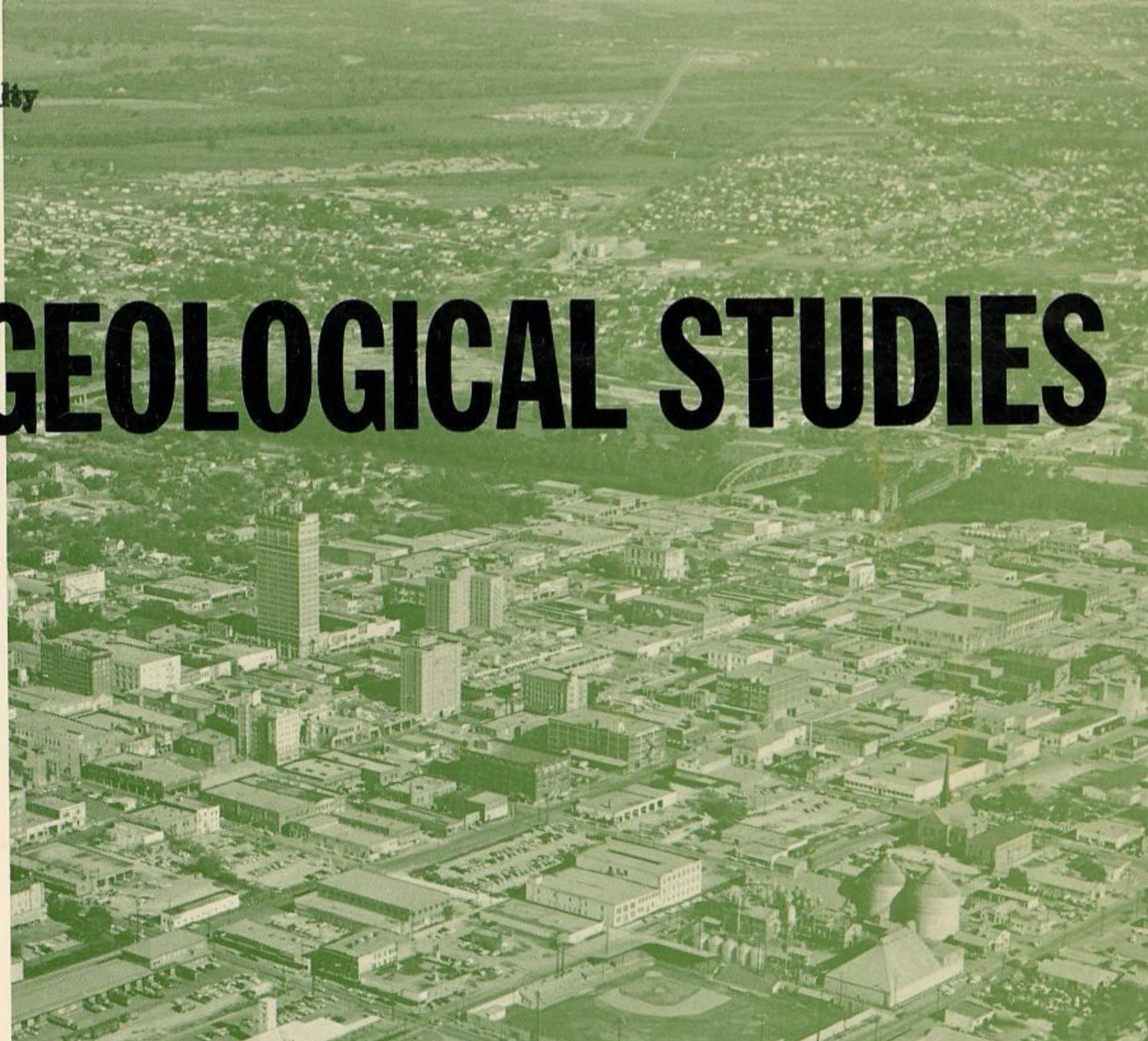
BAYLOR GEOLOGICAL STUDIES



SPRING 1965
Bulletin No. 8

URBAN GEOLOGY OF GREATER WACO
PART I: GEOLOGY

Geology and Urban Development
PETER T. FLAWN
Geology of Waco
J. M. BURKET

"Creative thinking is more important than elaborate equipment--"

Frank Carney, Ph.D.
Professor of Geology
Baylor University
1929-1934

Objectives of Geological Training at Baylor

The training of a geologist in a university covers but a few years; his education continues throughout his active life. The purposes of training geologists at Baylor University are to provide a sound basis of understanding and to foster a truly geological point of view, both of which are essential for continued professional growth. The staff considers geology to be unique among sciences since it is primarily a field science. All geologic research including that done in laboratories must be firmly supported by field observations. The student is encouraged to develop an inquiring objective attitude and to examine critically all geological concepts and principles. The development of a mature and professional attitude toward geology and geological research is a principal concern of the department.

The Baylor University Press
Waco, Texas

BAYLOR GEOLOGICAL STUDIES

IN COOPERATION WITH COOPER FOUNDATION

A SERIES ON

URBAN GEOLOGY OF GREATER WACO

PUBLICATION SCHEDULE

Part I: GEOLOGY

Bulletin No. 8, Spring, 1965

Geology and Urban Development by Peter T. Flawn, Director, Texas Bureau of Economic Geology, Austin, Texas.

Geology of Waco by J. M. Burket, Professor of Geology, Tyler Junior College, Tyler, Texas.

Part II: SOILS

Bulletin No. 9, Fall, 1965

Soils and Urban Development of Waco by W. R. Elder, Field Specialist-Soils, Soil Conservation Service, Temple, Texas.

Part III: WATER

Bulletin No. 10, Spring, 1966

Subsurface Waters of Waco by H. D. Holloway, Geologist, Texas Water Development Board, Austin, Texas.

Surface Waters of Waco by Jean M. Spencer, Resident Research Geologist, Department of Geology, Baylor University, Waco, Texas.

Part IV: ENGINEERING

Bulletin No. 11, Fall, 1966

Foundation Geology in Waco by A. M. Hull, Geological Engineer, Chief of Foundations Section, U. S. Corps of Engineers, Fort Worth, Texas.

Geologic Factors Affecting Construction in Waco by E. F. Williamson, Geologist, formerly Material Analyst, Texas Highway Department, Waco, Texas.

Part V: SOCIO-ECONOMIC GEOLOGY

Bulletin No. 12, Spring, 1967

Economic Geology of Waco and Vicinity by W. T. Huang, Professor of Geology, Baylor University, Waco, Texas.

Geology and Community Socio-Economics—A Symposium by authorities on Law, Appraising, Architecture, Public Works and other professions. Symposium Coordinator: R. L. Bronaugh, Professor of Geology, Baylor University, Waco, Texas.

Part VI: CONCLUSIONS

Bulletin No. 13, Fall, 1967

Urban Geology of Greater Waco—Summary and Recommendations by the Editorial Staff, Baylor Geological Studies, Baylor University, Waco, Texas.

FOREWORD

The development and early growth of Waco occurred primarily on the outcrops of the Austin Chalk and the Brazos Alluvium. Few geologically related problems appeared in the early development of the city primarily because of the stable nature of the chalk and alluvium underlying most foundations in the city; the light weight and simplicity of most early structures; the relatively light loads on streets and roads; the uncomplicated nature of sewage and pipe systems; and the low demands of a small population for water, sand and gravel, sewage disposal and storm drainage.

During and after World War II, Waco expanded from these stable outcrop areas onto the outcrop of the unstable, incompetent shales of the Taylor Formation to the east and Eagle Ford Group to the west. This geographic expansion of Greater Waco during the past twenty years has been accompanied by many new urban problems of geological origin in addition to many existing problems which became critical with rapid urban population growth and expansion.

Among these important urban geological problems are those involving sand and gravel, which are lost to the area by unplanned city growth; foundation problems, which result in the failure of foundations in one area, over-design in another; soil problems involving corrosion of pipes, failure of foundations, variation in excavation costs and drainage problems; water supply problems, including surface and subsurface sources, utilization and pollution; and the quality, quantity and location of economic rocks and minerals in the Waco region.

These and many other problems cannot be solved adequately and economically without considering the role of the earth sciences. Responsible long-range urban development must also involve other geologically related aspects, such as problems of legal nature, property evaluation, city planning, recreation, beautification and development costs.

In recent years the Baylor Geology Department has received a growing number of requests for geological advice in the aforementioned areas of urban development. Although Baylor geologists have supplied free consultation as a public service, there has developed an apparent need for more comprehensive and accessible data on the total spectrum of earth science-urban relationships. The Baylor Geological Studies editorial staff decided in 1962 that a comprehensive publication on the Urban Geology of Waco should prove an asset to the city and its citizens.

Late in 1962 a thorough survey was made to ascertain sources of earth science data pertaining to the Waco area, as well as to locate published references on Urban Geology. Many city, state, and federal agencies, as well as interested individuals, were invited to cooperate in the project.

The Cooper Foundation, a private civic philanthropic foundation in Waco, was approached in January, 1963, for financial support to aid in the preparation and publication of a Waco Urban Geology report. A detailed, budgeted proposal was approved by the foundation to cover the proposed cost of publication and related expenses, totaling $7,000. Baylor University, through its press, accounting facilities, geology department, and Baylor Geological Studies budget accepted the responsibility for the remaining expense. The editorial staff of the Baylor Geological Studies provided free coordination, cartographic-field supervision, and editorial service.

Since the project was initiated early in 1963, it has evolved in concept and scope. The number and nature of contributions expanded as the project matured. The URBAN GEOLOGY OF GREATER WACO includes major contributions from the Baylor Geology Department, Texas Bureau of Economic Geology, U. S. Soil Conservation Service, U. S. Corps of Engineers, Texas Highway Department and Texas Water Development Board. Shorter contributions include papers by an architect, attorney, real estate appraiser, public works engineer and others.

In the spring of 1964, a series of eight public evening seminars were held at Baylor to provide contributors with an opportunity to present a summary of their reports for comments and discussion. A student seminar was conducted at the same time to explore all areas of urban activities which are related to the earth sciences.

Originally, the proposed Urban Geology report was scheduled to be released as a single volume. During preparation the various reports were expanded and complex illustrations were added; other papers were solicited to cover additional areas of importance. Because of the increased scope of the project, ten major and numerous shorter papers are included in the Baylor Geological Studies urban series.

Beginning with Baylor Geological Studies Bulletin No. 8 (Spring, 1965), six successive semi-annual Bulletins will include papers grouped according to Geology, Soils, Water, Geological Engineering, Socio-Economic Geology and Conclusions. Included in the series are multicolor geologic, soil, isopach and structure maps (on U.S. Geological Survey topographic base), charts, illustrations and tables of various types prepared by the Baylor Geological Studies student cartographic staff. Thirty-five hundred copies of Baylor Geological Studies Bulletins 8-13 (Urban Geology series) will be published and sold for $1.00 each. Sale of URBAN GEOLOGY OF GREATER WACO will be handled by Baylor Geological Studies in agreement with Cooper Foundation.

The editorial staff and contributors intend to provide a comprehensive series on Waco Urban Geology, which may also serve as a model for others interested in this vital area of geologic application and public service. No precise estimate can be placed on the value of information supplied by governmental agencies and individual researchers, or on the value of time donated by authors, editorial staff and interested geologists. The Cooper Foundation grant and the Baylor Geological Studies budget for the six issues in the series will exceed $15,000—an amount which is conservatively estimated to be less than ten percent of the actual cost of the project if it had been contracted at regular professional and commercial rates.

The editorial staff appreciates this opportunity to provide a public service for the citizens of Waco. We sincerely thank the Cooper Foundation, Baylor University and the various State and Federal Agencies, as well as the many individuals, who made this series possible.

L. F. Brown, Jr., EDITOR
Spring, 1965

BAYLOR GEOLOGICAL STUDIES

BULLETIN NO. 8

IN COOPERATION WITH COOPER FOUNDATION

A SERIES ON

URBAN GEOLOGY OF GREATER WACO

PART I: GEOLOGY

Geology and Urban Development

PETER T. FLAWN

Geology of Waco

J. M. BURKET

BAYLOR UNIVERSITY
Department of Geology
Waco, Texas
Spring, 1965

Baylor Geological Studies

The Baylor Geological Studies Bulletin is published semi-annually, Spring and Fall, by the Department of Geology at Baylor University. The Bulletin is specifically dedicated to the dissemination of geologic knowledge for the benefit of the people of Texas. The publication is designed to present the results of both pure and applied research which will ultimately be important in the economic and cultural growth of the State.

Cover photograph: Aerial view of Downtown Waco. Photograph provided through the courtesy of Windy Drum Studio, Commercial Photography, Waco, Texas.

Additional copies of this bulletin can be obtained from the Department of Geology, Baylor University, Waco, Texas. $1.00 postpaid.

CONTENTS

ILLUSTRATIONS

Geology and Urban Development[1]

PETER T. FLAWN

Director, Bureau of Economic Geology,
The University of Texas, Austin, Texas

> *"The problem of uncontrolled population growth emerges as one of the most critical issues of our time since it influences the welfare and happiness of all the world's citizens. It commands the attention of every nation and society; the problem is no less grave for the technically advanced nations than for the less developed."*—
>
> FREDERICK SEITZ, *President*
> National Academy of Sciences, 1963

The problems of cities are the problems of population growth. It is in the cities that the spectre of a rationed future is first seen—a future where there are so many people that there is not enough to go around, not enough land or living space, not enough clean air, not enough water, not enough food, not enough goods or services. There are bacterial cultures that multiply to the point where their population exceeds the food reserves of their environment; thereupon they starve to death. There are bacterial cultures that multiply to the point where the toxic products they produce so befoul their environment that they poison themselves; pneumococcus, for example, produces enough peroxide to kill itself in a period of 24 hours if that poison is not removed from the system. Commonly, the self destruction results from both mechanisms operating simultaneously.

To draw an analogy with the human culture is not pleasant but I think it is clearly indicated. Only the time scale is different. Our population growth, together with the industrial and agricultural activities necessary to sustain it, has already put great pressure on resources and has gone far toward increasing the toxicity of our environment. We are stuck with the old compound interest formula—the geometric progression—and there is no way to repeal it. If population increases at the rate of 1.5 percent per year—as in the United States—it will double every 47 years. Through public health and safety campaigns, governments fight death at every turn but birth is such a sensitive area that few nations have national population policies. We have reached the point where growth is not, as it always has been in the past, necessarily a good thing.

In my opinion, as a direct result of population growth, the areas of *resources* and *environmental science and engineering* are the most important areas for scientific and engineering research in the coming decades. It is urgent that we intensify and expand our present feeble efforts in these fields—in training and in research. It is not a matter of whether we can afford such expansion—as in current debates over sending expeditions into space—it is a matter of survival and to hell with the cost!

The city has a gargantuan appetite for resources of all kinds. Mineral stuffs and food stuffs flow from the land into the city. There is a return flow of contamination from the city to the land. The city is the nucleus of the contamination, and the nuclei themselves are spreading. In the year 2000 cities with populations of 25 to 50 millions will not be unknown. Paradoxically, as we break through new frontiers on every side and the average citizen has a greater appreciation for science and engineering than ever before, we seem to be entering a dark or twilight age as far as appreciation for and understanding of the land is concerned. I do not mean that understanding and appreciation do not exist—I mean they do not exist for the great mass of the people. Resources specialists and conservation groups are more knowledgeable than ever before. But the mass of the people are turning their faces from the land to the city, and the new generation does not know the land. This is perhaps less true in Texas and the western states than elsewhere in the country, but it is true in the metropolitan centers of Texas.

Well, so what? Let's be nostalgic and sentimental about the land, and then let's forget it and think about hard facts.

The earth and the sun and the people are the ultimate resources. As the population grows, more pressure is put on the resources of the earth and there is less margin for waste. And as the population grows, violent or catastrophic natural events—the end members of

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[1] Text of an address made to a *Symposium on Geoscience and Urban Development*, Baylor University, Waco, Texas, February 13, 1964.

the gamut of natural processes which include tectonism, mass wasting, sedimentation, and atmospheric dynamics—do far more damage than ever before. This is because of the complexity of the urban system where so many factors are interdependent and all depend on a continued flow of power, transportation, water, sewage, and the continued stability of the earth's surface. As the system grows more complex, so it grows more vulnerable, and so the better must be our engineering.

Engineering improves as science advances. The engineer asks "how?"—the scientist asks "why?" True, the engineer can deal with most systems without understanding them but he must then work empirically without a precise knowledge of limits, and therefore his margin factors are large and expensive and his solutions sometimes more complex than necessary. If efficient engineering is the goal, and it must be, then natural processes must be thoroughly understood.

Geological considerations are important in the development of a city in two broad areas: (1) Resources and (2) Municipal Engineering.

Water is the prime municipal resource. With few exceptions, cities were built where there was a supply of water adequate for the original demand. However, nearly all cities have outgrown their local water supply and must transport water. And as cities become larger, their water appetites become more voracious. Two sources of water are available to a city—surface water and ground water. As surface water supplies close to the city become inadequate, the city constructs new reservoirs and reaches farther afield to tap lakes and rivers. Commonly this brings the city into conflict with other prior users. Another solution to the problem is the development of well fields to exploit ground water but not every city is fortunate enough to be located in an area where there are large supplies of potable ground water. In the future some cities will be forced to convert saline or brackish sea or ground water for municipal use. Pilot plants to remove salts from such waters are already in operation. Research and development in this area are at a high level. Of course all of these projects which involve construction of reservoirs and aqueducts, drilling of wells, and installation of plants to manufacture potable water from saline water raise the cost of water. Now the great metropolitan area of Southern California is reaching hundreds of miles into the northern part of the State, at a cost measured in billions of dollars, to meet its needs for water. Usually, because we live in a democracy, a great city which counts its voters in the millions is a political power and can achieve its objectives.

Less critical city resources are the construction materials. The kind and quantity of construction materials available certainly control a city's appearance and affect municipal engineering. Brick and tile clays, dimension stone, concrete aggregate—sand and gravel and crushed stone—are examples of this kind of resource.

The resources which are of concern to a city—water and construction materials—are measured in cents per 1,000 gallons, cents per yard, or cents per ton. They are commodities which are used in large volumes but which have a low value per unit of production. Of paramount importance, then, is the location of the resource—proximity to a city's growing parts. If a commodity has a value of $1.00 per ton at the quarry, and if it costs 5¢ per ton-mile to transport it, one can easily see that at the end of a 20-mile haul, one-half the cost of the commodity is haulage cost; at 40 miles the cost of transport is twice the value of the commodity at the source. When multiplied by a factor of thousands of tons, the cost increment is substantial indeed. This is another way of saying that a large deposit of sand and gravel within the city limits is a valuable asset, whereas a similar deposit 100 miles away may be worthless.

Construction materials are already in short supply around many large cities and growing smaller cities. For example, in Texas in 1963 the total value of sand and gravel produced was over half a million dollars less than in 1962, while all other construction minerals showed increases. The decline was not due to a lessening of demand. In some areas, sand and gravel deposits have been depleted so that they are being replaced in their former markets by higher priced crushed stone.

Several years ago, leaders of the Denver, Colorado, metropolitan area became concerned about the decline of sand and gravel reserves in the area. A study was initiated by the Intercounty Regional Planning Commission. Its report showed: (1) Original reserves available to the city were 925 million tons. (2) Remaining were 244 million tons (24 years supply at current rate of exploitation). (3) Since 1950, 50 million tons had been produced but because of new construction built on sand and gravel deposits, available reserves had diminished by 250 million tons. The Commission recommended that land use be regulated by zoning to protect and conserve sand and gravel resources.

Construction materials are not as vital to a city as is water supply, and probably the same degree of control and supervision is not called for. Clearly, however, it is practical for a city government to be concerned with construction costs within its limits, and, therefore, it is practical for a city to look to its reserves of construction materials.

The planning group of a city that suddenly is concerned about depletion of sand and gravel or crushed stone sources cannot simply find the least desirable land in the city—the old swamp—and zone it for quarry sites. Resources are where they are and cannot be created by legislation. The sand and gravel resources are in the terraces along the river that are being sold to developers for $8,000 per acre. Politically, there is not a chance in the world that a prime real estate area will be zoned for quarry development. Ten years earlier it could have been done, but the city planners (1) did not have a geologic map so they did not know the sand and gravel was there; (2) did not know the total reserves then being exploited or the rate of consumption so they could not predict the shortage that was imminent. In fact, they did not and still do not know anything about the resources of construction materials in and around the city. The same kind of advance planning used by city departments concerned with water, power, traffic, sewage, and parks must be applied to construction material resources. If sand and gravel are hauled in from distant points, the price of concrete will go up, construction costs will go up, and the bills will go up. Perhaps that school addition will not be built, perhaps the public education facilities will be rated as inadequate, perhaps the big plant will go elsewhere.

Demographers predict two giant cities or megapoli in Texas: one along the Gulf Coast between Houston and Corpus Christi and one on the black prairies between San Antonio and Dallas-Fort Worth including New Braunfels, San Marcos, Austin, Temple, and

Waco. In the United States, about 1 million acres of land per year are being converted to home sites. Bear in mind that most of this land is in and around existing population centers where the mineral producer competes for land. Every mile of new federal highway consumes 40 acres. The answer to the urban land shortage is multiple use. Mineral construction materials can be harvested, and then the land can be made available for construction sites.

Of course, there will always be resistance to planning—and it is true that exercise of eminent domain by a city can be reckless. The individual whose land is condemned by the city rarely feels that he has gotten a square deal. But in the future we will have to support planned urban complexes or live in chaotic urban jungles such as now exist around the old nuclei—Chicago and New York. It will be much cheaper to plan now. Los Angeles has attempted to bring mineral deposits into its plans for the future. The city surveyed sand and gravel deposits in the San Fernando Valley, evaluated them by drilling, and zoned a number of gravel pit sites. After the deposits are quarried, the pits will first be used for refuse disposal and then restored for urban use.

Under the general heading of *municipal engineering* we consider (1) what kind of geologic foundation the city rests on, (2) the structural fabric of the foundation, (3) the porosity and permeability of the foundation, (4) the topography and climate, and (5) the tectonic stability of the area. If we are going to pile great weights on top of rocks, anchor bridges or dams to rocks, drill holes and dig tunnels in rocks, lay slabs on top of rocks, or dispose of waste in rocks, we must know how the rocks or soils are going to react under a variety of conditions, e.g., when they are very dry or very wet, when they freeze or thaw, when the slope is flat to gentle or very steep, and when they are subjected to earthquake or gravity stresses. (I am, of course using rock in the broad sense to include earth materials in general.) The availability of these data not only determines where, if anywhere, there can be high-rise structures on the city skyline—the availability of these data can be a matter of life or death. This is particularly true in cities where pressure for land has resulted in construction on unstable slopes, in known slide areas, and over active faults. If poorly engineered city public works projects induce slope failure or slides, the city's liability may be a matter of millions of dollars.

These are all rather obvious points. What is not generally appreciated is the effect our degree of knowledge about these foundation properties has on costs. All engineering projects cost money, and if because of inadequate geological knowledge a bridge costs more than it should, or a disposal pit leaks, or a dam fails and must be repaired, the city pays the bill. It pays with revenue derived from taxes or bonds. And if, because of mismanagement and lack of appreciation of geological aspects of engineering problems, the city is overloaded with too-high taxes and heavy bonded debt, the city's growth rate can be adversely affected. For example, if construction costs are high because city planners were ignorant of the need to think ahead for construction materials or if the city has in the past paid more for streets, sewers, bridges, tunnels, and public buildings because of their engineering department's lack of appreciation of the geological side of municipal engineering, the city may have been unable to afford a modern auditorium. Or perhaps the by-pass was never completed. Or perhaps the jail is a disgrace. It is easy to point to spectacular events, such as a dam failure, and imagine the tangible and intangible cost to a city. But the nonviolent and unspectacular events probably have cost more. Consider the bridge that cost $700,000 instead of $300,000 because of inadequate geological advice on location of abutments and/or test borings.

To me, it is a fantastic truth that most cities do not have a geologic map and do not employ a geologist. The use of a geological consultant (except on special problems) is not the solution. What is needed is *continuing* geological supervision to permit day-to-day accumulation of data so that the city can take advantage of and exploit its terrain, foundation materials, and resources. In particular, the geologist's job should be the construction and maintenance of an accurate large-scale geologic map. Such a map will pay for itself time and time again, and for the geologist as well. When not employed on geological tasks, the geologist can run survey lines or do other routine engineering work. The geologist is necessary here because geologic maps made by engineers are notoriously inadequate. The engineer can log holes or describe sample pits, but the interpretative part of the map between holes is and should be the geologist's job.

Such a map, like a mine map, must be kept up to date with every new excavation dug or hole bored. It thus comes close to being a fairly accurate model of the surface. The city geologist should inspect every excavation. Although hundreds of excavations are made in a city in the course of a year, they are rapidly filled. What a tragedy the information is lost. What a tragedy the city does not realize how much it needs these data.

What good is the map? How can it pay for itself? Let us forget for a minute its obvious value in water and construction material resource evaluation and consider only engineering value. When a contractor bids blind on a city excavation job, for example, he bids high enough to cover unforeseen problems of water floods, hard rock, heavy ground, etc. If, however, the city lets a bid on an excavation job and specifies the job as removal of so many yards of a certain kind of rock, the bids are lower—substantially lower because the contractor can accurately calculate his costs. Savings over a period of years can be very large.

A geologic map is the difference between groping in the dark and working in a lighted room. With an up-to-date large-scale geologic map, a few confirmatory auger holes may do the job and make unnecessary a $20,000 test-drilling program. The scale of the map, of course, depends on the kinds of problems and may vary from one part of the city to another. In one large U.S. city, areas are now being mapped as 400 feet to the inch.

Most publicly financed geologic organizations, Federal and State, have trod lightly in the area of urban geology because of the political sensitivity of some aspects of it. To designate an area of a city as possessing undesirable or unsafe foundation materials is to invite political attack by the associated landowners. To classify an area as a potential slide area prior to the catastrophe is likewise an invitation to trouble.

The only conclusion that can be drawn from a study of the role of geology in urban development is that the city with a geologist or a geological department will be a more efficiently run city in a better position to meet the demands of the future when an urban area with a population of 1,000,000 is a small town.

Geology of Waco

J. M. BURKET

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ABSTRACT

Geologic factors control or substantially affect the growth and development of a city. Rock materials, soils, water, building sites, landscaping, and certain legal and socio-economic problems are related to geology. This report on the geology of the City of Waco is designed for use by city residents, builders, industrialists, and city planners. It is hoped that a better understanding of the local geologic framework will improve urban planning, structural designs, conservation, proper utilization of resources, and other factors vital to Waco development.

This is the first of a six-part series on the natural environment of the City of Waco. The geologic report (Part I) is divided into five sections: Introduction, Physiography, Structural Geology, Stratigraphy, and Summary and Conclusions.

Previous geologic research in the Waco area has been largely scientific and primarily of interest to geologists. In the current study, aspects of geology are emphasized, which are most critical to urban development.

Waco is situated principally on the Bosque escarpment, which separates the Black and Grand prairies of Texas. The major part of Waco rests upon the Black Prairie. Principal drainage in Central Texas is furnished by the Brazos River and its major tributary system, the Bosque River system. Waco and Cottonwood creeks drain most of Waco west of the Brazos River.

Waco is underlain by eastward dipping bedrock of the Gulf Coastal Plain. This homoclinal structure is broken in the Waco area by the complex Balcones fault system, which bisects the city along a north-south line.

The position of the Bosque escarpment or fault-line scarp coincides with major faults of the Balcones system, which are illustrated on geologic maps (Pls. I, II) and on structural maps (Pls. III, IV). Faults and joints, which are clearly evident on aerial photographs, are most conspicuous in areas of Austin Chalk outcrop. The age of Balcones faulting in the Waco area has not been precisely determined, but indirect evidence suggests that faulting continued from early Cretaceous to middle Tertiary time.

Complex fault patterns and a variety of rock formations in the Waco area have resulted in problems of foundation design, ground water and drainage, corrosion, septic and sewage disposal, and excavation. Engineering characteristics of bedrock formations are products, therefore, of rock types and superimposed structural (faults) complications.

Along major faults in Greater Waco, Austin Chalk is in fault contact with Taylor Marl and the Eagle Ford Group. Foundations may, for example, rest partly upon Austin Chalk and partly upon Taylor Marl, commonly resulting in foundation failure (or over-design). Soil thickness, which is dependent upon weathering rates, is controlled by faults and joints. Septic sewage effluent is conducted by "piping" along fracture systems resulting in pollution of lakes and streams. Shock waves from blasting are conducted or guided along fault zones, creating asymmetric blasting hazard zones. Fault and joint trends are zones of weakness, which can be utilized in quarrying and excavation. Major faults affect artesian water production from Lower Cretaceous sands, and faults may modify water chemistry by contaminating potable aquifer water with saline water from overlying and underlying formations.

Formations, which crop out in the Waco area, include Quaternary alluvium and terrace deposits of the Brazos and Bosque rivers; Upper Cretaceous (Gulfian Series) Lower Taylor Marl Member of the Taylor Formation, Austin Chalk, South Bosque Shale, Lake Waco Formation, and Pepper Shale; and Lower Cretaceous (Comanchean Series) Del Rio Clay.

Subsurface formations (fig. 3) of the Waco area include in descending order the Lower Cretaceous Georgetown Limestone, Edwards Limestone, Comanche Peak Limestone, Walnut Clay, Paluxy Sandstone, Glen Rose Limestone, Hensel Sandstone, Pearsall Formation, Sligo Limestone, and Hosston Sand. Paleozoic rocks of the Ouachita foldbelt underlie Cretaceous rocks in the Waco area.

Surface or outcropping formations in the Waco area are most significant to city growth and development because of their effect or control of topography, engineering properties, soils, construction, and other urban problems. Subsurface formations, however, are important to urban development only if they produce economic rocks or minerals along the outcrop within reasonable hauling distance of Waco, produce potable water in the Waco area, or provide for underground disposal of dangerous wastes.

Quaternary formations.—Brazos and Bosque river alluvial deposits occupy the lowest areas in Greater Waco. Alluvial areas are subject to occasional flooding, and channel migration introduces risk in development. Alluvium ranges widely in foundation and infiltration properties (table 2). Pointbar deposits are well drained and compact; filled meander scars are poorly drained. Ground water from alluvial deposits is polluted, although water is available in moderately large quantities (particularly from Brazos River alluvium).

Brazos and Bosque terraces are composed of sand and gravel. Terraces occur from 20 to 125 feet above present river level. Terraces provide gravel and sand, provide limited amounts of seasonal ground water (usually polluted), and provide reservoirs for underground disposal of minor quantities of waste water.

Brazos River terraces furnish excellent commercial siliceous sand and gravel, some ground water (polluted), and stable foundation sites for light structures. Bosque terraces furnish limited supplies of exceptionally good base material (consisting

of limestone gravel with clay binder), provide limited amounts of water (polluted), provide for modest underground disposal of waste water, and normally furnish stable building sites for light structures.

Cretaceous formations.—Cretaceous rocks in Greater Waco are bedded limestones and shale. The youngest Cretaceous formation in the Waco area is Taylor Marl, which crops out throughout east Waco although it is commonly overlain by Brazos terrace and alluvial deposits. The Lower Taylor Marl Member of the Taylor Formation is a highly bentonitic, calcareous clay, which is plastic when wet.

Some unweathered Taylor Marl will support up to ten tons per square foot, but commonly support strengths are much less. Foundations and footings in the Taylor should extend well into unweathered material, and excavations should be closed immediately to prevent swelling of bentonitic clays in unweathered marl. Foundation failures are common in weathered marl because of its plastic nature and high shrink-swell ratios. Buried structures such as septic tanks, storage tanks, or bomb shelters may be crushed by expansion of clays. Excavations and gentle slopes may be unstable, especially if cuts and slopes are in Taylor fill material. Taylor Marl does not produce water, and it will not effectively absorb septic sewage unless drainage fields are very large. Thin veneers of terrace deposits along the Taylor Marl outcrop cause wide variation in mechanical properties in local areas. Faults and joints further complicate urban problems along the Taylor Marl outcrop.

Austin Chalk crops out throughout much of west Waco. It provides fewer problems in foundations and septic disposal systems and more difficulty in excavation than any Cretaceous formation in Greater Waco. The formation is composed of alternating beds of resistant white chalk and less resistant gray marl, which form very stable foundation conditions. Normally soils on Austin Chalk are so thin that they are removed even in light construction. Soils derived from Austin Chalk have extremely high shrink-swell ratios, and may cause major foundation problems where they are sufficiently thick. Austin Chalk will support steep cuts and banks, can be quarried only with difficulty by conventional operations, and will support openings of considerable size. The formation produces some polluted ground water, and it absorbs moderate amounts of septic sewage effluent. Fluid transmission within Austin Chalk is complicated by fracture and joint systems.

The Eagle Ford Group underlies Austin Chalk. It is divided into South Bosque Shale and Lake Waco Formation. South Bosque Shale, which is exposed along the face of the Bosque escarpment, is a dark gray to black, blocky, homogeneous shale. The upper 40 feet are essentially noncalcareous, and the lower 120 feet are highly calcareous in the Waco area. The upper noncalcareous part of the formation is used in expanded aggregate production and in cement.

Because of thin limestone beds in the upper and lower parts, the Lake Waco Formation has an even greater range of support strengths than South Bosque Shale. In general Lake Waco outcrops support somewhat steeper faces and heavier foundation loads. In limestone sections, some fluid will be absorbed, but excessively large drainage fields are required for septic sewage disposal systems. Lake Waco Formation excavates easily in the shaly middle Cloice Member, but more difficulty is encountered when excavating the limestone sections of the basal Bluebonnet Member and upper Bouldin Member.

Pepper Shale, which underlies the Lake Waco Formation, consists of blue-gray, highly plastic, noncalcareous clay. Pepper Shale yields plastically under minimum loads, and the shale slumps readily even on very gentle slopes. It absorbs essentially no fluid, and it forms a highly corrosive environment for buried pipes. Pepper Shale is exposed only in the extreme southwestern part of west Waco.

Del Rio Clay, which underlies Pepper Shale, is composed of gray, calcareous, plastic clay with rare discontinuous stringers of fossiliferous limestone. In the Waco area Del Rio Clay is commonly exposed in excavations in the extreme northwestern part of west Waco. In its engineering properties, Del Rio Clay resembles the Lower Taylor Marl Member. Del Rio Clay is highly plastic when wet, forms corrosive soils, and is impermeable to drainage or infiltration. The formation is easily excavated and the clay fails by slumping even on gentle slopes.

In Greater Waco rocks older than Del Rio Clay occur only in the subsurface. These buried formations include in descending order Georgetown Limestone, Edwards Limestone, Comanche Peak Limestone, Walnut Clay, Paluxy Sand, Glen Rose Limestone, Hensel Sand, Pearsall Formation, Sligo Formation and Hosston Sand.

Georgetown Formation, which crops out in the Washita Prairie immediately west of the Bosque escarpment, exhibits high support strength. It resembles Austin Chalk in most of its properties. Georgetown Limestone produces essentially no water in the Waco area, but it furnishes a source of marginal road base material.

Edwards Limestone crops out in the Lampasas Cut Plain, 20 miles west of Waco. It furnishes dimension stone and crushed rock for the Waco area, and the Edwards Limestone produces very limited quantities of water in the Washita Prairie immediately west of Waco.

Comanche Peak Formation, which crops out along the hill slopes in the Lampases Cut Plain, is composed of soft, gray, marly limestone. It has no economic value, and the formation does not contain water in this region.

Walnut Clay crops out in valley floors of the Lampasas Cut Plain. It is dominantly clay, and the formation has no economic value except to support agriculturally important soils.

Paluxy Sand contains some potable water north and west of Waco, but it pinches out southward near Waco. It produces small quantities of oil in the South Bosque field immediately west of Waco.

Glen Rose Limestone is the thickest formation in the Waco area (700 feet). It produces some sulphurous water, and it may ultimately provide a reservoir for underground waste disposal by means of injection wells.

Hensel Sand is approximately 70 feet thick in the Waco area, and it produces large quantities of potable artesian water.

Pearsall Formation is composed principally of sandy calcareous shale in the Waco area, and it does not contain significant quantities of water.

Sligo Limestone grades westward into sand in the vicinity of Waco. The formation contains no water in the Waco area.

Hosston Sand is the deepest and most productive of the Trinity aquifers in the Waco area. It is 275 feet thick and contains 50 feet of saturated aquifer sand. In the eastern part of McLennan County, essentially all public and industrial artesian wells produce from this formation. Hosston water is of good quality.

Rocks older than Cretaceous age in the Waco area have been recognized in deep wells. These pre-Cretaceous rocks occur in the Ouachita foldbelt, and consist predominantly of low grade metamorphic rocks of Paleozoic age. In extreme southeastern McLennan County about 30 miles from Waco, rocks of possible Jurassic age overlie the Ouachita facies and underlie Hosston Sand in deep wells.

INTRODUCTION[1]

An understanding of geology constitutes essential background for appreciating the natural environment of a city. This review of the geology of Greater Waco (fig. 1) is designed to provide cultural and practical information for urban planning and development.

The geology of the city constitutes the framework within which all other natural factors are developed. Earth materials are the principal raw materials for building. Soils result from weathering of rocks. Both surface and subsurface hydrology are largely controlled by geology. Hydrology involves drainage, flood control, and quality and quantity of water. Successful foundation engineering depends upon an understanding of the properties of rocks or soils upon which structures are to be built. Horticultural and topographic landscaping depend primarily on geological factors. Legal and socio-economic problems of many types are related in a greater or lesser degree to geology.

The report is divided into five major divisions: (1) Introduction, presenting general information about Waco and its surroundings; (2) Physiography, the relationship of the topography to regional geology; (3) Structural Geology, the age, origin, distribution and importance of rock structures; (4) Stratigraphy, a description of sequence, properties, distribution, origin, and physical characteristics of the local rock formations; and (5) Summary and Conclusions, emphasizing geologic factors of major importance in the growth and development of Waco.

In order for this publication to have maximum usefulness, it has been necessary to use some technical terms. A glossary (p. 43) and tables (tables 1, 2) are supplied for those not familiar with geological language.

PURPOSE

The primary purpose of this report is the description of the surface and subsurface geology of the Waco area (fig. 1) which will aid in the future development of Greater Waco.

Survey of the geologic literature shows that the geology of Waco has been of interest for many years. In his monumental work on the Grand and Black prairies (fig. 2), Hill (1901, p. 542) discussed the geology of the Waco area. Other important early contributors to the geologic knowledge of the Waco area include Pace (1921), Adkins (1923), and Deussen (1924). Later significant contributions include many publications and open-file reports by the Department of Geology, Baylor University. These Baylor geology publications and open-file reports, which are available to all citizens, include detailed studies of the geology of Central Texas within at least a 50-mile radius of Waco.

In this report each formation within the Waco region (table 2) is described and particular emphasis is given to those formations exposed on the surface (Pls. I, II). The geologic structure of the City of Waco (fig. 3; Pls. III, IV) is described and special consideration is given to construction problems (figs. 4, 5, 6) which arise from differences in engineering characteristics of various rock formations.

Subsequent publications in this *Urban Geology of Greater Waco* series (*see* Foreword) will consider urban soil characteristics and problems of Waco; surface and subsurface water supply, contamination, drainage and other related factors in the Waco area; detailed geologic engineering and soil mechanics data related to construction in Waco; economic geology of such materials as sand, gravel, Portland cement materials, expandable shales and brick clays in the Waco region; and socio-economic geologic problems involving such areas as law, architecture, landscaping, appraising and other professions.

This study of the Waco area is based on extensive research of all available literature, maps, samples, and aerial photographs, as well as extensive detailed geologic field investigations. Surface geologic data have been compiled on geologic maps of the Waco area (Pls. I, II).

Subsurface structural geology for this report was mapped on top of the Georgetown Formation (Pls. III, IV) utilizing elevations and fault control extrapolated from surface and subsurface data. The top of the Georgetown Formation was used as the datum because of its uniformity and continuity throughout the area, and because the formation can be easily recognized in the subsurface with both electric logs (Pl. V) and drillers' logs.

LOCATION

The City of Waco, county seat of McLennan County, is located near the center of the county on the prairie lands of Central Texas (fig. 2). In 1960 the population of Waco was approximately 100,000. Waco is the business center for another 50,000 people in Central Texas.

In this report Waco is generally defined as the area of the East and West Waco quadrangle maps (Pls. I, II) published in 1957 by the United States Geological Survey. These quadrangle maps include a rectangular area of slightly more than 125 square miles extending 14.7 miles east-west and 8.6 miles north-south. The maps include Waco and suburban areas—Wood-

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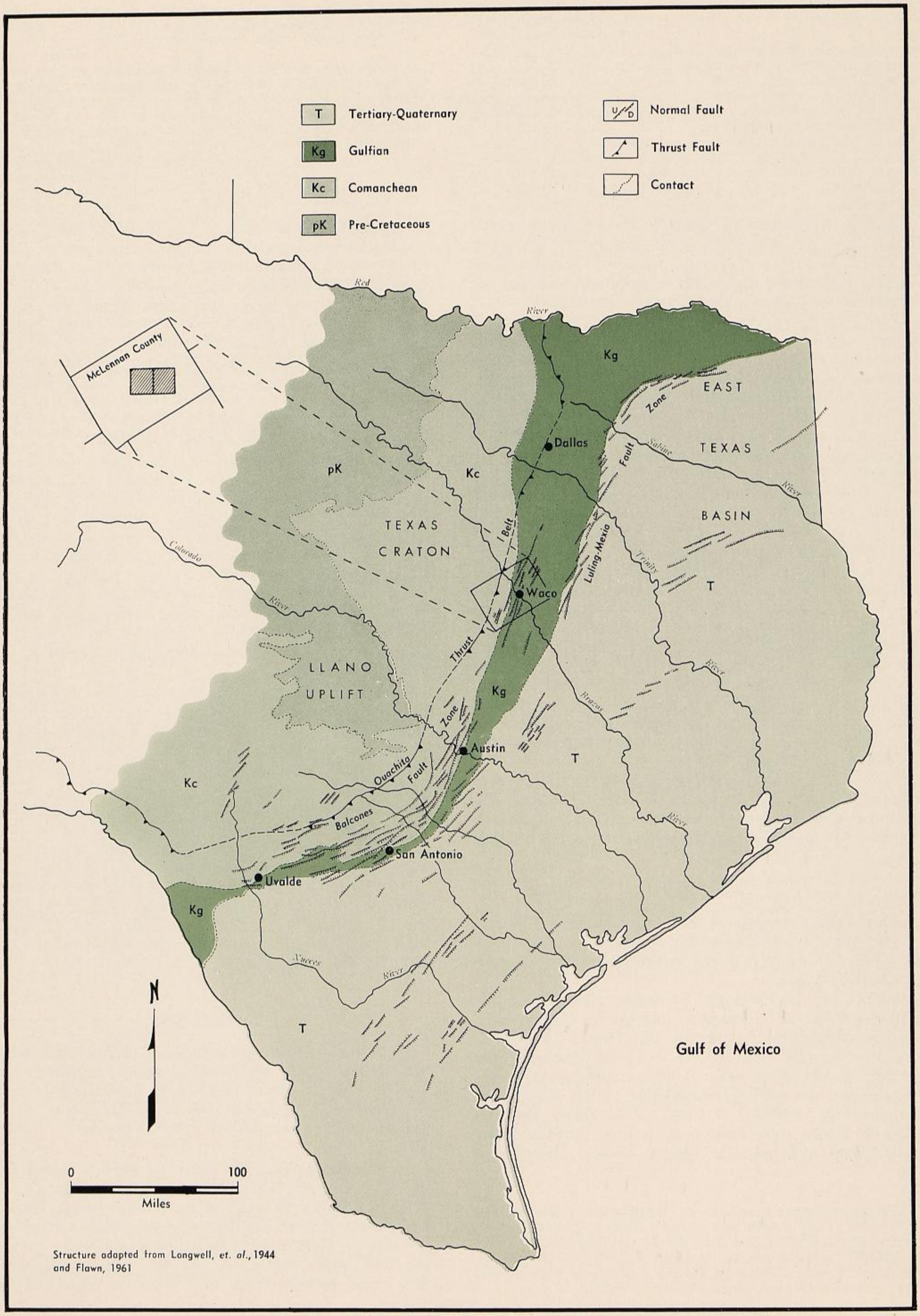
[1] Professor Burket completed the initial study of the Geology of Greater Waco in 1959 as a master's thesis at Baylor University. With financial support from the Cooper Foundation, Burket updated the study during the summer of 1963. Professor O. T. Hayward, Baylor Geological Studies staff, extensively revised and updated maps and manuscript early in 1965.



Structure adapted from Longwell, et. al., 1944 and Flawn, 1961

Fig. 1. Index and regional geologic map, Central Texas.

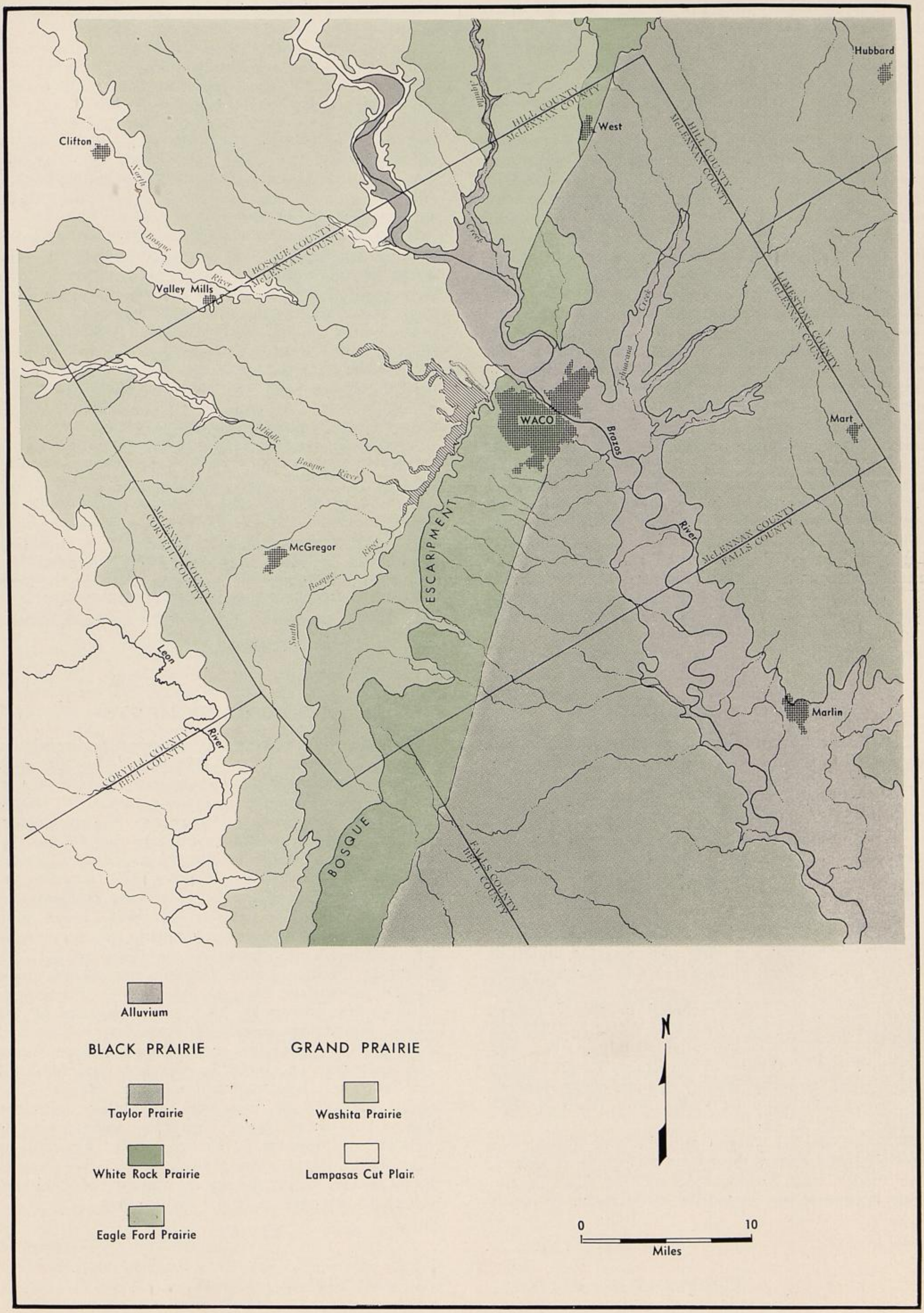


Fig. 2. Physiographic map, Central Texas.

way, Beverly Hills, Bellmead, as well as Lake Waco and the Municipal Airport.

McLennan County (fig. 2) is approximately 38 miles long and 29 miles wide, and it includes an area of 1,034 square miles. The eastern three-fourths of the county is on the Blackland Prairie of Texas, a physiographic subdivision named for dark-colored soils on an area of low relief, and the western one-fourth is located on the Grand Prairie, a physiographic subdivision marked by shallow calcareous soils (*idem*). The long axis of the county is at right angles to the general southeastward course of the Brazos River.

Waco is the center of a rich farming region. Some 875 square miles of McLennan County are prairie lands and most of the prairies are now in cultivation. Several highways and railroads pass through Waco assuring adequate transportation for this Heart of Texas area.

The Waco region has a humid subtropical climate and is near the eastern margin of the semiarid West Texas region. Summers are long with relatively high temperatures much of the time; winters are short and mild. Significant freezing weather occurs only during January and February. Cold spells normally last less than a week, and are succeeded by periods of cool pleasant weather. Occasional rainless periods of several months can be expected, but an annual rainfall of 32 inches is average. Generally, enough rainfall occurs to permit good growth of crops such as cotton and sorghums, but poorly distributed rainfall during the growing season frequently limits corn yield. Moderate fall and winter rainfall with low evaporation enables soils to absorb and store a large supply of moisture.

HISTORICAL BACKGROUND

The City of Waco occupies the site of two Indian villages, El Quiscat and Flechazos, which in the latter part of the eighteenth century were occupied by the agricultural Hueco (Tawakoni) Indians. According to Stephen F. Austin, the main village population was about 100 in 1824. The Hueco Indians were reported to have grown peaches and corn near Waco. Cultivated areas evidently were small and restricted to sandy soils on low terraces or on the flood plains along the Brazos River (Adkins, 1923, p. 7).

The first permanent white settler was George Barnard, who established a trading post near the mouth of Trading House Creek in 1842 (Pl. II). Survey of the T. J. Chambers grant in 1832 resulted in the first private ownership of land. Included in the Chambers grant was the south half of modern Waco. By 1836 the Republic of Mexico had granted all of the area near Waco and within 10 miles of the Brazos River. George B. Erath, the "father of Waco," was one of the Rangers who helped establish Fort Fisher near Waco in 1837 (Conger, 1945, p. 14).

Stockmen started moving into the area about 1845 when Neil McLennan, for whom the county is named, established a ranch headquarters west of Waco on the South Bosque River. Extensive cattle ranching began about 1850 and continued as the principal type of agriculture on the prairies until about 1880.

Range cattle were the so-called Texas Longhorns, unimproved stock originating from cattle brought to North America by the Spaniards. During these early times the prairies were generally considered unfit for farming, probably because of the distance from wood and water, as well as the lack of implements suitable for tilling the clayey soil. Over 1,000 slave laborers farmed vast acreage in the Brazos River alluvial bottoms (fig. 2) prior to the Civil War (Soil Conservation Service, 1959, p. 11).

Waco was surveyed in 1849 and soon became a thriving community. The location included a good spring and high ground. Waco was established near a favored crossing of the Brazos River on the main travel route from San Antonio to North Texas.

McLennan County was organized in 1850 from parts of Milam and Robertson counties (Conger, 1945, p. 38). The first bridge across the Brazos River was the 1870 suspension bridge at Waco, which is still in use. Railroads reached Waco in 1881 and Baylor University moved to Waco in 1889 (*idem*, pp. 15-26).

Since 1900 cotton has been the dominant crop on the Blackland Prairie (fig. 2), a gently rolling prairie underlain by clays, marls, and limestones. At various times, notably in the early twenties, cotton crops occupied as much as 80 percent of the cultivated land on this prairie. Approximately 75 percent of the Blackland Prairie was cultivated until about 1925. There has been approximately 33 percent reduction of cultivated acreage in the Blackland belt of McLennan County since 1925. Reduction of the cultivated acreage has coincided with expansion of livestock production.

ACKNOWLEDGMENTS

The writer acknowledges the assistance and continued support of Professors O. T. Hayward, who suggested this project and significantly contributed to field studies, cartography and manuscript revision, and J. W. Dixon, Chairman of the Geology Department, Baylor University. Additional acknowledgments are due R. L. McKinney and associates of the Waco District, Texas Highway Department, for the use of Highway Department information and for aid in solving problems encountered during the project. The Soil Conservation Service, United States Department of Agriculture, contributed soil information on the Waco area. H. D. Holloway, Texas Water Development Board, contributed sub-surface data on the Hosston Formation.

During the summer of 1963, funds provided by the Cooper Foundation supported extensive revision and updating of the geological study of metropolitan Waco. Chief cartographer, Jerry L. Goodson and assistant Don Baldwin, Department of Geology, Baylor University, prepared all maps and illustrations with the financial support of Baylor University and the Cooper Foundation. Professor L. F. Brown, Jr., Department of Geology, Baylor University, coordinated various aspects of the project during the summer of 1963 and throughout preparation of the final report.

PHYSIOGRAPHY

The City of Waco (fig. 1) is situated on the interior margin of the Gulf Coastal Plain and is underlain by eastward dipping Upper and Lower Cretaceous (table 1) bedrock.

Most of Waco (the eastern four-fifths) is situated on the Blackland Prairie (fig. 2), one of the major geographic regions of Texas. This north-south trending prairie belt about 50 miles wide is underlain by marls, clays, and limestones of the Eagle Ford Group, the Austin Chalk and the Taylor Marl (table 2). Some of the forested sandy Brazos terrace uplands and Brazos River bottoms or alluvium are included in this belt, although they are of a different geologic origin. These sandy terrace soils and alluvial soils support extensive timber belts.

The westernmost portion of Waco is on the Washita Prairie (fig. 2), a portion of the larger Grand Prairie, which is a major geographic division extending through the Central Texas region. The Washita Prairie is underlain by limestones of the Washita Group (table 2). The region is a maturely dissected rolling prairie with shallow calcareous soils, and it differs from the Blackland Prairie belt, which has gentle topography and deeper clayey soils. West of the Washita Prairie is a subdivision of the Grand Prairie, the Lampasas Cut Plain (fig. 2), a dissected plateau capped by Edwards Limestone.

The boundary between the Washita and Blackland prairies (fig. 2) is marked by the Bosque escarpment, a northwestward facing cuesta and fault line scarp which extends across the northwest part of Waco (Pl. I). This prominent stair-stepped, fault-controlled topographic feature is a portion of the longer White Rock escarpment, which has a northeast trend across Central Texas. Throughout much of the length of the White Rock escarpment, the Austin Chalk caps the highest parts of the scarp. Where the escarpment has two topographic steps, the lower one is held up by limestone beds in the Eagle Ford Group (table 2).

The Waco region is drained by tributaries of the Brazos River (Pls. I, II), which bisects the city from northwest to southeast along a broad flat alluviated valley. The Brazos floodplain and alluvial deposits vary from one mile wide in the northwest to four miles wide in the southeast, and the river traverses the outcrop of both resistant and non-resistant strata. The valley apparently developed on a higher land surface, and the Brazos maintained that general course as the land was lowered by erosion. The large deflection in the Brazos River channel north of the city, which is called Steinbeck Bend, is probably fault controlled.

On the Black and Grand prairies (fig. 2) where many tributaries of the Brazos River have developed on outcrop belts composed of weak rock, the drainage displays a trellis pattern characteristic of a belted coastal plain. Locally, in the eastern part of the Waco area where the relatively uniform non-resistant lower part of the Taylor Marl crops out, a more dendritic drainage pattern has developed.

The Bosque River system (fig. 2) is the largest tributary of the Brazos River in the Waco area. The South Bosque River, which receives the drainage of the entire Bosque system, empties into the Brazos in the northern part of Waco (Pl. I). The South Bosque River closely follows the base of the westward facing Bosque escarpment.

Waco storm drainage is carried principally by Waco Creek (Pls. I, II), which heads west of Heart O' Texas fairgrounds in northwest Waco. The creek flows southeastward to Beverly Hills, where it changes its course to the northeast and parallels the M. K. T. railroad tracks. Waco Creek meanders northeastward around Bell's Hill, and at Fourteenth Street part of its discharge is routed underground through a flood relief channel along Clay Avenue to the Brazos River. South and east of the junction with the flood relief channel at Fourteenth and Clay, Waco Creek flows to the Baylor campus where it is again routed underground between Fifth and Third streets. It enters the Brazos River immediately east of the Baylor campus. Some drainage formerly entering Waco Creek has been diverted southeastward along Twenty-sixth Street to Primrose Avenue and then northeastward to the Brazos River.

The area southeast of the city is drained by Cottonwood Creek (Pls. I, II), which originates south of Veterans Hospital and flows in a remarkably straight eastward course until it empties into Eastland Lake, an abandoned gravel pit where both runoff and ground water accumulate.

Flanking the Brazos River and its larger tributaries in the Waco (Pls. I, II) area are extensive stream terraces. These may be divided into two groups: (1) Low terraces (Qbr$_1$, Qbot)[2] adjacent to present streams (an aggregate area of about 40 square miles); and (2) remnants of old high gravel and sand terraces (Qbr$_2$, Qbr$_3$, Qbr$_4$) which cap many higher stream divides, especially east of the Brazos River (an aggregate area of about 30 square miles).

The terraces range from extensive flats less than 30 feet above the present flood plain to moderately dissected high terraces more than 200 feet above the present Brazos River. Minor drainage systems dissect the various terrace levels. Older, higher terraces are extensively dissected and frequently difficult to distinguish topographically.

Between Waco and Asa (southeast of Waco) various terrace flats extend along the west side of the Brazos River. On the east side of the river equivalent terraces occur between Tehuacana Creek and the Brazos River (Pls. I, II). Some of eastern Waco is built on these terraces. Other extensive terraces occur on the west side of the Brazos River north of Waco and along the north and west sides of Lake Waco. Along the present courses of the Brazos and Bosque rivers are other extensive bottomlands or floodplain and alluvium (Qbrf, Qbof, Qal).

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[2] Refer to map symbol on Pls. I, II.

Highest elevations (Pls. I, II) occur in the westernmost part of the city where the maximum elevation is 662 feet above sea level. This western section of the city is underlain by Austin Chalk which supports the crest of the Bosque escarpment. East of the Bosque escarpment crest, the land is inclined gently eastward on the dip slope of Austin Chalk. This eastward slope is interrupted by local stream dissection, which creates a gently rolling topography. Lower elevations in the city range from 414 feet at the city square and 380 feet between Baylor University and the Brazos River to as low as 366 feet east of the Brazos River near Tehuacana Creek. Another area of low relief lies within the area bordered by Washington Avenue on the north, Twenty-third Street on the west, and Franklin Avenue on the south.

Southwest of downtown Waco is a prominent high area (almost 500 feet elevation) known as Bell's Hill. From Bell's Hill the land surface slopes gently eastward to the Brazos River. Other areas above 550 feet elevation lie along the Bosque escarpment in Woodway and in the Veterans Hospital area.

STRUCTURAL GEOLOGY

FRAMEWORK OF CENTRAL TEXAS

Waco is situated on eastward dipping bedrock of the Gulf Coastal Plain (fig. 1) where Cretaceous and Tertiary rocks (table 1) crop out in belts parallel to the Gulf Coast.

Strata of the coastal plain occur in offlap superposition, like shingles on a roof, with the outcrop of each younger bed progressively offset toward the coast. Each formation forms a truncated wedge and each normally thickens coastward.

The homoclinal structure of the Gulf Coastal Plain is broken in Central Texas by a complex pattern of *en echelon* faults of the Balcones fault zone (fig. 1; Pls. III, IV). This fault zone, mapped in detail by Holloway (1961), marks the approximate boundary between outcropping Lower Cretaceous strata of the stable Texas craton to the west and the more steeply eastward dipping Upper Cretaceous rocks of the East Texas basin.

The Balcones fault zone (fig. 1) extends from near Uvalde to the vicinity of Dallas. Major faults of the Balcones system in the Waco area (fig. 3; Pls. III, IV) are down-thrown to the southeast with as much as 260 feet of vertical displacement. The date of this faulting is uncertain. However, evidence of early Miocene (mid-Tertiary; table 1) movement exists along certain faults of the apparently related Mexia system (fig. 1) southeast of the Balcones fault zone (Weeks, 1945, p. 1736). More recent investigators (Rogers, 1965; and Beall, 1964) suggested that the Mexia zone was active during deposition of the Glen Rose Limestone and the lower part of the Taylor Marl of Cretaceous age (tables 1, 2) and that faulting continued into the Tertiary Period.

The origin of the Balcones fault system is unknown. However, the distinct parallelism between Balcones faults and the deeply buried Paleozoic Ouachita foldbelt (figs. 1, 3) suggest possible genetic relationships (Hayward, 1957, p. 62).

The Ouachita foldbelt (fig. 1), an ancient buried Paleozoic mountain system, has been traced by means of well records from the surface of southeastern Oklahoma under Cretaceous rocks beneath Waco, southward around the eastern and southern flanks of the Llano uplift, then westward to the Marathon area where it is again exposed at the surface (Flawn, 1961, p. 122). Folding and faulting in the Ouachita Mountain system generally terminated by late Pennsylvanian time (table 1). Therefore, faults of the Balcones system are not related to active Ouachita folding. The Balcones fault system follows the course of this more ancient buried mountain belt, and the two systems of different age are apparently structurally related. The Ouachita system (figs. 1, 3) may have served as a fulcrum between the more stable Texas craton to the west and the subsiding East Texas basin. The Ouachita foldbelt, therefore, may be responsible for localizing later faulting along this zone (or Paleozoic fulcrum) where tensional forces were created in the overlying Cretaceous rocks.

The Bosque River (fig. 2) has eroded the Bosque escarpment from the original fault line to its present position. Recent floodplain and terrace deposits conceal bedrock in most areas where faults occur in the Brazos and Bosque valleys (Pl. III). Major faults in the Waco area have been located by examining outcrops, well records, and cores. Small faults are common throughout the Waco area, but faults of large displacement (*idem*) occur predominantly in the Bosque Valley north and west of Waco. In Cameron Park several small grabens and branching faults are visible in the Austin Chalk exposed in cliffs. Similar faults occur just above the mouth of White Rock Creek.

GEOLOGIC STRUCTURE OF WACO

The strike of the rock strata (Pls. III, IV) in the Waco area is approximately five degrees east of north (N5°E). The rocks dip eastward at ten to twenty feet per mile in western Waco, but the eastward dip increases to 90 feet per mile (one degree dip) in eastern Waco. Available well and bedrock data in the eastern section (Pl. IV) are insufficient to establish a detailed structural picture where the bedrock surface is concealed by thick black soil developed on the Taylor Marl (table 2).

Waco is located on the Balcones fault zone. The approximate western limit of the fault zone is the foot of the Bosque escarpment along the South Bosque River (fig. 2; Pl. III). Both up-to-the-east and down-to-the-east faults occur in Waco, but principal displacement is down-to-the-east. The fault zone, which consists of hundreds of faults ranging from a few inches to more than 200 feet in displacement, greatly complicates bedrock structure. Most major faults occur along the Bosque escarpment.

Faults in the Waco area were mapped by structural alignments observed on aerial photographs, faults visible in outcrops, interpretation of outcrop patterns, and well information (Pls. I-IV). Major faults, as well as the general attitude of the rocks in the area, are displayed on the structural map of the Georgetown Limestone (Pls. III, IV).

Outcrop studies and aerial photograph alignments point to other possible faults which correlate remarkably well with fault trends based on subsurface data (Pls. III, IV). Aerial photographs taken before western Waco was developed show fault alignments now concealed by homes and streets. Most of these linear features visible on photographs are definitely faults and the remainder apparently are smaller faults or joints.

Faulting and jointing are best delineated on aerial photographs where the faults and joints cut outcropping formations composed of alternating thin beds of resistant and non-resistant strata such as Austin Chalk. Thus, the highest concentration of photographic alignments on the geologic map (Pl. I) occurs in the area of Austin Chalk outcrop. It is probable that the same concentration of faults and joints occurs in the Taylor Marl outcrop area (Pl. II) but the trends are rarely visible on aerial photographs of the thick relatively uniform soft shales and marls of the Taylor Formation.

In summary, the structure of the Waco area is characterized by complex faulting superimposed on a sequence of eastward dipping strata. In the Central Texas area faulting probably occurred throughout most of Cretaceous time, and faulting probably extended into early Tertiary time. In the area of Waco, however, it is impossible to date the faulting precisely. There is no evidence of displacement along any of the Central Texas faults since deposition of the oldest Brazos terraces during middle Pleistocene time (Quaternary; tables 1, 2). Indirect geologic evidence from outside Central Texas suggests that faulting has been inactive since the Miocene (middle Tertiary).

GEOLOGIC STRUCTURE AND WACO DEVELOPMENT

Geologic structure in the Waco area poses no threat to construction or maintenance provided that each design is planned with knowledge of the structural conditions.

Until recent years construction in Waco was primarily based upon the Austin Chalk and Brazos terrace materials (Pls. I, II). Foundation problems were few and failures seldom occurred. For this reason builders have largely ignored the underlying geology. Now that Waco is growing eastward and westward off the Austin outcrop, bedrock geology is becoming a factor that should not be ignored.

Structure and stratigraphy are sufficiently complex and varied so that building procedures adopted for one part of town may almost insure failure in another (figs. 4, 5, 6). Evidence of this may be observed in various areas of eastern Waco where wall and foundation designs, which were so successful elsewhere in Waco on the Austin Chalk, have failed when constructed on different geological material such as the Taylor Marl.

Awareness of geological structure is particularly essential where heavy construction is planned, for it is this type of construction that commonly exceeds the bearing strengths of the underlying rocks. Increasing size and weight of structures—buildings, bridges, overpasses, and dams—seems to be a well established trend in our civilization. Geological information must, therefore, be part of the essential data on which urban planning is based.

Large displacement faults in the Waco area bring formations of widely varying mechanical properties into contact along sharp fault lines. Thus it is conceivable that a foundation may rest partly upon Austin Chalk with a bearing strength of twenty-five tons per square foot, and partly upon Taylor Marl with a bearing strength as low as two tons per square foot. Foundations designed for Austin Chalk are inadequate for Taylor Marl. Foundations designed for Taylor Marl are excessively heavy and costly for Austin Chalk.

Weathering rates, which depend largely upon degree of exposure to ground water, air, and biologic activity, are accelerated along fault and joint planes. Therefore, thick soil zones of limited areal extent may be developed in areas where thin soils are normally expected. This weathering phenomenon may localize failures in foundations and streets, as well as cause accelerated corrosion of buried pipes and cables at specific points where construction crosses a fault or joint.

In addition, septic tank fluids may be rapidly conducted along faults or natural "pipes" to surface drainage channels before bacterial and chemical action modify the sewage sufficiently for surface disposal, resulting in a significant pollution hazard. Faults and joints may also conduct fluids downward to deeper horizons so that the effective permeability of an area of bedrock may be much greater than expected from examination of surface rock samples. Joints or faults of even small displacement tend to conduct ground water, which creates drainage problems where faults and joints intersect streets, foundations, or excavations.

Because faults and joints in the Waco area are essentially parallel, they have the capacity to act as mechanical wave guides which can direct mechanical wave energy for considerable distances. Blasting in the fault zone may result in extensive damage to structures and foundations which occur at considerable distance along the same fault trend. However, nearby structures may not be affected by the blast if they occur at right angles to the fault trend which conducted the maximum mechanical wave energy.

Jointing and faulting in the Waco area created natural north-south planes or partings useful in quarrying. Bedrock excavation by blade in an east-west direction, for example, may be considerably easier than excavation in a north-south direction, particularly in the complexly faulted and jointed area of northwest Waco (Pls. I, III).

Although faults and joints may be difficult or impossible to detect on the ground, they can commonly be traced on aerial photographs by narrow linear bands of lighter or darker color. For example, drainage lines such as creeks and rivers tend to follow joints and faults. Faults may also be sharply delineated on aerial photographs by distinctively different types of natural vegetation which characterizes those formations in fault contact.

Larger faults of the Waco area extend to considerable depth—some to the base of the Cretaceous section and some possibly into the underlying Ouachita foldbelt (fig. 3). Water wells situated near large displacement faults in the Balcones system, particularly on the eastern side, may have lower rates of production, increased drawdown, and abnormally high salinities. These water production problems result from fault truncation and displacement of aquifer sands, by decreased permeability resulting from increased cementation of sands along and near faults, and by contamination of normally fresh water of the Hensel and Hosston sandstones by highly saline Glen Rose water which migrates downward along faults and joints.

Table 1. Geologic time scale.

ERA	PERIOD
CENOZOIC	QUATERNARY
	TERTIARY
MESOZOIC	CRETACEOUS
	JURASSIC
	TRIASSIC
PALEOZOIC	PERMIAN
	PENNSYLVANIAN
	MISSISSIPPIAN
	DEVONIAN
	SILURIAN
	ORDOVICIAN
	CAMBRIAN
PRECAMBRIAN EON	

STRATIGRAPHY

The City of Waco is located on the western edge of the East Texas basin and on the eastern edge of the stable Texas craton (fig. 1). The Bosque escarpment west of Waco (fig. 2; Pl. I) divides the outcrop areas of the Gulfian (Upper Cretaceous) rocks to the east and the Comanchean (Lower Cretaceous) rocks to the west. Southeast of Waco near Mart, some wells which penetrate the Cretaceous section have bottomed in evaporite deposits believed to be of Jurassic age (H. H. Beaver, oral communication). Near Waco, wells have encountered Paleozoic rocks of the Ouachita foldbelt beneath the Cretaceous strata (figs. 1, 3).

In the following section, geologic formations in the Waco area are discussed as to original definition, age, distribution, description, related soils and relation to urban development. The formations are considered in order of age from youngest to oldest. Formations which are exposed at the surface in the Waco area (Pls. I,

II) are discussed in detail since these outcropping rocks have greater effect on city development than do buried formations. In addition, the exposed section is far better understood than the subsurface rocks beneath Waco. The youngest formation in the Waco area (Pls. I, II; figs. 1, 2, 3) is Recent Alluvium, and the oldest formations are metamorphosed sub-Cretaceous rocks assigned to the Ouachita foldbelt. A type lithologic and electric log (Pl. V) for the Waco area is included for the reader's use.

SURFACE FORMATIONS

QUATERNARY SYSTEM

RECENT ALLUVIUM

BRAZOS ALLUVIUM (Qal, Qbrf)

CHARACTER AND DISTRIBUTION

Alluvial deposits of the Brazos and Bosque rivers are the youngest deposits in the Waco area (Pls. I, II). The Brazos River alluvium occupies a more extensive area than alluvium of the Bosque River.

The Brazos floodplain is presently undergoing alluviation by the deposition of fine-grained sediments. Little or no coarse gravels are being transported (Bronaugh, 1950, p. 2).

The Brazos alluvial belt is narrow where it transects the resistant Austin Chalk outcrop in the northern part of the Waco area, but as it progresses southeastward, the belt widens on the less resistant outcropping Taylor Marl (*idem*). In the easternmost part of the area, terrace soils are fertile. In this area the Brazos channel has migrated laterally, leaving alluvial deposits in a belt two miles wide, which extends southward beyond the Waco area.

Both the Brazos and Bosque river valleys exhibit floodplain scrolls and meander scars, visible on aerial photographs as arcuate darker areas on the light-colored alluvial flats.

The alluvial deposits of the Brazos and Bosque rivers support a heavy native growth of large deciduous trees, such as cottonwood, elm, pecan, and oak, and these trees are visible as mottled, light-colored areas on aerial photographs.

SOILS[3]

The alluvial bottoms are productive farmlands with light sandy loam soils. Soils of the Brazos alluvial bottoms grade downward from surficial clay-rich floodplain deposits, through bank load quartzose sands, into basal siliceous bed load sands and gravels. Areas of meander scrolls are characterized by particularly thick floodplain soils and thinner bank load sands.

RELATION TO URBAN DEVELOPMENT

Before construction of large upstream reservoirs, the Brazos River bottoms were subjected to frequent flooding. Flood hazard has been reduced through construction of various flood control and storage reservoirs, but the alluvial plains are still subject to flooding during excessively wet periods. Weather records for the Brazos and Bosque watersheds are inadequate to permit valid prediction of maximum storms. One can not accurately predict what the maximum storm in a hundred or a thousand year period would yield in runoff and flood.

In areas of thick alluvial deposits, a river is not constrained to occupy the existing channel. During floods the river channel may migrate rapidly through meander development or may develop a new channel some distance away from the existing channel by developing cutoffs. Construction in these alluviated areas should be undertaken only if potential loss due to infrequent flooding is acceptable.

Foundation problems in alluvial bottoms of the river are similar to those problems encountered in areas of thick soil cover; that is, total support must be furnished by the weathered mantle. While there are no available data on support values for Brazos River alluvial deposits, it may generally be assumed that foundation support values will vary inversely with the thickness of the floodplain clay-rich surface materials.

Point bar river deposits tend to be well-drained, well-compacted, sandy loams and sands with low shrink-swell values. Meander scars are poorly drained, plastic clay and organic-rich loams with higher shrink-swell characteristics. Foundation design should take into account the nature of the site—whether point bar, floodplain, or meander scar.

Deeper sands and gravel of Brazos River alluvial bottoms provide an excellent source of ground water for limited agricultural or domestic use. Because of the high permeability of the deposits, as well as the type of land use, all water derived from these shallow sands will likely be polluted. They should not, therefore, be used for human consumption without approved treatment. Since the sands are uncemented, well completions should involve a designed bottom-hole screen based on grain size of the sediment encountered in the well bore. In general the more productive wells will be located near the present river or in old meander channels where sands are particularly thick.

Water from these alluvial sands is derived principally from underflow of the river and from bank storage. A small quantity of water for recharge of alluvial sands is derived from drainage of adjacent terraces and from storm runoff in intermittent streams which discharge onto the alluvial bottoms or flow across the alluvium to the river.

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[3] Soils, engineering, water, and economic aspects are considered in greater detail in other parts of this Urban Geology series.

Alluvial sands can normally absorb large amounts of fluid because of the high permeability and porosity. Waste water and sewage carrying little or no solids are readily absorbed by the alluvium. During high water or wet seasons, however, the water table rises and effective subsurface drainage is diminished. A waste disposal system in alluvial areas should be constructed above the maximum level of the water table.

Brazos River alluvial sands from channel areas and adjacent floodplain are excellent sources of builder's sand. River silt and some plastic clays are suitable for certain ceramic applications. Terrace deposits reworked by the Brazos River furnish some commercial gravel.

BOSQUE ALLUVIUM (Qal, Qbof)

CHARACTER AND DISTRIBUTION

The alluvial bottoms of the Bosque River (Pl. I) are much narrower, and in the Waco area are exposed only in a small area below Waco dam.

Bosque alluvial deposits were derived from the dominantly limestone-clay provenance or source area of outcropping Lower Cretaceous rocks (fig. 1). Some Bosque sediments were derived by erosion of siliceous sand and gravel of older (higher) terraces of the Brazos River.

Alluvial valleys of the Bosque River system are narrow where they transect the Main Street Member of the Georgetown Formation northwest of the map area, and are moderately wide where they cross the Del Rio Clay outcrop.

The Bosque River below Waco dam flows in a relatively fixed channel locally entrenched in bedrock except for the last mile of its course before entering the Brazos River.

Other narrow alluvial deposits (Pls. I, II) occur within the city along Waco Creek and south of the city along Cottonwood Creek.

SOILS

The Bosque alluvium consists of thick clay-rich floodplain soils, bank load clay and sand deposits, and thin bed load limestone gravel deposits. Old bed load clayey limestone gravel deposits, which have been elevated and dissected, are the source of excellent road-building gravels. Floodplain soils have been a commercial source of rich topsoil in the Waco area.

RELATION TO URBAN DEVELOPMENT

Although it is probable that major flooding in the lower valley of the Bosque River has been largely eliminated by construction of the new Lake Waco dam, it is still impossible to predict the effect of simultaneous maximum floods in both the Bosque and Brazos watersheds.

Foundation problems should be anticipated in Bosque alluvial bottoms since these deposits contain a higher percentage of plastic clay and thicker clay sections when compared with Brazos River alluvium. The properties of Bosque alluvium are probably more uniform than those of Brazos alluvium. Thickness of the alluvium might be determined by refraction seismic methods or borehole investigations which would locate areas of shallow bedrock. Irregular thicknesses of Bosque alluvium are indicated by bedrock exposures along the river channel.

Deeper sands and basal (bed load) gravels of the Bosque alluvium should produce small quantities of ground water suitable for limited agricultural and domestic use. This shallow water potential will probably be maintained by normal seepage from Lake Waco. Bosque alluvial water will be polluted by seepage of polluted water from Lake Waco, from septic sewage disposal in Bosque alluvium, and from agricultural fertilizers used on the alluvial plain. Although Bosque alluvial soils and sediments are normally less permeable than those of Brazos River alluvium, Bosque alluvium will transmit properly introduced fluids in considerable quantity.

The Bosque alluvial sediments are a commercial source of black topsoil.

PLEISTOCENE TERRACES

The terraces of the Waco area are remnants of older river floodplains of Quaternary age left as "steps" by more recent river downcutting (Pls. I, II).

TERRACE SYSTEMS

There are two distinct terrace systems in the Waco area—the Brazos system and the Bosque system. The levels of earlier Brazos River alluviation are represented by remnants of terraces from 20 to 125 feet above present river level. The earlier Bosque River deposits are represented by terraces 10 to 40 feet above the present level of the Bosque River mouth.

DEPOSITIONAL CHARACTERISTICS

Both the Bosque and Brazos terrace systems display common depositional characteristics including cross-bedding, distinct contacts with underlying formations, and carbonate cementation resulting from solution of limestone gravel and precipitation at intergrain boundaries (Bronaugh, 1950, p. 5).

AGE OF TERRACES

Higher terraces of the Brazos River have yielded vetebrate fossils of Pleistocene age. Bosque terraces and lower Brazos terraces are of Recent age as determined by archaeological studies (*idem,* p. 9).

BRAZOS TERRACES (Qbr1-4)

TERRACE LEVELS

Brazos River terraces in McLennan County have been divided into two general groups: a lower terrace group varying from 20 to 50 feet above the river, and a higher terrace group varying from 70 to 200 feet above mean low water level (*idem,* p. 7).

For convenience in areal mapping, four Quaternary terrace levels of the Brazos River have been delineated on the basis of elevation above low mean water level: (1) the lower levels (Qbr1=0 to 50 feet) which comprise terrace material representing the 20 to 50-foot terraces; (2) the second level (Qbr2=50 to 75 feet) which is the 75-foot terrace; (3) a third level (Qbr3 =75 to 125 feet) which is the 125-foot terrace; and (4) a fourth level (Qbr4=125+) which consists of terrace material higher than 125 feet above mean low water level. This uppermost level extends northeastward beyond the map area to the vicinity of Elm Mott.

Remnants of Brazos gravels occur intermingled with Bosque River gravels near the mouth of the North Bosque River and in the vicinity of Bosqueville (Pl. I).

SOILS

Topsoils on higher Brazos River terraces vary from gray to brown and are largely noncalcareous. Subsoils are from 5 to 12 inches in depth and are slightly calcareous sandy clay. Lower terrace levels have dark brown silty soils which vary from slightly calcareous to noncalcareous. Porous subsoils have a good water-holding capacity.

COMPOSITION

Brazos River terraces are composed largely of siliceous sands and gravel (quartz, chert, quartzite) and minor amounts of reddish clay. Where they are in contact with Austin or Georgetown Limestone, the terraces also contain a large amount of limestone pebbles.

Brazos River terraces commonly support an extensive growth of deciduous trees and are visible on aerial photographs as light-colored, mottled areas. These terraces form good agricultural soils which are largely in cultivation.

RELATION TO URBAN DEVELOPMENT

Brazos River terraces, which are composed largely of sand and gravel, furnish stable, well-drained foundation sites for light structures. Bedrock commonly occurs at shallow depths beneath the higher level terraces.

High permeability of Brazos terraces makes them ideal for disposal of waste water. Terraces of considerable areal extent near the river store limited quantities of ground water suitable for domestic use after treatment for bacterial pollution. The high permeability of these terrace sands almost insures that septic sewage will find its way into any nearby well. As the area of a given terrace decreases, the storage capacity also decreases, so that only larger terrace areas furnish a dependable but limited water supply.

Brazos terraces constitute the principal source of construction sand and gravel for the Waco area. An estimated 1.2 million cubic yards of gravel were produced principally from Brazos terraces during 1964. Reserves within a ten-mile radius of the city are more than adequate to meet anticipated needs for the next 20 years.

BOSQUE TERRACES (Qbot)

CHARACTER AND DISTRIBUTION

In the Waco area, Bosque terraces are primarily west of Lake Waco (Pl. I). Commercial deposits of Bosque terrace gravels occur west and north of Waco along various tributaries of the Bosque system.

Bosque terraces are composed chiefly of clay and limestone gravels deposited by the Bosque rivers which have cut into Lower Cretaceous shales and limestones west and north of Waco.

SOILS

Soils of the Bosque River terrace system are normally calcareous alluvial clays varying from brown to black. These soils become lighter colored and increase in carbonate content with depth.

COMPOSITION

Bosque River terrace gravels are composed chiefly of limestone pebbles derived from lower members of the Georgetown Formation and a small amount of chert and limestone eroded from the Edwards Formation.

RELATION TO URBAN DEVELOPMENT

These gravels are locally consolidated by calcium carbonate and are capable of supporting substantial foundation loads. The soil cover is commonly thin and easily removed. Bedrock normally occurs only a few feet below the surface.

Some water is produced from shallow wells in thicker terrace deposits, but the water supply is limited since it is available principally during wet seasons.

Bosque terrace deposits are sufficiently permeable to provide excellent subsurface disposal of small quantities of treated waste water.

Limestone gravel in the Bosque terraces is grade A base material for street and highway construction because of the abundant clay binder. Much of the Bosque terrace material in the Waco vicinity lies below the conservation level of Lake Waco. The gravel cannot be exploited since dredging the gravel from beneath the water results in loss of the essential calcareous clay binder. Limited deposits above lake level occur at localities along North and Middle Bosque rivers, Hog Creek, and Harris Creek.

CRETACEOUS SYSTEM

Formations of Cretaceous age occur at the surface (figs. 1, 2) and in the subsurface (fig. 3; Pl. V) of the Greater Waco area. The entire Cretaceous section in the Waco area is composed of sedimentary rocks of marine origin. These Cretaceous rocks have been divided into an upper section of Gulfian age and a lower section of Comanchean age (table 2; Pls. I, II).

In the Waco area, the Gulfian Series (table 2) from top to base is composed of Taylor Marl, Austin Chalk, South Bosque Shale, Lake Waco Formation, and Pepper Shale. These Gulfian rocks, which are 890 feet thick in the J. L. Myers & Sons No. 1 Tiery well (Pl. V; Appendix I) are exposed at the surface in the Waco area and dip eastward (fig. 3) into the subsurface of the East Texas basin. Gulfian rocks in Greater Waco crop out (Pls. I, II) east of the eastern shore of Lake Waco. Approximately 1700 feet of Comanchean Series strata occur below Greater Waco (Pl. V; fig. 3), but only the uppermost formations (Buda and Del Rio formations) crop out locally in the northwest part of the map area (Pl. I).

TAYLOR MARL

ORIGINAL DEFINITION

In 1889, Hill (p. xiii) first called the Taylor Marl the "Blue Bluffs division" for exposures along the Colorado River four miles east of Austin. The term "Taylor Marl" was later applied (Hill, 1892, p. 73) to exposures near the town of Taylor.

AGE AND DISTRIBUTION

The Taylor Marl is middle Gulfian in age (Stephenson *et al.*, 1942, Chart 9). Exposures occur northeastward from the Rio Grande embayment to the Red River. The formation thins northeastward and southeastward from Waco. The Taylor Marl is 250 feet thick in the J. L. Myers & Sons No. 1 Pardo well (Appendix I).

The Taylor Marl unconformably overlies Austin Chalk and unconformably underlies the Navarro Group (table 2) in western Limestone County (Stephenson, 1929, p. 1328).

In Central Texas the formation is divided into four members (table 2). In descending order the members are Upper Taylor Marl, Pecan Gap Chalk, Wolfe City Sand, and Lower Taylor Marl. The Upper and Lower Taylor Marl members are informally named units in this area. Beall (1964, pp. 10-11) modified this classification. Only the Lower Taylor Marl Member is exposed in the Waco area (Pls. I, II). In the J. L. Myers & Sons No. 1 Tiery well, the Lower Taylor Marl is approximately 230 feet thick. The overlying members of the Taylor Formation crop out in eastern McLennan County and western Limestone County.

The lithology (marine shale and marl) of the Lower Taylor Marl Member indicates that it once covered all of the Waco area and extended some distance westward. The Taylor Marl has been eroded from most of the area west of the alluvial valley of the Brazos River and it is now exposed chiefly in the region east of the Brazos River.

Normally the Taylor Marl is in unconformable contact with the underlying Austin Chalk, but the Taylor is in fault contact with the Austin Chalk in the area of Waco Creek and 11th Street (Pace, 1921, p. 17), on the Baylor campus, and along White Rock Creek northeast of Steinbeck Bend of the Brazos River. Throughout much of its length, this fault contact is concealed by overlying Brazos River terraces. Five miles north of Waco along a major fault of the Balcones system, the Lower Taylor Marl Member is in fault contact with the South Bosque Shale of the Eagle Ford Group.

DESCRIPTION

The Lower Taylor Marl Member is a fine-grained, massive, uniformly bedded marl. It is normally gray, but weathers buff and grades rapidly to the dark, rich soil of the Texas Blacklands. Where erosion has stripped the soil cover, the buff-weathering marl forms conspicuous scars on hillsides. Clay minerals, chiefly montmorillonite and illite (Beall, 1964, pp. 16-19) compose approximately 60 to 70 percent of the member. The remaining 30 to 40 percent is composed principally of calcium carbonate, a cementing agent, and minor amounts of silt, calcite, glauconite, calcium phosphate, hematite and pyrite (*idem*, p. 16).

Beall (1964, pp. 22-25) concluded that the composition and areal uniformity of the Lower Taylor Marl indicate that it was deposited on a broad flat subsiding shelf. Rates of subsidence and deposition were approximately equivalent. The areal uniformity and the great thickness of the member suggested to Beall a long period of deposition in a relatively nearshore shallow marine environment. Marine conditions are indicated by foraminifers, ammonites, clams, scaphopods, and marine vertebrates (*idem*, p. 23).

The Lower Taylor Marl is principally clastic, varying in particle size from clay to silt but containing some sand. Sand content increases upward within the member, indicating marine regression in the latter stages of Lower Taylor Marl deposition. The culmination or climax of sand deposition is represented by the overlying Wolfe City Sand Member. The abundance of calcium carbonate in the Lower Taylor Marl Member suggests slow clastic deposition relative to biochemical precipitation of calcium carbonate. Oscillation of the strandline as well as climatic changes are possible causes for local variations in silt-clay and clay-carbonate ratios.

Weathering alters the blue gray color of the Lower Taylor Marl Member to light gray or tan. The marl becomes highly fissile where the calcium carbonate cement is leached. Some weathered marl samples display limonite stains which appear to be the alteration product of pyrite, the pigmenting material of the unweathered marl.

Drainage in the Lower Taylor Marl outcrop area is dendritic, due to the relatively homogeneous composition of the member, but fault or joint control of drainage is suggested by the northeast-southwest orientation of segments of Tehuacana, Tradinghouse and Williams creeks (Pl. II).

SOILS

Soils derived from the Taylor Formation are dark, plastic "black waxy" soils of the Blackland Prairie. They are deep dark-gray to black, calcareous, and crumbly soils. Parent materials are montmorillonitic clays, marls and minor amounts of silt-sized quartz. Noticeable swelling occurs in the wet montmorillonite clays at the upper surface of the *A* soil zone. Swelling of wet clays reduces surface permeability; drying produces a thin brittle crust over an open spongy soil. Shrinkage cracks extend several feet into the soil profile following long periods of drought.

RELATION TO URBAN DEVELOPMENT

Some structures built on soils derived from the lower part of the Lower Taylor Marl Member have subsided and shifted laterally. Unweathered Taylor Marl will support up to ten tons per square foot. To obtain maximum support, pilings or footings should extend well below the weathered zone. Unweathered Taylor Marl is blocky blue-gray clay, readily distinguished from the more friable buff-colored weathered material. In highly bentonitic zones, the marl may yield under loads much lower than those noted in short term tests. Weathered Taylor Marl and Taylor soils have particularly low yield points.

Foundation failures are common in areas underlain by Taylor Marl, largely because adequate footings are not provided and/or they do not extend into unweathered marl. Because of bentonitic clay beds in the Taylor Marl, excavations for piers and footings should be filled quickly before these highly expansive clays are altered through exposure to water and atmosphere. High shrink-swell ratios characteristic of bentonitic clays cause flexing of the surface soils with changing moisture conditions. Soil movement resulting from shrink-swell may be several inches, and pressures developed are sufficient to crack grade-beams and monolithic slabs.

When these clays are in contact with buried structures such as septic tanks, storage tanks, or bomb shelters, improper drainage may result in clay expansion which can crush or rupture a structure. This crushing phenomenon is compounded when the buried structure is covered by clay back-fill derived from the Taylor Marl. Such damage may be prevented by proper drainage and isolation of the structure from the surrounding clay by back-filling with gravel.

Loosely compacted Taylor Marl fill is highly plastic and prone to slump when wet, even on very low angle slopes. If Taylor Marl is adequately compacted and stabilized, it will support low embankments and reasonably heavy loads.

The low permeability of the Taylor Marl and the high proportion of bentonitic clays cause the marl to swell on wetted surfaces and to resist further fluid infiltration. Thus, septic sewage disposal in areas of Taylor Marl outcrop requires large drainage fields. During rainy weather sewage may find its way to the surface when the drainage field becomes saturated. Where population density is high and septic systems are used, Taylor soils will probably become contaminated during excessively wet periods.

Taylor Marl does not produce water because it is relatively impermeable and, therefore, water systems in areas of Taylor outcrop must depend on other sources. Low permeability, however, enables Taylor clay and soil to hold surface water; therefore, effective surface storage ponds may be constructed along the Lower Taylor Marl outcrop.

The low permeability of lower Taylor Marl Member also limits the water available for deep rooted plants and, therefore, the natural vegetation of the outcrop area consists largely of grasses and shallow rooted, low transpiration plants. Deep rooted trees can thrive where permeability is increased to a considerable depth by artificial means.

Over a significant part of the Lower Taylor Marl outcrop occur thin patches of Quaternary gravel and sand terraces (Pl. II). Such areas are characterized by reddish soil (in contrast to typical dark gray soils on Taylor Marl) and natural vegetation consists of post oak and other higher transpiration plants. Even in small areas where gravel veneers (terraces) are but a few feet thick, foundation and drainage properties resemble those of the larger, thicker gravel terraces, rather than those of the underlying Taylor Marl. For example, on these thin terrace deposits light construction is possible using foundations which would probably fail on Taylor Marl. Also, effective septic sewage disposal is possible in these thin gravel terraces.

Complex faulting and jointing, evident in the Austin Chalk outcrop area, are not apparent in the Taylor Marl, although aerial photographs and electric well logs of the Taylor Marl indicate that jointing and faulting occur. Since soils are normally thicker along faults and joints, the local thickness of the weathered zone above the Taylor Marl cannot be established by a single exploratory boring, but the depth should be determined by closely spaced holes.

AUSTIN CHALK

ORIGINAL DEFINITION

The name "Austin limestone" was first used in 1860 by B. F. Shumard (Wilmarth, 1938, p. 93) for exposures near Austin, Texas.

AGE AND DISTRIBUTION

The Austin Chalk is of Gulfian age (Stephenson *et al.*, 1942, Chart 9) and it crops out in a belt four to five miles wide from Sherman to San Antonio and thence westward. Because of pre-Taylor erosion, the Austin Chalk thins southward through the Waco area. The formation is exposed along the crest and dipslope of the Bosque escarpment (fig. 2; Pl. I) in the western part of Waco. Along South Fifth Street (Pl. II) beneath thin Brazos River terrace deposits, the Austin Chalk is in fault contact with the Lower Taylor Marl Member of the Taylor Formation. North of Waco the chalk is exposed along the Brazos River and White Rock Creek (*idem*). Quaternary terraces and alluvium of the Bosque and Brazos rivers overlie the Austin Chalk along most of the river valleys. Along the steep face of the Bosque escarpment (Pl. I) a few feet to more than 100 feet of the lowermost part of the Austin Chalk are exposed. The lower half (120 feet) of the Austin Chalk crops out at Lover's Leap in Cameron Park (*idem*). The Austin Formation penetrated by the J. L. Myers & Sons No. 1 Tiery well in eastern Waco is about 250 feet thick.

DESCRIPTION

The Austin Chalk is composed of alternating beds of resistant white chalk and less resistant blue-gray marl. Individual beds are rarely more than two feet thick. Bentonite seams commonly occur in the marl layers. A thicker bentonite-rich marl zone, which occurs 50 feet above the base of the formation, is readily distinguishable on electrical logs and in outcrop sections.

The distinctive alternation of chalk and marl beds is one of the most characteristic features of the Austin Formation. The apparent uniformity or similarity of alternating beds makes stratigraphic correlation within the Austin difficult on the outcrop. Electrical log correlations within the Austin Chalk, however, are precise because of the lateral uniformity of distinctive electrical "kicks" within the formation.

Balcones faulting complicates correlation of surface sections. Evidences of faulting include calcite veins with slickensided surfaces, offset beds, and dragfolds. Several sets of slickensided surfaces along faults indicate recurrent movement.

Faults are particularly evident on the outcrop (and on aerial photographs) by offset alternating marl and chalk beds of the Austin Formation. Thicker soil development along permeable fault and joint zones appears as darker lines on aerial photographs of the Austin outcrop.

The chalk layers in the formation average 85 percent calcium carbonate, principally microcrystalline calcite with minor amounts of foraminiferal tests. The chalky limestones contain minor amounts of silica, iron, aluminum, and magnesium in the form of clay minerals. The less resistant blue-gray marls, which contain less calcium, have a higher clay mineral content reflected by higher silica and iron oxides reported in chemical analyses. All beds within the Austin Chalk contain abundant pelecypods, foraminifers and unidentifiable fossil debris. Nodules and irregular masses of pyrite are commonly present in surface sections.

Chalk beds in the Austin Formation weather buff to white through oxidation of iron compounds (principally disseminated pyrite). Below the weathered zone the chalk is blue-gray. Marl beds are commonly gray to dull blue where clay mineral content is high and buff to dull gray where it is low.

The Austin Chalk is more resistant to weathering and erosion than any other formation in the Waco area. The formation underlies the prominent White Rock Prairie. Bluffs with protruding resistant chalk ledges and receding soft marl beds typify the steep-walled valleys dissected into the prairie.

The Austin Chalk is unconformably overlain by the Taylor Marl, and the chalk rests unconformably upon the South Bosque Shale. The basal Austin unconformity is marked by a phosphatic conglomerate which contains abundant fossil material reworked from the South Bosque Formation (Seewald, K. O., oral communication, 1965).

A phosphatic conglomerate also occurs at the base of the overlying Lower Taylor Marl. Fossil evidence suggests that the upper part (250 feet) of the Austin Chalk in the Dallas area is younger than any of the Austin Formation near Waco. The Austin-Taylor unconformity in the Waco area may represent local erosion of many feet of Austin Chalk prior to deposition of the Lower Taylor Marl Member (Stephenson, 1937, pp. 137-138).

The Austin Chalk thickens northward by adding beds at the top of the formation. The lateral continuity of these individual beds, which is well displayed on electrical logs, indicates that the beds may have extended southward beyond the present terminus prior to pre-Taylor erosion.

The composition and faunal content of the Austin Chalk indicate that deposition took place in a warm shallow marine environment, principally by biochemical precipitation of calcium carbonate. Cyclic variation in the sedimentary environment is indicated by the alternation of chalky limestone and marl beds. Argillaceous material (clay minerals) in the Austin Formation was probably land-derived and calcium carbonate precipitation resulted from marine biotic activity. Although the cause of this alternation in deposition of chalk and marl is not understood, it may have resulted from climatic variation rather than fluctuation of the strandline. Accordingly, the chalk layers perhaps were deposited during extended warm dry periods and the marl layers during wetter and cooler climatic periods.

SOILS

Soils derived from the Austin Chalk are normally plastic to granular, highly calcareous with permeable subsoils commonly containing chalk fragments. Brown to dark-brown soils are common when the soil zone is from 12 to 18 inches deep. Thicker soils in poorly drained areas are dark-gray to black with a crumbly surface and less permeable substratum.

RELATION TO URBAN DEVELOPMENT

The support strength of Austin Chalk ranges from 14 to 25 tons per square foot in areas where normal chalk and marl layers crop out, but engineering strengths may be much lower on the outcrop of the few thin clay-rich zones in the lower 50 feet of the formation. Few foundation failures can be attributed to failure of the Austin Chalk. Principal foundation problems originate in structures which rest upon thin plastic clays in the formation, or more commonly where a structure rests upon soil rather than bedrock.

Soils on the Austin Chalk, particularly in topographically high, well-drained areas, are normally so thin that they are completely removed in preparation for foundation construction. However, in low poorly drained areas and where Quaternary channel deposits rest on the Austin Chalk, such thick soils may accumulate that excavations may fail to reach fresh bedrock. Austin Chalk soils are particularly plastic, and exhibit high shrink-swell ratios. In areas with thick soils, it is particularly important that foundations extend to bedrock by deep excavations or by the use of piers.

Austin soils rarely cause foundation problems because the normally shallow soils are removed during foundation construction. However, in areas of thick soil accumulation, high shrink-swell properties will almost insure foundation failure if structures are supported by soil rather than bedrock.

Faulting and jointing in the Austin Chalk outcrop area lead to local abrupt changes in soil thickness. Thick soils are commonly developed along fault or joint planes. Also, soils developed on marl beds are normally thicker than soils on adjacent chalk beds.

Along steep banks and bluffs where Austin Chalk and the underlying South Bosque Shale are exposed, major foundation problems can be anticipated. If shale slopes are over-steepened by excavation, gravity slumping of the incompetent shale will occur. Failure of the steepened shale slopes removes support from beneath the chalk, resulting in failure and slumping of Austin Chalk blocks. Particular care must be exercised in order to maintain a natural slope angle along hillsides and escarpment faces if present structures are to be protected.

Excavation in the Austin Chalk is more difficult than in any other formation exposed in the Waco area. However, the friable nature of the chalk permits excavation by mechanical means, since it is possible to use heavy crawler tractors or powerful excavators. For small excavations such as home basements, air hammers or blasting may be required. Openings in the Austin Chalk do not require internal support during excavation because of the structural competence of the formation. The tendency of weathered marls to spall causes banks to cave following prolonged exposure. Exposed banks of Austin Chalk should be sloped or should be capped by a properly anchored surface seal. Unsupported excavation walls parallel to prominent north-south trending fractures are particularly prone to fail along joint or fault planes. This weakness along joint and fault planes permits easier excavation by blade or ripper where the direction of force is applied at right angles to the dominant north-south fracture system.

Fault and joint systems in the Austin Chalk may further complicate construction by serving as effective mechanical wave guides, filtering and conducting seismic energy for considerable distances. For example, blasting in the chalk may result in damage to structures a considerable distance from the shot point in directions parallel to fracture systems, but little or no damage may occur to nearby structures at right angles to the fracture system.

The Austin Chalk does not normally produce sufficient water for even modest domestic needs, but minor quantities of water have been produced from some wells in the chalk. Streams on the chalk outcrop may flow for days or weeks following a wet period, but the water supply declines rapidly during dry periods. The great areal extent of the outcropping Austin Chalk in the city, coupled with the great amount of septic effluent released in the area, insure that water produced from the formation is highly polluted.

Fluid infiltration in the Austin Chalk varies with topography and the local lithologic character of the formation. Drains excavated in chalk beds and properly bedded in washed gravel will normally dispose of reasonable quantities of fluid. An adequate drainage field for a private residence in such an area can be installed on a 100 to 125-foot lot. When an installation is located near a topographic depression, such as a valley or scarp face, drainage is accelerated and it is effective even during wet periods, although pollution may be increased downslope from the drain.

Drains into the thicker marl beds encounter problems similar to those faced when drains are installed in the Taylor Marl. Upon saturation the bentonitic clays of the marl tend to seal the drainage ways and filtration is drastically reduced. Soils of the Austin Chalk effectively swell when wet, preventing infiltraton and almost precluding successful operation of septic sewage disposal systems above Austin bedrock.

Fractured zones in the Austin Chalk may readily accept fluid and may conduct it like pipelines. Excavations encountering joints and faults often develop serious drainage problems, since water inflow along joints may exceed water loss through filtration into the chalk. Water from septic sewage systems may be conducted through these natural drains directly to the surface as highly polluted runoff.

The Austin Chalk probably provides fewer problems related to foundations and septic disposal systems and more problems in excavation than any other formation in the Waco area. A principal factor in the growth of the city has been the presence of this excellent foundation under a major part of Waco. Rock, not soil developed from rock, is essential for adequate foundations and drainage. Recognition of this fact would have prevented some of the foundation failures which have occurred in Waco.

SOUTH BOSQUE SHALE

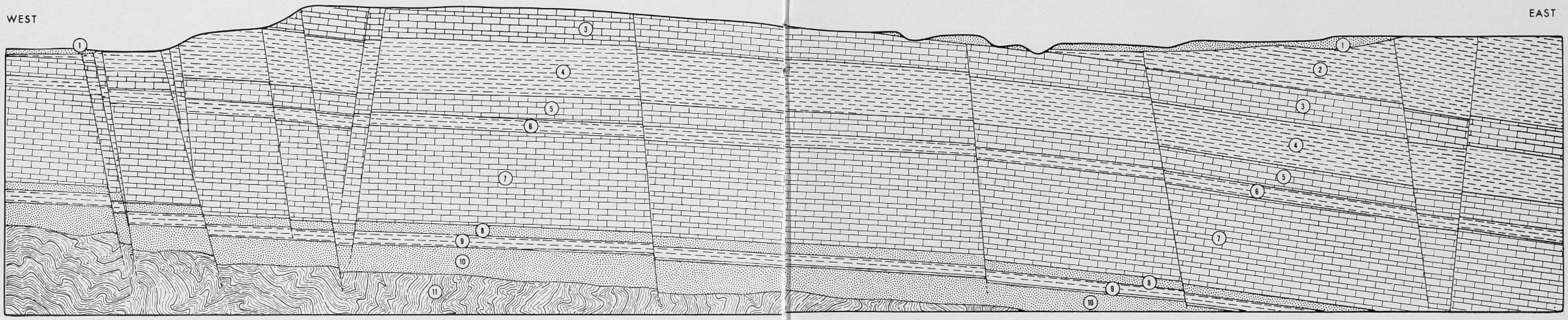
ORIGINAL DEFINITION

Rocks of the Eagle Ford Group underlie the Austin Chalk. The Eagle Ford Group, which was named by Hill in 1887 (p. 298) for exposures near Eagle Ford, Texas, is of early Gulfian age (Stephenson *et al*, 1942, Chart 9). The group crops out from the Red River to the Rio Grande. In the Waco area the Eagle Ford Group is divided into two formations (table 2), the South Bosque Shale and the underlying Lake Waco Formation. Both formations are composed dominantly of dark bentonitic shales, but each has distinctive mappable characteristics.

The South Bosque Shale (Prather, 1902) was revived by Adkins and Lozo (1951, p. 118-120) for exposures in Cloice Branch at the community of South Bosque, two miles southwest of Greater Waco.

DISTRIBUTION

The South Bosque Shale is exposed along the face of the Bosque escarpment (fig. 2). Along the escarpment in the Waco area (Pl. I), the shale outcrop supports a belt of rolling hills below the Austin Chalk caprock and above an intermediate topographic bench developed on the resistant upper flagstone (limestone) section of the Lake Waco Formation. This topographic bench extends from State Highway 6 (*idem*) southwest to Moody. The South Bosque Shale thickens eastward in the subsurface to 160 feet in the J. L. Myers & Sons No. 1 Tiery well (Pl. V); thickening continues eastward into the East Texas basin.



Legend: (1) Alluvium; (2) Taylor Marl; (3) Austin Chalk; (4) South Bosque, Lake Waco, Pepper, and Del Rio shales; (5) Georgetown, Edwards and Comanche Peak limestones; (6) Walnut Clay; (7) Glen Rose Limestone; (8) Hensel Sandstone; (9) Pearsall Formation and Sligo Limestone; (10) Hosston Sandstone; and (11) Pre-Cretaceous Ouachita Foldbelt.

Fig. 3. Diagrammatic east-west cross section, Waco area.

DESCRIPTION

The South Bosque Formation is dark gray to black, soft, blocky, homogeneous shale which weathers blue-gray to tan. The shale, which is very incompetent, commonly slumps throughout the outcrop belt. Outcrops are also normally concealed on gentle slopes by debris from the overlying Austin Chalk. Persistent bentonite seams are less common than in the underlying Lake Waco Formation (Chamness, 1963, p. 29).

The South Bosque Shale is unconformably separated from the Austin Chalk. The base of the Austin Chalk includes a conglomerate about one foot thick composed of shark teeth, fish remains, phosphatic nodules, and glauconite grains in a chalk matrix. Filled borings containing phosphatic and glauconitic material extend downward into the shale (*idem*, pp. 33-34). The South Bosque-Lake Waco contact is gradational. Thin limestone beds interbedded with the shales of the Lake Waco Formation decrease in number upward into more homogeneous shaly marl which characterizes the Lake Waco Formation. Marked fissility typical of the Lake Waco Formation is less common in the South Bosque Shale which is blocky in the upper part.

The upper 30 to 50 feet of the South Bosque Shale are composed of dark noncalcareous bentonitic shale beds which are plastic and tend to slump when wet. Low carbonate content (2-8 percent) contributes to the highly plastic behavior of the upper part of the South Bosque Shale. The lower part of the formation is composed of calcareous shales (30-35 percent) interbedded with silty limestone flags and bentonite seams. The transition from low carbonate to high carbonate clays occurs vertically in a few feet.

The formation contains abundant poorly preserved small ammonites (prominent in the upper 30 to 50 feet), pelecypods, and foraminifers. Some fish teeth and vertebrae are also present. Abundant fossils (nektonic), low carbonate content, absence of obvious lithologic variation and bedding, and abundant bituminous material suggest that this upper portion of the formation was deposited in a neritic marine environment with poor bottom current circulation. Absence of coarse land-derived clastic sediment and uniform eastward thickening indicate a distant northwestward shoreline.

There is a marked increase in the number of bentonite seams, disseminated carbonate, and limestone beds in the lower part of the South Bosque Shale. The lower part of the formation, therefore, reflects different climatic conditions and greater volcanic activity than the sediments in the upper part of the South Bosque Shale.

The upper, low-carbonate part of the South Bosque Shale weathers gray-blue, but the lower part of the formation weathers tan to brown. The pigmenting material is disseminated limonite derived by the alteration of pyrite, the principal pigment of the fresh dark blue-gray shale. The formation weathers rapidly and offers little resistance to erosion.

SOILS

Soils developed on the South Bosque Formation are gray to gray-brown, highly calcareous, and of variable depth, depending upon the slope of the land. South Bosque soils form rich agricultural lands, but they are extremely plastic and have high shrink-swell ratios.

RELATION TO URBAN DEVELOPMENT

The upper noncalcareous clay of the South Bosque Shale is raw material for expanded aggregate produced by the Waco Aggregate Company. The shale is also mixed with Austin Chalk for use in manufacturing cement by the Universal Atlas Cement Company. Both plants are located in the South Bosque Community.

The support strength of the South Bosque Shale varies from two to sixteen tons per square foot. This variation is related both to stratigraphic position within the formation and to the topographic slope of the building site. Noncalcareous shales in the upper part of the formation, which are more plastic than calcareous shales in the lower part, may fail on gentle slopes even without the additional load of man-made structures.

When used as fill material, the unstable shales of the upper South Bosque Formation must be stabilized, compacted, and adequately drained, and gentle slopes must be maintained to prevent slumping. The slumping problem is particularly acute when shales of the upper part of the South Bosque Formation are terraced. Throughout the outcrop belt where construction occurs, improper drainage, cut and fill modification of slope, superincumbent weight of added topsoil and structures, and constant saturation by watering combine to increase instability.

Construction in the outcrop area, especially along the Bosque escarpment, should maintain the natural slope. This factor is particularly important along the edge of the escarpments where the Austin Chalk is thin. Instability on slopes of the upper part of the South Bosque Shale (induced by oversteepening through injudicious excavation) causes failure in formerly stable overlying Austin Chalk.

Foundation loads placed on the unstable South Bosque Shale should be supported by underreamed piers or footings extending deep enough so that they rest in unweathered shale. The bases of piers and footings should be approximately horizontal or slightly inclined away from the hill slope. Such foundations transfer the load to more massive sections of the formation. Foundation excavations and borings should be filled immediately before surface water expands bentonitic clays.

Water which seeps downward into the shale along piers causes the shale to swell. Swelling is particularly evident in the non-calcareous part of the South Bosque Formation where wet expanding clays flow plastically upward and outward along the piers. Drying shrinks the clay and the pier settles slightly in the hole. This "mining" apparently continues as long as fresh water can penetrate along pier walls. Settling is uneven and the result is cracking of slabs, grade beams and superincumbent structures. These structural problems are much more acute in uncompacted South Bosque Shale fill where permeability is high, resulting in accelerated infiltration of fresh water.

Drainage or infiltration through the South Bosque Shale is retarded by swelling clays. When these clays contact fresh water, they swell and effectively seal against additional infiltration. Extremely large infiltration fields are required for effective septic sewage disposal. A 100-foot lot on the South Bosque Formation is probably inadequate for the construction of a septic field for the average home. During dry seasons high shrink-swell clays will crack and "fluff" to depths of several feet and drainage will temporarily be adequate, but during extended wet periods infiltration is vastly reduced by clay expansion and septic overflow will find its way to the surface in yards and streets to join surface drainage. Since the South Bosque Shale is exposed along the face of the Bosque escarpment, drainage polluted with sewage eventually finds its way into Lake Waco to become part of Waco's water supply.

In general, the lower part of the South Bosque Shale provides a more stable foundation than the upper part. Greater stability in the lower part results from higher natural calcium carbonate content (stabilizer) and thin limestone beds. Support strengths on the formation vary with stratigraphic and topographic position.

Drainage or infiltration problems in the lower part of the South Bosque Shale, which has a higher calcium carbonate content, are similar but less severe than those in the upper part of the formation.

Excavation in the South Bosque Shale is easily accomplished by any excavation machine. Thin limestone beds in the lower part of the formation may pose minor excavation problems, but the beds are easily broken. Excavation walls are subject to slumping, particularly when wet. Deep excavations with unsupported walls may be quite hazardous.

LAKE WACO FORMATION

ORIGINAL DEFINITION

The Lake Waco Formation was named by Adkins and Lozo (1951, p. 120) for exposures in the spillway of the Old Lake Waco Dam.

DISTRIBUTION

The Lake Waco Formation crops out along the Bosque escarpment from Moody to Lake Waco (fig. 2; Pl. I) and in scattered outcrops northward along the Brazos River. The formation, which is approximately 80 feet thick near Moody, thickens eastward into the East Texas basin.

DESCRIPTION

The Lake Waco Formation is composed of calcareous bentonitic shales interbedded with thin dense limestone beds. The formation, which is dark gray-blue, varies from buff to tan on weathered surfaces. The Lake Waco Formation is more calcareous, fissile, and resistant to erosion than is the overlying South Bosque Shale. Lower "steps" of the Bosque escarpment (fig. 2) are supported by thin limestone beds ("flag sections") near the top and base of the Lake Waco Formation.

The Lake Waco Formation (table 2) has been divided in descending order into the Bouldin, Cloice and Bluebonnet members (Adkins and Lozo, 1951, pp. 120-123).

The Bouldin Member is composed of highly bentonitic calcareous shales interbedded with limestone flags from one-fourth to six inches thick. The Bouldin Member of the Lake Waco Formation grades upward into the South Bosque Shale, and the contact between the two units is arbitrarily placed at the top of the highest bench-forming limestone bed. The Bouldin Member is approximately 14 feet thick in the Waco area (Chamness, 1963, Pl. VII). The Cloice-Bouldin contact, which is also gradational, is difficult to delineate and map.

The Cloice Member is a highly bentonitic, calcareous, extremely fissile gray shale containing bentonite seams up to 14 inches thick. Bentonite beds, however, occur throughout the Lake Waco Formation. The Cloice Member also includes a number of thin limestone beds from one-fourth to two inches thick, intercalated with bentonite and shale beds. The member weathers rapidly to pale tan and forms deep rich soils. The Cloice Member is approximately 35 feet thick in the Waco area (Chamness, 1963, Pl. VII).

The Bluebonnet Member is composed of interbedded highly calcareous, bentonitic, fissile shales and hard fossiliferous limestone flags. The upper two-thirds of the member is predominately shale. Bentonite beds range from less than one inch to ten inches thick; limestone beds are also one to ten inches thick. The member is dark gray-blue and weathers gray to light buff. The Bluebonnet Member ranges from six to twelve feet thick in the Waco area (Silver, 1963, pp. 42-43).

The basal limestone bed of the Bluebonnet Member rests unconformably on noncalcareous, highly plastic Pepper Shale. The Pepper-Bluebonnet contact marks a distinct change in lithology. A thin reworked conglomeratic zone occurs at the contact in the basal Bluebonnet limestone flags. Unweathered samples of Bluebonnet shale effervesce in contact with dilute hydrochloric acid, but noncalcareous Pepper Shale will not react to acid.

The Lake Waco Formation contains principally montmorillonitic clays with considerable disseminated calcium carbonate, numerous limestone beds, minor seams of bentonite, and rare kaolinitic clays and quartz sand. The Bouldin and Bluebonnet members contain more than 50 percent calcium carbonate represented by limestone beds and disseminated calcite; the Cloice Member is less calcareous.

Silver (1963) presented substantial evidence to suggest that the Bluebonnet limestone flags originated in a lagoonal environment, which was modified by slow marine transgression during Cloice deposition. Fauna and sedimentary structures suggest that the Cloice environment was also restricted, although deeper water and less agitation are indicated by more uniformly distributed sediments in the Cloice Member. Rocks of the Bouldin Member are similar to those in the Bluebonnet Member.

Sedimentary evidence, therefore, suggests that the Bouldin and Bluebonnet members accumulated in relatively similar environments, and that the lower South Bosque Shale and the Cloice Member of the Lake Waco Formation were deposited under similar conditions. Two depositional cycles can be recognized in the Eagle Ford Group—a Bluebonnet-Cloice cycle and a Bouldin-lower South Bosque cycle. The upper Bouldin-lower South Bosque cycle grades upward into more marine upper South Bosque Shale.

Bentonite seams throughout the Lake Waco Formation are marine deposits composed of altered volcanic ash. The altered ash beds are laterally discontinuous, apparently because of irregular distribution by depositing currents. Volcanic activity which provided the ash may have occurred along the Balcones fault zone (fig. 1), possibly in the Austin-Llano or Uvalde areas (Lonsdale, 1927, p. 24).

Streams along the Bosque escarpment (fig. 2) are commonly incised into Eagle Ford shale sections and in many places streams have cut into the Eagle Ford limestone flag beds. A trellis drainage pattern reflects the geometry of faults and joints of the Balcones system (Hayward, 1957, p. 31).

SOILS

The Lake Waco Formation weathers tan by alteration of disseminated pyrite (the principal pigment of the unweathered shale) to limonite which colors the weathered rock material. Soils formed on the Lake Waco Formation are olive or yellow-brown calcareous clays. Upper soil horizons grade downward into unweathered calcareous clay parent material at a depth of five to twenty inches. Yellow-brown soil occurs in areas of accelerated erosion along steeper slopes and "steps" of the Bosque escarpment.

RELATION TO URBAN DEVELOPMENT

Shale beds in the Lake Waco Formation will support up to 18 tons per square foot, but bentonitic clay sections will support considerably less weight. In general, support strengths of the Bluebonnet and Bouldin members, which contain numerous intercolated limestone beds, are far higher than in the Cloice Member.

Bentonite beds (up to 14 inches thick) in all three members of the Lake Waco Formation may fail under stress. Even limestone beds may fail when underlain by bentonite. Since the thickness of critical bentonite beds varies with stratigraphic and geographic position, occurrence at a local building site can be determined only by excavation or boring.

High shrink-swell bentonite beds, bentonitic shales, and soils of the Lake Waco Formation cause problems with foundations, excavations, and buried structures. Shrink-swell can be minimized by proper drainage and surface sealing, which insures that clays will remain properly hydrated and stabilized. Where thicker bentonite beds are encountered in foundation excavations, the best practice is to remove and replace them with stable fill material.

Excavations in the Lake Waco Formation will retain steep faces in dry weather, but slump failure commonly follows soaking rains. Therefore, excavation in this formation should be sloped well back from the vertical and the cut face sealed to control moisture content. Because of the tendency for massive failure, heavy retaining structures are required to maintain steep faces cut into the Lake Waco Formation.

Excavation in the Lake Waco Formation is moderately easy. In limestone flag sections, fractures facilitate removal by ripper and blade. Shale sections are readily cut by conventional excavating machinery.

Drainage or infiltration into the Lake Waco Formation is hindered by relatively impermeable bentonite beds, bentonitic clays, and dense limestone beds. Therefore, very large drainage fields are required for sewage disposal, and it is probable that during extremely wet periods, a normal residential lot will be inadequate for an effective septic system.

Since the Lake Waco Formation is normally exposed along the face of the Bosque escarpment, much of the contained septic disposal fluid will reach the surface and will ultimately flow into Lake Waco.

No productive aquifers occur in the Eagle Ford Group. Small "wet weather" wells capable of producing a few gallons to a few tens of gallons of water per day have reportedly produced from the Bouldin and Bluebonnet members. However, the water supply for these wells is from surface runoff and infiltration, since such wells cease to produce when cased. Uncased wells may produce small amounts of water for a few days or weeks following a rainy period.

PEPPER SHALE

ORIGINAL DEFINITION

The Pepper Shale was established by Adkins (1932, pp. 417-422) for exposures of dark pyritiferous shale on a branch of Pepper Creek near Belton.

Throughout the area Pepper Shale rests unconformably on Del Rio Clay or upon the locally discontinuous Buda Limestone. The Pepper Formation is unconformably overlain by the Lake Waco Formation (Silver, 1963, p. 8).

AGE AND DISTRIBUTION

The Pepper Shale is earliest Gulfian (table 2) in age (Stephenson *et al.,* 1942, Chart 9). On the outcrop the Pepper Formation thins southwestward from 150 feet at the Hill-McLennan county line to a pinchout near Austin. The shale is 60 to 70 feet thick in the subsurface of the Waco area and it can be easily recognized on electrical logs (Pl. V). North of Waco Pepper Shale interfingers with thin sand beds of the uppermost Woodbine Sand (Adkins and Lozo, 1951, p. 116).

Pepper Shale crops out along the base of the Bosque escarpment (fig. 2; Pl. I) east of the South Bosque River southwest of Waco. Exposures of unweathered Pepper Shale are rare because the formation rapidly weathers.

DESCRIPTION

The Pepper Formation is noncalcareous, black, dense, pyritic shale. Weathered Pepper Shale is lighter in color than the overlying Lake Waco Formation. Selenite crystals glisten on weathered outcrops and yellow jarosite also occurs along most minor joints and as irregular masses on weathered Pepper Shale surfaces. Selenite and jarosite are weathering products which do not occur in the unweathered shale.

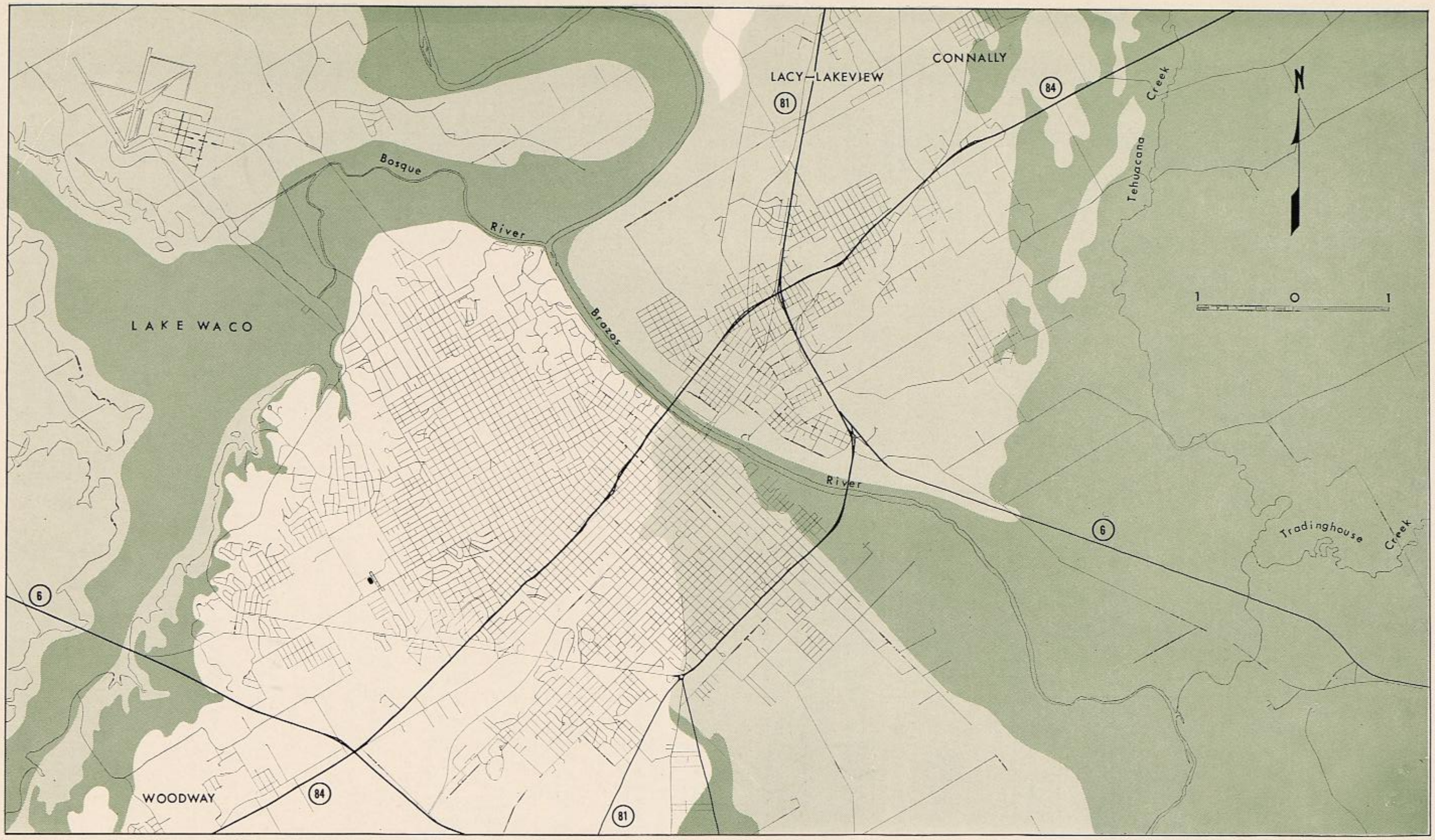
Pepper Shale contains about 20 percent montmorillonite, 20-25 percent illite, 20-25 percent kaolinite, 10-15 percent quartz and 20-25 percent amorphous material, probably silica and oxides of iron and aluminum. Within the upper 10 to 20 feet of the formation, mont-

Table 2. Sequence, classification, description and critical properties

System	Series, group, or division			Formation or member		Maximum Thickness (feet)	Description	Aquifer properties
Quaternary	Recent and Pleistocene				Alluvium and terraces	?	Sand, silt and gravel.	Yields potable water in some areas at shallow depth.
Cretaceous	Gulfian Series				Taylor	1170	Calcareous marls, sandy marls, lenses of calcareous sandstone, and chalky limestone.	Yields some potable water from Wolfe City member in eastern part of county at shallow depth.
					Austin	295	Marly limestone and limy shale with some bentonite seams.	Not known to yield water in McLennan County.
		Eagle Ford Group			South Bosque	140	Shale with limestone flags.	Yields no water in McLennan County.
					Lake Waco	145	Shale with limestone flags and bentonite seams.	Yields small amounts of water for domestic use in western part of McLennan County.
					Pepper	100	Noncalcareous shale with injected sandstone dikes in northern part of McLennan County.	Reported to yield some potable water in northeastern McLennan County.
	Comanchean Series	Washita Group			Buda	35	Hard to chalky fossiliferous limestone.	Yields no water in McLennan County.
					Del Rio	85	Fossiliferous clay with occasional limestone beds and sandy streaks.	Yields no water in McLennanCounty.
					Georgetown	210	Nodular limestones and marly shales.	Not known to yield water in McLennan County.
		Fredericksburg Group			Edwards	45	Limestone, rudistid reef material, and calcareous siltstone.	Yields some potable water in northwestern McLennan County.
					Comanche Peak	130	Nodular limestones and fossiliferous clay.	Yields no water in McLennan County.
					Walnut	175	Shale with some limestone and sand stringers.	Yields no water in McLennan County.
					Paluxy	20	Sands with some shales interbedded.	Yields potable water in northwestern McLennan County.
		Trinity Group	Upper		Glen Rose	800+	Alternating limestones and shales with some anhydrite.	Yields some water in McLennan County.
					Hensel	75	Fine to coarse sands with green shales.	Principal aquifer in western McLennan County. Yields large supplies for municipal, industrial, and domestic purposes.
			Middle	Pearsall Formation	Cow Creek	75	Limestone and shale.	Yields no water in McLennan County.
					Hammett	100	Shale with some limestone and sand.	Yields no water in McLennan County.
			Lower		Sligo	95	Limestone and shale.	Yields no water in McLennan County.
					Hosston	800+	Fine to coarse sand with some conglomerate and varicolored shale.	Principal aquifer in eastern McLennan County. Yields large supplies for municipal and industrial purposes. Water in sands in upper part of formation in southeastern part of county may be highly mineralized.
Jurassic	Cotton Valley Group				Schuler (?)	?	Sands and shales (?).	Yields no water in McLennan County.
Pennsylvanian (?)					?	?	Shales and metamorphics.	Yields no water in McLennan County.

of geologic formations, Waco area.

Slope stability	Economic geology	Excavation difficulty	Infiltration capacity	Foundation support strength
Moderate; will normally support slopes greater than 10° without shoring.	Major source of sand and gravel; some water for irrigation.	Readily excavated by light machinery.	High; adequate septic sewage disposal on average residential lot.	Moderate to low; requires some pier support for heavy structures.
Low; fails when wet in slopes less than 10°. Excavation requires continuous shoring.	None at present; may contain marginal economic ceramic clays.	Readily excavated by light machinery.	Low; inadequate disposal even in periods of moderate saturation.	Moderate to low; requires some pier support for heavy structures.
High; will support slopes greater than 45° without shoring, except near basal contact.	Furnishes some low subbase material for roads and streets; raw material for cement.	Difficult to excavate with light machinery. May require blasting or other breaking.	Moderate; adequate septic sewage disposal except in period of prolonged saturation.	High; requires conventional design even for heavy structures.
Very low in upper 40 feet; low in lower 120 feet. Along contact with Austin Chalk, basal Austin Chalk will fail by removal or modification of shale support.	Raw material for cement, expanded aggregate.	Readily excavated by light machinery.	Low; inadequate disposal even in periods of moderate saturation.	Low; requires flotation support or deep piers, particularly in upper part of formation.
Low to moderate. Lower in Cloice Member; higher in Bluebonnet and Bouldin limestone zones.	None at present; contains thin seams of bentonite—entire formation richly bentonitic.	Moderately easy excavation with light machinery. Limestone beds may require breaking by auxiliary methods.	Low.	Moderate; requires some pier support for heavy structures.
Very low; fails when wet on slopes less than 10°. Excavation requires continuous shoring.	None; may provide marginal economic material for ceramic products.	Readily excavated by light machinery.	Low.	Very low; requires flotation support or deep piers.
Too thin in Waco area to affect slope stability except on erosion resistant cap.	None; inadequate thickness. Produces oil in Falls County.	Extremely hard discontinuous limestone. Excavation will range from very difficult to moderate.	Low.	Discontinuous formation. Will support heavy foundation loads where present as bed greater than 2 feet thick.Overlies Del Rio Clay with moderate to low strength.
Moderate to low; fails plastically when wet, particularly in noncalcareous middle part.	None; may provide marginal economic material for ceramic products.	Moderately to easily excavated by light machinery. Discontinuous limestone beds may require breaking by auxiliary methods.	Low.	Moderate to low; requires some pier support; deep piers in noncalcareous parts of formation.
Will support slopes of greater than 45° without shoring, except in middle shaly part.	Produces marginal subgrade material within 5 miles of Waco.	Not exposed.	Not exposed.	Not exposed.
Not exposed—even in deep excavation in Waco area.	Produces high quality dimension stone, crushed rock within 15 miles of Waco.	Not exposed.	Not exposed.	Not exposed.
Not exposed.	None; not exposed in Waco area. Nothing economic in 50-mile radius.	Not exposed.	Not exposed.	Not exposed.
Not exposed.	None; not exposed in Waco area. Nothing economic in 50-mile radius.	Not exposed.	Not exposed.	Not exposed.
Not exposed.	None; may contain marginal glass sand within 50 miles of Waco.	Not exposed.	Not exposed.	Not exposed.
Not exposed.	None; has produced attractive rough building stone within 50 miles of Waco—operation submarginal.	Not exposed.	Not exposed.	Not exposed.
Not exposed.	None.	Not exposed.	Not exposed.	Not exposed.
Not exposed.	None.	Not exposed.	Not exposed.	Not exposed.
Not exposed.	None.	Not exposed.	Not exposed.	Not exposed.
Not exposed.	None.	Not exposed.	Not exposed.	Not exposed.
Not exposed.	None. See aquifer properties column.	Not exposed.	Not exposed.	Not exposed.
Not exposed.	None.	Not exposed.	Not exposed.	Not exposed.
Not exposed.	None.	Not exposed.	Not exposed.	Not exposed.



□ HIGH

▨ MODERATE

🟩 LOW

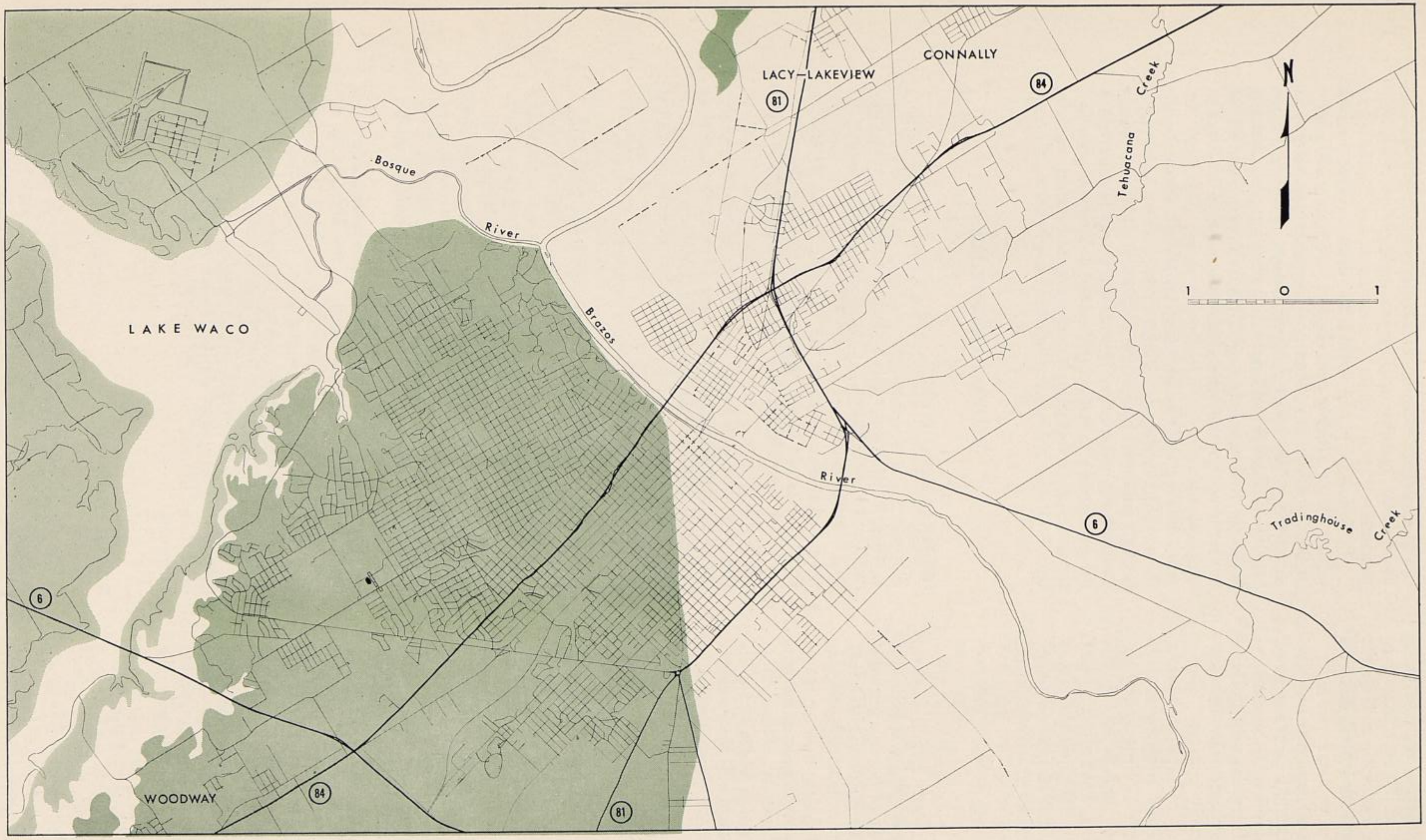
Foundation support strength of bedrock in the Waco area is based on foundation design essential to support heavy to moderately heavy structures with adequate safety margins.

High foundation support strength exists where heavy structures may be supported by conventional footings and grade beams without recourse to piers and caissons. Support strength in these areas is normally in excess of 15-20 tons per square foot, although local jointing may significantly modify these values at a specific building site. High foundation support strength exists in areas of Austin Chalk outcrop.

Moderate foundation support strength exists where heavy structures may require some pier support to insure stability, although significant parts of the foundation load will be supported by beams and footings. Moderate foundation support strength exists in most outcrop areas of Lower Taylor Marl, lower part of the South Bosque Shale, Lake Waco Formation, Del Rio Clay, alluvium and terraces of the Bosque and Brazos river and terraces of both systems.

Low foundation support strength exists where heavy structures must be supported largely by floating foundations or by piers sunk into adjacent more resistant units. Low foundation support strength exists in outcrop areas of local bentonitic portions of Lower Taylor Marl, upper 40 feet of South Bosque Shale, Pepper Shale, and middle noncalcareous part of Del Rio Clay.

Fig. 4. Foundation support strength of bedrock, Waco area. (Applies *only* to foundations resting directly on unweathered rock *below* the soil zone.)



🟩 SEVERE

▨ MODERATE

☐ SLIGHT

Difficulty of excavation of bedrock in the Waco area is based upon utilization of light excavation machinery, such as back-hoe and light crawler tractor and rippers. Difficulty is listed as slight, moderate, or severe. The principal property controlling excavation is rock tenacity, although bedding and fractures may significantly reduce difficulty of excavation in large cuts made with heavy machinery.

Severe excavation difficulty exists in outcrop areas of massive limestone formations, essentially the area of Austin Chalk outcrop. Open cuts need no internal shoring and steep faces may be maintained for extended periods. In massive chalk beds near the base of the Austin Formation or for small excavations such as drainage lines and basements, air hammers and/or blasting may be required. Locally, Quaternary drainage channels filled with thick soils (10 feet or more) occur along the Austin Chalk outcrop; excavation difficulty will be reduced in such channel areas.

Moderate excavation difficulty exists where limestone and shale beds are interstratified or where terrace gravels are cemented by calcium carbonate. Normally tractor-ripper operations will be able to break and remove hard beds without prior breaking. Back-hoe and shovel operations may require mechanical breaking or blasting before removal of harder beds.

Moderate excavation difficulty exists principally in outcrop areas of Lake Waco Formation, Buda Limestone, certain limited zones of Del Rio Clay, and Brazos and Bosque terraces.

Slight excavation difficulty exists in outcrop areas of homogeneous clay, and uncemented sand and gravel where back-hoe and shovel operations proceed without requiring auxiliary equipment to prepare material for easy removal. Slight excavation difficulty exists principally in outcrop areas of Lower Taylor Marl, South Bosque Shale, Pepper Shale, Del Rio Clay, and Bosque and Brazos alluvium.

Fig. 5. Difficulty of excavation of bedrock, Waco area. (Applies *only* to materials *below* the soil zone.)

morillonite content decreases downward from 50 to 25 percent; a corresponding downward increase from 5 to 25 percent illite also occurs, but kaolinite and quartz content display no apparent vertical variation (McAtee and Johnson, 1963, pp. 2-3).

Foraminifers and ammonoid casts, some thick-shelled pelecypods, and abundant siderite and pyrite suggest that the Pepper Shale was deposited in a brackish to marine, nearshore environment. The relatively uniform lithology of the Pepper Shale is evidence that the depositional environment was essentially constant, except for possible minor salinity and pH-Eh variations. Minor fluctuations in the depositional environment are evidenced by a coquinoid limestone 27 feet below the top of the formation, a phosphatic nodule bed 5 feet above the base, and local hematite layers throughout the shale. Hematite layers are probably altered (oxidized) siderite-rich clay zones, which originated under reducing conditions in the depositional environment.

SOILS

Calcareous brown soils, which normally overlie the Pepper Shale, are commonly derived from calcareous clays transported from the overlying Eagle Ford Group. North of Lake Waco, however, where the Pepper Shale interfingers with the Woodbine Sand, Pepper soil is brown to gray, sandy, and noncalcareous with a mottled clay subsoil of low permeability. This soil is normally covered by Bosque terrace deposits and is rarely more than a few inches thick where it is commonly exposed on steep slopes.

RELATION TO URBAN DEVELOPMENT

Pepper Shale yields plastically under normal loads because of the absence of disseminated calcium carbonate, which serves as a binding and stabilizing material in many shales. Maximum support strength of this unit is very low, although exact figures are not available. Slumping commonly occurs along steep slopes. Under heavy loads or along shear surfaces, the formation fails plastically. High montmorillonite clay content of the Pepper Shale leads to excessive shrink-swell properties which cause failure of slabs and grade beams resting upon the shale.

The homogeneous nature of the shale precludes the possibility of locating a satisfactory foundation zone within the formation. Where very heavy structures are to be constructed on the outcrop of the Pepper Shale, foundation piers should be carried through the shale into the more stable underlying Del Rio Clay. Highway and street construction in the area of Pepper Shale outcrop requires adequate drainage, compaction of the shale, well-drained base material, and preferably the use of a flexible paving.

Pepper Shale is easily excavated. The shale spalls immediately after exposure to weathering and it soon fails by slumping. Excavations should, therefore, have gentle slopes, and shale surfaces should be sealed by an impervious material.

Water is not produced from the Pepper Shale. Drainage or infiltration within the Pepper Shale is hindered by impermeable montmorillonitic clays. Therefore, septic disposal systems on Pepper Shale outcrops are impractical.

Oxidation of pyrite within the shale by near-surface waters yields a highly acid effluent which may kill plants in the overlying soil. Since the Pepper Shale outcrop is characterized by paucity of vegetation, it can be traced readily in the field and on aerial photographs. Because of highly acid weathering products, Pepper Shale forms a corrosive environment for buried pipes and other metal objects.

In the Waco area the outcrops of the upper South Bosque Shale and the Pepper Shale are areas which present the most difficult foundation, drainage, corrosion and stability problems. Construction on the outcrop of these two shale formations should be designed with full recognition of the complex specific properties and severe limitations displayed by these formations.

BUDA LIMESTONE

ORIGINAL DEFINITION

All pre-Pepper Shale Cretaceous formations in Central Texas are within the Comanchean Series (table 2). The Buda Limestone, Del Rio Clay and Georgetown Formation compose the Washita Group (table 2) which crops out in the Washita Prairie (fig. 2).

The Buda Limestone, originally called the "Shoal Creek Limestone," was named by Vaughan (1900, p. 18). At the type locality near Buda in Hays County, the formation is a yellowish dense limestone overlying Del Rio Clay (Wilmarth, 1938, p. 286).

AGE AND DISTRIBUTION

The Buda Limestone, which is late Comanchean (table 2) in age (Stephenson *et al.*, 1942, Chart 9), crops out from Eagle Pass to Waco. The limestone occurs in the subsurface east of the Waco outcrop where it thickens downdip into the East Texas basin.

In the Waco area the Buda Limestone rests conformably upon Del Rio Clay, and is unconformably overlain by Pepper Shale (Ray, 1964, p. 8). Where Buda Limestone is absent, Pepper Shale rests unconformably upon Del Rio Clay.

East of the outcrop the Buda Limestone occurs in the subsurface throughout most of the area. It is six feet thick in the J. L. Myers & Sons No. 1 Tiery well (Pl. V). Buda Limestone crops out in the Waco area as discontinuous beds of blocky limestone from a few inches to two feet thick, but it has not been recognized on the outcrop north of China Springs. On aerial photographs the formation can be traced as a thin light-colored discontinuous line near the base of the Bosque escarpment.

DESCRIPTION

The Buda Limestone in the Waco area is hard, massive, buff to gray, dense bed containing abundant pelecypods. It contains approximately 85 percent calcium carbonate, grains and pebbles of hematite, some pyrite and siderite. Glauconite is relatively common (Ray, 1964, p. 16). The formation also contains quartz sand which increases northward to about 52 percent near China Springs (*idem,* p. 11-12).

Abundant calcium carbonate, abundant large thick-shelled pelecypods, some quartz sand, and filled borings suggest that the Buda Limestone was deposited under relatively warm, shallow marine conditions. Glauconite in the outcropping Buda Limestone, as well as rapid downdip thickening, indicates that the updip facies of the Buda was slowly deposited in a nearshore marine environment. The discontinuous outcrop of the Buda Limestone and the Buda-Pepper unconformity are evidence that at least part of the updip thinning of the Buda resulted from pre-Pepper erosion. Sand in the outcropping Buda in the Waco area also suggests that part of the updip thinning may have been depositional (*idem*).

SOILS

Soils of the Buda Limestone are relatively insignificant in the Waco area since the outcrop is narrow and discontinuous. Light-colored soils from the Buda can be distinguished on aerial photographs.

RELATION TO URBAN DEVELOPMENT

The Buda Formation is so variable in thickness and distribution in the Waco area that its effect on construction and engineering is unpredictable. The limestone is too thin and discontinuous to be of value in supporting large heavy structures. It is insufficiently thick to absorb significant volumes of infiltrating fluids; in addition it occurs between impervious shales.

At Satin oil field in northern Falls County, the formation is an oil reservoir. Buda Limestone quarried at Pendleton in Bell County, was used locally in constructing stone fences and older buildings. The stone is an excellent building material, but it is insufficiently thick for commercial exploitation in the Waco region.

DEL RIO CLAY

ORIGINAL DEFINITION

The Del Rio Clay was named by Hill and Vaughan in 1898 (p. 2) for exposures of laminated clay overlying the Fort Worth Limestone (of the Georgetown Formation) in the Rio Grande Valley near Del Rio, Texas.

AGE AND DISTRIBUTION

The Del Rio Clay is late Comanchean (table 2) in age (Stephenson *et al.,* 1942, Chart 9). It is exposed along the eastern edge of the Washita Prairie (fig. 2) of Central Texas and southward to the Big Bend of the Rio Grande. The Del Rio Formation is about 85 feet thick in the J. L. Myers & Sons No. 1 Tiery Well (Pl. V), and it does not thicken significantly eastward across McLennan County.

The formation crops out on higher divides between eastward flowing tributaries of the Bosque River (fig. 2). Exposures of Del Rio Clay are poor, and the outcrop is commonly covered by soil. The Del Rio Clay occurs beneath Bosque terrace deposits (Qbot) along most of the western side of Lake Waco (Pl. I).

DESCRIPTION

The Del Rio Formation is blue-gray, blocky clay with rare thin lenticular beds of highly calcareous siltstone and limestone composed predominantly of pelecypods. The clay is also fossiliferous and contains abundant disseminated and concretionary pyrite, some marcasite and siderite.

In the Waco area Del Rio Clay is unconformably overlain by the Pepper Shale where the Buda Limestone is absent. The Del Rio Clay grades downward into the Main Street Member of the Georgetown Formation. The Del Rio Clay-Georgetown contact approximately coincides with the boundary between the *Exogyra arietina* zone (Del Rio Clay) and the *Turrellites brazoensis* zone (Georgetown Formation). This faunal boundary occurs in the uppermost part of the Georgetown Limestone in the Waco area.

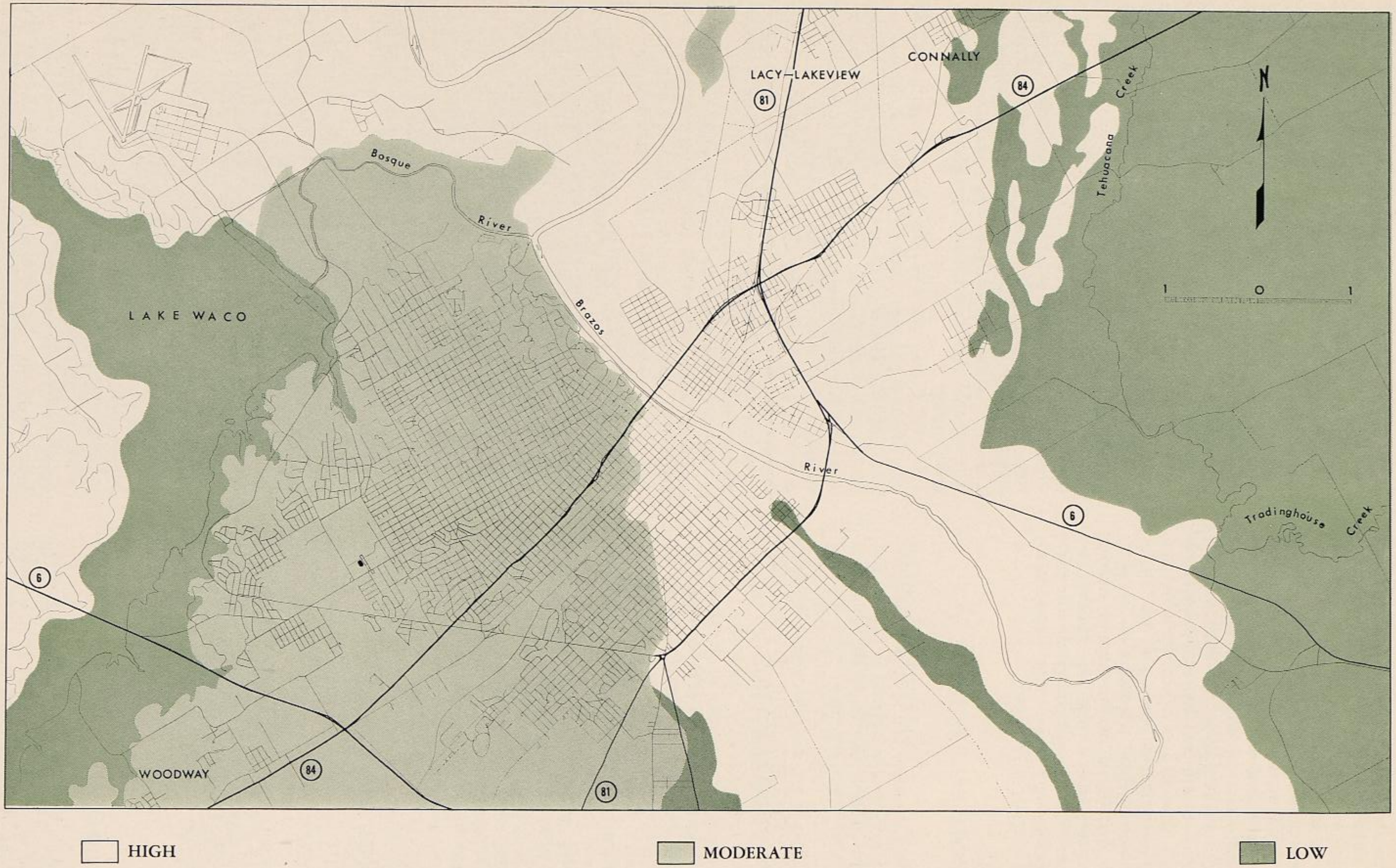
The Del Rio Clay is approximately 10 percent montmorillonite, 20 percent illite, 20 percent kaolinite, 10 percent quartz, 30 percent calcite, and 10 percent amorphous material. Calcite is least abundant near the middle of the formation.

The Del Rio Clay was probably deposited during a minor marine regression and transgression—the lower part of the formation reflects regression and the upper part reflects transgression. The lower regressive phase of the Del Rio Clay, which is in transitional contact with the underlying Georgetown Formation, displays from the base to the middle of the formation an upward decrease in calcium carbonate and an increase in sand content and pyrite. In addition, a normal marine fauna at the base of the Del Rio Clay grades upward to oysters and a dwarf pyritized fauna near the middle of the formation.

The upper transgressive phase of the Del Rio Clay exhibits vertical mineralogic and faunal trends which are the reverse of those observed in the regressive phase. From the middle of the formation upward (transgressive phase), calcium carbonate increases, sand content and pyrite decrease, and a more normal marine fauna appears.

Del Rio Clay weathers from blue-gray to light gray or buff as pyrite is oxidized to hematite and hydrated iron oxides. Oxidation of pyrite is accompanied by the production of sulphurous and sulphuric acids, which react with carbonates to form selenite crystals on weathered Del Rio outcrops.

The Del Rio Clay is easily eroded. The formation is readily cut by rill wash, and streams are commonly intrenched in the clay. Minor drainage on the Del Rio Clay displays a dendritic pattern because of the lateral homogeneity of the clays.



Infiltration capacity of rock in the Waco area is determined from performance of septic sewage disposal system in which drainage tiles, properly bedded in washed gravel, are laid in trenches within the unweathered rock below the soil zone. Capacity is listed as high, moderate or low.

High infiltration capacity exists where the average homesite lot provides adequate drainage field for septic sewage disposal, even during wet periods. These areas may also constitute problem areas for drainage of excavations because of the shallow water table and ready infiltration and transmission of water into excavations. High infiltration capacities exist principally in areas of Brazos alluvium and thicker lower terraces of the Brazos system.

Moderate infiltration capacities exist where the average homesite lot provides adequate septic sewage disposal except during prolonged periods of excessive rainfall. Moderate infiltration capacities exist in the area of Austin Chalk outcrop, in thinner Bosque and Brazos terraces and in Bosque alluvium northwest of Lake Waco.

Low infiltration capacities exist in areas where septic sewage disposal systems are continuously inoperative or become effectively inoperative during each wet period. These are principally outcrop areas of bentonitic clays and shales, which swell and seal when wet. This includes outcrops of lower Taylor Marl, South Bosque Shale, Lake Waco Formation, Pepper Shale and Del Rio Clay.

Fig. 6. Infiltration capacity of bedrock, Waco area. (Applies *only* to fluids introduced directly into the fresh rock *below* the soil zone.)

SOILS

Soils derived from the Del Rio Clay are dark gray-brown and highly productive. Del Rio soils are best developed in the area immediately northwest of the South Bosque River along the eastern edge of the Washita Prairie (fig. 2). A few small isolated outcrops of Del Rio Clay occur in the Greater Waco area (Pl. I).

RELATION TO URBAN DEVELOPMENT

The Del Rio Formation possesses engineering properties similar to those of the Lower Taylor Marl Member. The Del Rio Clay becomes highly plastic when wet, forms corrosive soils, is relatively impermeable to drainage or infiltration, excavates easily, and fails by slumping and plastic failure on relatively gentle slopes. The calcareous sections of Del Rio Clay will support up to a maximum of seven tons per square foot, but the less calcareous sections will fail under much lower loads and will readily slump on cut faces.

SUBSURFACE FORMATIONS

Rocks older than Del Rio Clay are not exposed at the surface in the Greater Waco area. Interpretation of subsurface geology in the Waco area is based upon electrical logs, drillers' logs, well cuttings, core holes, and extrapolated outcrop information. Description of these formations is abbreviated since only surface properties are important to Waco urban development.

In Greater Waco wells have penetrated about 1700 feet of Comanchean strata (Lower Cretaceous) and have drilled into underlying slightly metamorphosed rocks of Paleozoic age (table 2), which are part of the Ouachita foldbelt (Flawn, 1961).

GEORGETOWN FORMATION

ORIGINAL DEFINITION

The formation was named by Hill for Georgetown in Williamson County, but Vaughan (1900) formalized the term in a report on the Uvalde area.

AGE AND DISTRIBUTION

The Georgetown Limestone is late Comanchean (table 2) in age (Stephenson *et al.*, 1942, Chart 9). The formation crops out from the Rio Grande to Red River (fig. 1). In the Waco area the formation grades conformably into the overlying Del Rio Clay and rests unconformably upon the Edwards Limestone. The Georgetown Formation crops out west of Greater Waco in the Washita Prairie, which occurs west of the Bosque escarpment (fig. 2).

DESCRIPTION

The formation is divided into seven members (table 2), which are in descending order: Main Street Limestone, Pawpaw Shale, Weno Limestone, Denton Limestone, Fort Worth Limestone, Duck Creek Limestone, and Kiamichi Shale.

Only the Main Street Limestone Member is exposed in the vicinity of Greater Waco (Pl. I, II). It was encountered in the excavation for the stilling basin below the spillway of Lake Waco Dam. The Main Street Member crops out along the North Bosque River and along tributaries of the South Bosque River. The Main Street Member is 37 feet thick along the Bosque River west of Waco (Dixon, 1955, p. 22).

RELATION TO URBAN DEVELOPMENT

The Main Street Member, which crops out north and west of Waco, has high support strengths ranging to more than 25 tons per square foot. The member weathers to thin rocky soils, and in permeability it is similar to Austin Chalk. Excavation is difficult but can be accomplished by ripper and blade. The member disintegrates under abrasion, and, therefore, is less suitable for road material than Edwards Limestone or terrace gravels, although certain horizons make good subbase road material. The Main Street Member slakes upon weathering, but is capable of maintaining steep excavation faces.

The physical properties of lower members of the Georgetown vary with the clay/limestone ratio, but they are not exposed in the Greater Waco area. The lithology of these members is illustrated on the type electrical log (Pl. V).

EDWARDS LIMESTONE

The Fredericksburg Group (table 2) in the Waco area is composed of formations which are, in descending order, Edwards Limestone, Comanche Peak Limestone, Walnut Clay and possibly some thin sand beds of the Paluxy Formation. Rocks of the Fredericksburg Group, which are mid-Comanchean in age (Stephenson, *et al.*, 1942, Chart 9), crop out in the dissected Lampasas Cut Plain (fig. 2).

The Edwards Limestone was named by Hill and Vaughan in 1898 (p. 2). The original description was based upon exposures in the Edwards Plateau of south-central Texas, but the presently accepted type locality is along Barton Creek near Austin (Adkins, 1932, p. 339).

The Edwards Limestone is exposed in a belt trending northeast-southwest across Central Texas, and in the Edwards Plateau of south-central Texas.

The Edwards Limestone is exposed west of Waco near Crawford, and westward into the Hill Country where it caps the flat-topped hills of the Lampasas Cut Plain (fig. 2). Within the Waco area from 20 to 40 feet of Edwards Limestone occurs in the subsurface (Pl. V). Thickness varies because of reef "build-ups" in the patch reef facies of the Edwards Formation (Frost, 1963). Examples of reef structure are visible along the Middle Bosque River near Crawford. The reef facies of the formation furnishes excellent crushing stone for road base material and quarry blocks for riprap. Part of the riprap used in construction of Lake Waco Dam and associated structures is Edwards Limestone. Quarries in Edwards Limestone near Oglesby, Crawford, Valley Mills and Gatesville have supplied abundant building stone. High purity limestone is obtained from reef facies of the Edwards Formation in Central Texas.

The Edwards Formation contains ground water west of Waco, but it does not yield potable water within the Greater Waco area.

COMANCHE PEAK LIMESTONE

The Comanche Peak Formation was named by Hill in 1889 (pp. 14, 17-19) for exposures on Comanche Peak in Hood County. The formation is exposed in the Hill Country or Lampasas Cut Plain (fig. 2) of Central Texas, where it crops out beneath the Edwards Limestone on upper steep slopes of the distinctive flat-topped hills.

The Comanche Peak Limestone is composed of alternating layers of dark gray, nodular, earthy limestone and calcareous clay. In the subsurface of the Waco area, it is approximately 150 feet thick (Pl. V). It is conformably overlain by Edwards Limestone and rests conformably upon the underlying Walnut Clay.

WALNUT CLAY

Walnut Clay was first defined by Hill in 1891 (pp. 504, 512) for yellow clays, coquinoid oyster banks, and flaggy limestones overlying the Paluxy Sand near Walnut Springs, Bosque County. In Central Texas it is exposed along valley floors and lower valley walls in the Hill Country or Lampasas Cut Plain (fig. 2).

The Walnut Clay consists principally of an upper shale unit and a lower unit of coquinoid (oyster) limestones and thin dense limestone beds. The formation is 195 feet thick in the subsurface of the Waco area (Pl. V). It is the thickest clay unit encountered in drilling the sub-Del Rio rocks of the Waco area.

The Walnut Clay is conformably overlain by Comanche Peak Limestone, and it rests conformably upon and interfingers laterally with the Paluxy Sand.

PALUXY SAND

The Paluxy Sand was named by Hill in 1891 (p. 504) for exposures of sand near Paluxy townsite in Somervell County. In Central Texas the formation is the lowest unit of the Fredericksburg Group (Lozo, 1959, p. 18). The Paluxy Sand crops out as a sandy oak-covered belt in the Hill Country northwest of Waco.

In the northwestern part of Greater Waco the Paluxy Sand is represented by thin, fine-grained, calcareous sandstone beds below the Walnut Clay and above the Glen Rose Limestone. Sands of the Paluxy Formation grade upward into Walnut Clay and rest conformably upon Glen Rose Limestone.

Waco occurs at the southeastward pinchout of the Paluxy Sand. South and east of the Waco area, the Paluxy Sand is absent. For example, the J. L. Myers & Sons No. I Tiery well (Pl. V) occurs immediately east of the Paluxy pinchout. Therefore, Walnut Clay rests directly upon Glen Rose Limestone throughout much of the eastern part of Greater Waco.

The Paluxy Sand thickens northward and westward from Waco, where it is an important shallow aquifer. Flowing wells have been completed in Paluxy Sand near China Springs, and the South Bosque oil field has produced from Paluxy Sand for 65 years.

GLEN ROSE LIMESTONE

The Trinity Group[4] includes the oldest Cretaceous rocks of the Coastal Plain of Texas. In Central Texas the Trinity Group (table 2) consists, in descending order, of Glen Rose Limestone, Hensel Sand, Pearsall Formation, Sligo Formation, and Hosston Sand.

Rocks of the Trinity Group in Greater Waco rest upon pre-Cretaceous slightly metamorphosed rocks (figs. 1, 3) assigned to the Ouachita foldbelt (Flawn, 1961).

The Glen Rose Limestone was named by Hill in 1891 (pp. 504, 507) for exposures near Glen Rose, Somervell County. The formation is exposed in the Glen Rose Prairie, a limestone outcrop belt between the sandy outcrop belts of the Paluxy and pre-Glen Rose Trinity sand sections.

In the Waco area, the Glen Rose Formation is approximately 715 feet thick in the J. L. Myers & Sons No. I Tiery well (Pl. V), and it is divided into an upper and lower Glen Rose Limestone separated by a massive anhydrite section. In the type well (*idem*) the massive anhydrite occurs between the depths of 1970 feet and 2030 feet.

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[4] Aquifer properties of the formations of the Trinity Group of the Waco area are described in detail in a later publication of this series.

In a report on the Trinity aquifers of McLennan County, Holloway (1961, p. 16) presented the following description of the Glen Rose Limestone in the subsurface of the Waco area.

> "The upper Glen Rose limestone is tan porous shelly limestone, slightly glauconitic at the top and partly oolitic with gray thinly laminated interbedded shales. Miliolid Foraminifera are present.
>
> The massive anhydrite is white crystalline anhydrite interbedded with tan chalky highly porous limestone and gray thinly laminated shale. The anhydrite thins rapidly westward and is rarely encountered in wells of western McLennan County; the anhydrite affects drilling fluids in the eastern part of the county.
>
> The lower Glen Rose limestone is tan porous chalky limestone with gray thinly laminated interbedded shale. The foraminifer *Orbitolina texana* is common in this unit.
>
> Hill (1901) and Adkins (1923) recognized water horizons in the Glen Rose limestone. Several wells within the county produce from the Glen Rose limestone, but the water is highly mineralized."

HENSEL SAND

The name Hensel Sand (table 2) was proposed by Hill (1901, pp. 141-144, 152) for outcrops in Burnet County. Pre-Glen Rose Trinity formations crop out in the sandy Western Cross Timbers belt. Holloway (1961, p. 16) described the Hensel Sand in McLennan County.

> "The Hensel sand member (t^2 of Hill and T_1 of Adkins), within McLennan County, is the first sand encountered in drilling below the basal limestone beds of the Glen Rose Limestone. It is white, fine to coarse-grained, sub-rounded to sub-angular unconsolidated sand. Green shales are interbedded in the Hensel sand member in the western part of the county.
>
> Electric logs indicate that the sand thins in the northwest part of the county. The Hensel sand member contains abundant high quality water; many wells near Waco produce from the sand."

In the western part of the Waco area, a large volume of artesian water is produced from Hensel Sand, which is approximately 70 feet thick (Pl. V). Wells producing from this sand are numerous, and more are drilled each year for public, industrial, and domestic use.

In drilling for deep potable water the first productive zone encountered in the Waco area will be the Hensel Sand.

PEARSALL FORMATION

The Pearsall Formation was named by Imlay (1944) for a subsurface formation in Frio County. The formation is composed of two members (table 2), an upper Cow Creek Limestone Member and a lower Hammett Shale Member. These two units, recognizable in the East Texas basin, grade northwestward to sand in the vicinity of Waco, and they are difficult to distinguish west of Waco.

In the Waco area the Pearsall Formation is approximately 80 feet thick (Pl. V) and does not produce significant quantities of water. It is an excellent subsurface marker between Hensel Sand and the underlying Hosston Formation (Holloway, 1961, p. 16).

SLIGO FORMATION

The Sligo limestone (table 2) was named by Imlay (1940, p. 33) from the Sligo field in northeastern Louisiana. The Sligo Formation consists of brown to gray oolitic to crystalline limestone. It occurs in the subsurface east of Waco, and is approximately 20 feet thick in the J. L. Myers & Sons No. 1 Tiery water well (Pl. V). West of Waco it grades into sand and shale difficult to distinguish from the underlying Hosston sand.

HOSSTON SAND

The Hosston Sand was named by Imlay (1940, p. 29) from wells in northwestern Louisiana. Holloway (1961) described the nature and characteristics, as well as the aquifer properties of the Hosston sand. He stated that the Hosston Sand is composed of "fine to coarse, red to white, silty porous sand, locally cemented with calcite" (*idem*, p. 16). In the J. L. Myers & Sons No. I Tiery well (Pl. V) the Hosston Formation, which is 275 feet thick, is composed of approximately 150 feet of aquifer sand. Holloway (*idem*, p. 16) noted that the "Hosston formation is the more productive of the two Trinity aquifers of McLennan County. In the eastern part of the county all public and industrial artesian wells produce from this formation. Water from the Hosston formation is normally good quality."

PRE-CRETACEOUS ROCKS

Rocks older than Cretaceous have been recognized in deep wells in the Waco area. These rocks belong to the folded, faulted, and somewhat metamorphosed strata of the Ouachita foldbelt (Flawn, 1961). Rocks of the Ouachita foldbelt are predominantly phyllites, slates, metaquartzites, and schists of Paleozoic age. Foldbelt rocks, however, include igneous and sedimentary, as well as metamorphic types. Various degrees of metamorphism have been recognized (*idem*).

Deep wells within McLennan County have encountered Paleozoic foldbelt rocks composed of dark limestone, feldspathic and quartzose sandstones with calcite and disseminated garnet.

In southeastern McLennan County, possible Jurassic rocks (table 2) overlie rocks of the Ouachita foldbelt and underlie initial or basal deposits of Cretaceous age. Little is known of the detail structure of pre-Cretaceous rocks of the Waco area.

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Editor's note—Additional published and unpublished references are available on Central Texas geology, soils, water, engineering and other aspects. The Baylor Geology Department has available for perusal many published and unpublished master's theses related to Central Texas; several hundred open-file reports pertaining to Central Texas earth science; and extensive library references, aerial photographs, electric well logs, maps and other pertinent data. The Geology Library contains State and Federal reports, maps, and charts, as well as extensive bibliographic references. Citizens are invited to use this source of earth science data.

SUMMARY AND CONCLUSIONS

(1) Greater Waco (figs. 1, 2) is located on the Bosque escarpment, which marks the boundary between two major physiographic divisions of Texas—Grand and Black prairies—and two major structural-stratigraphic divisions—Texas craton and East Texas basin.

(2) Waco is underlain by eastward dipping bedrock (Pls. I, II) composed of Cretaceous limestone and shale beds of the Gulf Coast homocline. This homocline (Pls. III, IV) is complicated by the north-south trending Balcones fault zone which transects Greater Waco. Alluvial and terrace deposits of the Bosque and Brazos systems overlie Cretaceous bedrock throughout much of Greater Waco, especially in east Waco (Pl. II).

(3) The geology of Greater Waco, which controls or affects foundation properties, excavation problems, permeability of bedrock, thickness of soil cover, aquifer potential, blasting hazard, and other important factors, exerts a significant control on Waco urban growth and development.

(4) Heavy construction in the Waco area will be most affected by bedrock geology of the region. Light construction conversely will be affected significantly by soils developed on bedrock of the Waco area. It is critical that *rock* and *soil* behavior be clearly distinguished when utilizing and interpreting geological information.

(5) The variety of geologic formations and the local fault pattern create situations where plastic shales and resistant limestone beds are in contact along narrow zones or lines.

Foundations designed for structurally competent beds are inadequate for adjacent plastic bedrock material, and foundations designed for the plastic bedrock formations are over-designed for adjacent resistant bedrock. Excavation methods adopted for plastic clay-rich sections are not adequate for more resistant limestone areas. Slopes which are stable in limestone areas are excessively steep for areas of clay outcrop. Bedding and fractures provide natural partings which expedite excavation.

Permeability of formations is affected by lithology, faults, and fractures. Faults and joints provide effective transmission (in some cases piping) of fluids through rock.

Thick soils develop along faults and joints with attendant problems. Bedding and fractures may serve as wave guides, which direct shock (seismic) energy for considerable distances, creating blasting hazards related to fault and joint alignments.

Major faults influence the depth of aquifers, and may significantly modify water availability, migration and chemistry.

Engineering and construction procedures effective in one part of Greater Waco may be wholly inadequate in another part of the city.

(6) Formations which crop out (Pls. I, II) in the Waco area range in age from Recent to Middle Cretaceous (table 2).

Brazos and *Bosque alluvial deposits* are the youngest geologic materials in the Waco area. Construction upon these units include risks such as occasional flooding, lateral migration of river channels, foundation failure due to plastic nature of substratum, existence of shallow ground water, and water pollution from agricultural and human wastes. These alluviated areas provide sand and gravel for construction. They are normally well drained and agriculturally important.

(7) The Brazos and Bosque terraces occur 20 to 125 feet above present river levels.

Brazos terraces are composed of siliceous gravels and sands; they furnish the principal gravel sources for the Waco area. Terraces normally support stable, well-drained foundation sites for light structures. Brazos terraces readily absorb large quantities of waste water, but because of high permeability, water within the terraces is polluted.

Bosque terraces are composed of limestone gravels with clay cement or binder. These terraces are locally cemented by calcium carbonate, and they will support substantial building loads. Bosque terraces are normally thin, absorb moderate quantities of waste water, and produce limited quantities of polluted water during wet periods.

(8) Rocks older than Quaternary, which crop out in the Waco area, include from top to base, Taylor Marl, Austin Chalk, South Bosque Shale, Lake Waco Formation, Pepper Shale and Del Rio Clay.

Taylor Marl underlies essentially all of east Waco (Pl. II) (commonly beneath terraces and alluvium). The formation also crops out in the extreme southeastern corner of west Waco (Pl. I). Because of its plastic nature and high bentonite content, Taylor Marl absorbs fluids slowly, and it displays high shrink-swell ratios. The marl readily fails under light loads on gentle slopes. Shallow excavations in the Taylor Formation are unstable and require shoring. Complex faults also complicate urban development along the outcrop of this formation.

(9) *Austin Chalk* crops out over the greatest area of west Waco (Pl. I). The formation is composed of porous chalky limestone beds interstratified with somewhat less resistant marl beds. Austin Chalk provides strong foundations, and it will absorb significant quantities of waste water. Because of the tenacity of chalky limestone beds, relatively steep slopes cut in Austin Chalk are stable. Shallow excavations do not require internal support. Soils developed on Austin Chalk have high shrink-swell ratios. However, Austin soils are normally thin, and most structures will, therefore, rest upon unweathered chalk bedrock. In local areas of thick Austin soils, foundation damage is common.

(10) *South Bosque Shale* is plastic, calcareous to noncalcareous, gray shale exposed along the base of the Bosque escarpment beneath Austin Chalk (Pl. I). South Bosque Shale readily slumps on even gentle slopes, and failures of foundations, streets, highways, and septic tanks are common along the South Bosque Shale outcrop. The calcareous lower part of the formation is somewhat more stable and permeable than upper noncalcareous South Bosque Shale.

(11) *Lake Waco Formation* (Pl. I) is composed of calcareous, bentonitic shales interbedded with thin limestone beds. The formation is divided into three members: An upper *Bouldin Member*, dominantly fissile shale with some limestone beds from four to six inches thick; a middle *Cloice Member*, principally

bentonitic, calcareous, fissile shales; and a lower *Bluebonnet Member,* dominantly fissile, calcareous shale which includes several limestone beds from one to ten inches thick. Suitability of Lake Waco outcrops for construction sites depends largely upon the number and thickness of thin interstratified limestone beds. Zones with abundant limestone beds will support substantial foundation loads, but plastic clay sections fail under very small loads and on gentle slopes. Lake Waco clays have high shrink-swell ratios, and the formation absorbs fluids very slowly, if at all.

(12) *Pepper Shale* crops out at the foot of the Bosque escarpment in the extreme southwestern part of the west Waco area (Pl. I). The shale is composed of dark, blue-gray, noncalcareous, highly plastic shale. Pepper Shale is essentially impermeable. Soils which develop on the formation form a highly corrosive environment for buried pipes and metal structures.

(13) *Buda Limestone* is dense, discontinuous, resistant limestone normally less than two feet thick. It is absent throughout much of the Waco area. Buda Limestone is, therefore, of little engineering significance. The limestone is exposed principally in excavations north and east of Lake Waco.

(14) *Del Rio Clay* is gray, plastic, calcareous shale exposed principally in excavations north of Lake Waco. Unweathered clay will support moderate foundation loads, but the formation fails plastically when wet. Del Rio Clay absorbs fluids slowly, if at all.

(15) Rocks older than Del Rio Clay do not crop out in the Waco area, but they do crop out west and north of Waco. These Waco subsurface formations (Pl. V) include *Georgetown Limestone, Edwards Limestone, Comanche Peak Limestone, Walnut Clay, Paluxy Sand, Glen Rose Limestone, Hensel Sand, Pearsall Formation, Sligo Limestone, Hosston Sand,* and rocks of the pre-Cretaceous *Ouachita foldbelt.*

Some subsurface formations in the Waco area are significant to urban planning and development because they contain economic materials along outcrops north and west of the Waco area, contain potable water, and provide permeable reservoirs for subsurface waste disposal in the Waco area.

Edwards Limestone provides crushed rock and dimension stone within the Waco region. *Paluxy Sand* contains potable water north and west of Greater Waco. *Glen Rose Limestone* contains limited quantities of sulphurous water, and may ultimately provide a disposal reservoir for injected waste fluids. *Hensel* and *Hosston sands* produce artesian water in the Waco area, and they constitute the principal water supply of most communities in the Heart of Texas.

(16) Three summary maps (figs. 4, 5, 6) are presented, which show suitability of Waco bedrock for foundation, excavation and infiltration.

APPENDIX*

WELL LOCALITIES

Well No.	Well Description
1	J. L. Myers & Sons**, No. 1 Tiery.
2	J. L. Myers & Sons, No. 1 Pardo.
3	J. L. Myers & Sons, No. 2 McLennan County Water Control District No. 1.
4	Casey & Wimpee, No. 1 Housing Division.
5	City of Bellmead, No. 2 City of Bellmead.
6	Layne-Texas Company, No. 1 McLennan County Water Control District No. 1.
7	Layne-Texas Company, No. 3 Lacy Lakeview.
8	H. C. Buchanan, No. 1 H. C. Buchanan.
9	Joe Thompson, No. 1 Paul Shelby.
10	Pure Milk Company, No. 1 water well (Garrison Street).
11	Pure Milk Company, No. 1 water well (Jefferson Street).
12	Layne-Texas Company, No. 1 Bryan-Maxwell-Bryan.
13	Texas Water Company, No. 3 Texas Water Company.
14	R. F. Caraway, No. 1 Powell.
15	J. L. Myers & Sons, No. 1 J. W. Broughton.
16	C. M. Stoner, No. 2 Midway Water Company.
17	C. M. Stoner, No. 1 Midway Water Company.
18	Jackson et al., No. 1 J. D. Lovelace.
19	Jackson et al., No. 2 J. D. Lovelace.
20	Midway Park, No. 1 Midway Park.
21	U. S. Corps of Engineers Core Hole (Station 56.00).
22	Fulton Place, No. 1 F. M. Orelup.

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*Refer to Pls. III, IV for location of wells in the Greater Waco area.

**Refer to Pl. V for electrical and lithologic log of this reference well.

GLOSSARY*

Acidic Effluent. Sewer wastes which have acidic properties.

Alluviated Valley (Bottomlands). A valley in which sediments have been deposited by a stream. See Floodplain.

Alluvium (Alluvial Deposits, Floodplain Deposits). Sediments deposited by streams during floods.

Alternating Bedding. A sequence of bedded rock composed of interlaminated beds of two or more rock types.

Ammonites. An extinct class of molluscs closely related to the modern Nautilus; commonly coiled in a plane.

Amorphous Material. Solid material which does not display significant crystal structure.

Aquifer. A geologic formation which produces water.

Artesian Water. Underground water which rises above the level of the aquifer in wells.

Balcones Fault Zone. Zone of *en echelon* down-to-the-east faults which pass through the Waco area.

Bank Load Deposits. Fine-grained silts and clays deposited by a river on its floodplain.

Bank Storage. Ground water stored in alluvial material along stream banks and derived or charged from the stream.

Bed Load Deposits. Coarse sand and gravel which move along the floor of the main river channel during flood.

Bedding. Stratification in sedimentary rock resulting from changes in sediment type or rate of accumulation.

Bedrock. Fresh (unweathered) rock material below the lowest soil zones.

Belted Coastal Plain. Parallel bands of outcrops bordering the coast.

Bentonite. A group of clay minerals derived from decomposition of volcanic ash.

Biochemical Precipitation. Extraction of dissolved solids in water by organisms to build a shell or skeleton.

Bituminous Material. Coal or coal-like material of plant origin.

Black or Blackland Prairie. Originally a fertile grassland area underlain by Upper Cretaceous shales. Presently almost wholly in cultivation.

Blocky Shales or Clay. Lacking fissility or bedding. Breaks into irregular masses.

Bosque Escarpment. The west-facing cuesta which parallels the south bank of the South Bosque River from Moody to Waco.

Calcareous. Containing or composed of calcium carbonate.

Calcite. A mineral composed of calcium carbonate ($CaCO_3$). Principal constituent of limestone.

Calcite Veins. Tabular masses of calcite cutting across bedding. Common along faults and joints.

Calcium Phosphate. A dark detrital or concretionary bone-like material.

Caprock. A resistant bed of rock which caps higher hills and protects them from rapid erosion.

Carbonate. An informal term referring to minerals composed of iron, calcium and magnesium carbonate. For example, calcite.

Cementing Agent. Bonding material in sedimentary rock. Commonly calcareous or siliceous.

Chalk. Porous, fine-grained, soft limestone of marine origin.

Chert. (Flint, Jasper). Rock composed of microcrystalline or amorphous silica.

Clastic Deposits or Deposition. Accumulation of fragmental sediments such as sand, silt, or clay.

Clay. Sediment composed principally of clay minerals less than 0.002 mm in diameter.

Clay Minerals. A major mineral clan composed of aluminum, silicon and oxygen with lesser amounts of calcium, sodium, potassium and iron.

Conglomerate. A rock composed of cemented gravel.

Coquinoid Limestone. Limestone composed primarily of fossil shells and shell fragments.

Craton (Texas Craton). Structurally stable crustal block lying west of the Balcones fault system.

Cross Beds. Laminated sediments deposited at sharp angles to the major bedding planes. Normally indicative of current action.

Cuesta. Asymmetric topographic ridge underlain by gently dipping resistant bedrock layers.

Dendritic Drainage Pattern. Stream system in which the major stream and tributaries form a tree-like pattern.

Depositional Cycles. Repetition of sedimentary environments through time, reflected by repetitious alternation of rock types.

Dip. The angle and direction of inclination of a sloping bed of rock always measured perpendicular to strike. Commonly expressed in degrees of inclination below horizontal (or in feet per mile) and compass direction of dip.

Dip Slope. Sloping topographic surfaces approximately parallel to the dip of the underlying inclined rock beds.

Disseminated Minerals. Mineral grains distributed at random throughout a rock mass.

Drag. Minor folding of strata along the walls of a fault caused by movement of the beds on either side.

Driller's Log. Tabulation of rocks encountered in drilling a well. Recorded by the driller.

Eagle Ford Prairie. Prairie region underlain by rocks of the Eagle Ford Group.

East Texas Basin. Crustal block east of the Balcones fault zone which subsided and was filled with sediments during Mesozoic and Cenozoic time.

Edwards Plateau. A large physiographic region principally west of San Antonio, composed of high tablelands capped by Edwards Limestone.

Eh. Oxidation-reduction potential. A scale used (in geology) to describe the general degree of oxidation of minerals in rocks deposited in ancient aqueous depositional environments.

Electric Log Correlation. Determination of equivalence of geologic units encountered in two or more wells based on similarity in recorded electrical log properties.

Electrical Log (E-Log). Record of electrical properties of rocks encountered in well bore. Printed on scaled paper strips.

En Echelon Faults. Pattern of faults composed of off-set parallel faults.

Expandable Shales. Shales composed of clay materials which "pop" like popcorn when heated to high temperatures. Used as lightweight aggregate.

Facies. The total aspect of a body of rock which reflects its origin (composition, sedimentary structures, fossils, etc.).

Fault. Fracture along which there has been relative displacement of the two sides parallel to the fracture.

Fault Contact. A contact between two bodies of rock or formations along a fault.

Fault Displacement. Dislocation of a given rock bed or formation along a fault. Generally measured in feet of vertical movement. Commonly fault displacement is referred to as up-to-the-east, down-to-the-east, down-thrown to the southeast, etc.

Fault-Line Scarp. Escarpment produced by differential erosion of beds of differing resistance brought together by faulting.

Fault Scarp. Escarpment which owes its relief directly to faulting.

Fauna. A natural assemblage of animals.

Feldspathic. Rock or sediment composed in part of feldspar grains.

Filled Borings. Burrows of marine organisms which have been filled by sediment and have been preserved in sedimentary rocks.

Fissile. The property of shales which permits them to separate into thin flakes in planes parallel to bedding.

Flagstone. Rock bed which breaks into thin flat plates of considerable size.

Floodplain. The part of the valley floor subject to flooding.

Floodplain Deposits. See Alluvium.

Foraminiferal Tests. The commonly microscopic shell (=test) of a protozoan (one-celled animal). The test is normally composed of calcite or quartz fragments.

Foraminifers. Order of protozoan organisms.

Formation. A mappable, traceable body of rock. May be composed of a single rock type or a mixture of rocks bounded by recognizable beds.

Formational or Geologic Contact. Interface or surface between formations.

Foundation Load, Support Strength, or Engineering Strengths. Foundation load refers to the stress per unit area applied to the earth by a building or structure. Support strength or engineering strength refers to the capacity of rock materials to support foundation loads.

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*Terms used in this glossary were specifically defined for the *Geology of Waco*. The glossary is, therefore, oriented toward Central Texas Geology and Urban Geology.

Fracture. Crack in the rock generally related to jointing or faulting, reflected by alignments visible on outcrops and on aerial photographs.

Friable. The tendency for a clastic rock to crumble readily because of the absence of intergrain cement.

Geologic Map. Map showing geographic distribution of outcropping formations.

Glauconite. A soft, green, clay-like mineral composed of hydrated iron aluminum magnesium silicate.

Glen Rose Prairie. Grasslands developed on the outcrop of the Glen Rose Limestone.

Graben. Down-faulted linear block of earth's crust bounded by faults.

Gradational Contacts. A lithologic transition from one rock type or formation to another.

Grand Prairie. Grassland developed on Lower Cretaceous strata (Washita and Fredericksburg groups). Now cultivated areas or grasslands.

Gravels. Unconsolidated sediment composed of pebbles from 2 to 75 mm in diameter.

Gravity Slumping. Failure of rock material or soil by sliding and plastic flow down an unsupported face or slope.

Group. Two or more superposed formations which are grouped because of related origin and/or composition.

Gulf Coastal Plain. Extensive physiographic plains extending from Florida to Yucatan, underlain by Mesozoic and Cenozoic rocks.

Hematite or Iron Oxide. The mineral Fe_2O_3. A common mineral and the principal ore of iron. Has a characteristic red color when powdered.

Homocline. Uniformly dipping rock strata.

Hydrated. Minerals containing water in the crystal structure.

Hydrology. The study of the mechanics of water movement. May involve surface or subsurface water.

Illite. A family of clay minerals which display intermediate shrink-swell properties.

Incompetent Strata. Rocks which yield readily under load or other stresses.

Infiltration. Seepage of water into or through rock.

Infiltration or Septic Fields. An area of underground drainage of septic sewage effluent.

Intercalated Bedding. See Alternating Bedding.

Jarosite. A family of complex, yellow, hydrated, potassium, iron sulfates which form by weathering processes or by vein origin.

Kaolinite. A family of clay minerals which do not exhibit shrink-swell properties.

Lagoonal Environment. Sedimentary environment characteristic of a lagoon or enclosed bay.

Lampasas Cut Plain. A part of the Grand Prairie (Fredericksburg Group) which has been deeply dissected to produce a rolling plain of Walnut Clay bedrock with scattered bluffs and mesas capped by resistant Edwards Limestone.

Leaching. Removal of soluble constituents of rock or soil by natural solutions.

Limestone. Sedimentary rock composed of calcite (calcium carbonate).

Limonite or Hydrated Iron Oxide. A family of hydrated iron oxides which provide the yellow and brown pigments in many rocks.

Lithologic Log. Description of the rocks encountered in drilling a well.

Lithology. The study of rocks. Informally used to refer to the composition of rocks.

Llano Uplift. The region in which erosion has exposed elevated ancient rocks in the vicinity of Llano, Texas.

Loam. A soil composed of a mixture of clay, silt, sand and organic matter.

Luling-Mexia Fault Zone. Zone of *en echelon*, down-to-the-west faults east of the Balcones fault zone.

Mantle. The layer or "mantle" of loose, incoherent rock material which nearly everywhere forms the surface of the land and rests on bedrock.

Marcasite. Mineral composed of iron sulfide (FeS_2) similar to pyrite (fool's gold).

Marine Regression. The slow seaward migration of the shoreline.

Marine Rocks or Strata. Rocks composed of sediments deposited under oceanic conditions.

Marine Transgression. The slow movement of the sea over the land.

Marl. Calcareous shale.

Massive Anhydrite. An informal name given to a subsurface member of the Glen Rose Formation composed of limestone and anhydrite. Anhydrite is a mineral composed of calcium sulfate ($CaSO_4$).

Meander. Large bend in river channel incised into floodplain deposits.

Meander Cutoffs. Meander loop or bend of a river which was isolated or cut off from the stream when the main channel cut across the loop to shorten its stream course.

Meander Scars (Floodplain Scroll). Filled abandoned meander.

Mechanical Wave Guides. A system of bounding surfaces which tend to confine and direct earth shock waves in specific directions.

Member. A subdivision of a formation. A minor mappable unit of rock.

Metamorphosed. Altered by extreme pressure and/or heat.

Metaquartzite. Quartzite of metamorphic origin.

Microcrystalline Calcite. Limestone composed of microscopic calcite crystals.

Miliolid Foraminifera. A type of foraminifer (order of protozoan) characterized by a distinctly coiled shell or test.

Montmorillonite. A family of clay minerals which exhibit extreme shrink-swell properties.

Nektonic. Refers to swimming marine organisms.

Neritic. Marine environment characterized by shallow water (from low tide to a depth of 600 feet).

Nodules. Rounded concretionary bodies which can be separated as discrete mineral masses from the formation in which they occur. Commonly composed of quartz, calcite, gypsum, or hematite.

Nonresistant Strata. Rock beds which readily weather and erode. Principally shale in the Waco area.

Normal Fault. Tensional fault. Fault which results in lengthening of crust.

Offset Beds. Beds or strata which have been fractured and displaced by movement along a fault.

Oolitic. Texture of sedimentary rock composed of small accretionary spherical grains, commonly calcite.

Ouachita Foldbelt or Thrust Belt. Deeply buried, eroded, ancient, folded mountain belt beneath the Balcones fault zone.

Outcrop or Outcrop Belt. Geographic region or belt where a specific rock formation is exposed at the surface or covered only by mantle.

Oxidation. The process of combining with oxygen. For example, iron will oxidize to various minerals such as hematite (Fe_2O_3). An element that has been oxidized has lost electrons or has become more positive in valence charge.

Parent Material. Rock material from which a specific soil is derived by weathering and soil-forming processes.

Pelecypods. Clams and related molluscs. An important group of bivalved molluscs.

Permeability. The property of a rock which permits it to transmit fluids.

pH. Refers to acidity or alkalinity. Scale ranges from extremely acidic (1) to extremely basic (14); neutrality is approximately 7. A measure of the hydrogen-ion concentration.

Phosphatic. Composed largely of calcium phosphate.

Phyllite. Metamorphic rock with characteristics midway between a schist and a slate.

Physiography. In this report, the configuration of land forms, especially the relationship of topography to underlying strata and structure.

Pigmenting Material. Material which provides the color in rocks. Normally iron oxide or carbonaceous material.

Pinch Out. The lateral disappearance of a bed or formation by thinning. Disappearance of a unit is commonly called a pinchout.

Point bars. Sand or gravel bars deposited on the inside of a river meander.

Porosity. Pore space in a rock or sediment. In this paper it refers to the capacity to store fluids.

Pyrite. Mineral (FeS_2) composed of iron sulfide (fool's gold).

Quadrangle Map. Map of a geographic region bounded by specific meridians and parallels.

Quartz. Silicate mineral (SiO_2) which is the dominant constituent of sand and silt; highly resistant to weathering.

Quartzite. Rock composed of quartz grains tightly cemented or welded by quartz matrix. Extremely resistant to weathering; commonly occurs in terrace gravels.

Quartzose. Composed of quartz grains.

Reef and Patch Reef Facies. In this report, parts of the Edwards Limestone composed of massive reefs and isolated small reefs with detrital limestone in interreef areas.

Refraction Seismic Methods. Geophysical exploration method based upon transmission of elastic waves through earth materials.

Resistant Strata. Rock beds which weather and erode slowly. Principally limestone in the Waco area.

Restricted Environment. Aqueous depositional environment characterized by limited water circulation.

Rio Grande Embayment. A crustal block (or structural basin) which subsided and filled with sediments principally during the Cenozoic Era. Occupies an area of the Gulf Coastal Plain along Texas-Mexican border.

Rock. Aggregate of minerals.

Igneous Rock. Rock derived from solidification of molten material.

Sedimentary Rock. Rock composed of sediments.

Metamorphic Rock. Rock altered by heat and pressure from previously existing rocks.

Runoff. The portion of rainfall which enters the drainage systems by surface flow.

Salinity. The concentration of dissolved salts in water. Normally measured in parts per million (ppm).

Scaphopod. A tusk-shaped mollusc.

Scarp. Escarpment or steep face of a cuesta.

Schist. Metamorphic rock composed of planar and linear mineral grains with parallel orientation.

Sedimentary Environment. The conditions (physical, chemical, and biological) which exist in a specific area receiving sediments.

Sedimentary Structures. Textural and bedding variations in clastic sediments resulting from sedimentary processes. Examples are bedding, ripple marks, etc.

Selenite (Gypsum). Platy transparent mineral composed of hydrated calcium sulfate ($CaSO_4 \cdot 2H_2O$).

Shale. Bedded rock composed predominantly of clay minerals.

Shelf. Shallow submarine platform.

Shrink-Swell. A process of expansion and contraction which occurs in soils, shales or clays containing those clay minerals which expand when wet and contract when dry. These clays have crystal lattices which accept water molecules and expand, and conversely, lose water molecules and contract. Forces generated by shrink-swell clays can be intense.

Siderite. Mineral composed of iron carbonate ($FeCO_3$).

Silica. SiO_2; silicon dioxide.

Siliceous. Pertaining to silica; containing abundant quartz or related minerals composed of SiO_2.

Silt. Fine-grained sediment varying in grain size from 0.05 to 0.002 mm.

Slate. Metamorphic rock characterized by well developed cleavage planes. Commonly derived by metamorphism of shale.

Slickensides. Polished and striated (scratched) surface that results from abrasion along a fault plane.

Soil. Granular unconsolidated mineral and organic material which develops by soil-forming processes and overlies bedrock. May or may not have been derived from the underlying bedrock.

Soil Mechanics. Study of the physical behavior of soil material under load or stress.

Soil Zone. Refers to discrete compositional and textural layers present in some soils.

Strandline. Shoreline.

Stratigraphic Correlation. Determining time equivalence and/or continuity of formations or beds. Continuity can be demonstrated by tracing along the outcrop, by position in a sequence, or by distinctive lithology. Similar techniques can be used in tracing subsurface formations. Over great distances, fossils may be used to determine approximate time equivalence.

Stratigraphic Position. Position of a bed of rock in a sequence of strata.

Stratigraphy. The study of the sequence, properties, distribution and origin of stratified rocks.

Strike. Line of intersection between a dipping rock bed and a horizontal plane. Normally expressed as a compass direction (acute angle from north).

Structural Alignments. Linear features related to fractures visible on aerial photographs, by stream patterns, by soil color, etc.

Structural Geology. That part of geology devoted to the study of the geometric configuration of rock beds or bodies.

Structural Map. A contoured map which illustrates the configuration (relative to sea level) of a bed or formation of rock.

Subsoils. Lower zones of a soil.

Subsurface Geology. The study of rocks beneath the surface, normally based on well information.

Superposition. Sequence of beds of rock stacked like a deck of cards.

Surface Geology. The study of those rocks exposed at the surface.

Swelling Clays. A family of clay minerals (montmorillonite, bentonite) which swell or expand greatly when wet.

Taylor Prairie. See Black Prairie.

Tensional Forces. Stresses which tend to stretch the rock, normally resulting in fractures and faults (normal faults).

Terrace. Elevated remnant of older floodplain deposit left by downcutting river.

Thrust Fault (Reverse Fault). Compressional fault. Fault displacement in which crust is shortened.

Top Soil. The uppermost zone of a soil.

Topographic Bench. Small elevated flat areas along valley walls or escarpments, commonly supported by resistant rock beds.

Trellis Drainage Pattern. Parallel stream system (with short right-angle tributaries) which follows parallel fractures and faults.

Unconformable Contact or Formations. Surface of nondeposition or erosion separating two formations or beds.

Unconformity. See Unconformable Contact.

Underreamed Piers or Footings. Concrete foundation columns or beams which are larger at the base than at the top.

Vertebrate Fossils. Fossilized remains of vertebrate animals. Commonly elephant, shark, horse, etc. in vicinity of Waco.

Water Table. The level of water in a well. Below the water table all pores are filled with water.

Weathered Rock. Rock which has been partially decomposed by the action of water and atmosphere.

Weathering. The group of processes such as the chemical action of air and rain water, the activities of plants and bacteria, and the mechanical action of temperature changes whereby exposed rocks change in character, decay and finally crumble into soil and/or sediment.

Western Cross Timbers. A timber-covered belt of sandy soil on the outcrop of Lower Cretaceous sands in Texas.

White Rock Escarpment. Cuesta which is formed by the eastward dipping Austin Chalk (locally called the Bosque Escarpment).

White Rock Prairie. Prairie region underlain by Austin Chalk.

INDEX

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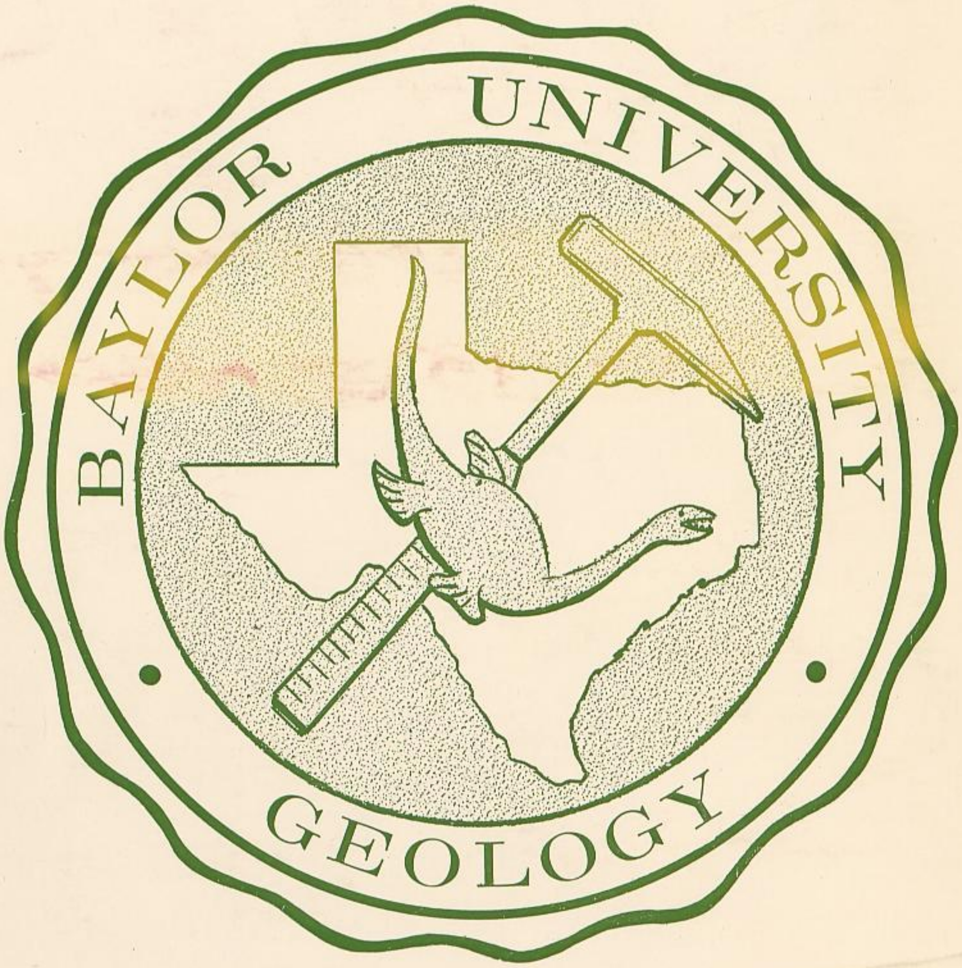
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