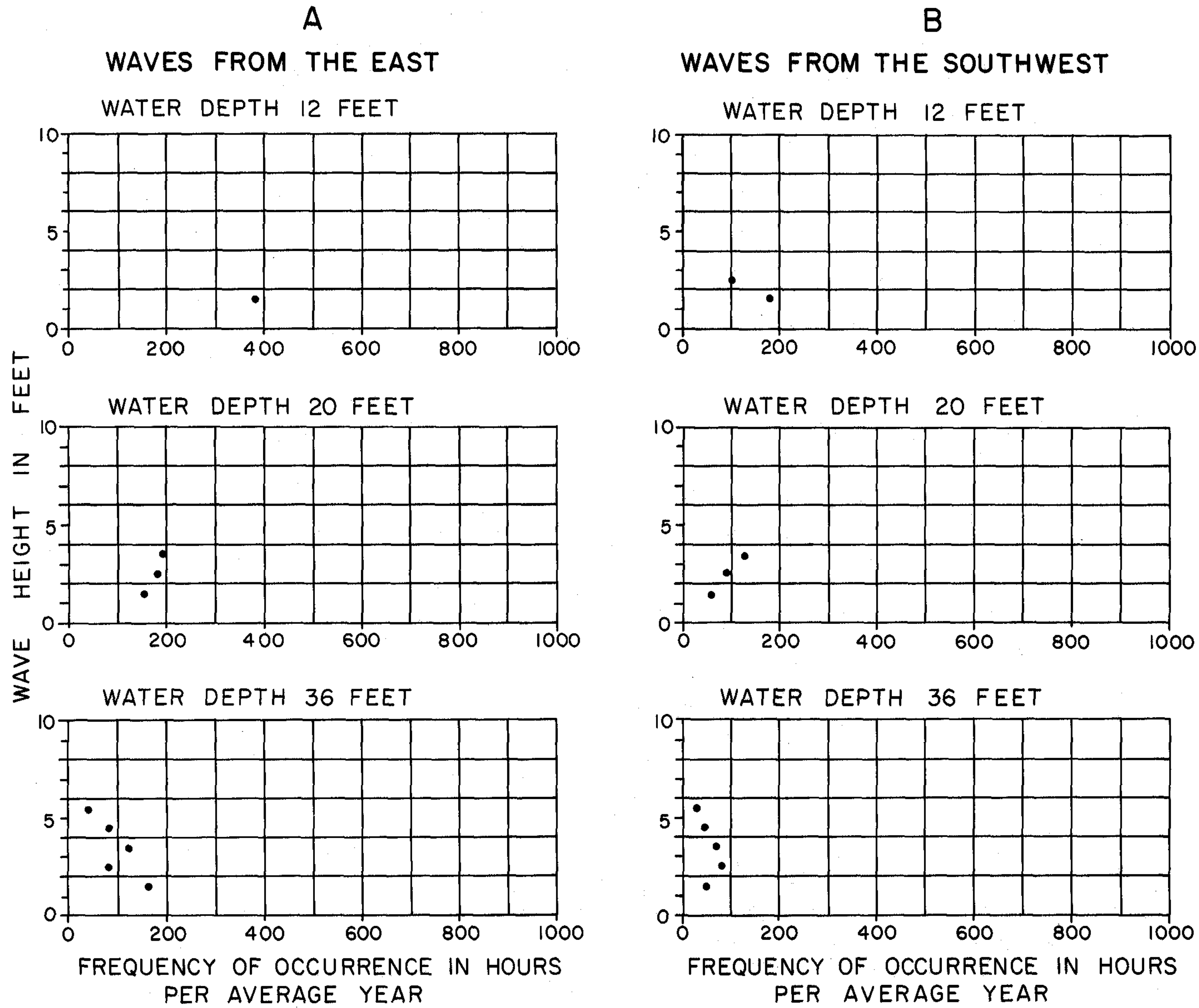

Figure 7. Wave data from the Caplen, Texas station (after Bretschneider and Gaul, 1956). Wave approach from the east and southwest.

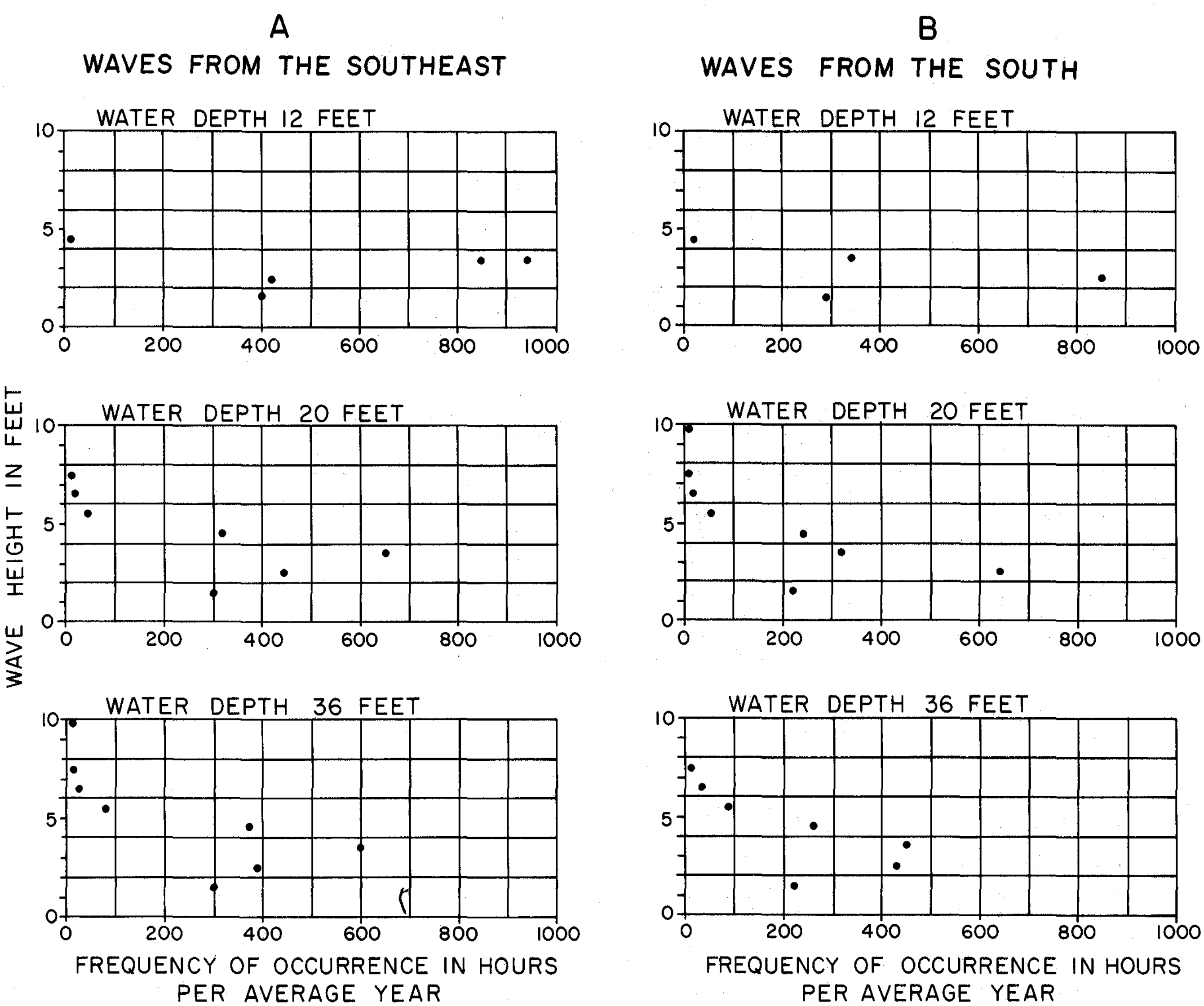

Figure 8. Wave data from the Caplen, Texas station (after Bretschneider and Gaul, 1956). Wave approach from the southeast and south.

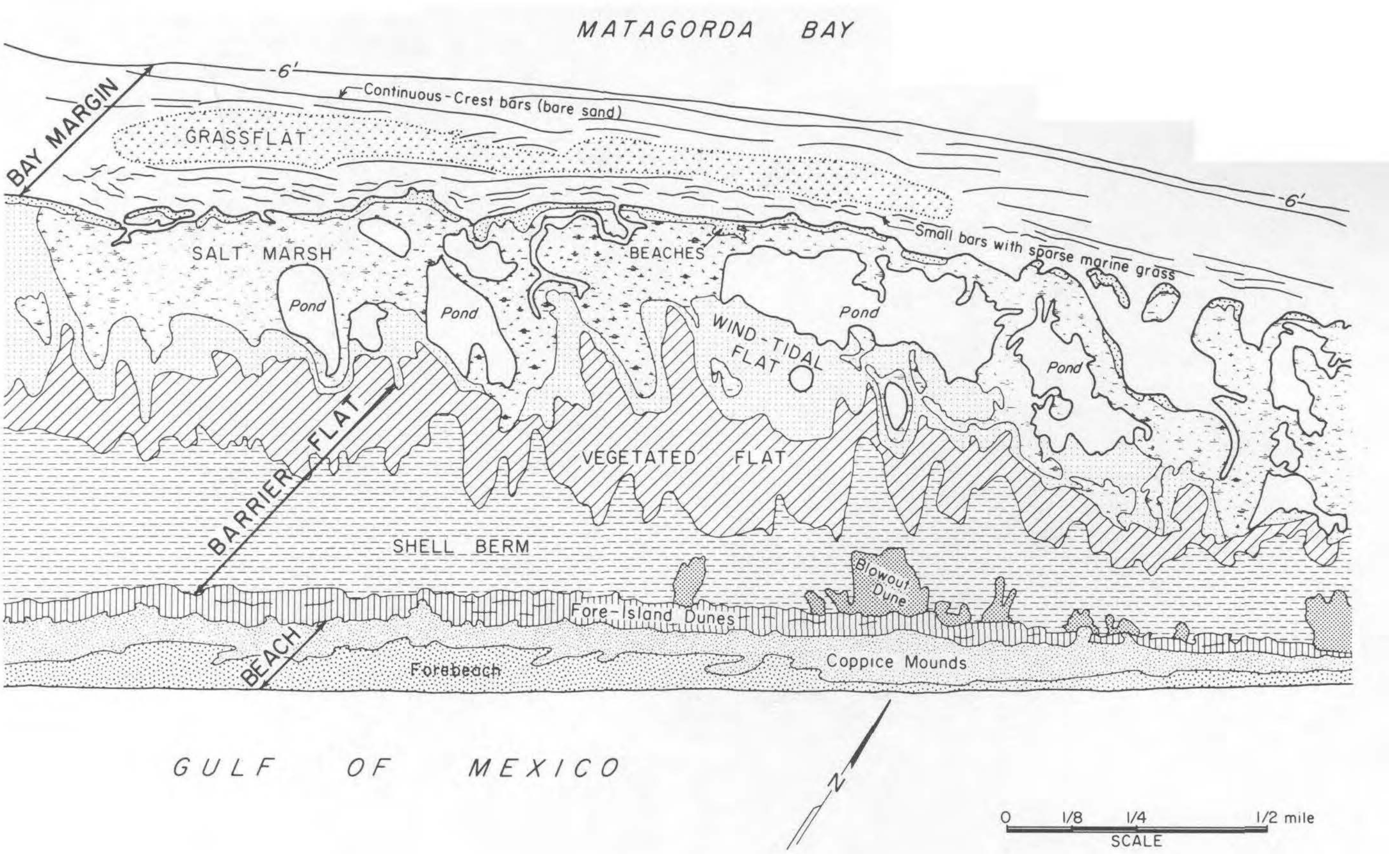

Figure 9. Depositional environments of a segment of Matagorda Peninsula beginning 1.5 miles west of Greens Bayou (see fig. 1, B). Mapping derived from USDA photography (May 1952).

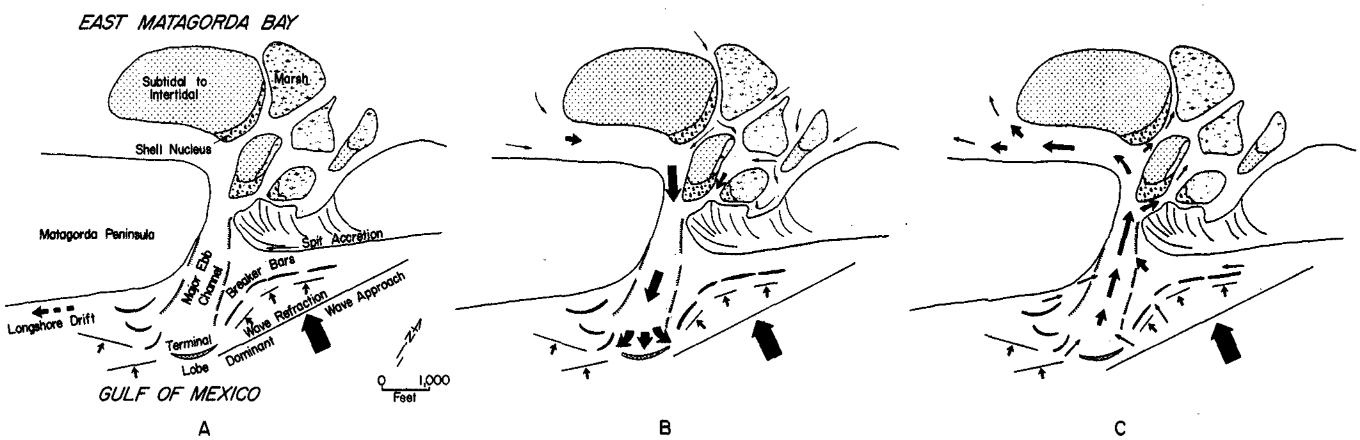

Figure 10. Generalized tidal delta, Matagorda Bay area. (A) Depositional features associated with tidal deltas (nomenclature after Hayes, 1973). Ebb delta is, for the most part, entirely inundated. Ebb features are the major ebb channel and terminal lobe. Flood delta consists of shell nuclei, marsh islands, and subtidal to intertidal sandflats. (B) Water movement during ebb tide. Widths of arrows indicate relative current strength. (C) Water movement during flood tide.

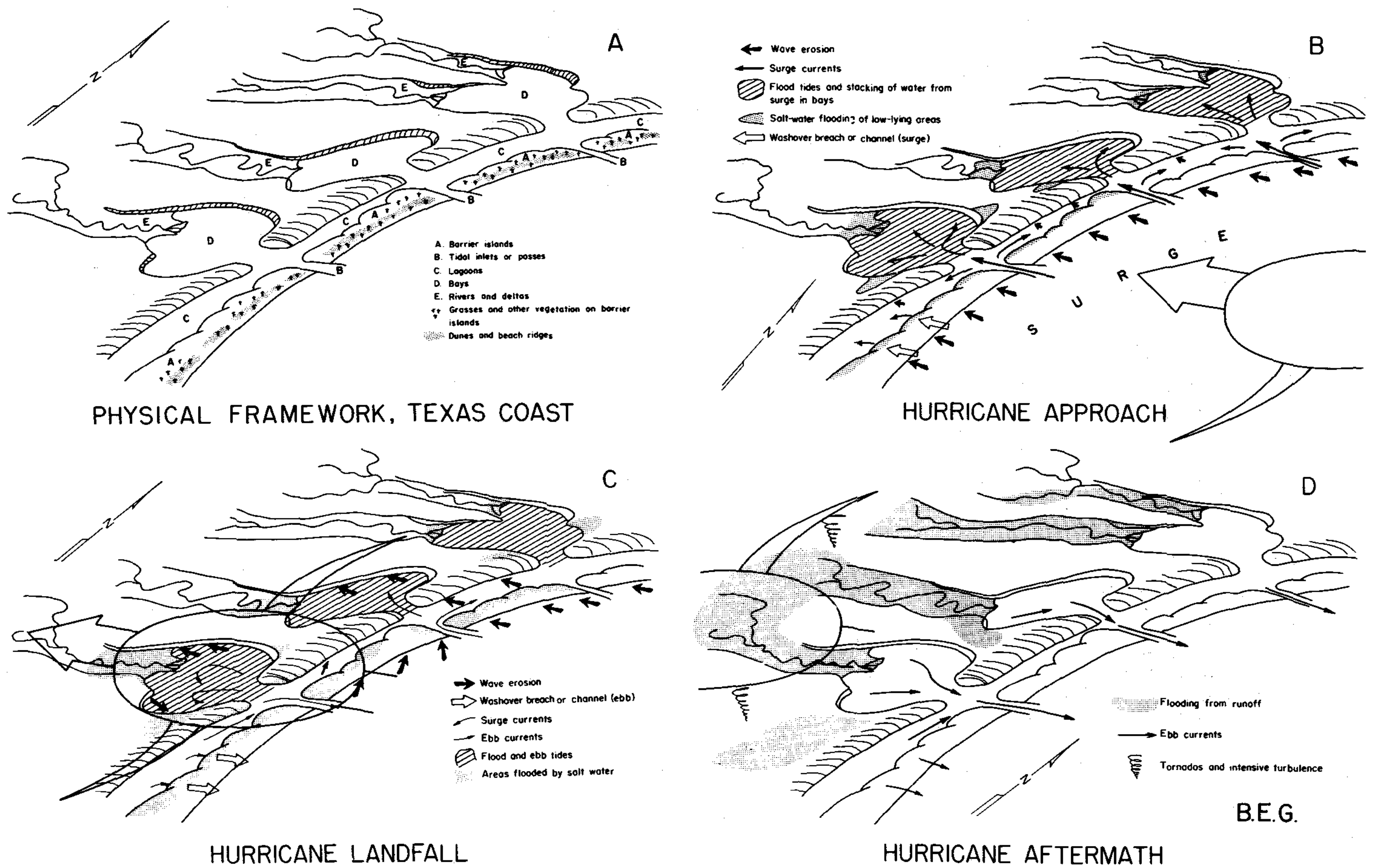

Figure 11. Schematic model of hurricane effects on the Texas coastline. (A) Physical features characterizing Texas Coast. (B) Effect of approaching hurricanes. (C) Effect of hurricanes upon impact with the coast. (D) Aftermath effects of hurricanes (after McGowen and others, 1970).

area *(hurricane aftermath),* longshore currents construct bars that close the mouths of hurricane channels, and waves restore the normal beach profile (fig. 11).

The most spectacular geological effect produced by hurricanes is erosion by breaking waves. Waves may grow to 40 or 50 feet when a storm extends over a large area (Bigelow and Edmondson, 1947). Barrier-island and peninsula morphology determine the extent of shoreface, beach, and dune erosion (McGowen and Scott, 1973). Fore-island dunes afford protection from storm surge and waves only to the area immediately behind them. Fore-island dunes in the immediate area of the Colorado River (fig. 1, J) are 9 to 12 feet above mean sea level; they may be overtopped by large hurricanes such as Carla (1961).

Large hurricanes wash over all but about eight miles of the model area. Hurricane Carla (1961) severely eroded and segmented barriers (fig. 12). As much as 800 feet of shoreline erosion occurred to the west of the Colorado River (Shepard, 1973).

Relative Changes in Sea Level

The processes that have been discussed previously produce changes that can be observed over a relatively short period of time. A process that proceeds at a slow pace and is not readily apparent is subsidence.

Subsidence in the Trinity-Galveston Bay area has caused flooding of business and residential areas. Subsidence in this area is attributed to groundwater withdrawal (Fisher and others, 1972). From the border of Alabama and Mississippi to the Texas-Mexico boundary (National Geodetic Survey, 1972), subsidence is an important coastal process.

Summary

Waves are the major moving force eroding and depositing sediment in the Coastal Zone. Wind tides move and pile up larger amounts of water than do astronomical tides, but the sediment volume that is moved through tidal passes and channels by astronomical tidal currents must be considered in land use planning. The most spectacular processes in the area relate to seasonal hurricanes when large forces move abundant sediment. These exemplary processes as well as others must be monitored and understood to plan man's use of the Coastal Zone. The coastal processes used as examples strongly affect day-to-day changes of the Coastal Zone, but the interpretation of all the processes mentioned are directly related to historical changes also.

MAN-INDUCED CHANGES

Some shoreline changes can be attributed to man's activities; others are thought to be related, but cannot be positively labeled as such without additional monitoring. Some of man's activities that affect shorelines or have the potential of affecting shorelines are: (1) land and water use in major drainage basins, (2) river diversion, (3) shell dredging, (4) dredging of canals, (5) dune destruction, (6) mining of beach and barrier sand, and (7) construction of jetties and bulkheads. As in the discussion of processes, only certain of man's activities will be cited as they influence Coastal Zone changes. Some of these activities are presently being conducted in the model area, and most activities have been carried on in the past.

Bay Shorelines

Several of man's activities have directly, or indirectly, influenced the stability of bay shorelines. The activities that have changed shoreline erosion to accretion, or that have tended to bring a shoreline segment into a state of equilibrium are: (1) construction of jetties, (2) canal dredging, (3) removal of logjams within rivers, and (4) construction of bulkheads.

Effect of jetties is to trap sand that would normally move in the direction of drift. Jetties may also cause downdrift erosion.

As a result of canal dredging, about 500,000,000 cubic feet of spoil have been placed along the bay margin. Results of dredging and spoil disposal adjacent to bay margins are (1) destruction of certain physiographic and environmental units and (2) filling of the bays through shoreline accretion (fig. 13). Bay shorelines also go through periods of erosion. Erosion occurs (1) during extended dry periods, (2) in areas where spoil volume is low, and (3) in areas where dense vegetation inhibits the bayward movement of sediment by sheetwash.

Effects of shell dredging on bay shoreline stability are not definitely known. Accelerated erosion has been attributed to the death of marine grasses and oyster clumps because of high turbidity created by dredging. Some live reefs have been physically removed by shell dredging, and others have been killed by excessive siltation (fig. 14).

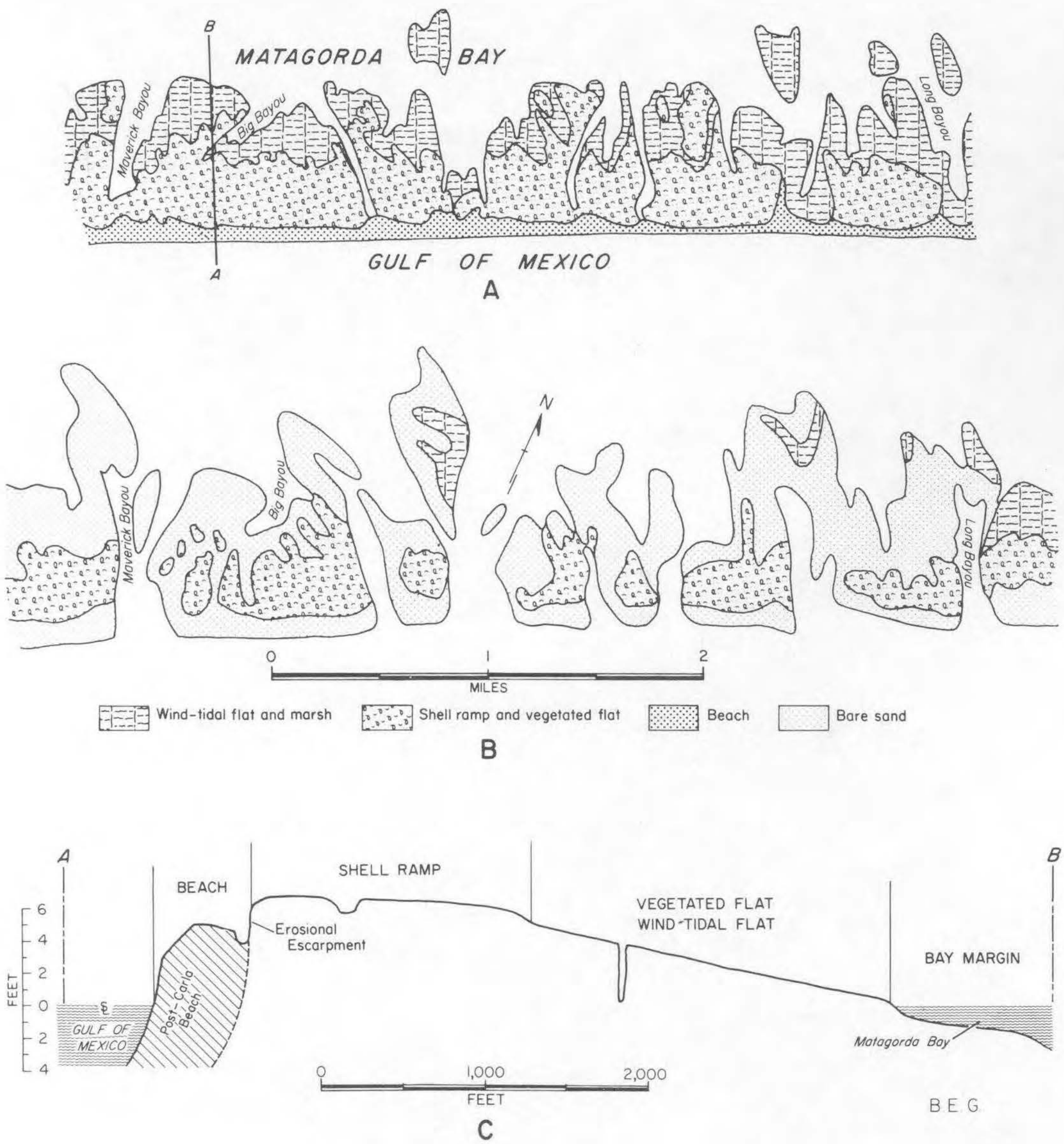

Figure 12. Effects of Hurricane Carla, 1961, on a segment of Matagorda Peninsula that lies 1.5 to 6.0 miles west of the Colorado River (see fig. 1, J). (A) Matagorda Peninsula as it appeared in 1957. (B) Matagorda Peninsula shortly after the passage of Hurricane Carla. This shoreline segment was eroded as much as 800 feet. (C) Profile across Matagorda Peninsula (May 1971); parts of the shoreline had accreted 500 feet (300 feet landward of its pre-Carla position).

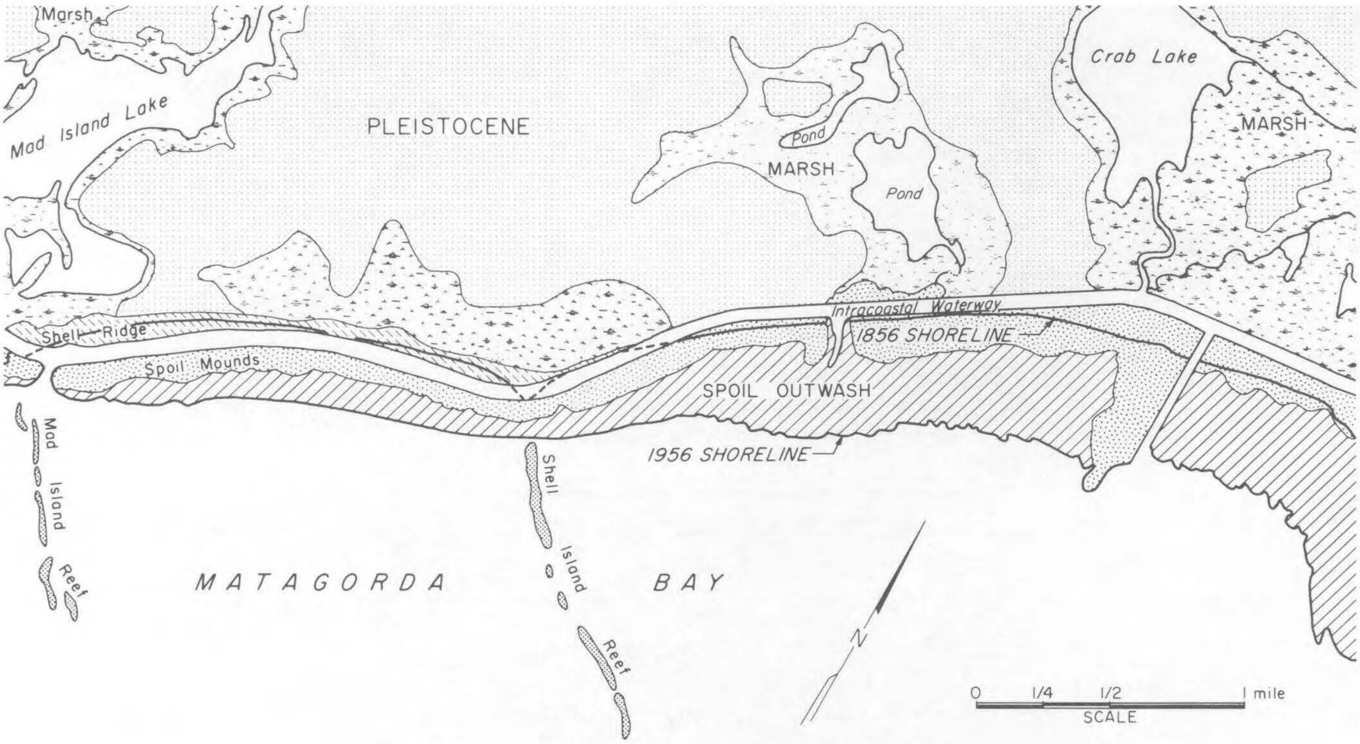

Figure 13. Accretion of the north shore of Matagorda Bay resulting from spoil outwash. The area lies between the Colorado Delta and Oyster Lake (see fig. 1 for location).

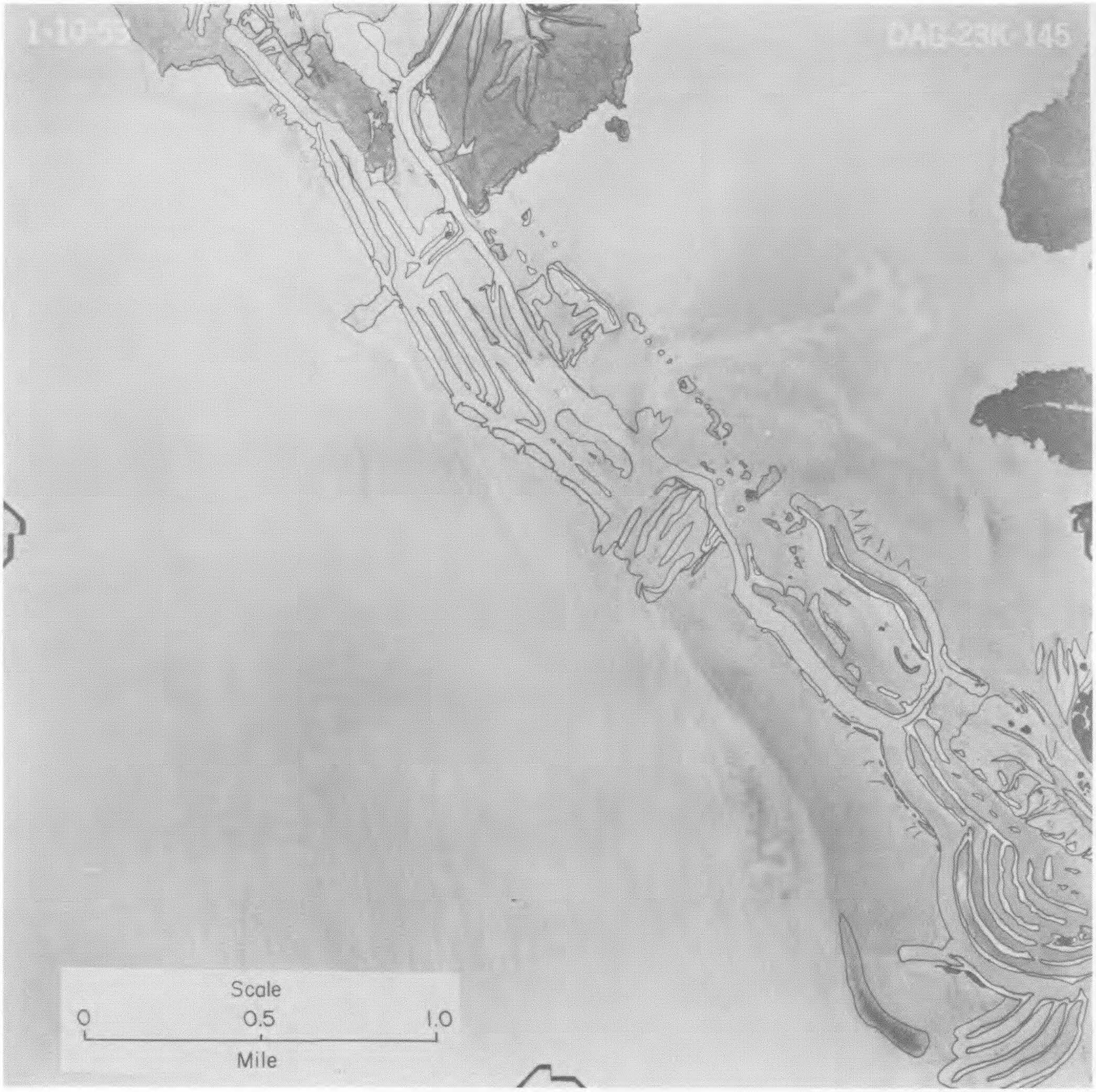

Figure 14. Dredging of Dog Island Reef for oyster shell (photo 1953). Dog Island Reef is situated west of the Colorado Delta (see fig. 1 for location).

Mining beach and spit deposits has been common in some locales. Beach ridges in the bay area are up to ten feet high and provide considerable protection to man-made structures during storms. Mining of shell from these ridges created some gaps that are easily breached during storms. Also, continued mining of shell which behaves as a protective ramp on beaches could bring about serious erosional problems, particularly during hurricanes. Jetties of ship channels trap all sand that is transported by longshore currents. Downdrift of the ship-channel jetties, the shoreline has been dominated by erosion (fig. 15).

CONCLUSIONS

Shorelines in the Matagorda Bay area are mostly in an erosional state, and historical data indicate that this has been the trend for at least 118 years. Historical data predate any major coastal or inland activity of man that could have caused shoreline erosion. Man's activities, inland and along the Coastal Zone, have altered the natural environment. Effects of man's activities have been to alter the sources of sand that nourish bay and Gulf shorelines, to trap sand that moves alongshore, and to locally increase rates of bay-shoreline accretion.

Erosional rates are high along most of the Gulf shoreline in the Matagorda Bay area. Shoreline retreat progresses relatively slowly (0.4 foot to 14 feet per year) under normal sea and wind conditions. High winds, storm-surge flood, and storm waves associated with hurricanes erode the Gulf shoreline as much as 800 feet in a matter of a few hours. Severe erosion occurs where there are no fore-island dunes to prevent breaching during storms. Where fore-island dunes are continuous, beaches are eroded during storms, but breaching of the island is inhibited.

Where man-made structures intercept longshore-sediment transport, accretion occurs on the upcurrent side and erosion on the downcurrent side during normal wind and wave conditions.

With the exception of the areas of bayhead deltas and spoil outwash, the bay shoreline is eroding. Rate of erosion is relatively slow along the eastern shore of the lesser bays, along shoreline segments that are adjacent to rather dense development of oyster clumps, and generally, along the higher bluffs.

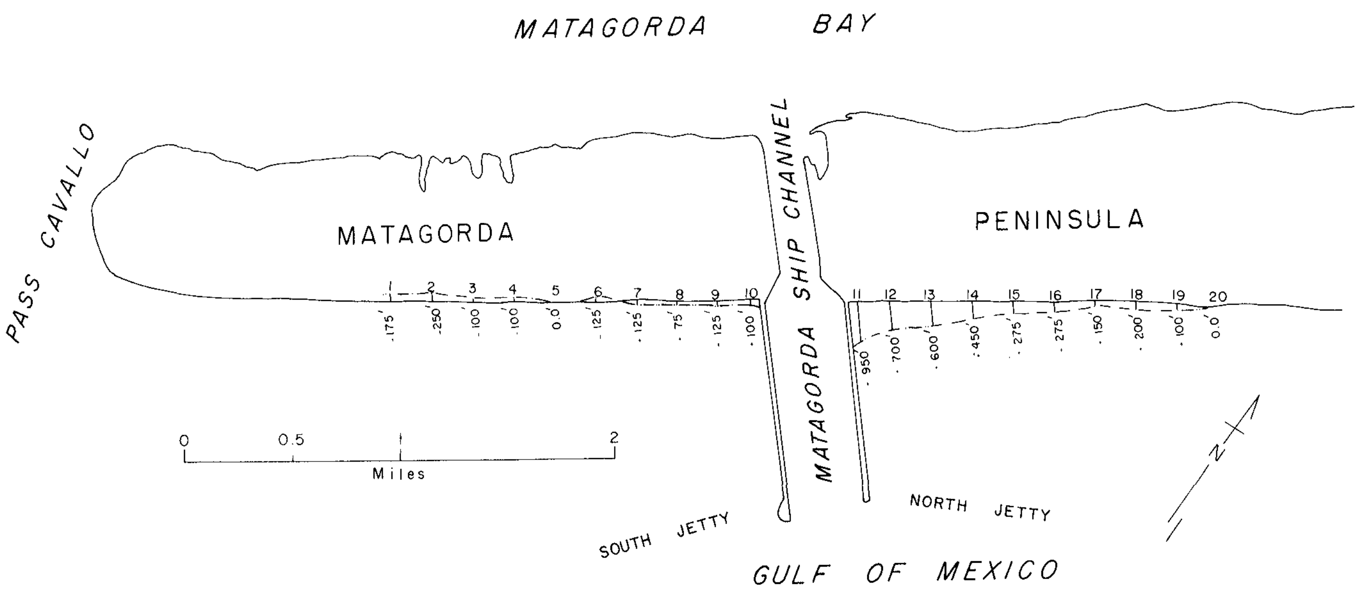

Figure 15. Effect of jetties on shoreline stability. Accretion occurs adjacent to the upcurrent (north) jetty, and erosion occurs on the downcurrent side (downcurrent from the south jetty).

Loss of land is minimal in the areas where rivers discharge into the bays (bayhead deltas), and in areas of spoil outwash. Both of these areas are low lying and are subjected to excessive flooding and wave attack during storms. When a hurricane such as Carla (1961) makes landfall and moves inland, there is excessive flooding. Because the bay system is wide to the southeast and becomes narrow toward the northwest, its funnel shape causes storm-surge flood to increase in height from south to north.

Knowledge of rates of shoreline retreat and accretion and susceptibility of particular shoreline segments to both coastal processes and man's activities is essential in order to insure that the Coastal Zone will be managed wisely.

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DELINEATION AND ENVIRONMENTAL APPLICATION OF ACTIVE PROCESSES MAPPED IN RECHARGE AREA OF THE EDWARDS AQUIFER

Robert A. Morton

INTRODUCTION

The southern Edwards Plateau of Central Texas (fig. 1) provides a unique opportunity for studying

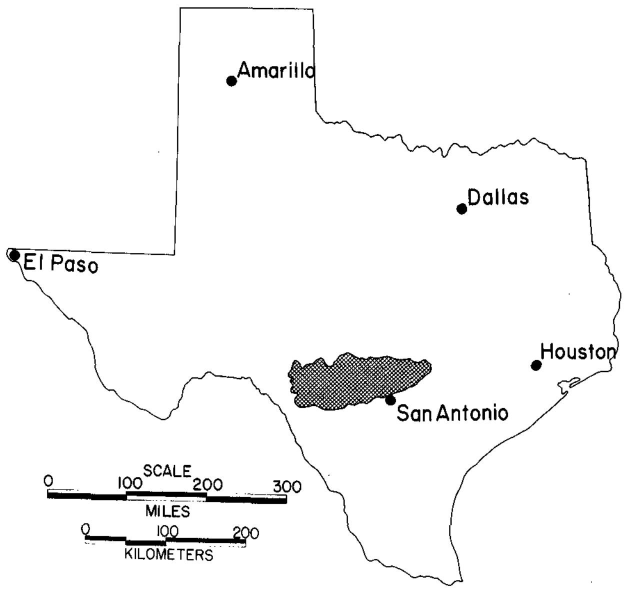

Figure 1. Location of southern Edwards Plateau and adjacent interior Coastal Plain.

active surficial processes in an area of limestone aquifer recharge. Understanding the interaction of climate, rock type, and physiography is essential in determining man's proper utilization of the recharge area while safeguarding the quality and supply of water available for recharge.

This paper describes processes which are active in the southern part of the Edwards Plateau, the recharge area of the Edwards aquifer. The approach used not only identifies critical processes in the area but provides insight as to the utility of such information in determining effective land use. Emphasis is placed on the relative importance of surface water runoff versus recharge and their relationship to other processes that may ultimately affect recharge.

The basic data for this study were derived from maps using the following bases: (1) 7.5-minute quadrangles, (2) air-photo mosaics, and (3) stereo photos. Supplementary information was obtained from field observations and a literature search.

GROUND-WATER RESOURCES-- SOUTHERN EDWARDS PLATEAU AND VICINITY

In the southern Edwards Plateau and vicinity, public, domestic, and livestock consumption lead the list of principal ground-water uses. Industrial and irrigation operations are also dependent on ground-water sources for their supplies. Depths of wells range from 10 to 1,000 feet with most wells being between 200 and 600 feet deep; withdrawal is accomplished by mechanical (windmill) or electrical pumps.

Ground water in this region occurs in two genetically distinct limestone lithologies. Shallow reservoirs exist in carbonate alluvium of gravel, sand, and mud clasts associated with alluvial fan, terrace, and flood-plain deposits. Except for local caliche cementation, these deposits exhibit primary interstitial porosity with moderate to relatively high permeability. Local aquifers in alluvium occur adjacent to major streams within the Plateau and below the Balcones escarpment as described by Wermund (p. 52). The second type of aquifer occurs in limestone and dolomite with transmission and storage of ground water concentrated in joints, fractures, and solution channels. There is a paucity of data concerning porosity and permeability in these carbonate aquifers, and therefore, it is difficult to estimate reserves or storage capacity. A brief summary of the water-bearing properties of geologic units for the southern Edwards Plateau and vicinity is presented in table 1.

Edwards and Associated Limestones

Although the term "Edwards aquifer" is used generally to denote the extensive subsurface reservoir which supplies ground water for San Antonio and vicinity, the Edwards and associated limestones actually form two separate and independent aquifers (Livingston and others, 1936). In the outcrop area of the plateau along the divides of the Guadalupe, San Antonio, and Nueces Rivers north and west of the Balcones fault zone, these carbonate rocks provide temporary subsurface storage for ground water in a local reservoir system used by ranchers for both livestock and domestic supplies. Recharge of this unconfined plateau aquifer is by direct infiltration of precipitation (Alexander and

Table 1. Water-bearing properties of geologic units for southern Edwards Plateau and vicinity (modified after Alexander and others, 1964; Reeves, 1969).

System	Series	Geologic unit	Approximate thickness (ft.)	Lithologic character	Water-bearing properties
Quaternary	Holocene	Alluvium	0-30	Clay, silt, sand, gravel	Yields small to moderate quantities of fresh water
	Pleistocene	Leona Fm.	0-80	Silt, sand, gravel	Yields small to moderate quantities of fresh water
Tertiary (?)	Pliocene (?)	Uvalde gravel	0-30	Residual concentrate and caliche-cemented flint and limestone gravel	Does not contain appreciable quantities of water
Cretaceous	Gulf	Escondido Fm.	450-1300	Shale and sandstone with thin beds of limestone	Locally yields small quantities of fresh to slightly saline water
		Olmos Fm.	400-920	Clay, sandy clay, and thin beds of sandstone	Yields no water
		Corsicana Marl	300-600	Marl, clay, lenticular sandstone and limestone	Yields no water
		*Anacacho Limestone	240-500	Limestone, chalk, marl, and sandy clay	Locally yields small quantities of water for domestic and livestock uses
		*Taylor Marl	230-550	Nodular marl, locally chalky, and calcareous clay	Locally yields small quantities of water
		Austin Chalk	135-1030	Chalk, marl, limestone	Yields small to moderate quantities of fresh to slightly saline water
		Eagle Ford Shale	20-300	Shale and sandy limestone	Locally yields small quantities of water
	Comanche	Buda Limestone	30-180	Limestone	Locally yields small quantities of water
		Del Rio Clay	30-220	Clay with thin beds of limestone	Yields no water
		Edwards and associated limestones	555-1400	Limestone and dolomitic limestone with some thin beds of marl	Yields moderate to large quantities of fresh water
		Glen Rose Limestone upper	400-?	Alternating beds of shale and marl with thin beds of impure limestone	Yields small quantities of saline water
		lower	50-380	Massive limestone with thin beds of marl and limestone	Yields small to moderate quantities of fresh water
		Hensel Sand	20-150	Sandstone, limestone, and dolomite	Yields small to moderate quantities of fresh to slightly saline water
		Cow Creek Limestone	50-75	Massive limestone, sandy limestone, and dolomite	Yields small quantities of fresh water
	Coahuila of Mexico	Sligo and Hosston Fms.	100-180	Conglomerate, sandstone, and dolomite	Yields moderate to large quantities of fresh water to wells in Kerr County

*The Anacacho Limestone and Taylor Marl are time equivalent. The former crops out in the Nueces drainage basin and the latter crops out in the San Antonio and Guadalupe drainage basins.

others, 1964); water migrates downward through fractures and solution channels to the lower part of the formation.

Where the streams are incised below the resistant Edwards Limestone, the ground-water table is commonly perched on the alternating beds of limestone and marl (Glen Rose) above valley floors. The ground water moves laterally by gravity and is discharged as springs and seeps along the alternating beds of limestone and marl which have low permeability. It is this discharge which provides perennial streamflow for the headwaters of the Blanco, Guadalupe, Medina, Frio, and Nueces Rivers. The plateau aquifer is limited by thickness and lateral extent of the outcrop, both of which decrease away from the drainage divides as a result of erosion (fig. 2).

The subsurface artesian aquifer is bounded by the Balcones fault zone and the "bad-water" line (fig. 3), which is essentially the transition zone between potable and highly mineralized water (1000 ppm dissolved solids) that occurs downdip in the area of limited mixing or nonmixing. Recharge into this artesian reservoir is partially attributed to rain falling on the outcrop, but the predominant mechanism is loss of discharge from streams flowing across the outcrop in the fault zone. The nature and extent of this phenomenon are discussed in another section.

Glen Rose, Hensel, and Cow Creek Formations

In areas where the Edwards Limestone is laterally discontinuous or has been completely removed by erosion, the lower Glen Rose, Hensel, and Cow Creek Formations supply ground water for domestic and livestock consumption. Although some wells penetrating these limestone and dolomite aquifers produce large yields, most would be classified as small- to moderate-yield wells (Alexander and others, 1964). Because yields are small and usually contain higher quantities of sulfate, wells which penetrate the Hensel interval commonly are completed in the underlying Cow Creek Formation. The Hensel and Cow Creek Formations crop out and are recharged in the Pedernales drainage and the ground water migrates downdip beneath the surface drainage divide.

Leona Formation and Alluvium

The Leona Formation includes stream terraces and alluvial fans between the flood plain (Holocene) and high terrace gravels (Pliocene?) that cap the drainage divides south and east of the Balcones fault zone. The high terrace flint and limestone gravels, referred to as Uvalde gravels (table 1), generally are not capable of ground-water storage because (1) they are commonly cemented by caliche, and (2) they occur as erosional remnants and are laterally discontinuous. However, both the Leona Formation (0 to 80 feet thick) and Holocene alluvium (0 to 30 feet thick) yield small to moderate amounts of fresh water. In addition, they provide storage for ground water that is released as seeps during low streamflow. The Leona Formation may also provide ground water for recharge where the formation is underlain by permeable strata (DeCook, 1960; Follett, 1966), but even where the Leona overlies rocks with low permeability such as the Taylor Marl, only the lower few feet (<15) are saturated (George, 1947; Shafer, 1966).

Other Local Aquifers

Stratigraphic units between the Leona Formation and the Edwards and associated limestones contain minor aquifers that provide water of variable quality to a few wells throughout the region. Included in this group of local aquifers are the Sligo and Hosston Formations, Buda Limestone, Eagle Ford Shale, Austin Chalk, Anacacho Limestone, and Escondido Formation (table 1). They are important primarily because they can provide water in areas such as portions of Uvalde and Kerr Counties (Welder and Reeves, 1962; Reeves, 1969) where the major aquifers contain salt water or have been removed by erosion and in either case are not available for ground-water supplies.

ACTIVE PROCESSES—SOUTHERN EDWARDS PLATEAU

Active processes are discussed in terms of their potential capacity to affect recharge, an approach which requires the inclusion of other factors such as fractures. Processes considered to be significant in the southern Edwards Plateau are: (1) flooding, (2) sheetwash and headward erosion, (3) slope failure, (4) bank undercutting, (5) calichification, (6) discharge of ground water, (7) karst development and solution, and (8) recharge of the Edwards underground aquifer.

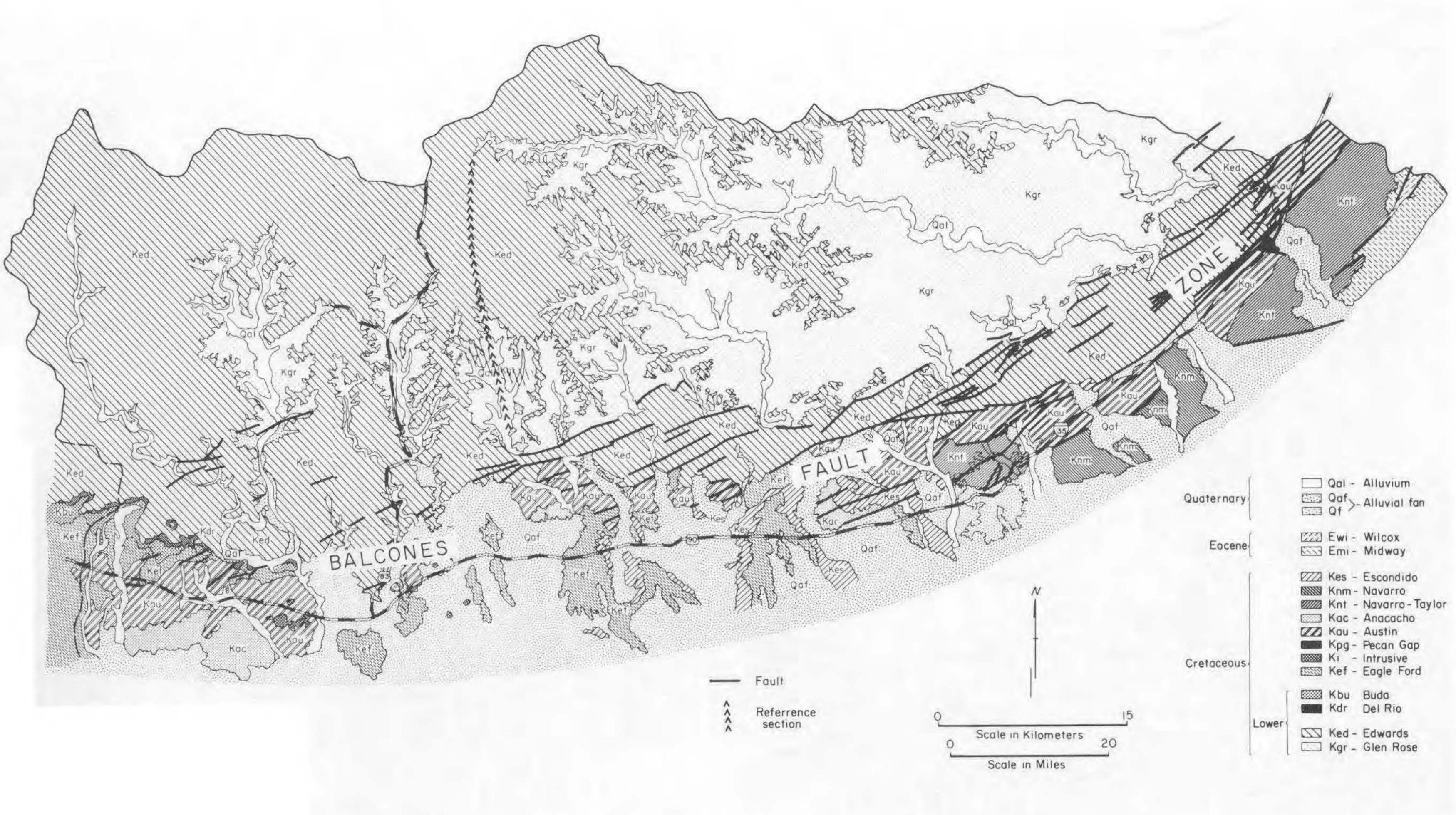

Figure 2. Geologic map of southern Edwards Plateau and adjacent interior Coastal Plain.

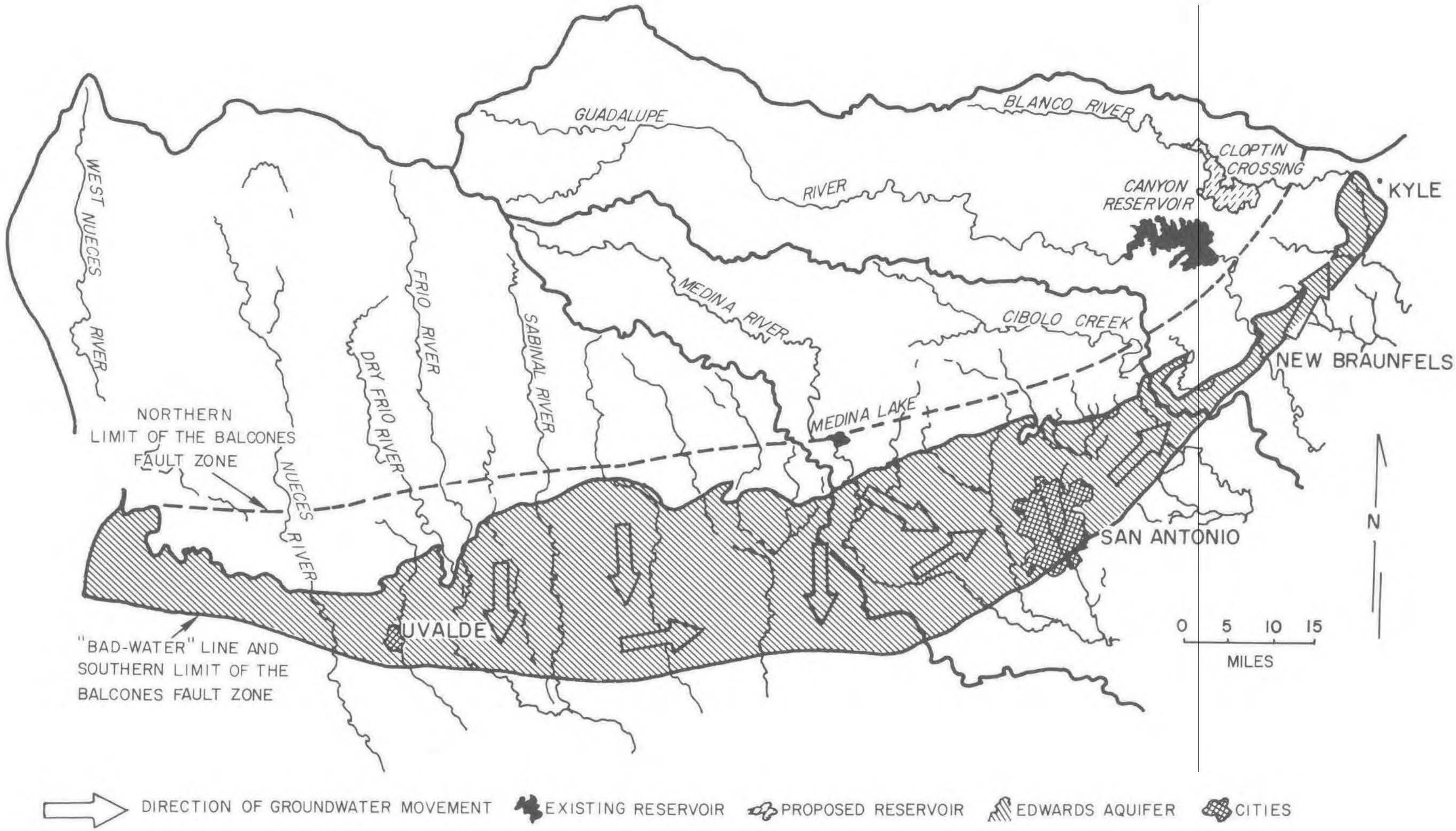

Figure 3. Direction of ground-water movement in underground Edwards aquifer. General directions from Garza (1962).

Flooding

Flooding is an important process particularly in the vicinity of the Balcones fault zone (figs. 2, 3). The physical relief caused by differential erosion across the fault zone creates dramatic climatic conditions which result in torrential rainfalls. Based on a comparison of drainage basins of 300 square miles in size, Leopold, Wolman, and Miller (1964) concluded that South-Central Texas is one of two areas in the United States having the greatest potential for moderate floods. Two types of flood-producing storms are common: localized thunderstorms produce intensive rainfall over small areas, resulting in local flooding, while major widespread flooding is associated with tropical storms that move inland from the Gulf during the summer and early fall. An example of the latter type of storm is illustrated in figure 4. Such extreme precipitation periodically causes inundation of surfaces adjacent to both minor and major drainage systems.

Flood-prone areas were mapped on aerial photographs using geomorphic criteria (Dickerson, p. 220), and therefore, they do not represent the upper elevations of a flood event with a particular probability of occurrence. In addition to the shortcomings mentioned above, the technique used does not permit the estimation and incorporation of runoff from urbanization or the backwater effect created by the addition of structures along the flood plain. This method is considerably different from the computer technique employed by the U. S. Army Corps of Engineers; nonetheless, it is hoped that the mapped limits approach those of the "standard project flood" as defined by the Corps of Engineers. The few opportunities for checking this statement, i.e., comparison of mapping where both the Corps of Engineers and the Bureau of Economic Geology have delineated flood-prone areas for the same stream segment, indicate close agreement between the areas included in the flood hazard category. Reports prepared by the Corps of Engineers (1969, 1971) contain maps that show the limits of the intermediate regional flood as well as the standard project flood for segments of Salado Creek and the San Marcos and Blanco Rivers. Comparison of these maps with maps prepared by the Bureau of Economic Geology that include these same stream segments indicates that the upper boundary of the low-probability flood-prone area as defined by the Bureau compares favorably with the limits of the standard project flood mapped by the Corps of Engineers. Therefore, extension of the mapping technique based on aerial photographs into areas without hydrologic data appears to be justified.

Flood plains and terraces.—The areal extent of flood-prone areas is controlled by lithology in the Edwards Plateau. Because of deep incision, flood plains of streams flowing on the hard Edwards Limestone are restricted laterally to narrow bands approximately 200 to 500 feet in width adjacent to the active channel. This is observed in the headwaters as well as in the Balcones fault zone where the Edwards is downfaulted (fig. 2). The same lithologic control is expressed where streams flow across the massive indurated limestone in the lower Glen Rose Formation. However, between the headwaters and the Balcones fault zone, wide alluvial terraces and associated flood plains characterize these same streams where they flow over the more easily eroded alternating marl and limestone beds of the upper Glen Rose Formation (fig. 2). Along the fault zone, the combination of thin soil, narrow canyons, and excessively high rates of rainfall create flash-flood hazards of catastrophic proportion. Spreading floodwaters inundate low-lying areas downstream from the fault zone causing extensive damage. A recent example of this was the flooding in May 1972 in the canyon of the Guadalupe River near New Braunfels (fig. 3) that damaged and, in some instances, completely destroyed personal property (homes, outbuildings, equipment, and vehicles), public property (roads and bridges), and agricultural land. Almost without exception, during every flood, loss of vehicle and/or life occurs when individuals attempt to ford low-water crossings under high-water conditions.

Alluvial fans.—Similar flooding occurred in the vicinity of the Balcones escarpment during July 1973 where damage occurred along Cibolo Creek, in the San Antonio River drainage basin, and throughout the drainage basins of the Frio and Nueces Rivers in the Edwards Plateau. Flooded areas included both flood plains and alluvial fan surfaces. Flooding of alluvial fan surfaces, attributed to low relief, poorly defined drainage, and close proximity to the escarpment, was responsible for considerable damage to crops and agricultural land.

Flooding is an important process in terms of aquifer recharge because the yearly rainfall (fig. 5) is not uniformly distributed. Although recharge is accelerated during flooding by an increase in stream discharge and by direct infiltration into alluvium and alluvial fan aquifers, considerable surface water is lost because of increased runoff.

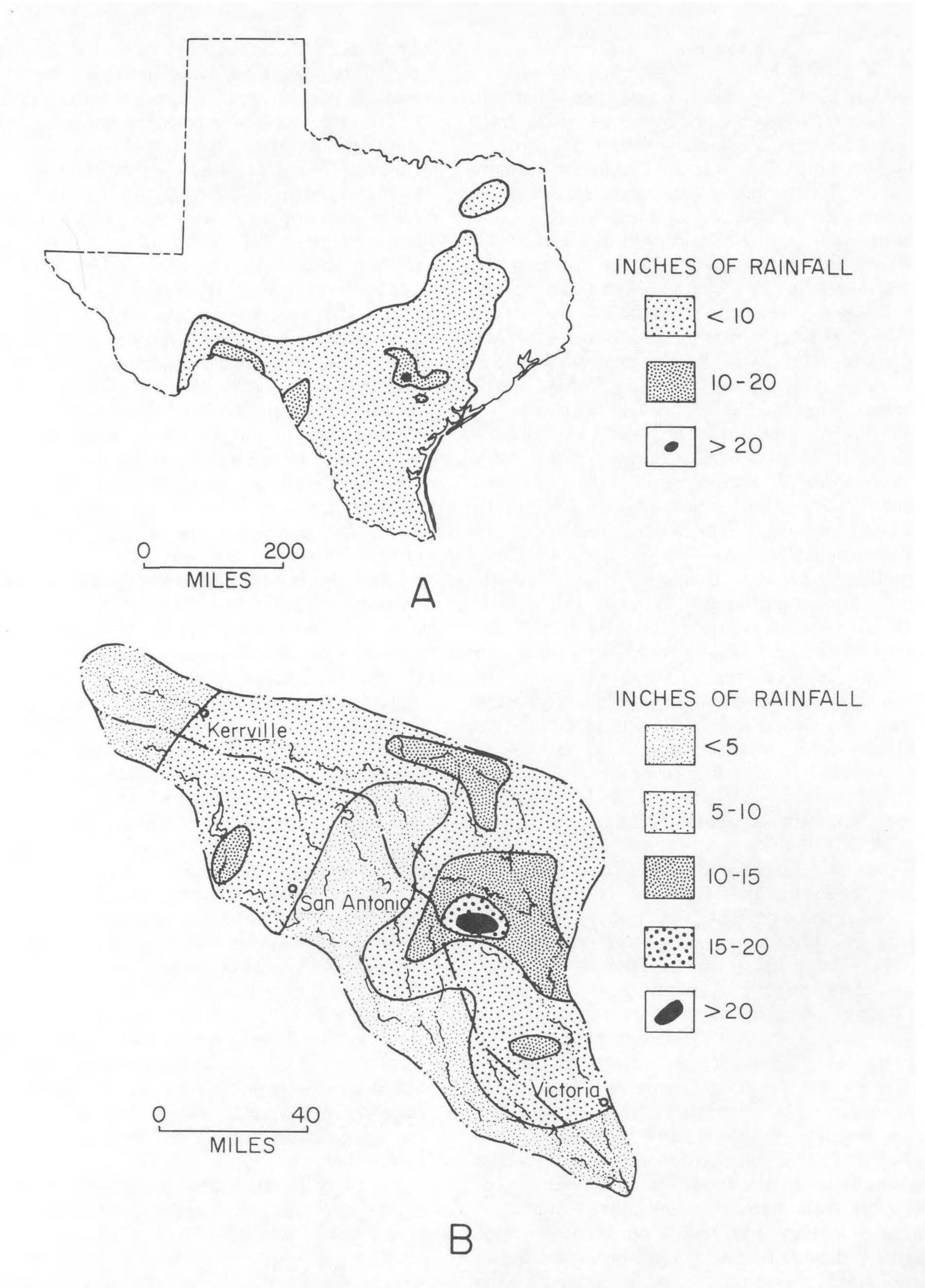

Figure 4. Isohyetal map of rainfall, in inches, observed June 28 to July 1, 1936 for (A) Central and South Texas, and (B) the Guadalupe and San Antonio River Basins. Modified from Dalrymple and others (1937).

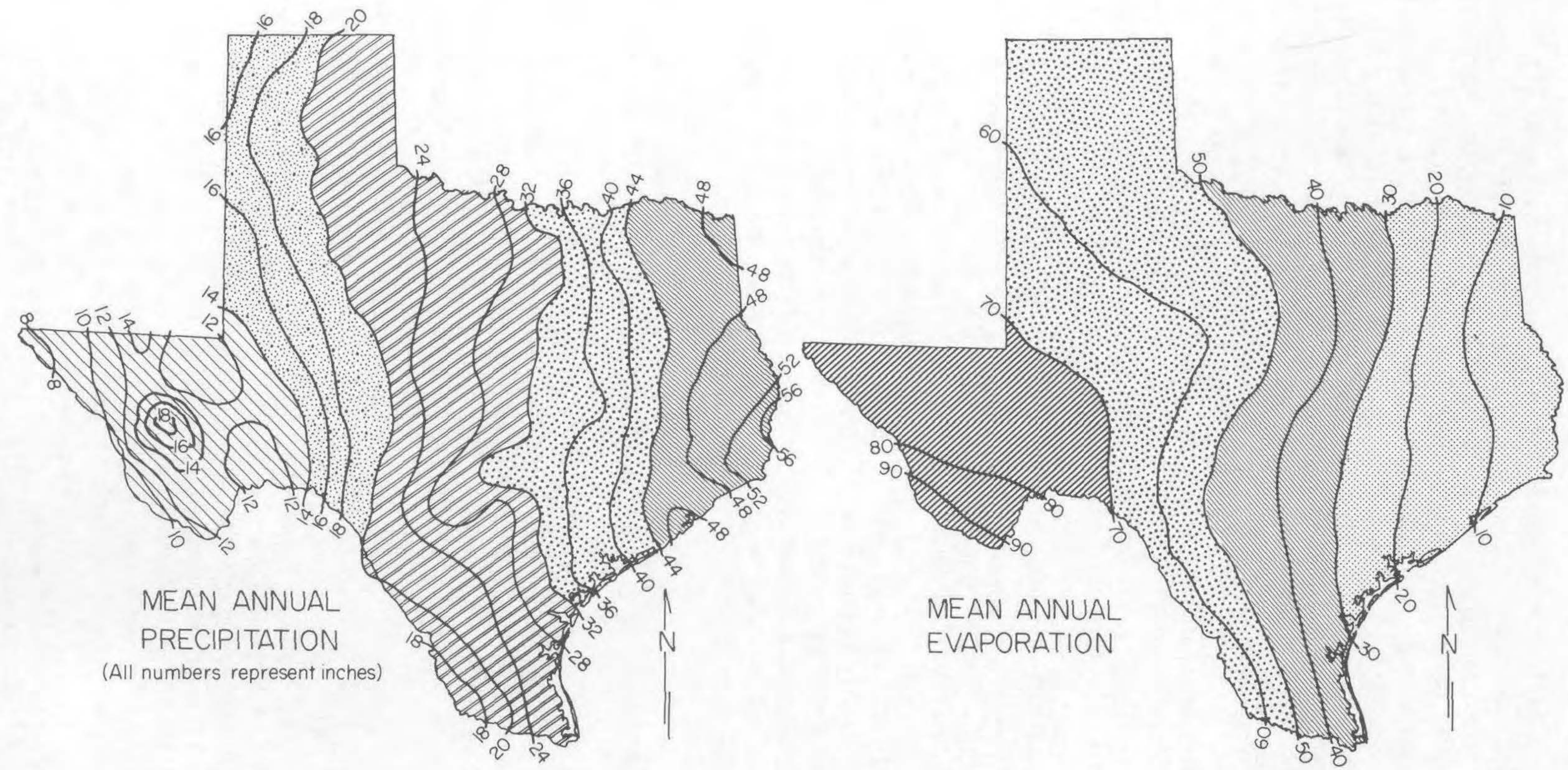

Figure 5. Mean annual precipitation and mean annual evaporation for Texas based on records for 1931-1960 and 1940-1957, respectively. From Arbingast, Kennamer, and Bonine (1967).

Sheetwash and Headward Erosion

Sheetwash and headward erosion occur on relatively steep slopes, and in both processes surface runoff predominates over recharge. Colluvium transported and deposited by slopewash is commonly concentrated along steep slopes. Although colluvium can be highly permeable, in this area well-developed caliche cement reduces greatly vertical infiltration of rainfall. Sheetwash also occurs on bedrock slopes of the Glen Rose Formation where alternating beds of limestone and marl are exposed.

Headward erosion is an active process along the divides of major and minor drainage basins, but the degree of dissection is not always equal on both sides of the same divide. In fact, rather marked differences exist where spring sapping promotes rapid headward erosion on the downdip side of divides capped by the Edwards Limestone. Evidently stream piracy has been an important agent in the evolution of these headwater drainage basins.

Sheetwash and headward erosion may not directly affect recharge other than by exclusion of water from the aquifer, but certainly the quality of surface water is critical to ultimate water quality of the aquifer. Thus, this process has an indirect effect on water resources of the Plateau and aquifer.

Minor Processes With Local Importance

In certain areas within the study region, several minor processes are active which have local importance but generally are not related to recharge. Included in this category are: (1) slope failure, (2) bank undercutting, and (3) calichification. Slope failure in this region is associated with the creep and flow of unstable slopes underlain by the Del Rio Clay, a clay with high shrink-swell properties. The Del Rio is less resistant to erosion than the underlying and overlying resistant limestones, the Edwards and Buda Limestones, respectively; therefore, it tends to develop a recessive oversteepened slope. Large blocks of Buda on the Del Rio slopes indicate the low slope stability related to creep and the lack of lateral support. The Buda Limestone normally has a high bearing capacity except near these steep slopes.

Bank undercutting occurs throughout the region where streams are laterally impinged against resistant near-vertical bluffs of carbonate rocks. Continued erosion eventually causes local landslides and rockfalls that usually are not extensive but can affect property boundaries and homes located close to the undercut bank.

Apparently calichification is controlled to some extent by climate (fig. 5) as it is more prevalent in the semiarid region than the subhumid region of the study area; both transported and *in situ* caliche have been reported by Blank and Tynes (1965). Although their study was not confined to Cretaceous carbonate lithologies, their observations and conclusions are applicable to the formation of caliche in the southern Edwards Plateau. Even though *in situ* formation of caliche by replacement may be an active process, observations suggest that widespread formation of caliche is the result of capillary action and the evaporation of calcium carbonate solutions in a porous and permeable medium.

Discharge of Ground Water

Springs (natural discharge) and water-well withdrawal (artificial discharge) compete for groundwater resources in the Edwards Plateau. Minor springs, distributed throughout the headwaters of the three drainage basins, are located along bedding planes and fractures on slopes where permeable beds, underlain by less permeable beds, crop out. Judging from data recorded by the U. S. Geological Survey (1972), the combined discharge of these small headwater springs provides base flow that probably slightly exceeds the combined discharge of major springs that are located and controlled in part by the eastern boundary of the Balcones fault zone (fig. 6). Average discharge from two of the larger springs, San Marcos Springs and Comal Springs, is 157 cfs (16 years of record) and 283 cfs (40 years of record), respectively. Thus, even though small springs individually may be of minor importance, collectively they contribute considerable discharge to the headwater streams.

Karst Development and Solution

Chemical quality of ground water and surface water provides an estimate of the magnitude of carbonate material removed by solution. According to George (1947), approximately 200 tons of rock material is transported daily by the water discharged at Comal Springs. Ground water and surface water in the area are generally hard to very hard because they contain considerable bicarbonate and are low in dissolved solids (Rawson, 1968; Alexander and others, 1964).

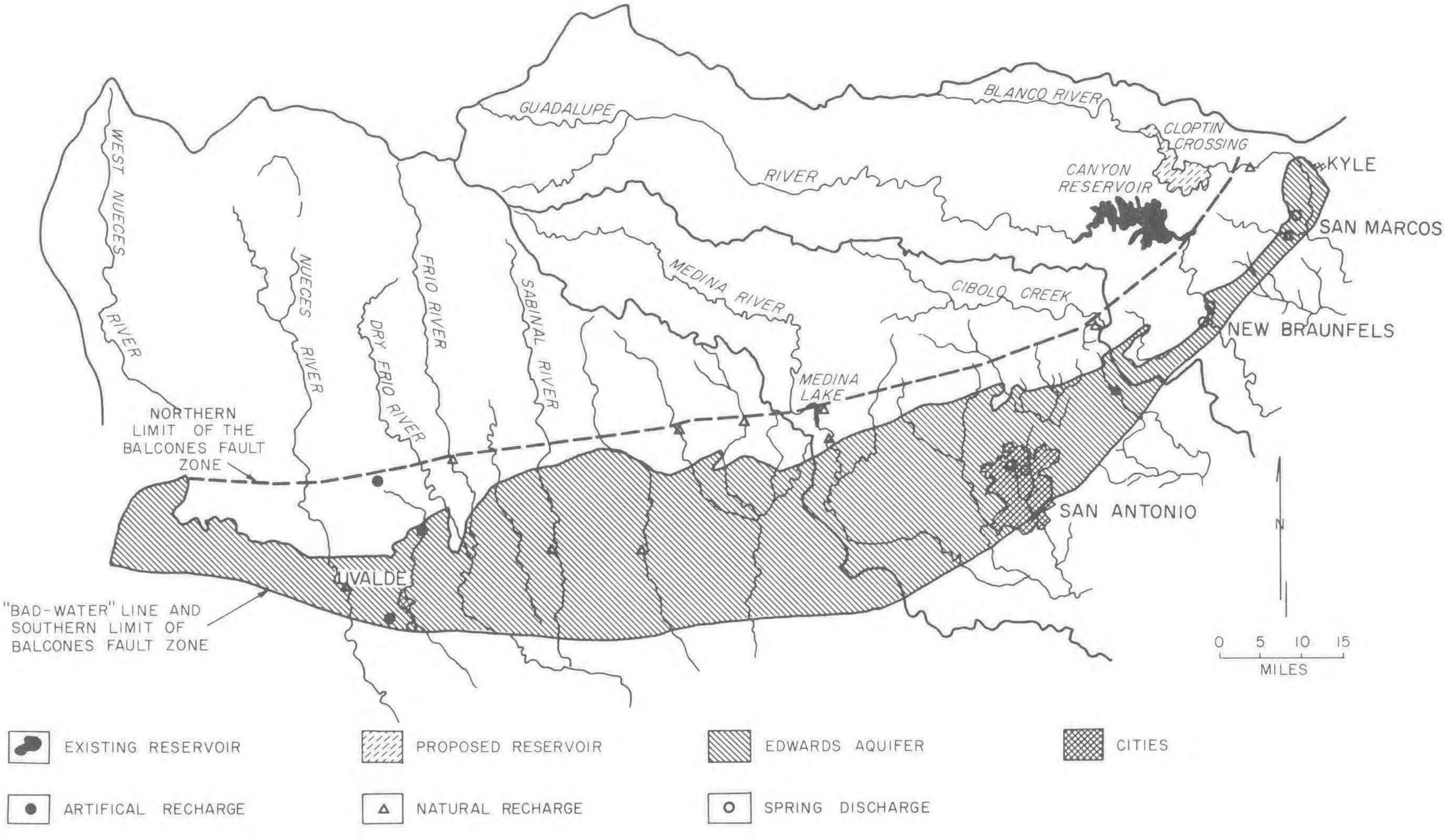

Figure 6. Areas of natural and artificial recharge and major spring discharge, southern Edwards Plateau. Data compiled from various sources.

Although solution takes place continuously to some degree throughout the Edwards Plateau, discussion of the process here is restricted to outcrops of the lower Glen Rose and the Edwards and associated limestones. Both small- and large-scale solution features are found in the southern Edwards Plateau. Honeycomb limestone and collapse structures are common in the Edwards; however, evidence presented by Rose (1972) and Fisher and Rodda (1967) suggests that at least the collapse structures were penecontemporaneous with deposition or formed shortly thereafter from removal of gypsum by solution. Abbott (1973) emphasized the preponderance of porosity along or within bedding and suggested that considerable solution enlargement of primary porosity and fractures occurred during the Miocene as a result of uplift from movement along the Balcones fault zone. Regardless of time of formation, these zones of solution have been conduits for ground-water movement during the Pleistocene or Holocene. Rose (1972) reported that effective porosity within the outcropping Edwards consists of "caverns, vugs, enlarged fractures and bedding seams, and leached burrows." Extensive cavities and interconnected porosity in the subsurface Edwards are demonstrated by the quick response in pressure and increase in well level after rainfall.

Water well records contain numerous reports of cavities in the lower Glen Rose. In addition, honeycomb limestone, caverns, and sinkholes occur in outcrops of this massive limestone unit much as they occur in the Edwards Limestone.

Solution has been and probably continues to be an active process where the carbonate terrain is characterized by sinkholes, but these karst features are not "active" in contrast to karst features in Alabama (Newton and Hyde, 1971) and South Africa (Foose, 1967) where ground-water withdrawal has caused loss of rock strength and catastrophic collapse has occurred. Sinkholes in the southern Edwards Plateau range from a few hundred feet in diameter to 15 acres in area. Most are nearly circular with low relief and gently sloping sides. Some of the larger sinkholes are loci for the accumulation of soil eroded from the surrounding terrain, and because of the impervious nature of the accumulated clay, considerable water can be ponded following rainfall.

Fractures play an important role in the development of karst and other solution features. Faults exert considerable control not only on the location but also on the areal distribution of sinkholes. For example, the karst terrain is generally restricted to particular fault blocks and surficially within these fault blocks some sinkholes are aligned along fractures. Field observations such as deposition of travertine at springs and along joints in quarries and road cuts suggest that solution is an ongoing process.

Recharge of Edwards Underground Aquifer

Recharge is an integral and dependent part of many of the processes previously mentioned. However, one of the main objectives of the project is to gain a better understanding of the relationships of plateau geology and recharge; therefore, recharge is also viewed as being an active process.

The slope of land surface and attitude of beds are to the south and southeast. The general direction of ground-water movement is also in the same direction except in areas where withdrawal from wells has formed cones of depression. But it appears that the faults act as conduits allowing ground water to migrate to the east (fig. 3) as indicated by the geographic locations of major recharge and natural discharge. Stream segments where major recharge occurs are located to the west in the drainage basins of the Nueces and Frio Rivers, whereas the major springs are located to the east in the drainage basins of the Guadalupe and Blanco Rivers.

Location and nature of recharge.—When the region is viewed as a hydrologic system, the specific direction of ground-water movement becomes considerably more complex. A generalized model showing various components within the system is presented in figure 7. DeCook (1963) listed the mechanisms for recharge of the Edwards aquifer as (1) direct infiltration of precipitation on the outcrop, (2) influent seepage from streams that flow across the outcrop, (3) interflow from adjacent formations, and (4) underflow from adjacent areas within the ground-water reservoir. As previously mentioned, the plateau aquifer is recharged by direct infiltration from precipitation and minor channels that carry storm runoff (fig. 7A). Ground water migrates downdip and generally emerges along the Edwards-Glen Rose contact. Discharge of effluent streams increases after heavy rainfall and then gradually decreases. But sustained spring flow can be maintained even during prolonged droughts. Spring-fed streams catch and transport surface runoff along the entrenched valleys, and minor additions to base flow occur as a result of seepage from alluvial terraces adjacent to the channel (fig. 7B). Along some reaches in the Nueces drainage,

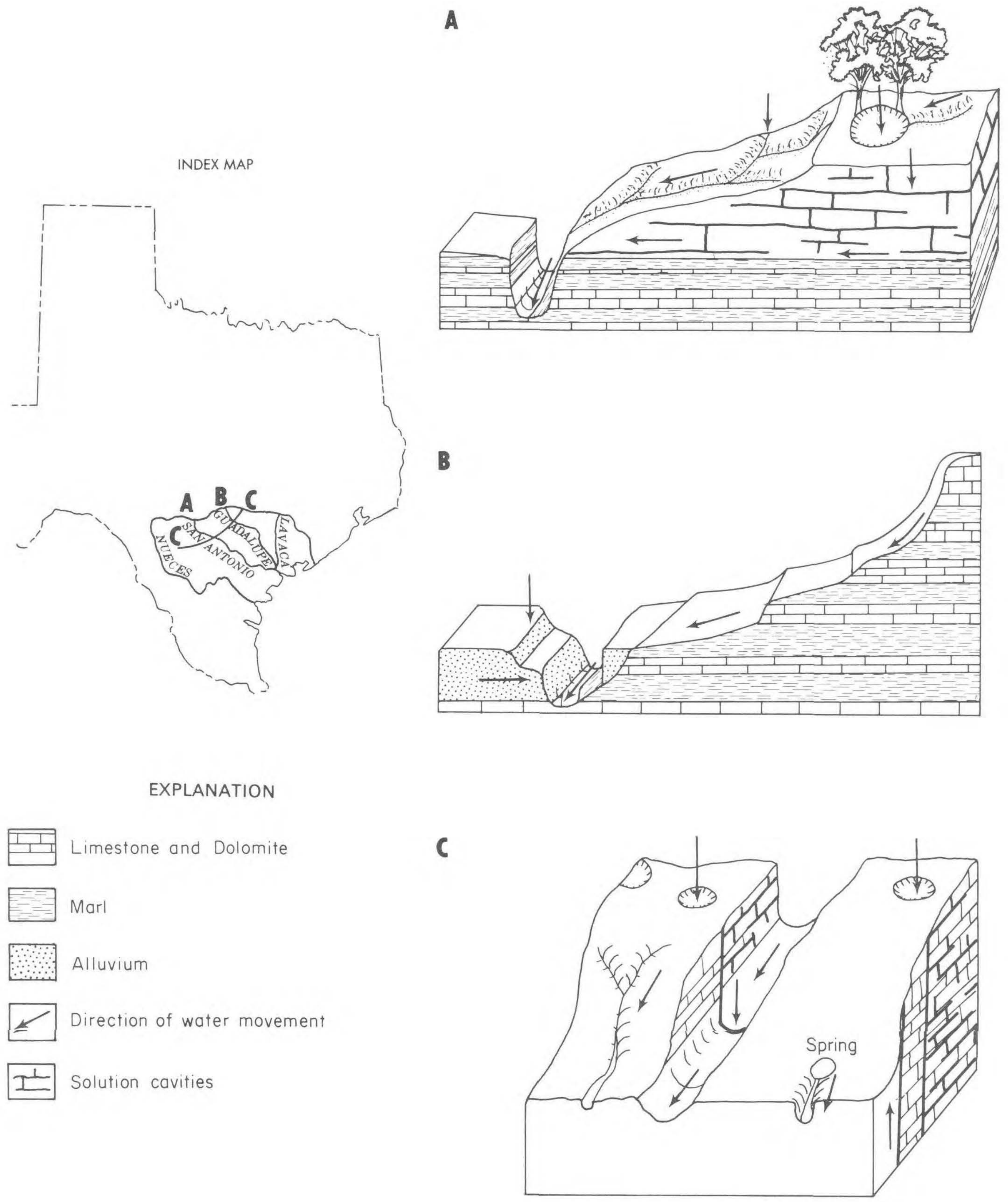

Figure 7. Schematic diagram of recharge and ground-water movement, southern Edwards Plateau. Numbers on map represent general locations of blocks.

the entire base flow is contained within gravel deposits of the channel bed. Temporary storage of ground water in the plateau aquifer, alluvial terraces, and stream-bed gravels eliminates some surface water loss which normally would occur from evaporation. Recharge in the fault zone is mainly indicated by discharge losses (fig. 7C); the saturated zone in this area is considerably below the surface level. Low flows up to approximately 500 cfs can be lost entirely to the aquifer from streams in the Nueces and San Antonio drainage basins. Livingston and others (1936) estimated that annual losses from these basins might be as much as 150,000 acre-feet. Locations of high recharge areas such as the outcrop in the vicinity of the Medina River are delineated by an area of relatively high artesian pressure. Areas of observed and measured streamflow loss are shown in figure 6. Discharge data indicate that only minor losses occur in the Guadalupe River Basin except on the Blanco River which contributes approximately 15 cfs (DeCook, 1963). Losses that occur intermittently along the Guadalupe are returned to the river downstream. Recharge by underflow (fig. 3) and penetration of rainfall on the outcrop also occur within the fault zone. Additional recharge may be the result of lateral migration (interflow) of ground water between the lower Glen Rose and the Edwards where they are in communication by faulting (Livingston, 1947; George, 1947).

Recharge versus discharge.—The combined total of estimated annual recharge to the Edwards aquifer ranges between 400,000 and 500,000 acre-feet per year (Green, 1967; Alexander and others, 1964); this recharge is primarily from loss of streamflow in the fault zone. At the present, long-term total recharge and long-term total discharge (including springs and withdrawal) are nearly equal, and the potential for discharge to exceed recharge is currently a serious problem as a result of additional demands on ground-water resources from increased population and industrial needs. Green (1967) suggested that the Edwards aquifer is on a depletion schedule because of withdrawal from approximately 4,000 wells that began about 1880 (Sayre and Bennett, 1942). The consequences of accelerating ground-water withdrawal are twofold: (1) a decline or cessation of spring discharge, and (2) the potential encroachment of highly mineralized water into areas of high withdrawal. Decreases in spring discharge have already been experienced during periods of low rainfall, as documented at Hueco and San Antonio Springs. Droughts have an added effect on the balance between recharge and discharge because increased demands on ground water for stock and irrigation purposes occur when recharge is limited.

Surface water impoundment and artificial recharge.—Water supplies from surface water impoundment and/or artificial recharge have been proposed and are currently being utilized to supplement the natural recharge into the Edwards aquifer. Two major reservoirs, Medina Lake and Canyon Reservoir (fig. 3), are presently in operation and a third, Cloptin Crossing on the Blanco River, has been approved for construction. Additional reservoirs for storage of runoff and controlled recharge have been investigated and proposed by the Corps of Engineers (1964), but further action on them has not been approved. Throughout the area, numerous small reservoirs exist which retard but do not prevent surface runoff.

Medina Dam was constructed in 1911 for irrigation and water conservation purposes. Its original purposes are still served to some extent but excessive leakage has been a major problem with losses estimated at 42,700 acre-feet per year (Green, 1967). Although artificial recharge was not intended, the idea has subsequently been used in proposals to justify construction of additional reservoirs which would control streamflow such that released discharge would not exceed that amount capable of being absorbed by the aquifer. Several small projects for artificial recharge in the Nueces River Basin (fig. 6) are located in stream beds where highly fractured and cavernous limestone crops out. Low dams are constructed downstream so that all base flow and considerable flood flow are diverted into the recharge area.

Some of the uncertainties and attendant problems associated with artificial recharge are: (1) variable rates of injection or infiltration, (2) variable water quality, (3) excessive evaporation, and (4) uncertain cost-benefit analysis. It appears that high rates of injection or infiltration can be sustained for short periods of time based on observations by personnel of the U. S. Geological Survey (Welder and Reeves, 1962). But neither large infiltration rates over extended periods nor the effects of contamination on infiltration are known at this time. Small projects in Uvalde County provide only minor control on water quality with regard to suspended sediment and organic debris (logs and brush), and the long-term effect of plugging by sediment and debris is not fully understood. However, Green (1967) reported that sedimentation in Medina Lake had no notice-able effect on recharge. High evaporation rates in the western part of the area (fig. 5), where artificial recharge is most feasible, could cause excessive losses in large reservoirs; the Corps of Engineers (1964, p. 94) estimated that a 5,000-acre reservoir would experience evaporation losses of 15,000 to 23,000 acre-feet per year. The above problems may seem minor in view of the fact that no accurate estimates of artificial recharge for an economic analysis are available because of insufficient data. For example, benefits attributed to the small artificial recharge projects in Uvalde County are unknown (U.S. Army Corps of Engineers, 1964, p. III-24). Additional problems would exist if water quality becomes critical because water treatment is not included in proposed artificial recharge projects at this time. It is conceivable that the cost of impoundment and treatment of water for artificial recharge would make surface water storage economically more attractive than artificial recharge. Similar ideas have been expressed by Reeves (1969).

APPLICATION FOR LAND USE

A map of active processes in the southern Edwards Plateau would not by itself provide sufficient information for land use capability, but rather it would complement other maps prepared for that purpose. The nature and appropriateness of derived information can best be determined by specific situations; nonetheless, the following example is presented to demonstrate the utility of such a map.

The correlation between environmental geologic map units and active process map units is presented in figure 8. As shown, the active process units are derived almost entirely from the environmental geologic units with the exception of combining clay and the overlying low rolling limestone. Characteristics and limiting factors are as follows: (1) Karst development and solution are restricted to areas of thick-bedded limestone with low relief that exhibit karst features and have internal drainage (fig. 9). These are also sites of local recharge and therefore should be regarded as sensitive areas. The thin soil, which commonly overlies this unit, thickens slightly in some topographic depressions where impermeable clays associated with the soil form natural ponds. (2) Sheetwash and headward erosion are the principal processes on steep slopes where runoff predominates. Because of erosion, there is usually no soil and the surface is composed of bedrock on steepest slopes and rubble or

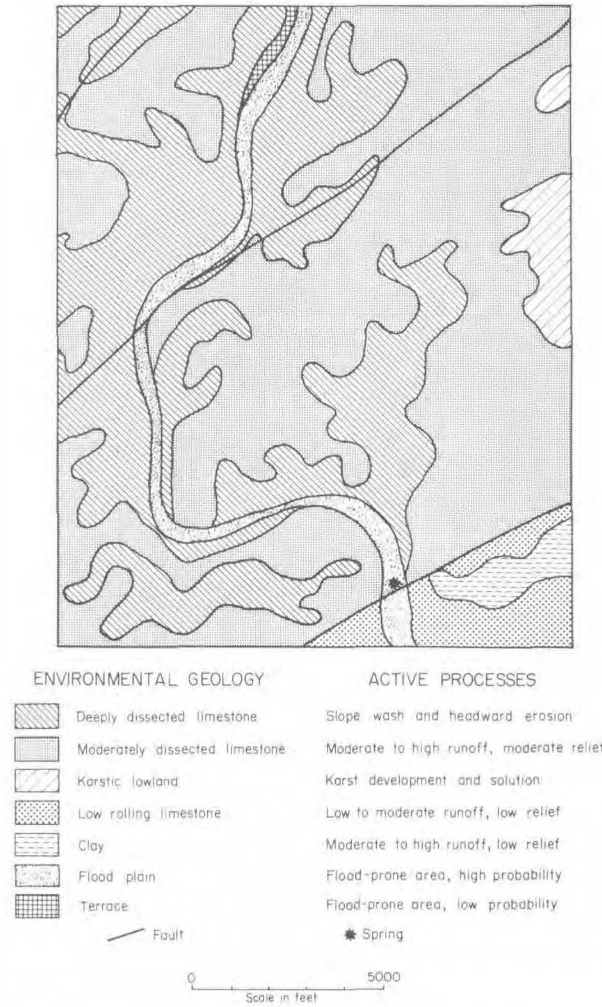

Figure 8. Relationship of environmental map units and active processes. Taken from the southeast portion of the Sattler, Texas quadrangle, Guadalupe River Basin.

caliche-cemented colluvium just above a slope break. As previously indicated, slope and lithology exert the greatest control on runoff and infiltration; as a result three other units are depicted from their slope and lithologic properties.

Thus areas of (3) low relief and low to moderate runoff differ from areas of (4) low relief and moderate to high runoff mainly in terms of rock type, the latter being associated with impermeable clay. Moderate to high runoff occurs on any slope, whereas low runoff is generally related to low slope and permeable lithology. The unit with low relief and low to moderate runoff is similar to the karst development and solution unit but it does not display sinkholes or internal drainage and it may be less susceptible to recharge.

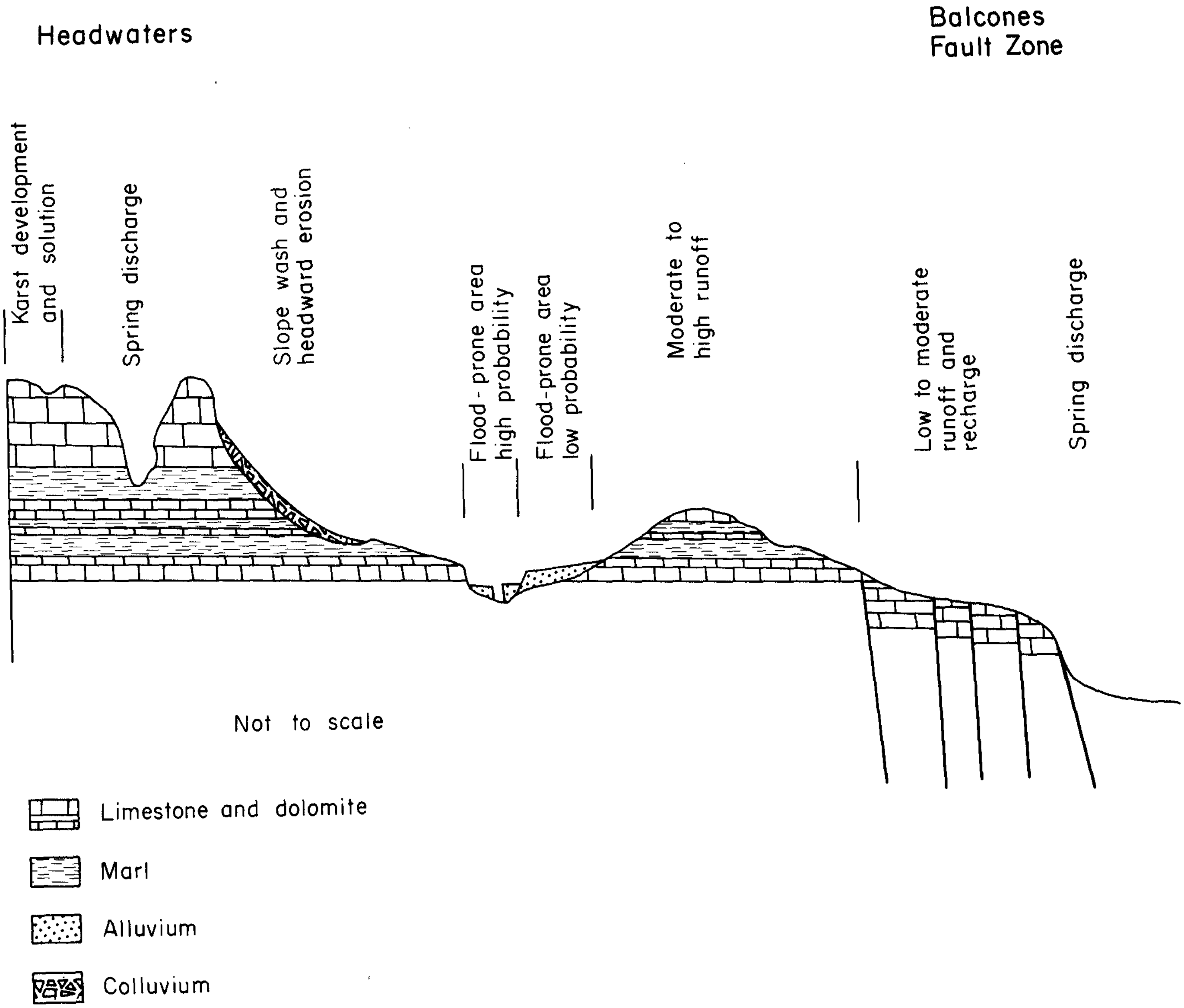

Figure 9. Generalized cross section showing the relationship of rock type, topography, and associated active processes.

The unit mapped as (5) moderate to high runoff with moderate relief is transitional with units 2 and 4. Erosion on these surfaces is proportional to their relief. The remaining units shown are (6) flood-prone area of high probability, and (7) flood-prone area of low probability. These units are somewhat similar in geomorphic form but differ in a statistical sense as well as in the overall land use. Areas subject to frequent flooding include the active channel and adjacent low-lying terraces. Fortunately, most of this area has not been developed for residential or commercial purposes, and it remains either in its natural state or as improved agricultural land. Soils from six inches to a few feet thick are common on both units where they include alluvial fans and terraces. The areas which are inundated infrequently include higher terraces and areas adjacent to surface drainage of alluvial fans emanating from the fault zone. The significant distinctions between the two flood-prone areas other than frequency of flood recurrence are the greater (1) areal extent, (2) importance as local aquifers, and (3) agricultural use of land falling under the low probability classification.

CONCLUSIONS

Use of the active processes map in conjunction with other thematic and derivative maps provides practical and concise information which enables the land use planner to make sound judgments as to the factors that should be considered during formative stages of land development. Obviously, flood-prone areas should be limited to uses which incur low economic losses as a result of flooding. In a similar fashion, areas of high ground-water infiltration, recharge, and discharge should be protected and construction should be discouraged on unstable slopes. Even though these are just a few of the many applications of the active processes concept, it should be emphasized that any decline in water quality throughout the southern Edwards Plateau can both directly and indirectly have a drastic effect on the fate of the Edwards aquifer.

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ENVIRONMENTAL GEOLOGIC MAPPING OF FLOOD-PRONE AREAS: AN ALTERNATIVE TO ENGINEERING METHODS

E. J. Dickerson[1]

INTRODUCTION

Environmental geologic mapping of flood-prone areas and its application toward preventing flood damage have become important in recent years. In the past, fluvial sediments were generally lumped as "Quaternary alluvium" or "overburden," and they were despised because they obscured bedrock geology. Definition and designation of areas likely to flood were generally left to engineers who used quantitative and statistical methods based on hydrologic data. These data were gathered, in many localities, over time intervals that were relatively short (Dowell, 1964).

Recently, there has been growing public awareness of the importance of geology in day-to-day and long-term land use planning. In environmental geologic mapping, flood-prone areas can be singled out as areas of real or potential hazard (Leopold, 1973). Certainly this mapping should be performed before residential or commercial development is undertaken.

Floods of catastrophic effect in 1972, such as in New Braunfels, Texas and Rapid City, South Dakota, and record spring flooding in 1973 in the drainage area of the Mississippi River remind us all too frequently that planners and developers do not always consider the destructive forces of nature. Areas of potential flood hazard can be mapped reliably using geologic criteria. This information must be made available for public use.

SCOPE

The need for mapping areas of potential flood hazard exists, but it is difficult to produce accurate and meaningful maps of hazardous areas using traditional geologic map units and engineering terminology. The difficulty is compounded if the concept of flooding is restricted to areas affected by stream channels.

"Flood" as used in this paper will include any sort of rising water. Specifically excepted are rising waters associated with, or interacting with, tides or storm surges in the Coastal Zone and overflowing man-made lakes or reservoirs. Coastal Zone flooding will be adequately covered by others. Geologic criteria alone generally cannot be applied to lake and reservoir flooding; hopefully, areas affected by reservoirs have already been studied adequately.

In this paper we will consider not only a "flood plain" map unit in the classical sense, but also a variety of flood-prone units. The morphology of flood-prone areas varies geographically with changing climate and geologic conditions. We will discuss criteria for environmental geologic mapping of flood-prone areas in a part of Southwest Texas. This geographic restriction carries with it further restrictions in climatic type and bedrock geology. The time available for mapping and a general lack of quantitative hydrologic data necessitate a qualitative treatment here. Indeed, the main point of this paper is that environmental geologic mapping is a valid alternative to gathering hydrologic data for evaluation of flood-prone areas. It is hoped that most of the criteria used in Southwest Texas can be applied in other regions.

SETTING

Texas has numerous large drainage basins (fig. 1) which cross areas of varying topography, bedrock geology, and climate. This paper pertains primarily to drainage basins south and southeast of the Balcones fault zone (fig. 2). These drainage systems originate in the topographically high Edwards Plateau that is composed mainly of carbonate rocks of Cretaceous age. Topographic relief from the Edwards Plateau surface to the adjacent upper part of the coastal plain is about 1,500 feet; this relief is largely structural in origin. Major streams emerge from the plateau and cross low-lying coastal plains that are developed on sandstones and shales of Tertiary age and that slope gently toward the Gulf of Mexico.

In general, the climate in Texas becomes less humid toward the west, ranging from 56 inches of precipitation per year along the Sabine River to 8 inches per year at El Paso. In the study area, average precipitation at the eastern part of the Guadalupe River Basin is 36 inches per year, whereas the western edge of the Nueces River Basin receives only 18 inches per year. Isohyets bend sharply westward along the upper coastal plains, indicating a narrow band of higher rainfall along the Balcones escarpment (Carr, 1967). All parts of the area are subject to episodes of violent weather that may produce torrential rainfall, yet any one storm cell may affect parts of only one or two drainage basins.

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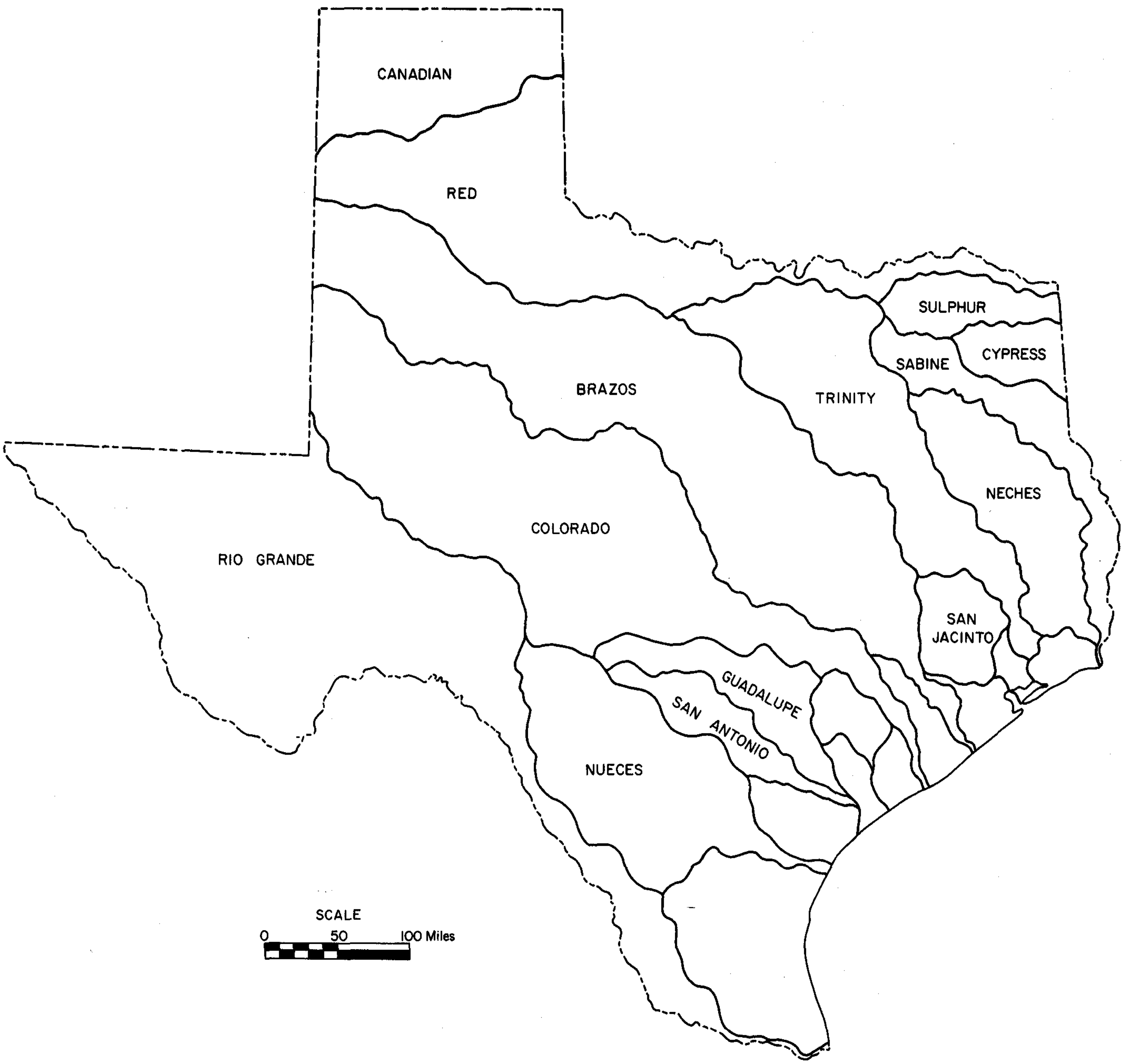

Figure 1. Major drainage basins of Texas (Texas Board of Water Engineers, 1958).

Figure 2. The Edwards Plateau-Coastal Plains boundary heads several drainage basins. Line pattern locates the Balcones fault zone and related escarpment.

The important point is that rainfall extremes in Southwest Texas are likely to be episodic and unpredictable. It is for this reason, and because hydrologic data have been gathered on relatively few streams, that environmental geologic mapping of flood-prone areas may well be the most reliable, rapid, and economical method. It is likely that many other regions with flood-prone areas will exhibit geologic criteria analogous to those seen in Southwest Texas.

METHODS: ENGINEERING AND GEOLOGICAL

Engineering

A complete, perhaps even an adequate, summary of hydrologic methods is beyond the scope of this paper. All levels of government, as well as private firms who use engineering methods, have developed a complex technology. This technology is well represented in the literature and in standard texts. It is generally adequate in flood evaluation (Breeding and Dalrymple, 1944; Dalrymple, 1939).

In general, engineering data are gathered using streamflow gages, flood-stage gages, reservoir-level gages, surveys, historical flood descriptions, and other means. In recent years computer technology has broadened engineering capabilities. It is now possible to study hydrological data more rapidly and in more ways. Perhaps the most important capability of all is the ability to develop mathematical models that permit evaluation not only of flood potential of rivers but also of secondary and tertiary back-flow effects of tributaries and effects of flood control, urbanization, and the like (L. E. Garner, 1973, personal communication).

Although various governmental agencies have regulatory and planning responsibility, they may be hindered by a lack of data. In Texas, permanent or long-term stream and reservoir gaging stations average less than two per county; these, of course, are augmented by topographic surveying and short-term gaging stations. But most data are gathered on large streams, and especially on those that affect more densely populated areas. Some reasons for this clustering are obvious: major streams produce the most destructive floods, urban areas have the most potential for disaster, and funding for studies is easily justified if expenses are reckoned on a per capita basis.

An example of a detailed engineering study is in urban Chicago, where flood-hazard areas were mapped and quantitative data gathered (Shaeffer and others, 1973). In the first phase of the study in the six-county area, costs per 7.5-minute quadrangle averaged \$6,975 and required 869 direct man-hours per quadrangle; this phase included emplacement of simple pipe flood-stage gages. Phase II involved mapping and application of Phase I data; this nearly doubled the cost. A third phase, yet to be completed, will involve further mapping, evaluation, planning, and administration, all of which will add to the ultimate cost. Clearly, this costly quantitative approach is neither economically feasible for mapping large nonurban areas, nor is it necessary.

An unfortunate aspect of quantitative data analysis is the tendency to extrapolate data locally, using methods or criteria developed elsewhere. It is likely that this is true in many areas of Southwest Texas where data have been gathered over relatively short periods. To define "10-year," "100-year," and "standard project" floods (U. S. Water Resources Council, 1972) is to define a flood frequency that cannot always be demonstrated. In Austin, Texas, in a setting essentially the same as in Southwest Texas, the location for the new Austin High School is ". . . defined by engineers as part of the 100-year flood plain. This site has been underwater an average of every 20 years" (Baker and others, 1973).

To summarize, engineering methods are desirable in long-term analysis of flood-prone areas, but they are both costly and slow, and tend to be concentrated in developed areas. These studies are generally restricted to specific areas or projects and are not readily extrapolated upstream or downstream. In addition, they may be misleading to engineers and beyond the grasp of nontechnical land use planners.

Geological

There are several methods that can be used in mapping flood-prone areas. Wolman (1971), in a discussion of flood-plain mapping, cited six methods, in increasing order of relative precision: physiographic, pedologic, vegetation, occasional flood (highest of record, major, recent major), regional flood of selected frequency, and flood profile and backwater curve.

He stressed that "uncertainty is inherent in the determination of the hydrology of the flood magnitudes and frequencies," and that hydrologists, recognizing the uncertainties, have developed the several methods to be used singly or in combination to meet given user needs or to meet increasing demands for flood data. He used the terms "flood plains" and "flood-prone areas" interchangeably and described only floods related to stream channels. The physiographic method is listed as the least precise, yet its proponents claim to be able to assess the frequency of floods associated with given features. Stated more accurately, specific topographic features, among them "flood plain," are defined on the basis of correlation with floods of known frequency and magnitude. A similar relationship exists in the other methods. That is, the methods are based primarily on flood data already gathered. A major drawback is obvious: flood-prone areas cannot be defined where data have not been gathered. Therefore, the methods as described are not suitable for regional studies in nonurban areas except for certain streams or drainage systems.

Environmental geologic mapping includes much of the methodology of the first four methods listed above; the geologist would substitute the broader term "geomorphologic" in place of "physiographic" used by the geographer. Although we can delineate many map units, we will discuss here only those that are subject to flooding as defined earlier. Mapping is done on aerial photographs—stereo pairs and controlled mosaics; unit boundaries are subsequently transferred to available topographic maps. Field checks and low-level overflights provide sufficient control to relate ground conditions to mappable units. The few published hydrologic data, particularly the highest recorded flood stages, are applied locally on major streams. There is not sufficient time available to pursue historical accounts of floods, and it is likely that some of these accounts would be distorted or exaggerated.

Geologic features related to flooding activity are discussed in detail in standard texts on geomorphology, physical geology, and photogrammetry. Perhaps, in defining flood-prone areas, the most important aspect of using geologic criteria visible on aerial photographs is the fact that visible geologic features related to flooding have taken a relatively long time to form. Geologic features produced during the development of drainage systems generally leave visible records that represent periods of from hundreds of years to tens of thousands of years. In this sense, one can think of a "time base" that is much longer than that provided by formal or informal human records of flooding events.

Environmental geologic mapping offers other advantages. It is relatively fast and inexpensive, making it possible to map hundreds of small streams and drainage systems for which no hydrologic data are available. Formal hydrologic studies may never be undertaken in large nonurban areas, nor are they necessary for mapping flood-prone areas.

In environmental geologic mapping, some recognizable units that are subject to flooding are not related to streamflow. Certainly these units are not candidates for hydrologic studies, but they are real problem areas in many localities.

Environmental geologic map units are summarized in table 1 and are schematically shown in figures 3 and 4. It should be emphasized that all units listed are subject to some type of flooding, particularly during episodes of heavy rainfall. Also, there are no size limits on any unit—a flood plain of a small creek may be only a few feet wide, while a less active swale may be a hundred feet wide. The units are ranked on the basis of visible evidence of flooding activity. In this sense, "activity" relates to both magnitude and frequency. Geologic criteria alone cannot be used directly to define either magnitude or frequency of flooding since, for example, areas in Southwest Texas that have not experienced flooding during historic times may yet be flooded on some of the units of lower activity.

Because of the episodic nature of rainfall in the project area, some of the units of relatively high activity may go for months, or even years without flooding. In other seasons, they may be flooded two or three times in a single month. It is certain that evidence of high activity is directly related to frequency, but we will make no effort to evaluate frequency of flooding for any map unit. The units are mapped areally on topographic maps; flood magnitude may thus be determined if necessary.

DISCUSSION

Environmental geologic mapping is no panacea—there are obvious drawbacks—but land use planners, individuals, architects, and engineers can readily use the maps. Undeveloped areas and areas in smaller communities can be evaluated at low cost. Priorities can be established quickly for more elaborate studies of locations being considered for development.

One aspect of using geologic criteria to define and map flood-prone areas is that some features visible now were created under no longer existing climatic conditions of the geologic past. For this reason, the method may be considered by some as being too conservative, in that fairly large areas may be relatively safe from flooding but may not be considered suitable for certain land uses. Along major streams for example, intermediate terraces

Table 1. Map units listed in decreasing order of flood activity and land use risk (see figs. 3, 4).

Code of Figs. 3, 4	Map Unit, Flooding Characteristics	Visible Characteristics	Suitability for Development
E	Flood plain—continuous low flow or active flow with measurable rainfall; high flow with intense rainfall	Scoured channels; point bar deposits, braided channels, terraces with visible evidence of flooding; generally brushy up to historical high water level; usually incised in bedrock or old alluvium in Southwest Texas	Not suitable; on large streams, road crossings and bridges should be carefully engineered
D	Low terrace—no evidence of flooding; may flood with unusually heavy rainfall	Terrace form; may be alluvium or, locally, alluvium-veneered bedrock; no visible flood evidence; generally undergoing dissection now; commonly vegetated	Generally not suitable except for pasture or light agricultural use
G	Swale—rising, running, or standing water with measurable rainfall	Generally dark tone, with low grasses or brush; some fairly straight, developing, with tributaries; others sinuous, apparently relict channels on alluvial plains	Not suitable except for pasture; many localities under heavy agricultural use, but crops are sometimes ruined
C	Intermediate terrace—very little likelihood of flooding even with heavy rainfall; may flood with catastrophic rainfall	Stand well above large stream channels; generally undergoing dissection along present streams	Marginal from the safety standpoint for building development; usable for pasture/agriculture if soil is suitable
F	Alluvial plain—standing water or sheetwash during heavy rainfall; little surface drainage	Broad, nearly planar except where dissected by active modern drainage; low slopes, generally well above flood plains and terraces of larger streams; swales common on most plains	Generally suitable for development, agriculture, most uses, but is poorly drained and building contents may suffer slight damage during heavy rainfall; local foundation problems caused by standing water
A	Interfluve—local sheetwash on slopes during heavy rainfall	Low rolling bedrock knobs on coastal plains; steep ridges to undissected bedrock in Edwards Plateau	Generally suitable from flood standpoint if standard architectural practices are followed

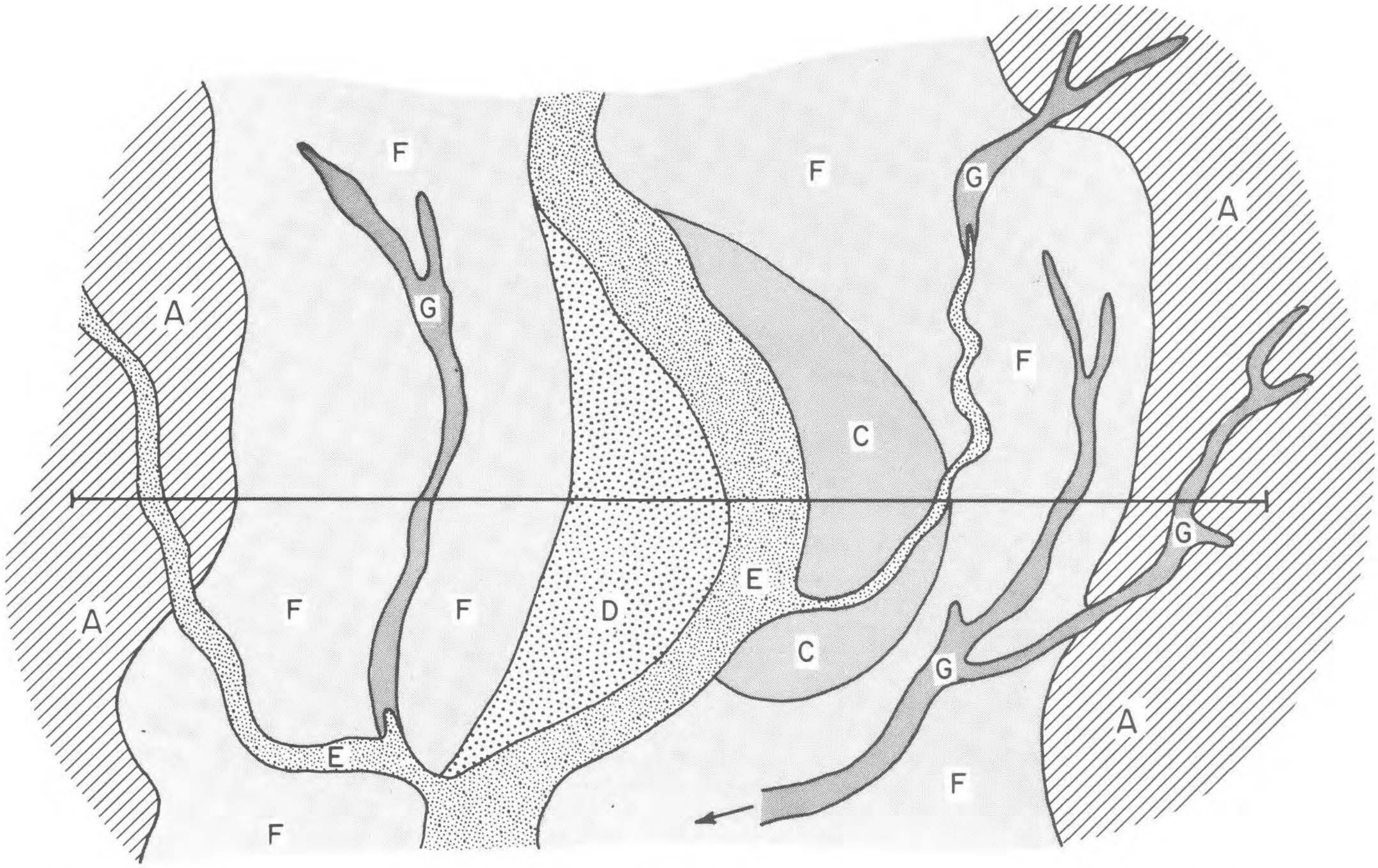

Figure 3. Schematic map of flood-prone environmental geologic units, mapped near the Frio River in coastal-plain sedimentary rocks. Not to scale. Refer to table 1 for description of map units.

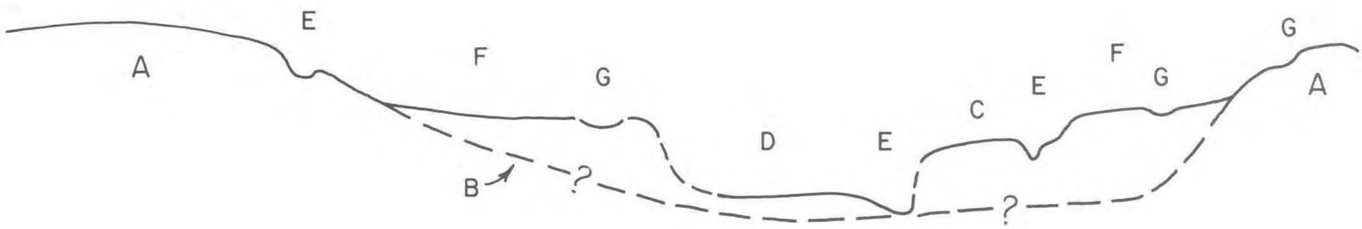

Figure 4. Generalized cross section from figure 3 showing relationship of environmental geologic map units. Not to scale.

are quite large and stand well above present incised channels in the project area. In all likelihood they were formed in Pleistocene time by streams that were much more active than are their modern counterparts. The user must decide to what degree he is willing to risk development, considering the worst combination of interrelated factors involving heavy rainfall, drainage basin land use, state of vegetation cover, and the like. Table 1 lists intermediate terraces as "marginal" for development. As a matter of record (U. S. Geological Survey, 1970), this unit has been flooded several times in the last 40 years, in places on the Nueces, Frio, Sabinal, and Blanco Rivers, on the Seco and Hondo Creeks, and on other lesser streams. Thus, the worst combination of factors involved in modern flooding can approximate the normal level of activity of the ancestral streams that formed the terraces. The wise or conscientious developer would not attempt to build permanent structures on this map unit, but could, with some confidence, use the areas for agriculture, livestock, and recreation areas or greenbelts. Other units of higher and lower risk can be evaluated similarly.

It must be emphasized that flood-prone areas, particularly in small drainage systems, may be significantly altered if the natural setting is sufficiently changed. Flooding of any unit may shift toward either greater or lesser activity. Examples of changes which can upset the level of activity indicated by geologic criteria include commercial or residential developments, land clearing, drought cycles, fire, reservoir building, or systematic flood control on tributaries.

Examples of Texas localities where flood activity has been shifted to lower levels, at least in theory, are New Braunfels, on the Guadalupe River, and Austin, on the Colorado River. Reservoirs on each river provide some degree of flood control, but in each area, too much reliance may have been placed on this control. Disastrous flooding occurred in New Braunfels in 1972 when extremely heavy rain fell in the drainage basin below the flood-control reservoir. Recreational, commercial, and residential buildings constructed on flood plain, low terrace, and intermediate terrace units suffered great damage. The geologic criteria defining areas of high hazard (table 1) were accurate in spite of flood control on the stream.

The Colorado River has an extensive system of flood-control reservoirs in its drainage system. Some have been in existence for more than 30 years and have been adequate in controlling floods on the river. In response to urban sprawl, many areas in Austin on low and intermediate terraces have been heavily developed. As stated above, geologic criteria alone cannot be used to evaluate flood potential for these terraces. Extended heavy regional rainfall in 1957 saturated the flood-control system and filled the "100-year flood plain." Since then, there has been extensive development of resort areas on all the reservoirs, causing greatly increased runoff. One can only wonder what will happen if similar rainfall conditions occur again.

Examples of areas where low-activity units have been shifted to higher levels are easiest to find. The communities of Hondo, D'Hanis, Sabinal, Knippa, and Uvalde, Texas are built on alluvial plains with low slopes; newer housing additions in some of the towns are on interfluvial areas. During rain showers of about one-fourth inch or more, streets and buildings cause ponding on the alluvial plains. On interfluves, gridded streets become effective drainage systems that may flood local areas and add to the flooding on the alluvial plains. Flood effects are minor, but sometimes are expensive, and occur simply because runoff has been increased greatly while the water has nowhere to go.

CONCLUSION

It is likely that most areas have not yet experienced the ultimate flood. If some have, it may not yet be apparent that such flooding has occurred. Existing hydrologic data may not have been collected over a period of time sufficiently long to properly evaluate past flooding.

Environmental geologic map units indicate areas that have been flooded at some time in the past. Those assigned high-risk categories probably will be flooded fairly often in the future; areas of intermediate risk may be subject to flooding under the worst combination of conditions; units assigned low-risk levels must be evaluated relative to flooding that is not necessarily associated with streams. In all categories, the land user would be well advised to consider what effects his use will bring about; he should also take notice of the works of others to see how his own plans will be affected.

As the Southwest Texas environmental mapping moves coastward, it is likely that the flood-prone units described here will be augmented, both by the addition of new units and by the recognition of more visible criteria to define units already named. It is hoped that the final maps will enable people in small communities, subdivisions, resorts, and rural regions to properly use areas subject to flooding without the necessity for a big-city or governmental budget.

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THE APPLICATION OF RADAR IMAGERY TO ENVIRONMENTAL GEOLOGIC MAPPING

P. Jan Cannon

INTRODUCTION

The purpose of this paper is to consider side-looking airborne radar imagery as a possible aid to the compilation of environmental geologic maps and for the periodic updating of completed maps.

Side-looking airborne radar (SLAR) has been promoted as a remote sensing technique with great but unproven possibilities. Radar is an acronym devised from radio detection and ranging. It is an active system which means that it generates the energy that is ultimately recorded. Taking normal photographs in the dark with a flash bulb is an example of an active system. Of all the operating imaging sensors, radar operates at the longest wavelengths and the lowest frequencies. The wavelengths most commonly used for imaging radar systems are between 0.86 cm and 3.3 cm (table 1).

Table 1. Commonly used radar bands.

Bands	Frequency	Wavelength
P	300 MHz	1 meter
UHF	300 MHz - 1 GHz	1 meter - 30 cm
L	1 - 2 GHz	30 - 15 cm
S	2 - 4 GHz	15 - 7.5 cm
C	4 - 8 GHz	7.5 - 3.75 cm
X	8 - 12.5 GHz	3.75 - 2.4 cm
$K\mu$	12.5 - 18 GHz	2.4 - 1.67 cm
K	18 - 26.5 GHz	1.67 - 1.13 cm
K_α	26.5 - 40 GHz	1.13 - 0.75 cm
$M\mu$	40 GHz	0.75 cm

One Gigahertz (GHz) is equal to 10^9 cycles per second and one Megahertz (MHz) is equal to 10^6 cps. The wavelengths most commonly used for imaging radar systems are between 0.86 cm and 3.3 cm.

The radar frequencies range from 36.0 Gigahertz (GHz) to around 10.0 GHz. One Hertz is equal to one cycle per second and one GHz is equal to 10^9 cps. The present-day radar systems use only a single wavelength of great spectral purity which means the systems are monochromatic.

Radar imagery is a spatial display of the relative differences in returns of radar energy from surface features. It should be kept in mind that although the radar imagery gives the appearance of a black-and-white photograph with low illumination, it is not a photograph, but an electronically constructed image of the various ways in which surface features reflect the radar energy. Some of the advantages of radar imagery are listed in table 2.

Table 2. Some advantages of radar imagery.

1. Technique is independent of weather and time of day.
2. Affords much greater areal coverage than cameras, like the aerial metric cameras, carried at the same altitude; provides a different perspective.
3. Does not produce the foreshortening or convergence effect seen in oblique aerial photographs.
4. Saves time and money in some cases due to the increased areal coverage per flight-line mile.
5. Commonly shows more stream detail than a topographic map at the same scale (this depends upon the system used).
6. Can provide quantitative geomorphic data.
7. By use of a synthetic aperture antenna system, radar resolution is (theoretically) rendered independent of height of the aircraft above the terrain.
8. Data can be stored on magnetic tape.

The radar imagery used in this study was obtained by both real and synthetic aperture (K-band) systems. Real aperture refers to radar systems using the physical size of the antenna to determine the region of ground that is discriminated by the beamwidth. Synthetic aperture radar systems use only a part of the beamwidth; the signals returned are stored, and then processed in the same way that a physically larger antenna would process them. In other words, the returned signals are electronically interpreted to the sum equivalent of the same return as would be received by a physically larger antenna. The imagery provided by the real aperture (K-band, see table 1)

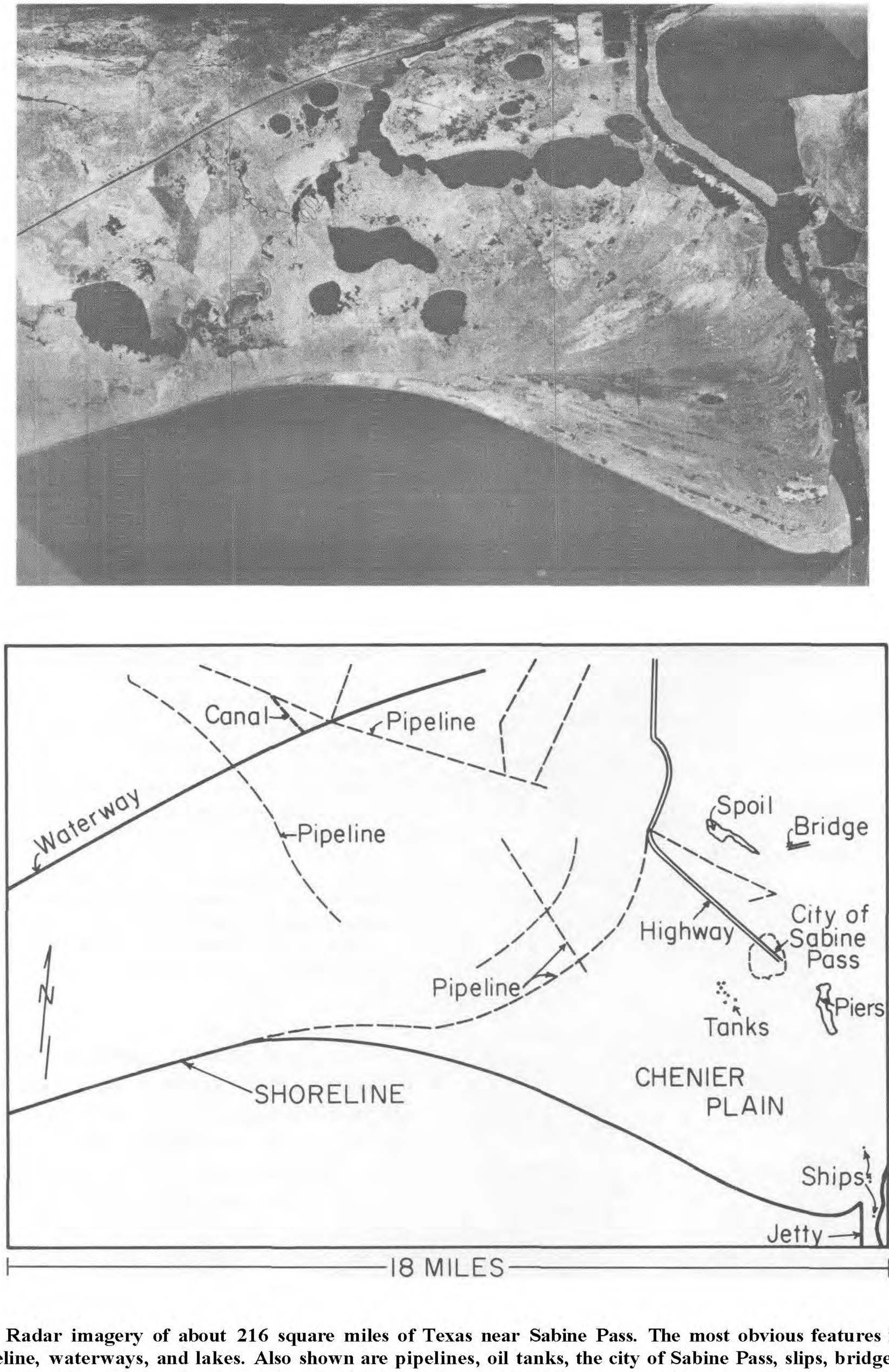

Figure 1. Radar imagery of about 216 square miles of Texas near Sabine Pass. The most obvious features in the imagery are the shoreline, waterways, and lakes. Also shown are pipelines, oil tanks, the city of Sabine Pass, slips, bridges, spoil banks, roads, and beach ridges on the chenier plain. The jetties at the mouth of the pass are shown and the bright points in the pass are ships.

system is considered to be the optimum source of information for environmental geologic mapping because of its greater dynamic range relative to the synthetic aperture system and more useful resolution. Therefore, only data from real aperture systems are presented with this paper.

ENVIRONMENTAL GEOLOGIC MAPPING

Environmental geologic mapping is the major tool to employ in an approach to understand the natural environment and to confront environmental problems. The Texas Bureau of Economic Geology is constructing environmental geologic maps of large portions of the State in order that the potential problems caused by increased population and development can be confronted with adequate information for planning and management. The Texas Coastal Zone has been mapped and portions of South-Central Texas are currently being mapped.

COASTAL ZONE MAPPING

The units on an environmental geologic map are the components of natural systems and man-made features. In the Texas Coastal Zone the natural units that have been previously mapped from interpretation of aerial photographs and that can be delineated on radar imagery are those with some obvious physical characteristics such as stream channels, lakes, lagoons, barrier islands, tidal creeks, tidal inlets, and cheniers (beach ridges). All land-water contacts, the coastline as an example, appear extremely sharp on radar imagery due to the strong contrast in reflective properties of the land and water. Forested areas and grassflats can be discerned but tree type can only be inferred.

Figure 1 is radar imagery of about 216 square miles of Southeast Texas west of Sabine Pass. The radar imagery demonstrates how the physical characteristics of water-related features on the chenier plain are evident because of the enhancement of the low relief and the linearity of vegetation and minor lakes. Natural features of the coastal plain are also shown in the radar imagery of the Clear Lake area on the west side of Galveston Bay (fig. 2). The cultural features around Clear Lake are well exemplified in the imagery. The Johnson Space Center, Ellington Air Force Base, a large tank farm, and the high-tension towers are the most outstanding man-made features.

MAPPING AREAS WITH MODERATE RELIEF

Figure 3 is radar imagery of part of the city of Austin. Using the imagery as a source of information, the city of Austin could be zoned as to the Capitol complex, The University of Texas campus, urban, and metropolitan areas. Major features like the airport, shopping centers, parks, and schools can be located also. The relief of the area along the eastern edge of figure 3 is enhanced on the radar imagery, making the hills and valleys along Barton Creek show up well.

The Central Texas Hill Country provides a better setting for application of radar imagery to the identification and mapping of natural environmental units than does the Coastal Zone. Figure 4 is radar imagery of an area along the Guadalupe River in the Hill Country. The rugged topography of the area is enhanced in the imagery and various units can be isolated, based on the differences of local relief. The natural environmental units such as the moderately dissected terrain and the deeply dissected terrain can be mapped. Physical features such as stream terraces and flood plains are easily recognized. Detailed drainage nets and structural lineaments, which cannot be discerned on the radar imagery of the Coastal Zone, show up well on the imagery of the Hill Country.

SUMMARY

Using SLAR, man-made features are readily identified in any natural setting. Water-associated features such as harbors, ship channels, spoil banks, piers, jetties, ships, bridges, and seawalls show up best. Cities, urban and residential areas, parks, sports arenas, and industrial complexes, along with support systems, sewage disposal plants, water treatment sites, major highways, railroads, large high-tension towers, and airports can be identified. Individual railroad cars can be located as well as the tracks. Other features such as tank farms, quarries, and cemeteries can also be located and inventoried.

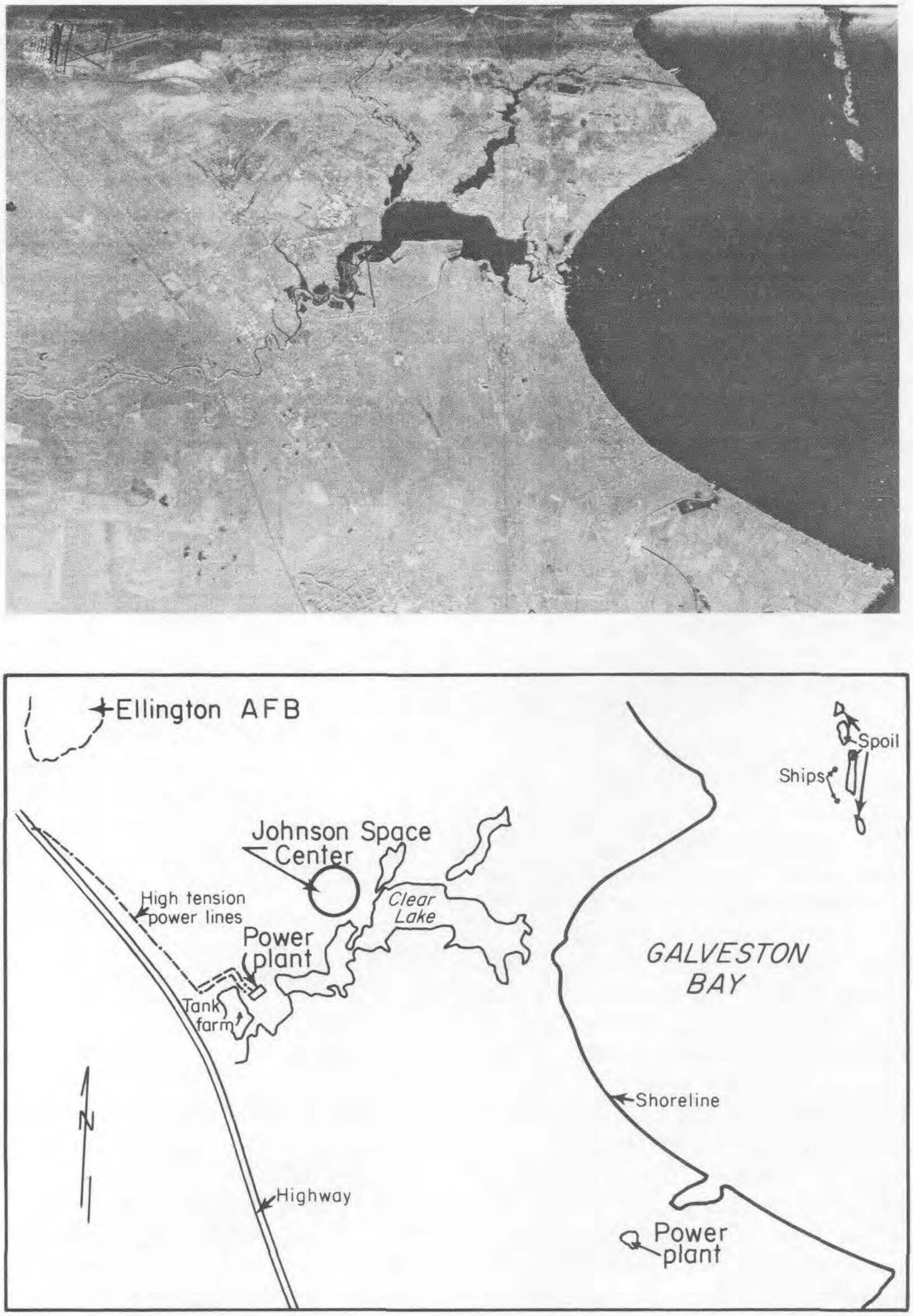

Figure 2. Radar imagery of about 200 square miles of Texas around Clear Lake. The complex of buildings at the Johnson Space Center provides excellent returns of the propagated radar energy. The high-tension towers that carry power from the various plants are distinctive because of their pattern as are the petroleum tanks.

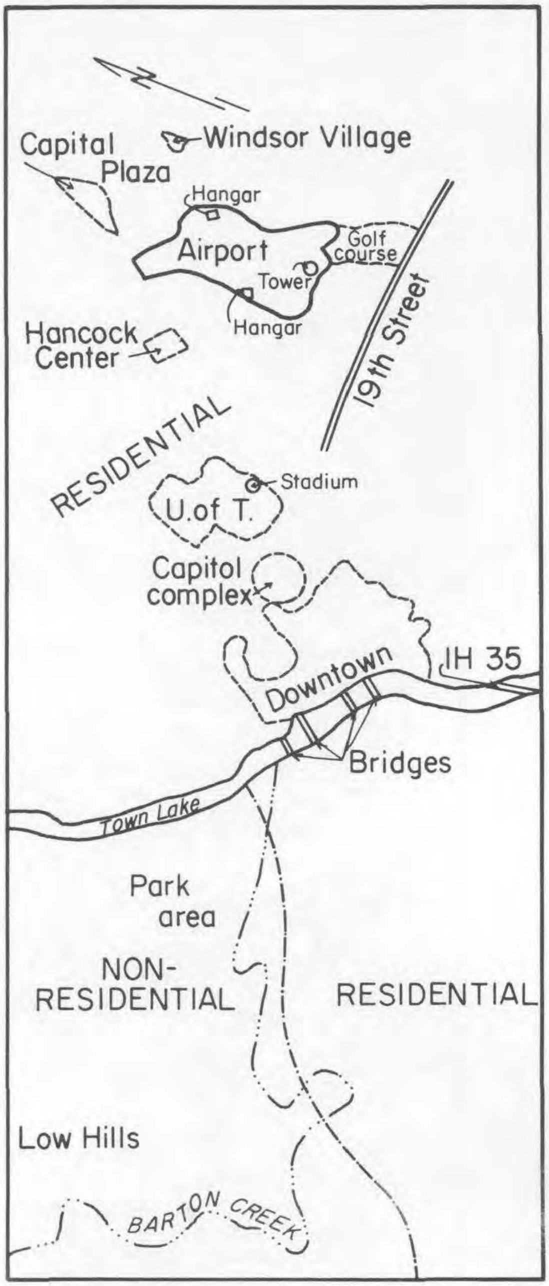

Figure 3. Radar imagery of the heart of Austin, Texas. Individual metropolitan features can be easily identified. The high-return areas in the center of the image are due to the large buildings of downtown Austin, the Capitol complex, and The University of Texas, which reflect large amounts of the propagated radar energy back to the aircraft.

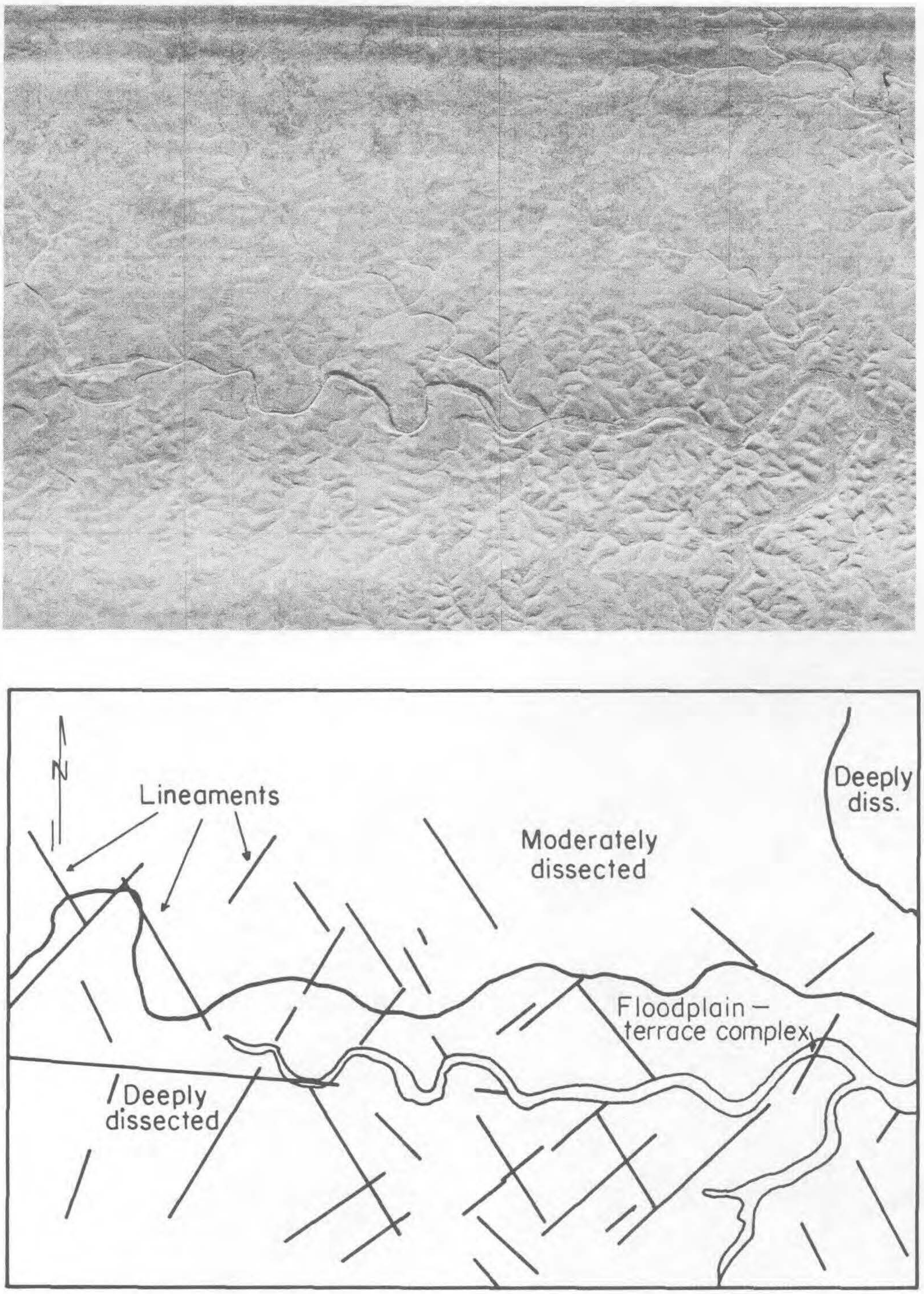

Figure 4. Radar imagery of the Texas Hill Country along the upper reaches of the Guadalupe River. The natural environmental units such as the flood plain-terrace complex, the moderately dissected terrain, and the deeply dissected terrain can be mapped. Numerous structural lineaments can be located and detailed drainage nets can be drawn on this imagery.

Radar imagery is an adequate tool to use in the mapping of natural environmental geologic units where the topographic relief is great enough to provide discrimination of physical characteristics, and where changes in vegetation can be differentiated. In mapping large regions, radar imagery would be less expensive than photographic coverage of the same area, and it would take less time to map from radar imagery than it would from low- or intermediate-altitude aerial photographs. Aerial photographs must be viewed stereoscopically in order to observe what can be seen with the unaided eye on radar imagery, hence the difference in map compilation time. Radar imagery would be more advantageous for the mapping of natural environmental units than would conventional aerial photography in areas similar to the southwestern United States, or in any area where the relief is greater than 100 feet and the natural units cover large areas.

The best application of radar imagery in environmental geologic mapping is in location and identification of man-made features. It would provide the least expensive method of monitoring the growth and development of environmentally significant man-made features over areas of several hundred square miles. The effectiveness of radar imagery in environmental geologic mapping is dependent upon the physical properties (relief and extent) of natural features and the reflective nature of man-made features.

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ADAPTING BIOLOGIC ASSEMBLAGE DATA FOR ENVIRONMENTAL NEEDS

E. G. Wermund and Claudia True Waddell

INTRODUCTION

Environmental mapping has become an established tool for providing planning and management data. To be of maximum use, these management data should include an inventory of all natural resources, their location, and their composition. An integral part of these natural resources is the endemic biologic assemblage.

A Soil Conservation Service series of publications on grassland restoration (Passey, H. B., and Hicks, V. M., 1970; Passey, H. B., and Smith, H. N., 1966; Rechenthin, C. A., Bell, H. M., Pederson, R. I., and Polk, D. B., 1964; Rechenthin, C. A., Bell, H. M., Pederson, R. I., Polk, D. B., and Smith, J. E., 1965; Rechenthin, C. A., and Smith, H. N., 1967; and Smith, H. N., and Rechenthin, C. A., 1964) makes clear the great value of one natural resource—the productive grasslands for grazing. The value of forest land and its products is readily appreciated. Also, the wild animal population of a region is a valuable resource. Along the seacoast, varied environments include the spawning grounds and food chains for both brackish and marine fauna which ultimately become a significant source of commerce—the harvesting and selling of oysters, shrimp, and fish. In the uplands, the wild game population provides an important recreation for many hunters; in Texas, money acquired from game leases is frequently a major income for ranchers with marginal incomes.

The objectives of the following discourse include: how the biologic assemblages are identified; where sources are located for gathering the data; ways of collating biologic data with environmental units; and the construction of the final product—a biologic assemblages map. Examples will be drawn from the (1) estuarine, (2) arid, wind-dominated coastal plain, (3) upland forest, and (4) hill country regions (fig. 1).

GATHERING THE DATA

It may seem strange that the mapping of plants and animals becomes the responsibility of a geologist. Yet this is what happens. It is the rare geologist who can identify all the living floral and faunal species in diverse areas. But, it is also the rare botanist or zoologist who has a mapping concept, especially a regional concept, for inventorying floral and faunal problems. For example, state maps showing the gross distribution of plant or animal assemblages are nearly unique on a scale useful for planning.

According to Kuchler and McCormick (1965), only two states have vegetation maps useful for state planners. California has twenty-three 15-minute quadrangles mapped at 1:62,500, and Michigan has eight counties mapped at 1:63,360. Most states have maps with as few as three and as many as 18 vegetation types mapped on scales ranging from 1:8,000,000 to 1:1,000,000. Five have no vegetation maps of their state.

The geologist must depend on the botanist and zoologist to identify each ecosystem or assemblage of coexisting plants and animals. The life scientist must also describe the niche occupied by each ecosystem including climatic limits and geographic ranges. Presently, the most helpful assistance is provided by an applied biologist, often a government employee, who is concerned with maintaining a deer herd, providing game fish, or developing a commercial food base. From this information, the geologist can assess the importance of elevation, slope, and substrate or a soil as determinants governing the distribution of each biologic assemblage. It is then a matter of translation to extend the areal ranges of known biologic assemblages.

Direct sources identifying biologic assemblages and listing local flora and fauna include publications and files of the Texas Parks and Wildlife Department and the U. S. Department of Agriculture, Soil Conservation Service. In addition, regional descriptions of flora like those of Blair (1950) and Tharp (1926) are essential.

Indirect sources include formats from which biologic assemblages can be interpreted, given other information. The major indirect sources which the Bureau of Economic Geology has used for constructing biologic assemblages maps include:

1. U. S. Geological Survey Topographic Quadrangle Maps
2. U. S. Coastal Geodetic Survey Bathymetric Charts
3. Aerial Photography
    a. Black-and-white controlled mosaics—1:24,000 and 1:120,000

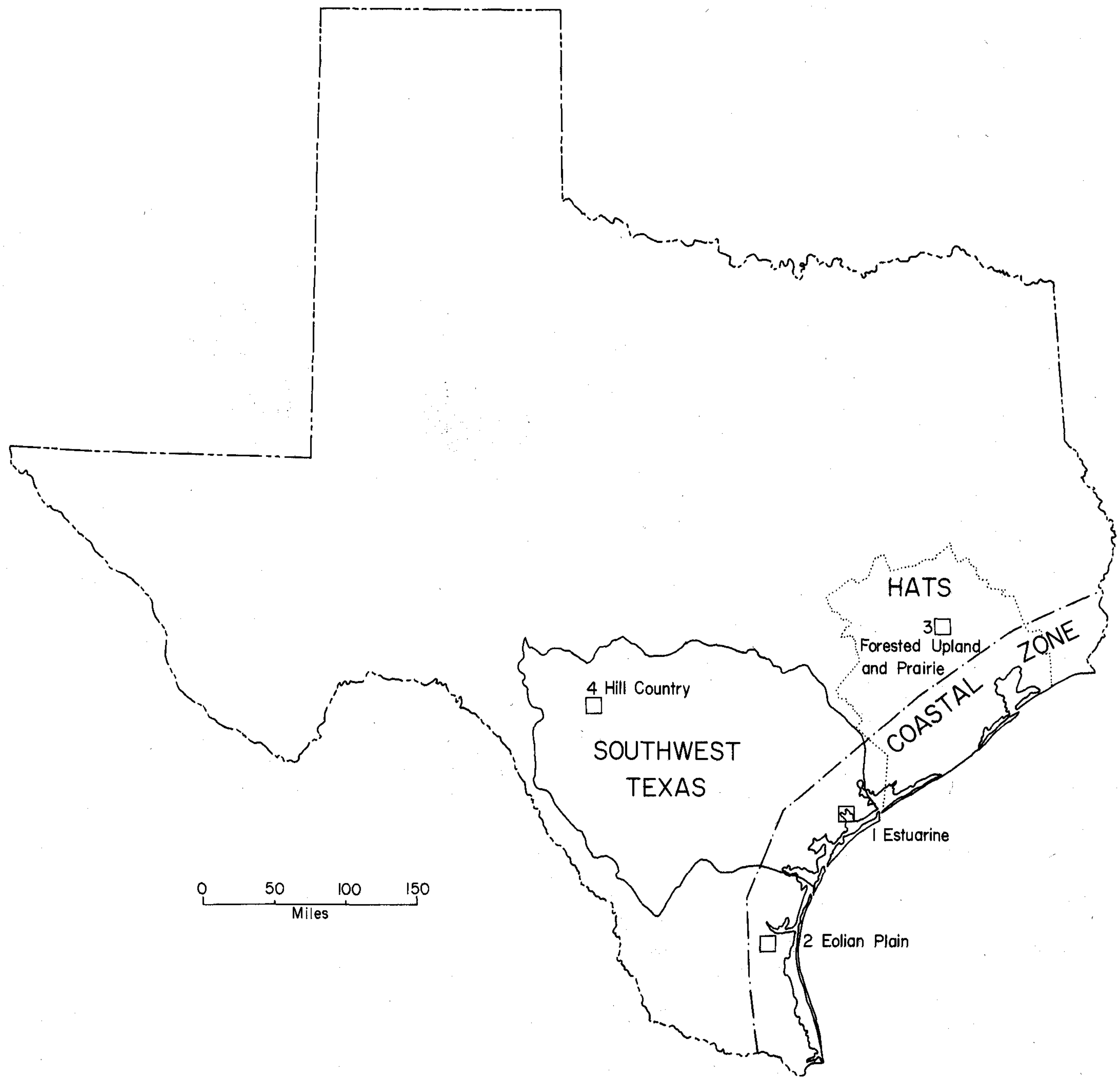

Figure 1. Map of Texas showing the location of the Coastal Zone, HATS area, and Southwest Texas region where biologic mapping has been completed. Also shown are four areas for which biologic assemblages maps are derived in this paper.

b. Black-and-white stereoscopic prints—1:10,000, 1:20,000, 1:40,000, 1:65,000, and 1:125,000
c. Color infrared stereoscopic prints—1:120,000

EXAMPLES OF BIOLOGIC ASSEMBLAGE MAPPING

The intent of our biologic assemblage mapping is to develop regional maps. Therefore, a first step is to order the factors determining distributions of flora and fauna. The major factors controlling the distribution of subaerial biota are climate including the availability of water, elevation, and substrate. In wetlands, both water depth and water chemistry are critical.

Looking at the following isolated examples of small areas, it may be difficult to see regional controls. However, note that two examples are from Southeast Texas, a region of high rainfall, whereas the other two examples are from low rainfall areas—one near Kingsville and one near Uvalde. The flora are more complex in the higher rainfall areas. All but one of the examples occur in low-relief terrains.

Estuarine Environment

In developing biologic assemblages maps for estuarine environments of the Texas Coastal Zone, Fisher and others (1972) made considerable use of the bathymetric charts of the U. S. Coastal Geodetic Survey. For example, figure 2 shows a biologic assemblages map of a portion of San Antonio Bay in South Texas with a bathymetric chart of the same area.

The biologic assemblages of the estuary are listed in table 1. The critical factors determining their distribution are height above and depth below sea level substrate, and salinity of the water in which the plants and animals live. This information may be inferred from bathymetric and topographic maps (figs. 2A and 2B). The oyster reefs, including dead shells of the reef flank, occur in bay waters generally less than 3 fathoms deep. Living reefs appear in water less than 1 fathom deep and could be mapped on very detailed bathymetric charts. Upper parts of spoil banks protrude above sea level. Salt-water marsh occurs nearly at sea level. A good preliminary map displaying an estuarine biologic assemblages map can be made rapidly from a bathymetric chart and map accuracy readily improved in a reconnaissance field check.

Table 1. Biologic assemblages observed at the confluence of the inland ship channel and the delta of the Guadalupe River in San Antonio Bay (after McGowen and others, in preparation).

REEF:
Abundant *Crassostrea virginica* (oyster); *Anomia, Brachidontes, Diplothyra* (clams); *Anachis, Mitrella, Thais, Crepidula* (snails); *Cliona* (sponge); *Balanus* (barnacle); bryozoans; *Crangon* (crustacean)

REEF FLANK AND MARGIN:
Clumps of *Crassostrea virginica,* broken shell, *Callinectes sapidus* (blue crab)

BAY WITH RIVER INFLUENCE:
Rangia, Macoma, Crassostrea, Petricola (clams); **Littoridina** (snail); *Callinectes, Macrobrachium,* (crustaceans)

BRACKISH- TO FRESH-WATER MARSH:
Spartina spartinae (coastal sacahuista), *Spartina patens* (marsh hay cordgrass), *Spartina cynosuroides* (big cordgrass), rare *Spartina alterniflora* (cordgrass), *Scirpus* spp. (bullrush), *Typha latifolia* (cattail), *Juncus* spp. (rushes); nutria, muskrat, rare mink, snakes, water fowl

SALT-WATER MARSH:
Spartina alterniflora (cordgrass), *Salicornia perennis, S. bigelovii* (glasswort), *Suaeda* spp. (seepweed), *Batis maritima* (maritime saltwort), *Borrichia frutescens* (sea-oxeye); water fowl

VEGETATED FLAT:
Andropogon littoralis (bluestem); *Uniola paniculata* (sea-oats), *Paspalum monostachyum* (Gulf-dune paspalum), *Cenchrus incertus* (coastal sandbur), *Galactia* sp. (milk-pea), *Senecio* spp. (groundsel), *Iva ciliata* var. *annua* (sumpweed); marsh plants such as *Salicornia bigelovii* (glasswort), *Spartina alterniflora* (cordgrass); *Ocypode* (ghost crab); rodents, snakes, fowl

FRESH- TO BRACKISH-WATER BODIES:
Marsh plants *(see* marsh); *Littorina, Neritina* (snails); *Uca, Cambarus* (crustaceans)

CHANNEL

SPOIL:
Barren

Arid, Wind-Dominated Coastal Plain

This example shows the derivation of a biologic assemblages map from an environmental geologic map in a low-relief area, about 30 miles southwest of Kingsville (fig. 1). Maximum relief in the area is approximately 20 feet; the highest contour equals 45 feet, whereas the lowest contour is 25 feet.

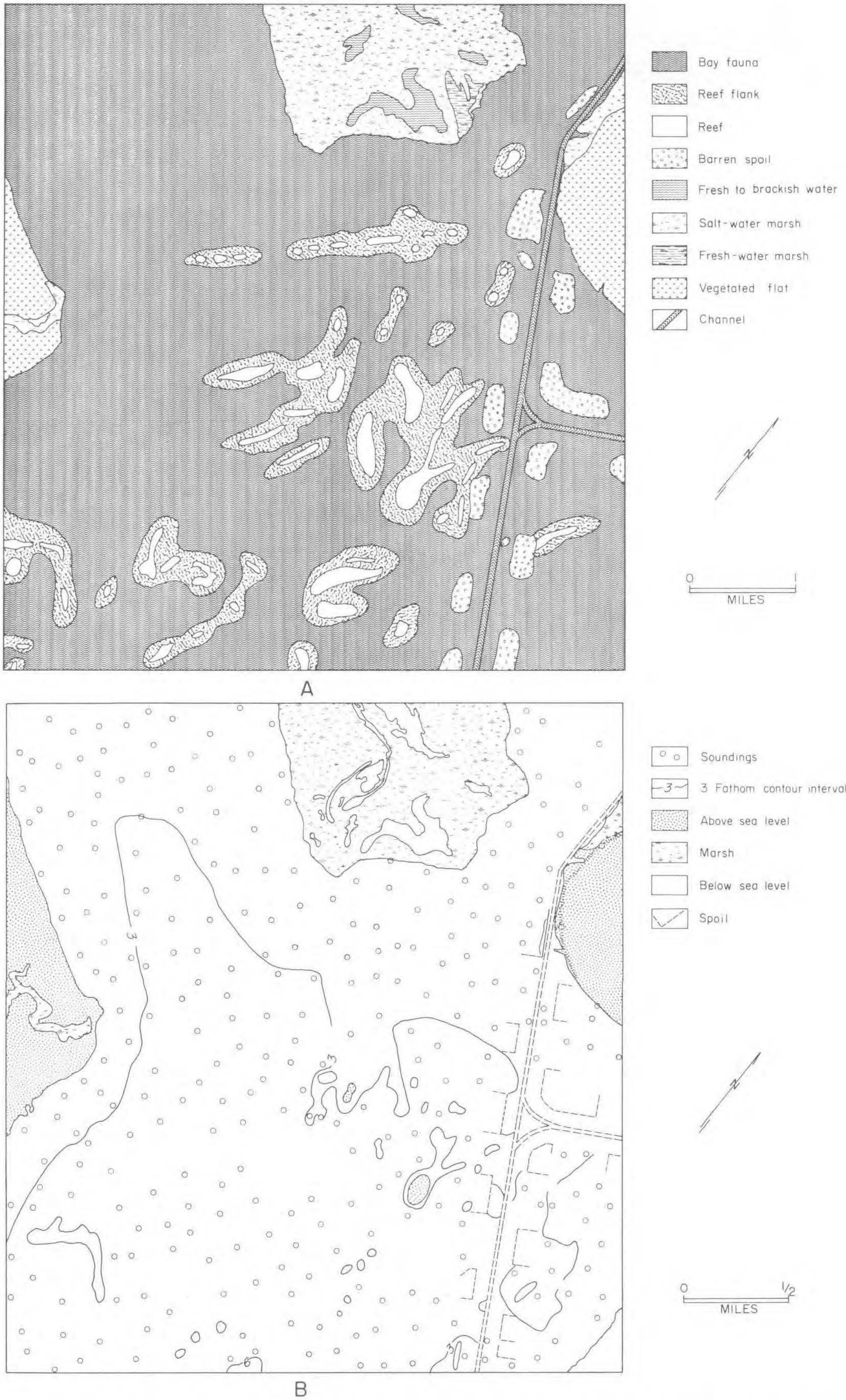

Figure 2. (A) Biologic assemblages in San Antonio Bay at the mouth of the Guadalupe River delta where the major control for interpreting biologic distribution is (B) A bathymetric chart of the U. S. Coastal Geodetic Survey.

Table 2. Equivalency of environmental and biologic units in a part of the wind-dominated coastal plain.

ENVIRONMENTAL GEOLOGIC	BIOLOGIC
Active dune complex, sand, commonly banner dunes, locally barchan dunes Barchan dune orientation	Active dunes, coppice dune, blowouts, back-island dunes, inland dunes, barren, relief 3 to 40 feet, rodents, snakes
Active dune blowout areas, sand, local depressed relief, eolian grain prominent, hummocky, locally fresh-water marsh in wet seasons Sand sheet with strong relict grain of base-leveled dunes, sparse grass Sand and loess (silt) sheet with no relict grain, sparse grass	Loose sand and loess prairies, bunch grasses, commonly overgrazed, scattered oak mottes, fresh-water marsh in blowouts and depressions in wet cycles, rodents, mammals, snakes, fowl
Moderately stabilized dunes, sand and loess (silt) sheet, brush-covered	Brushland, moderately stabilized dunes, inactive clay-sand dunes, some loess deposits, mesquite, chaparral, other scrub, distinctive grasses, cactus, game, fowl, climax vegetation
Well-stabilized dune sands, dense live oak mottes and scrub	Live oak mottes, stabilized sand dunes and ridges, hummocky, dense moderate to dwarf oak, distinctive grasses, fowl, abundant game, climax vegetation
Sand and loess (silt) sheet deflation area, active, grass, high water table, occasionally flooded, poorly drained	Poorly drained depressions, sand substrate, shallow water table, occasionally flooded, seasonal high-moisture plants, transitional with loose sand prairie plants
Clay-sand dunes, accretionary, active, locally sparse grass, wind-tidal flat or playa source common	Eolian ridges and active clay-sand dunes, accretionary, intense wind, salt-tolerant grasses, snakes

Mean annual rainfall is about 25 inches, and the same area has a high evaporation rate. The area is dominated by eolian processes moving relatively fine materials northwestward. The environmental geologic map (fig. 3) was interpreted from black-and-white 1:24,000 controlled aerial photomosaics and from some black-and-white stereo aerial photography. To a lesser degree, the aerial photography supplemented biologic interpretation.

The equivalency of environmental geologic and biologic units is shown in table 2. In this instance, six biologic units are derived from nine environmental units (fig. 3). Greater or lesser generalization may be warranted in deriving the biologic units for biologic assemblages maps of other areas (*see* fig. 4).

According to Johnston (1955), there are two parameters that directly affect the distribution of vegetation in the eolian coastal plain. They are elevation and substrate composition. Substrate composition indirectly influences moisture available to plants in that clay soils tend to hold moisture while sandy soils do not. Examples are: (1) elevated and stabilized dune sands have mature stands of live oaks and sparse grass; (2) loose sand at a low elevation supports sparse brush and grass *(Borrichia, Batis, Monanthocloe)*; and (3) moist clay substrates are dominated by bushy thickets *(Celtis laevigata, Acacia farnegiana, Acacia schaffneri)* and coarse bunch grass. Johnston also points out that although mesquite normally likes clay-dominated soils, there are now no mesquites within the range of salt spray blown inland from the Gulf and bays.

Upland Forest and Prairie

Upland forest and prairie, two miles south of Conroe (fig. 1), include an area elevated above the recent coastal plain that receives 50 inches of rainfall annually. The area is inland of the influence of both airborne salt and major winds of hurricanes. By coincidence, the area is now a critical area of land use because of the construction of numerous large housing developments. The location within 45 minutes of downtown Houston

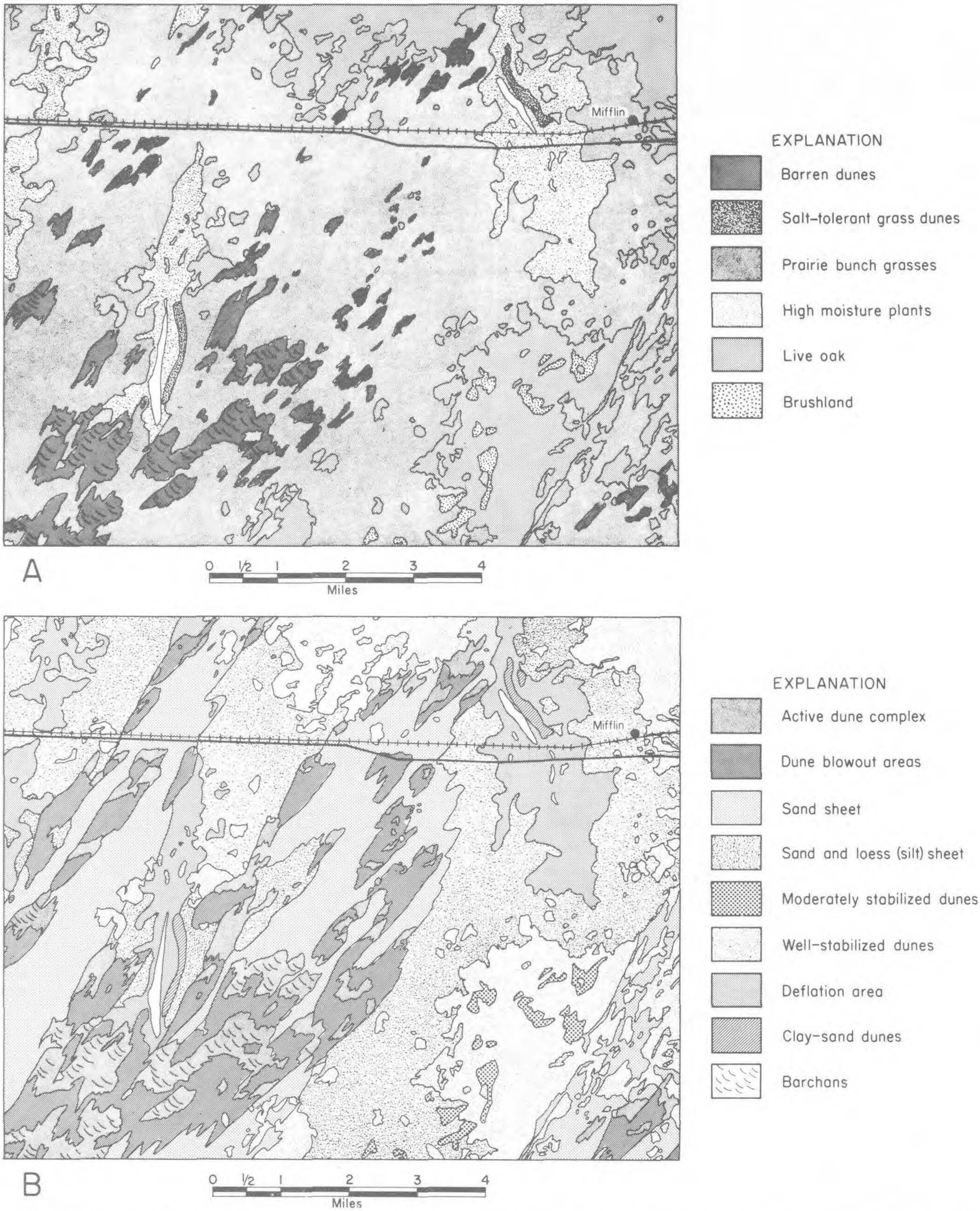

Figure 3. (A) Biologic assemblages in eolian plain near Kingsville, Texas as derived from the (B) environmental geologic map of the same area (after Brown and others, in preparation).

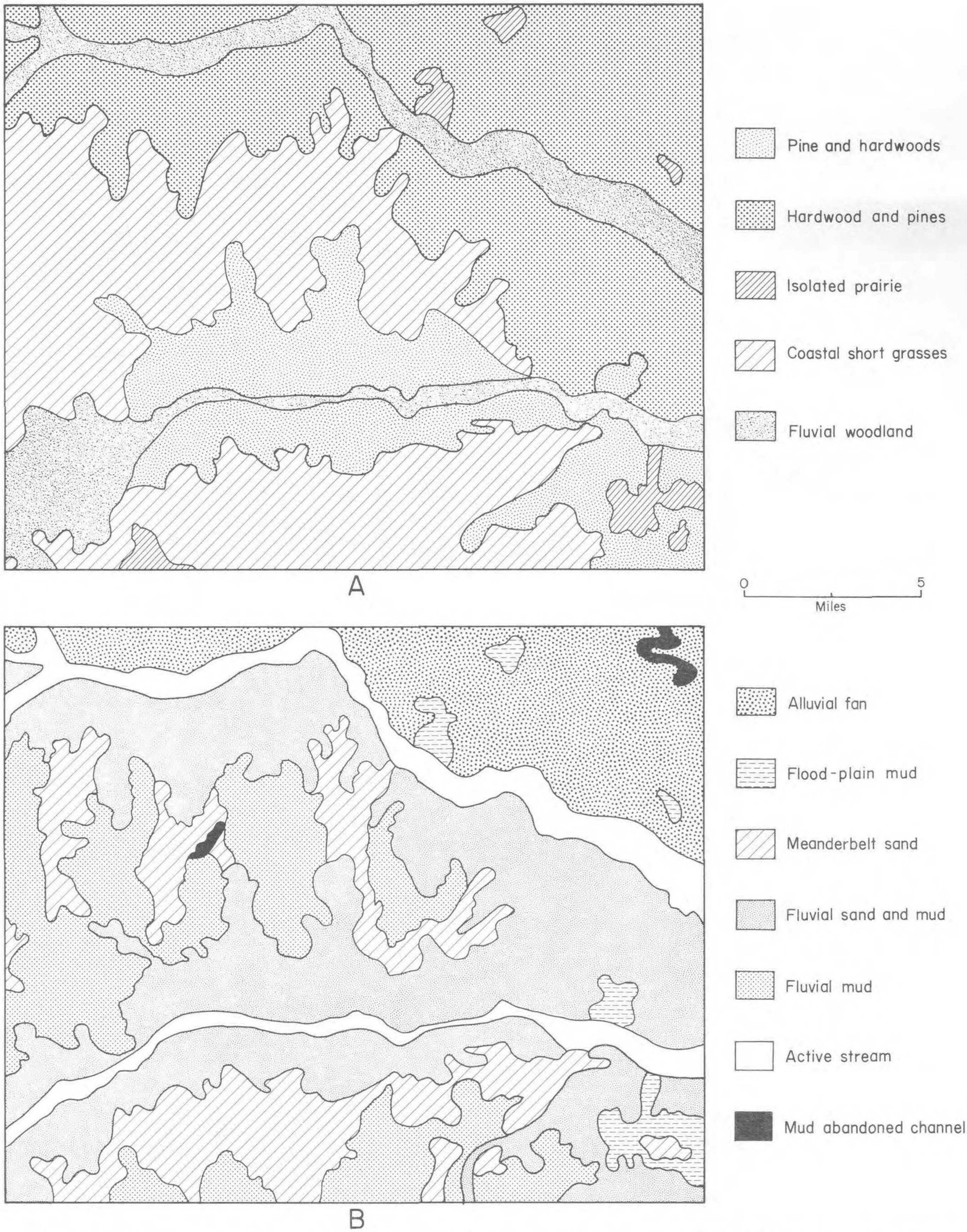

Figure 4. (A) Biologic assemblages in a forested area as derived from the (B) environmental geologic map of the same area for which color infrared photography is available.

via interstate highways, the beauty of its vegetation, and its greatly sculptured terrain give the land a high real estate value. Several large housing developments are completed and some are under construction.

For comparison, the environmental geologic map and the biologic assemblages map are shown for the upland forest and prairie near Conroe (fig. 4). Note that the coastal short grass assemblage grows on abandoned meanderbelt sands and on the fluvial sand and mud. Also the fluvial woodland follows the modern drainage. Neither the pine and hardwood forest nor the hardwood and pine forest shows good agreement with substrate although it is known that pines prefer sandy substrates. The two forests were interpreted from aerial color infrared photography, and the boundary between the two forests is arbitrary (C. V. Proctor, personal communication).

Hill Country

The hill country example is located about 10 miles northeast of Uvalde, Texas (fig. 1). Two physiographic divisions are included—the dissected escarpment of the Edwards Plateau and the adjacent Cretaceous coastal plain. The Balcones fault system marks the boundary between the two provinces. The area has about 1,000 feet of relief and includes three important streams, the Dry Frio, Frio, and Sabinal Rivers. Mean annual rainfall here approaches 25 inches. This example was selected because the rugged topography (fig. 5B) strongly influences the distribution of the derived biologic assemblages map (fig. 5A).

The most obvious associations, looking at a 250-foot contour interval, are that the bottomland cypress-pecan assemblage is confined to flood plains and the rugged scrub live oak assemblage occurs only in the high-relief, deeply dissected hill country (fig. 5). Within the southern Edwards Plateau, the rolling live oak - juniper assemblage flourishes in the valley of the Frio River because there are fewer terraces and less rainfall than in the valley of the Sabinal River which sustains the terraced live oak - elm - hackberry flora. All map units, including classical geologic, environmental geologic, geomorphic, and biologic, complement one another.

Table 3. Complete biologic assemblages of the Hill Country.

BOTTOMLAND
- Wooded: Oak sp., mesquite, elm, hackberry, sycamore, willow, black walnut, pecan, bald cypress, mulberry, hoptree, grape, yaupon, poison ivy, honeysuckle, and peppervine
- Grasses: Indiangrass, big and little bluestem, switchgrass, Texas wintergrass, Virginia wildrye, Eastern grama grass

BUSHY BLACKBRUSH - GUAJILLO
- Wooded: Blackbrush, guajillo, whitebrush, blue salvia, scrub mesquite, cacti sp.
- Grasses: Perennial threeawn, red grama, annual weeds, Texas wintergrass, curly mesquite, and buffalograss

HILLY LIVE OAK - ELM - MESQUITE
- Wooded: Live oak, juniper, Texas persimmon, agarito, yucca, sumac sp., mountain laurel, prickly pear, rare mesquite
- Grasses: Red grama, red threeawn, curly mesquite, hairy tridens, Texas wintergrass, sideoats grama, panicum, green sprangletop, annual forbs

PRAIRIE MESQUITE - WHITEBRUSH
- Wooded: Mesquite, whitebrush, condalia sp., huisache, spiny hackberry, cacti sp., guayacan, desert yaupon, Texas colubrina
- Grasses: Texas wintergrass, buffalograss, curly mesquite, hooded windmillgrass, red grama, purple threeawn, ragweed, tasajillo, annual forbs

ROLLING LIVE OAK - JUNIPER
- Wooded: Live oak, juniper, mesquite, whitebrush, agarito, spanish oak, post oak, elm, tasajillo, prickly pear
- Grasses: Little bluestem, sideoats grama, blue grama, buffalograss, prairie coneflower, annual forbs

RUGGED SCRUB LIVE OAK
- Wooded: Live oak, juniper, yucca, prickly pear, blackbrush, coyotillo, condalia sp., guayacan, Texas persimmon, paloverdes
- Grasses: Hairy grama, Texas trioda, perennial threeawn, perennial dropseed, fall witchgrass, white trioda, curly mesquite

SHALLOW SOIL SHIN OAK
- Wooded: Live oak, shin oak, juniper, agarito, whitebrush, elbowbrush
- Grasses: Threeawns, red grama, Texas grama, hairy forbs, curly mesquite, buffalograss

TERRACED LIVE OAK - ELM - HACKBERRY
- Wooded: Like oak, hackberry, elm, greenbrier, yaupon, dewberry, bumelia
- Grasses: Texas wintergrass, meadow dropseed, little bluestem, threeawn, Texas grama

UPLAND DIVIDE LIVE OAK - SHIN OAK - POST OAK
- Wooded: Live oak, shin oak, post oak, blackjack oak, elm, sumac sp., juniper
- Grasses: Bluestem, lovegrass, dropseed, Texas wintergrass, curly mesquite, buffalograss, feathery bluestem, threeawns

ASSEMBLING THE DATA

It cannot be overemphasized that geologists in their field mapping experiences develop considerable *a priori* knowledge of biologic distribution. They are constantly observing variations of rocks and soils in the context of differences in the endemic flora. They also note changes in flora and

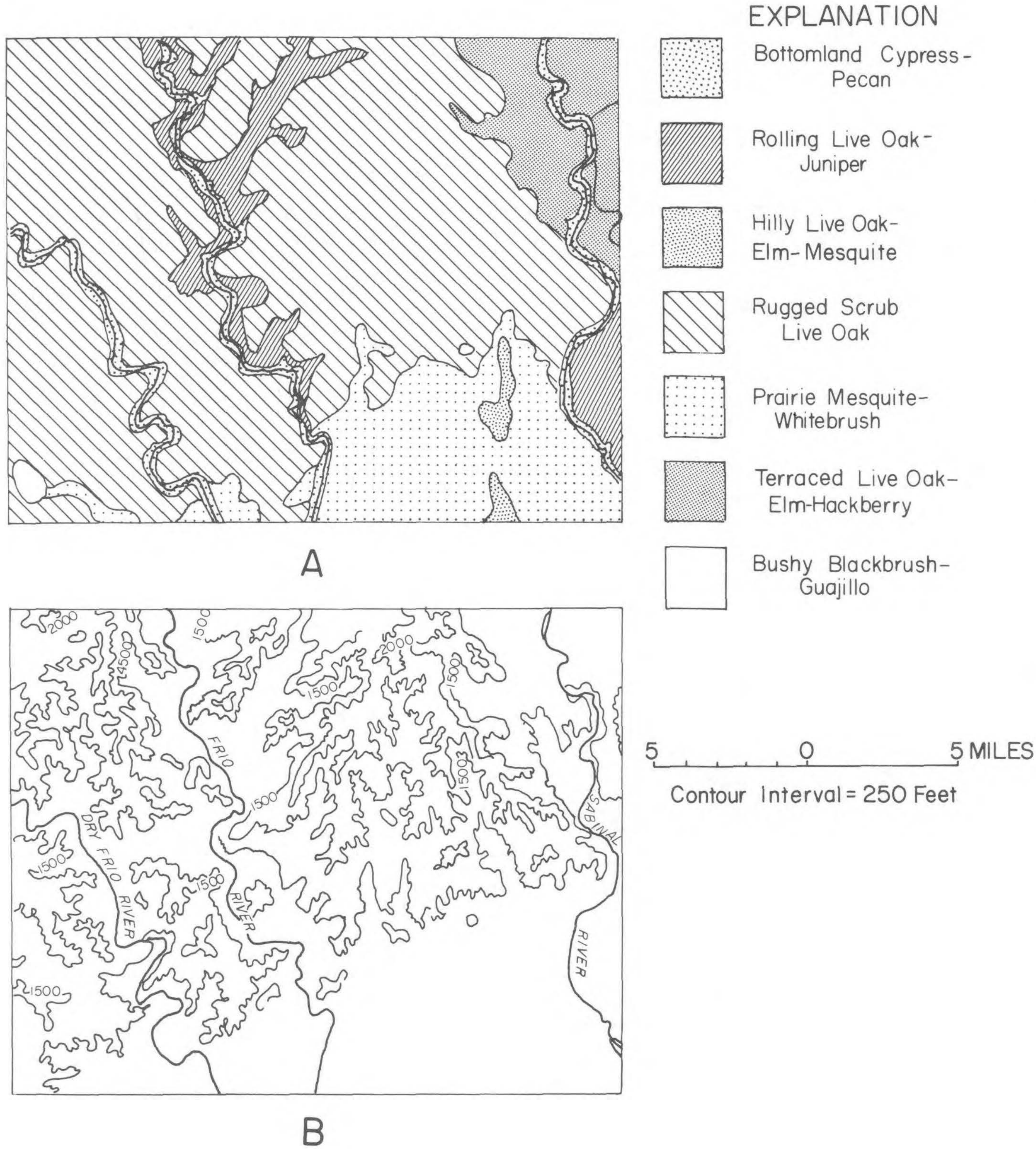

Figure 5. (A) Biologic assemblages in the hill country north of Uvalde, Texas where (B) topography strongly influences the location of fauna and flora.

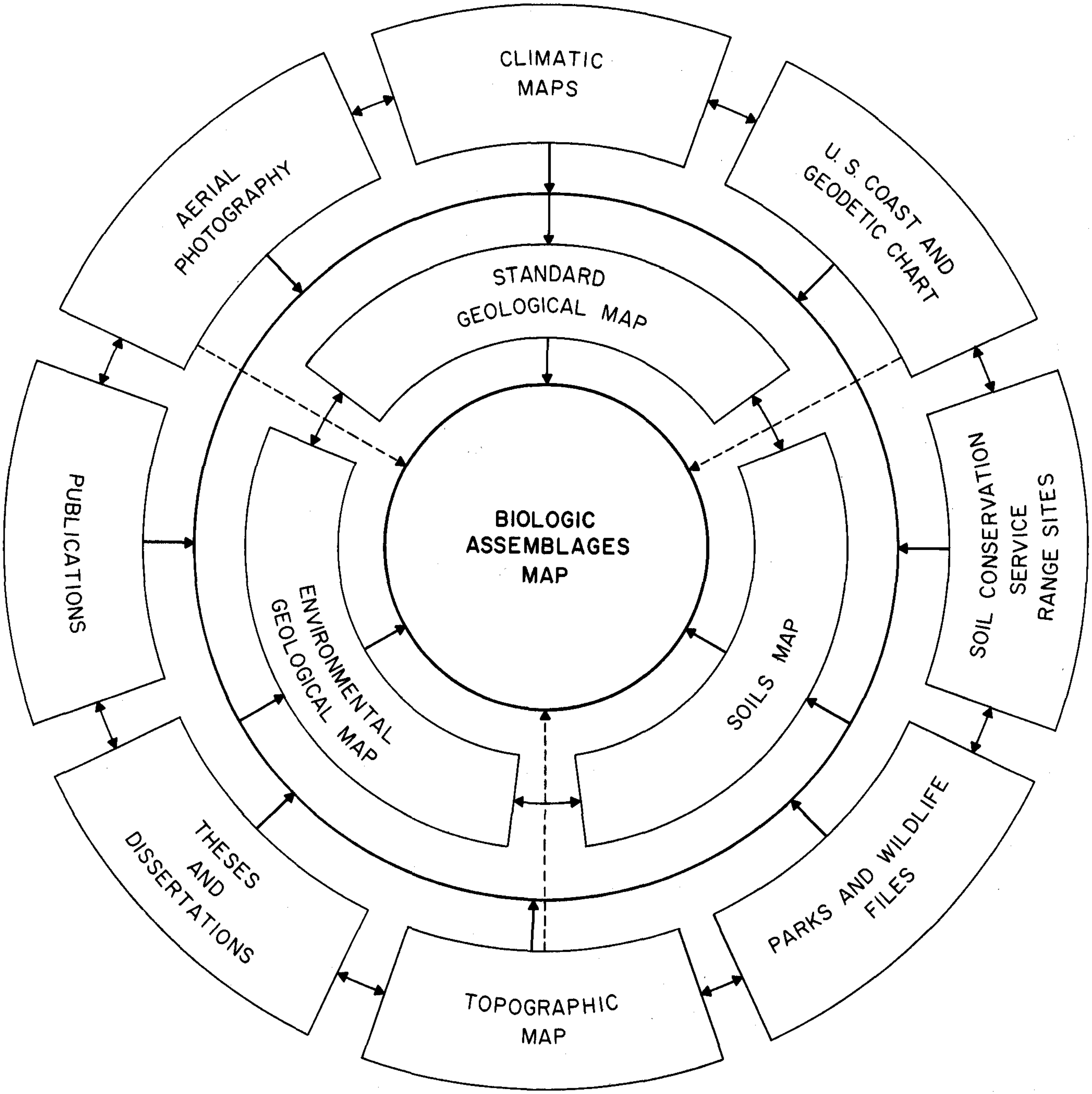

Figure 6. Systematics of constructing a biologic assemblages map. Dotted lines show direct interpretation of biologic assemblages from other maps and charts. Solid lines and arrows show interrelated data used in interpretation.

fauna related to drainage variables: size, valley width, valley depth, patterns, and age. All such knowledge or experience is always integrated into the derivation of a biologic map.

A system for constructing a biologic assemblages map is shown in figure 6; it assumes that the end point of the system is in the center of the rings. This system is like the procedure used to produce a biologic assemblages map in the Southwest Texas area (fig. 1). As pointed out in the case examples (figs. 2–5), one may derive biologic distributions directly from bathymetric charts, aerial photographs, and topographic maps. Direct interpretation is illustrated in figure 6 by dotted lines, direct paths from base data to interpreted maps. Normally, though, one assembles data from sources of the exterior ring to produce the maps in the central ring. In turn, filtered data of the outer two rings (related by solid arrows in figure 6) are employed to derive a biologic assemblages map.

Detailed listing and mapping of biologic assemblages in the Southwest Texas Hill Country (table 3) were derived as follows. Quantitative listings of floral assemblages were located in files of U. S. Department of Agriculture Soil Conservation Service. The listings or range sites describe floral groups relative to soil types and climate. Each floral group was then located on a soils map. The soils were then related to standard geological and environmental geological units on maps. A final map of the floral assemblages was interpreted as an entity. Information about animals, particularly game animals, was collected from files of the Texas Parks and Wildlife Department and later integrated with floristic mapping.

CONCLUSIONS

Geologists, because of their experience at regional mapping, are uniquely trained to map biologic assemblages. A caution is that they must seek out competent practical botanists and biologists who will fairly critique the recognition of ecologies and assemblages.

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STATEWIDE MAPPING OF SURFACE MINES—A TEXAS INVENTORY

C. G. Groat

UTILITY OF MINED-LAND INVENTORIES

Mining has received more negative publicity and has been the subject of more environmental concern than nearly any other kind of land use. As a result, the word “mining” brings visions of ravished landscapes and huge wastelands to a large portion of the population, most of whom have had little or no firsthand experience with mines. It becomes important, therefore, in light of this widespread lack of understanding, that unbiased, factual information be on hand when laws that seek to regulate mining are formulated. Without such information, legislators have a tendency to make assumptions about mining conditions that are based on the well-publicized situation in the coal-mining Eastern States, and to model regulations after laws in effect in those areas. This practice can produce laws that are ineffectual and unnecessarily restrictive.

A mined-land inventory provides the information needed to properly assess the mining situation in an area, the environmental problems caused by mining, the need for reclamation, and the physical realities that determine the methods of reclamation. This information has utility beyond being the basis for sound, informed legislation directed at regulating mining and reclamation. City and regional planners should know about the types and distribution of mines, both active and abandoned, in their areas when zoning in order to insure adjacent compatible land uses. They also need to consider these facts when determining traffic patterns that may be influenced by the heavy truck traffic associated with some types of mines. Abandoned surface mines are readymade disposal sites; water pollution problems have resulted when the geological conditions in the mine area are not considered before the holes are used for garbage pits or sanitary landfills. A comprehensive mined-land inventory provides the necessary physical information for appropriate use of abandoned mines.

The concept of multiple use is a sound one that has not been fully utilized in connection with mining. More innovative sequential-use requirements could result in predetermined uses for land after it is mined, thus allowing the mining to be planned with a certain subsequent use in mind. There is also room for originality in finding uses for land that has already been mined and abandoned. People in recreation planning, notably the U. S. Bureau of Outdoor Recreation, have taken an initial look at mined lands as possible sites for a variety of recreational developments. The terrain that is left after mining is well suited to several uses including hiking and motorbike trails, camping, and water-based recreation. The consensus of opinion stemming from a series of regional conferences on the reclamation of mined land for outdoor recreation (U. S. Bur. Outdoor Recreation, 1973a, 1973b) is that a thorough inventory of mined land is necessary before an evaluation of its recreation potential can be made.

Mined-land inventories, when conducted with considerable field work, can provide current information on mineral production patterns and developments. The Bureau of Economic Geology has the responsibility for disseminating information on mineral resource developments and potentials; the mined-land inventory has aided this effort considerably.

INVENTORY TECHNIQUES

Approaches to obtaining an inventory of mined lands range from compiling existing information gathered by various regulatory and resource agencies to thorough mapping projects utilizing aerial photographs and extensive field work. Obviously, the type of information needed, the time and money available, and the technical competence of the inventory staff are all prime factors in planning the inventory. Equally obvious, for reasons of efficiency, is the desire to gather the most comprehensive information possible given the time and resources available for the study. For these reasons, geologists experienced in mapping and in the field of mineral resources are the most appropriate people to do the job.

The ideal inventory procedure would utilize color infrared or color aerial photographs that were flown yesterday; these photos would be at a scale of 1:30,000 to 1:60,000. Combined with existing information on mine locations, including topographic maps, mineral producers lists, U. S. Bureau of Mines lists, and U. S. Soil Conservation Service information, the locations of mines and their dimensions could be plotted on a suitable base map. Field checking and interviews would then focus on areas of greatest interest.

The ideal situation does not exist for most of us and we must make do with what we have—generally a collection of black-and-white aerial photographs at several scales and ages, incomplete topographic mapping of the area, and very scattered and incomplete records of mining operations. Patience and perseverance become key ingredients in a study founded on these conditions. The chief difference between operating under these conditions and ideal conditions is that the former takes more man-hours dedicated to rounding up data and to field checking.

Data Gathering

Compilation of existing data is the first step; plans for the rest of the study hinge on how much new information is needed. Even if the study has limited immediate objectives, such as determining the total area disturbed by mining or locating areas of possible water pollution by mining, as much new and comprehensive information as possible should be gathered. Thus all aspects of mining should be examined and all possible types of data that can be collected should be determined before the study begins. A checklist or form to be filled out for each mined area is a convenient way to be uniformly comprehensive.

Once mines have been located, their dimensions determined, and all information plotted on a suitable base map, the program of field checking should be instituted. There is no good substitute for firsthand information; in describing surface mining by mine type or by commodity mined, representative information from selected mining areas assures that mistakes are not made simply because the only vantage point the observer had was from two feet above an aerial photograph. Interviews with mine operators are extremely useful in obtaining a realistic appraisal of mining conditions and problems. Interviews are also the only way to acquire current information on the transportation, markets, and future outlook for the commodity being mined. This information is particularly useful for estimating the potential for increased mining activity in an area.

Base Maps and Data Storage

In order for surface mine information to be most useful, the user must be able to see the location and distribution of mined land and to efficiently obtain the specific statistical information he needs. A combination of maps and computer-based information storage accomplishes these goals efficiently.

Mine locations and areas are best portrayed on maps that have a suitable scale (1:125,000), drainage and landform information, and an up-to-date cultural base. It is the interactions of mining with these natural and man-made features that are the cause for the environmental concerns that motivate many studies of surface mining.

Assuring a convenient form of retrieval for statistical information is important if the data is to be used by a large number of people. The most convenient form of data storage and manipulation allows the information to be accessed by several categories and can provide lists that rank mine size, production, and producing companies. A simple programming language is also an asset. System 2000, developed by Management Research Institute of Austin, Texas, provides all of these features.

Presentation of Information

There are many aspects of surface mining that need to be stressed in any evaluation of mining activities, but none is more important than a thorough description of physical conditions. The nature of the geologic and physiographic terrain, the climate, and the type of mining must all be clearly described and classified. It is a lack of appreciation for the physical realities of mining and the great variety of mining conditions that has led to a considerable amount of misunderstanding of the environmental effects of mining and the remedies for those effects.

The first step in presenting mined-land information is to characterize the types of mining practices (open pit, quarry, strip) in terms of geologic terrain, depth, type and thickness of overburden, overburden-disposal technique, and areal extent. This will provide a framework in which to discuss reclamation practices and economics. Quarries, for example, are in hard rock, commonly have little waste material or overburden, and are deep and precipitous. Environmental problems and reclamation techniques are similar for most quarries, regardless of whether the rock mined is granite, limestone, or something else.

In discussing mined land it is also important to separate disruption of the land surface from other environmental effects. The seriousness of destroying a previous land use by disrupting the surface—aside from aesthetic considerations—depends on the productivity of the land prior to mining. But aesthetic and economic considerations should be separated from mining effects of a polluting nature. Acid waters, sediment discharge, and heavy metals yielded by some mining operations are detrimental in most cases and are first-order considerations in evaluating mining from an environmental viewpoint.

Mined-land information presented on suitable base maps, retrievable through a well-designed data manipulation system, and structured on a physical framework is best suited for use by persons making land use or reclamation plans. Failure to communicate the information in a usable form will result in the exclusion of a scientific basis for mined-land decision making.

SURFACE MINING IN TEXAS

Method of Study

The study of surface mining in Texas was implemented to determine the types and areal extent of mining and to document the variety of geologic, physiographic, and climatic conditions under which mining is carried out (Groat, 1973). The chief motivation for the study was provided by proposed State legislation to regulate surface mining. It was clear that little information was available on mining in Texas. Given the great variety of physical conditions in the State, it is important that legislation be addressed to the Texas situation rather than modeled after laws in another state with totally different physical conditions. The Bureau of Economic Geology, with no ties to industry or environmentalists yet with the necessary expertise, seemed a logical organization to conduct the study. In addition to Bureau funds and manpower, support was provided by The University's Division of Natural Resources and Environment. Considerable time and logistic support was contributed by the General Land Office of Texas.

All available information was utilized to locate and describe surface mines. Topographic maps, published reports, U. S. Bureau of Mines lists, aerial photographs, and telephone directories were all used extensively. Mine locations and outlines were plotted on county highway maps at a scale of 1 inch = 2 miles (fig. 1) and a file card was made for each mine for which descriptive information was available. Pits smaller than one acre, chiefly borrow pits used for secondary road maintenance, and counties with no significant mining activity were excluded from the study. Regions of intense mining were visited and described in detail; large-scale maps of mined areas were constructed. These areas were flown over and photographed from the air. Field work was also aimed at insuring that representative examples of all mining operations were visited.

Mined-land information was compiled by county on forms designed to allow ready transfer to the System 2000 program. The type of information collected and stored is indicated in table 1.

Table 1. Types of information collected for Texas mined-land inventory.

MINE INFORMATION
- Location
- Type (strip, open-pit, quarry)
- Active or inactive
- Machinery used
- Mine dimensions (area, depth)
- Overburden type and thickness
- Disposal of overburden (in mine, adjacent to mine, etc.)
- Area covered by overburden piles
- Area disturbed per year
- Observable adverse environmental effects
- Reclamation procedures
- Area reclaimed
- Physiography and climate

COMMODITY INFORMATION
- Commodity produced
- Geology of the deposit (formation, lithology, etc.)
- Markets—location, mode of transportation
- Processing facilities

COMPANY INFORMATION
- Company name and address
- Parent company
- Mine manager or supervisor

DOCUMENTATION
- Aerial photographs
- Ground photographs
- Field maps and notes
- Literature references

Summary of Mining Types and Conditions

Texas is a mineral-producing state. Of the total mineral production, about 93 percent is of petroleum; the remaining 7 percent—nonpetroleum minerals—provides a large enough volume that Texas is ranked 11th in the Nation in nonpetroleum mineral production. Many mineral materials—sand and gravel for construction, crushed limestone for construction and for the manufacture of lime and cement, gypsum for wallboard, lignite and uranium for fuel, iron ore

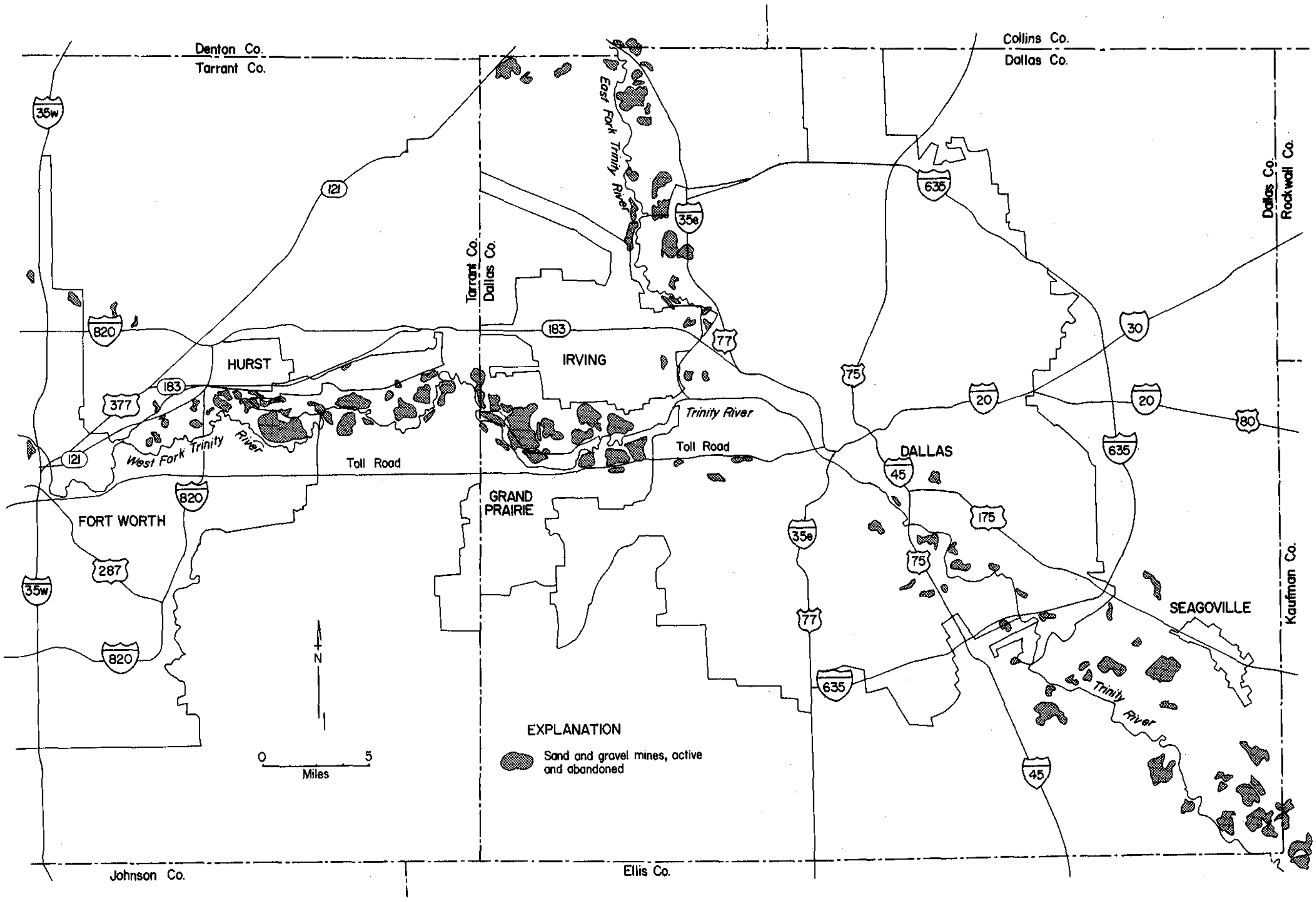

Figure 1. Mined land in Dallas County, Texas. On the actual map, mines are numbered, and information for each mine is recorded on a data card.

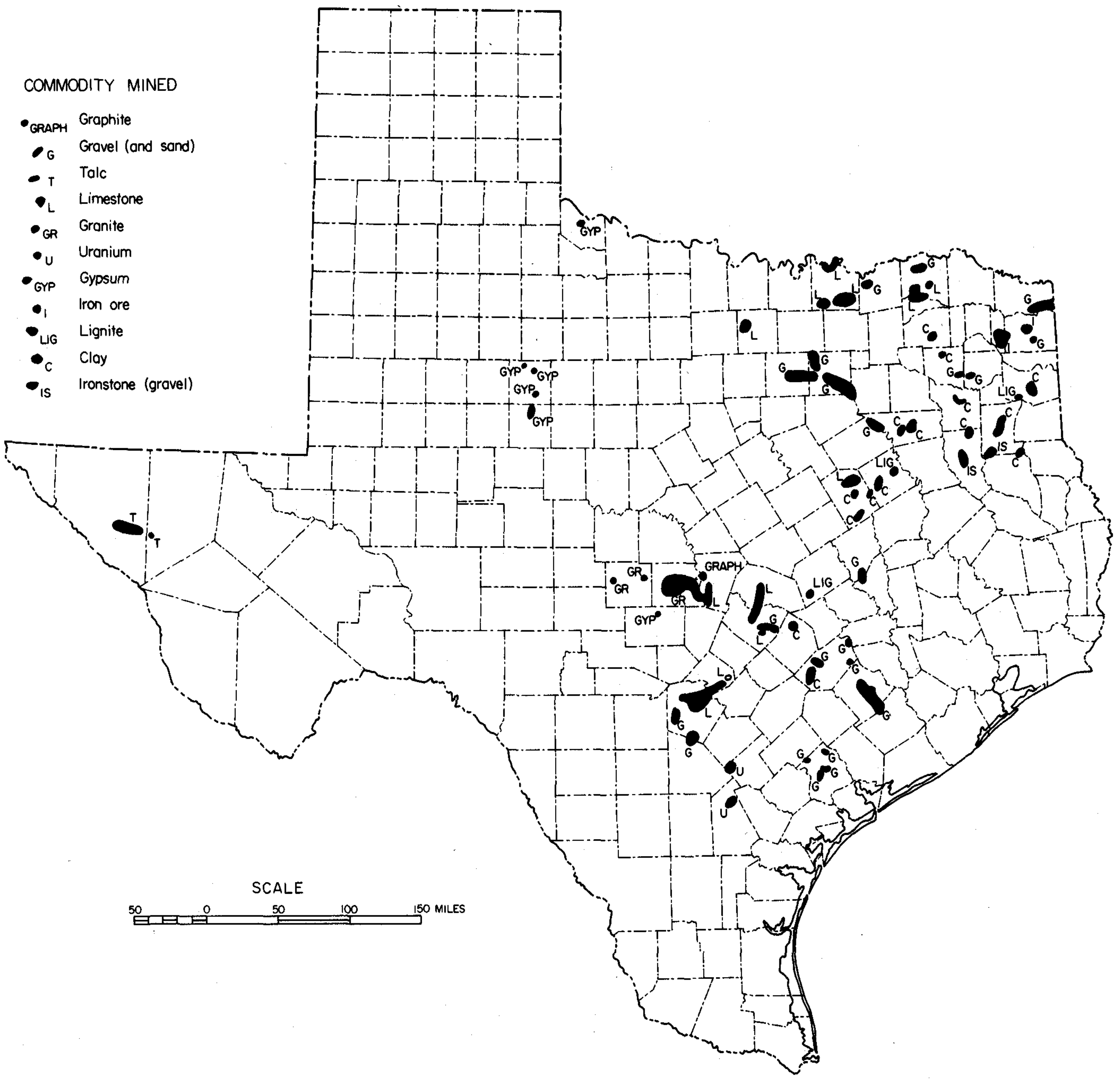

Figure 2. Location of major mining areas in Texas.

for steel, and clay for ceramic products and other industrial uses—are produced from surface mines.

Surface mining has resulted in disturbance of about 60,000 acres of land. In other terms, surface mining has disturbed about 0.04 percent of the total land area of the State; or, it affects one-sixteenth the amount of land that is involved in highways and rights-of-way.

There are several areas of the State that have large numbers of surface mines (fig. 2). Most of these mines supply low-unit-value constructional raw materials (sand and gravel, crushed limestone), chiefly to the urban areas in Texas, but there is considerable expansion of surface mines producing other commodities. Expansion is most pronounced with lignite and uranium, and it is the mining of these energy resources that will likely show the most dramatic growth over the next 20 to 30 years.

Strip Mines

Strip mining disturbs large areas of land and has produced many of the adverse environmental effects that have received wide publicity. Environmental problems associated with coal mining in the East and Midwest have been the chief contributors to the bad image of strip mining.

There are two types of strip mining, however only one of these is presently used in Texas. Contour stripping is practiced where the sought-after layer is exposed on the sides of hills; much of the land disturbed in the Appalachian area is the result of contour stripping. Area stripping, the type practiced in Texas, is utilized in flat or gently rolling areas where large areas of surface materials are removed to reach the layer of value. Sand and gravel and lignite are the principal commodities produced by strip mining in Texas.

Area strip mining is used where the ore or commodity is continuous over a large area but is covered by a few feet to as much as 150 feet of overburden that must be removed to get to the ore. Mining is accomplished with shovels or with draglines that have large buckets (3 to 200 cubic yards) and that are capable of only slow movement. After an initial cut, the overburden is removed in long, parallel cuts and piled in rows adjacent to the active cut. The ore, exposed on the floor of the cut, is loaded into trucks or railroad cars for transport to the mill. The distinguishing feature of strip mining is that the overburden is kept in the mine. The resulting landscape is a large area—commonly several hundred acres—characterized by parallel ridges or windrows of conical piles of overburden that vary in height from a few feet to nearly a hundred feet.

Strip mining for sand and gravel has disturbed nearly 40 square miles of land in the two largest areas of mining in Texas, the Dallas-Fort Worth area and Colorado County (fig. 2). Sand and gravel is mined from the flood plain and terraces of the Trinity and Colorado Rivers where the terrane is flat, vegetation abundant, and the annual precipitation is 40 inches or greater. Individual operations cover from 2 to 300 acres with one mine in Colorado County covering 1,300 acres. A disrupted land surface is the chief environmental effect of strip mining for sand and gravel.

Area stripping for lignite is carried on near Fairfield, Rockdale, and Darco in East Texas. New mines have been announced for Mount Pleasant, Tatum, and Athens. Approximately 3,300 acres have been affected. Thorough reclamation is practiced at Fairfield, has been initiated at Rockdale, and will be carried out at all of the new mines. Existing and proposed mining takes place in gently rolling country where the annual precipitation is 35 to 40 inches and post oak is the dominant type of vegetation. Texas has huge reserves of strippable lignite and the present and future energy situation dictates that this lignite will play a more important role as an energy supply. The result will be a dramatic increase in the number of lignite strip mines in Texas.

There are significant physical differences between strip mining for sand and gravel and strip mining for lignite. Lignite overburden is generally 40 to 100 feet thick, and composed largely of slightly to moderately indurated Eocene sand and clay. The mines are located in rural areas on land used for unimproved pasture, forage crops, and some feed-grain crops. Sand and gravel deposits are generally overlain by less than 30 feet of overburden which is mostly unconsolidated fine sand and silt. Large-scale sand and gravel mine locations range from the heart of the Dallas-Fort Worth area to rural Colorado County, and land uses in and around mined areas range from urban development to cultivated pasture and grain crops. Appreciation of these differences is critical in designing workable reclamation and subsequent land use plans.

Open-Pit Mines

Open-pit mining is practiced where the sought-after material is of limited extent, where it is disseminated throughout a large volume of rock, or where only a limited amount of the material is needed. An open-pit mine is a large hole with overburden piled outside the mine; the overburden is usually piled along the edges, but as mining progresses some of the waste may be deposited in the pit. The large copper mines in Arizona and Utah are open pits. The size of open-pit mines in Texas varies from a few acres to nearly a thousand acres, and depth varies from a few feet to nearly two hundred feet.

Several commodities are mined in Texas by open-pit methods; these include clay, iron ore, uranium, talc, graphite, and volcanic ash. In addition, there are thousands of small caliche and road metal pits along Texas highways. Materials from these pits, most of which are less than an acre in size, are used in road maintenance and construction.

The most extensive open-pit operations in any one area are those in Morris and Cass Counties (fig. 2) where nearly 4,800 acres have been affected by iron ore mining. Mines are shallow, 10 to 30 feet deep, and waste material is minimal.

Uranium is mined in Karnes and Live Oak Counties (fig. 2) from discontinuous, low-grade, sandstone ore bodies. Scrapers and heavy earth-moving equipment are used to remove the 100 to 200 feet of overburden that covers the reduced ore zones. The overburden is piled adjacent to the deep pits and graded in such a way that the surface of the waste rock slopes toward the pit. Overburden piles are 30 to 50 feet high.

Uranium pits and waste rock cover more than 1,500 acres. Mines are large, as much as 200 feet deep, and have vertical walls. One mine, in western Karnes County, is nearly three miles long. With increasing emphasis on nuclear energy, it is quite likely that uranium mining in South Texas will expand greatly. Water encountered in the deep mines must be disposed of and its disposal provides some environmental problems. Discharging the water into streams has been prohibited by the Texas Water Quality Board because mine water is high in sulfates and other dissolved substances that degrade the quality of area streams. The present practice is to pump this water into nearby abandoned mines, recharging it into the aquifers from which it originally came.

Very little sediment from the 30- to 50-foot-high spoil piles adjacent to the uranium pits has washed into adjoining areas during rainstorms. This is chiefly because the piles are sloped toward the pits, causing runoff to go into rather than away from the mines. The degree to which the spoil is blown by the wind was not determined during this study.

The mining of clay, iron ore, and talc has posed no major environmental problems beyond disruption of the surface. Many of the clay pits fill with water, but this is more of a problem to mining than it is to the surrounding environment. Iron ore pits are generally shallow and dry. Overburden and waste piles are small because very little overburden is encountered. There is a significant volume of tailings from the processing operation that must be disposed of. Tailings are pumped to settling ponds and the clarified water removed. Disposal of this water must be accomplished in compliance with existing water quality standards. Talc mines are in the desert country of Culberson and Hudspeth Counties (fig. 2) and are all dry; no toxic substances are involved in the mining operation to pose a threat to surrounding areas. Talc mills in the Allamoore area produced great quantities of particulate material which was discharged into the air before strict air quality standards and their enforcement curtailed this practice.

All open-pit operations are basically holes in the ground with the overburden piled next to them. This sets a broad framework in which to consider subsequent uses. The physiographic, geologic, and climatic variations that exist among talc pits, uranium pits, and iron ore pits cannot be overlooked in planning reclamation or subsequent uses for open-pit mines in Texas. Talc pits are developed in hard rock in the desert of Trans-Pecos Texas where the terrane is rugged, vegetation sparse, and annual precipitation less than 15 inches; deep, extensive uranium pits are excavated in soft sand and mud in subhumid South Texas; and large, very shallow iron ore pits occur in the piney woods of East Texas where relatively soft Tertiary sediments are mined from a rolling terrane in an area with an annual rainfall exceeding 45 inches. A blanket regulation or plan based on any one of these open-pit situations will not fit the other two, neither will it fit the clay or caliche open pits in the State. Inventory information is invaluable in realizing this and in designing laws and plans to fit the situation.

Quarries

Quarrying is practiced where most of the material mined is to be used. The method is restricted to hard-rock areas and the materials obtained in this way are most commonly used for construction and building stone. Waste material and overburden are generally piled adjacent to the quarry; volumes are not large because quarries are purposely located in areas where sought-after material is exposed at the surface and covering material is thin. Much of the material quarried is of low unit value and must be mined near markets to keep transportation costs low. Because most construction occurs in growing cities, quarries are commonly located in or near expanding urban and suburban areas. The landscape feature resulting from quarrying is usually a rock wall, or a large pit in the ground or hillside; such a pit can be from a few feet to nearly a hundred feet deep.

Commodities mined from quarries account for the highest value of nonpetroleum mineral resources produced in Texas. Nearly all of the products are derived from limestone; some are simply crushed limestone used as road base, as aggregate in concrete, and in industrial processes; others are processed limestone (cement and lime). Asphaltic limestone, a unique natural road construction material, is also produced from quarries in Uvalde County.

Most of the quarries are located along the eastern edge of the Hill Country in a narrow band of faulted limestone that constitutes the Balcones escarpment. Relief varies from flat to locally rugged; rainfall is 25 to 30 inches; and vegetation varies from cedar in the south to hardwoods in the north. The quarries are concentrated around San Antonio, New Braunfels, Austin, Round Rock-Georgetown, Waco, and west of Dallas-Fort Worth (fig. 2). Many are located in or near the urban areas because their primary product is crushed limestone, a low-value commodity that must be produced near markets. There are quarries away from the urban areas, generally because the particular area is the site of the nearest suitable rock. This is the case with a large area of quarries near Bridgeport in Wise County. Rock from the area is marketed in Dallas and Fort Worth. Quarries for limestone production are also located in Burnet County and in scattered areas near larger cities throughout the State. Their presence along the Balcones zone and across the State makes it clear that they occur under widely variable climatic and topographic conditions.

Limestone is quarried where overburden is essentially absent. Nearly all the rock mined is used, thus waste is minimal and the topographic result is a large, open hole. Many quarries are extensive, 100 to 300 acres with depths from 20 to nearly 100 feet. Most of those near cities are operated for very long periods of time because the supplies of suitable rock are large and the market is long-lived. Abandonment of these quarries most commonly occurs as the population encroaches on the mined area. The majority of abandoned quarries are those that were developed in remote areas for large highway construction projects. These are abandoned when the project is finished but commonly are worked sporadically by mobile rock-crushing plants when repairs are needed or work is carried on in nearby areas.

Quarries are usually dry and, except for a few dimension-stone operations, do not produce large quantities of waste rock. Because of this, there have been no water quality problems or problems resulting from overburden leaching or washing. However, quarrying in a dry pit is a dusty operation. Blasting, loading, and the continual movement of numerous trucks all tend to create dust. Strict standards regulate dust emission. Control of dust has been accomplished by liberal use of water trucks which keep the mine surfaces wet.

Reclaiming of quarries by alteration of their configuration or by filling is very difficult because they are developed in hard rock and there is generally little overburden or waste material to work with. Finding subsequent uses for quarries is thus a challenging reclamation problem.

SUMMARY

Land resource planning should take into account mineral resources and the land areas mined to obtain them. In most parts of the United States, mining occurs under a variety of geologic, physiographic, and climatic conditions. These physical variations must be appreciated in planning reclamation and subsequent land use if this reclamation, and the regulations to enforce it, are to be practical and acceptable. Current land use and economic considerations should also be brought into planning that relates to mined lands. A thorough inventory, including detailed mapping and field studies, provides the needed information plus a picture of the current state of an area's mineral industry.

Texas illustrates the considerable variation in mining conditions that occur. Geologic, physiographic, climatic, and land use conditions in the State exhibit extreme variations; types of mines and conditions under which mining occurs reflect these differences. Thus Texas provides a good example of the necessity for the detailed appreciation of surface mining conditions that should precede the integration of mined-land planning with broad, land resource planning and management.

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Editor

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