GEOLOGICAL ENGINEERING SURVEY OF THE TUCSON BASIN, PIMA COUNTY, ARIZONA

by

Ronald Joel Tanenbaum

A Thesis Submitted to the Faculty of the

DEPARTMENT OF MINING AND GEOLOGICAL ENGINEERING

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE
WITH A MAJOR IN GEOLOGICAL ENGINEERING

In the Graduate College

THE UNIVERSITY OF ARIZONA

1 9 7 2

STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his judgment and proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: ____________________

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

RICHARD D. CALL Assistant Professor of Mining and Geological Engineering	August 4 1972 Date

ACKNOWLEDGMENTS

The author is grateful to Dr. Richard D. Call who suggested this topic and served as thesis advisor, and to Dr. William C. Peters and Dr. Thomas Mitcham who served on the committee. The author also wishes to acknowledge Dr. Christopher C. Mathewson of Texas A&M University and Dr. Wes Peirce of the Arizona Bureau of Mines for providing additional advice; Dr. John F. Abel and Dr. William H. Dresher, for reviewing this thesis; and Mr. Roy E. Hunt and Mr. Robert S. Woolworth of Joseph S. Ward and Associates, Consulting Engineers, Caldwell, New Jersey, for their support and advice. Reproduction of this thesis was made possible through a grant from the Harrison-Schmitt Memorial Fund, College of Mines, The University of Arizona.

TABLE OF CONTENTS

TABLE OF CONTENTS--Continued

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS--Continued

LIST OF ILLUSTRATIONS--Continued

LIST OF ILLUSTRATIONS Continued

LIST OF TABLES

ABSTRACT

No area is entirely free of geologically-induced problems. An environmental and geological engineering study is needed to evaluate the full extent of the geological engineering parameters which must be considered whenever development or construction is being planned. In a populated urban area this is particularly important in order to protect property values, to avoid problems with utility services, and even to protect human life. These parameters must be considered to assure engineering soundness of a construction project and to avoid property damage and loss through non-observance of the dynamic geologic processes which are natural to the region or man-induced by development. In the Tucson Basin, a number of geologic factors exist, or have the potential to exist, which affect man; and in some cases, man himself has created or enhanced particular "geologic impediments." Those geologic factors that are of primary importance in the Tucson Basin are collapsing and expanding soils; flooding and associated aggradation and degradation; piping; deep subsidence; earthquakes; caliche; and landslides, mudslides, and creep. The amount of information pertaining to these factors is limited. A great deal more research is required to update this information and expand it to cover the entire basin.

CHAPTER 1

INTRODUCTION

In the Tucson Basin, foundation failures have occurred in small buildings constructed by competent engineers and contractors in accordance with building code requirements. Why? In the Picacho area, northwest of Tucson, the ground surface has subsided approximately eight feet since 1960. Will this also happen in the Tucson Basin? Almost every year, the dry washes traversing the basin create serious flooding during torrential rains, which, in the past, have destroyed homes, roads, bridges, and, in some cases, lives. Why? In the late 1800's, the Southwest was shaken by a major earthquake causing little damage in the Tucson area. Can the Tucson Basin expect major earthquakes in the future? The cost of excavation in a construction project rises unexpectly due to the encountering of caliche in the excavation. Why? Can these and other geologic hazards and impediments existing in the Tucson Basin be delineated and mapped?

Purpose

The conditions existing in the Tucson Basin exemplify the fact that no area is entirely free of geologic impediments. The purpose of this thesis is to conduct a geological engineering survey of the basin, that is, to gather all known information pertaining to the hazards and impediments of geological origin which pertain to construction and habitation of the region under study. A convient way of presenting the data of such a study is by mapping the geologic factors in the basin. It is not the author's intent to solve the existing problems, but to determine what the problems are, where they occur, and what the outlook for the future might be with recommendations for further studies to complete our knowledge of the geologic factors of the Tucson Basin. Although this study is of local conditions, the geologic factors discussed exist in many other areas, and the supporting theories summarized in this manuscript have widespread application.

Procedure

In order to gather all the known information together into one report, a thorough library-type search had to be conducted. All important maps were condensed and reproduced on a 1:62500 scale. A summary of the pertinent theory pertaining to each geologic parameter was prepared. To update and check the existing soils information, a spot field survey was conducted with corresponding laboratory identification tests. The preliminary geologic factor map was prepared by overlaying each map, one on top of the other. Finally, from the information gathered, recommendations have been made summarizing the studies that the author feels should be conducted to complete the geological engineering survey of the Tucson Basin.

Previous Work

In the past, university students and faculty have conducted a number of studies about individual geologically induced problems existing in the Tucson Basin and related areas. Among those who have done research in this field are D. B. Cooley, R. W. Crossley, Z. U. Kidwai, R. Streitz, F. J. Anderson, A. A. Abdullatif, H. A. Abu-Obeid, E. F. Pashley, W. S. Platt, N. O. Jones, W. C. Lacy, W. B. Bull, and H. A. Sultan. Additional studies have been conducted by E. S. Davidson, R. Morrison, B. E. Lofgren, and R. L. Klausing of the U. S. Geological Survey. The work of each of the above authors will be specifically referred to in the remaining text of this manuscript.

CHAPTER 2

GEOLOGIC HISTORY AND CHARACTERISTICS OF THE TUCSON BASIN

Geography, Physiography, and Location of Study Area

The Tucson Basin is located in the Santa Cruz River Valley, Pima County, Arizona and is bordered on the north and northeast by the Santa Catalina Mountains, the east by the Tanque Verde and Rincon Mountains, the southeast, south, and southwest by the Empire, Santa Rita, and Sierrita Mountains, respectively, by the Tucson Mountains to the west, and by the Tortolita Mountains to the northwest. The area of study incompasses Townships 13 through 16 South and Ranges 13 through 16 East (Figures 1 and 2). Some of the following comments are based on information taken from Lindeke and Pajaczkowski (1970) and Anderson (1968).

The physiography of the area is a typical Basin and Range province (Figure 3) with mountains surrounding a broad, fairly flat, alluvial valley that is 30 miles long and 13 miles across. The climate at the valley floor, which has an average elevation of 2,400 feet, is semi-arid receiving from 10 to 15 inches of precipitation per year. The average precipitation is 10.9 inches per year. The surrounding mountains rise to nearly 10,000 feet and receive from 20 to 25 inches of precipitation per year.

The drainage in the Tucson Basin consists of ephemeral and intermittent streams, most of which flow only as a result of direct

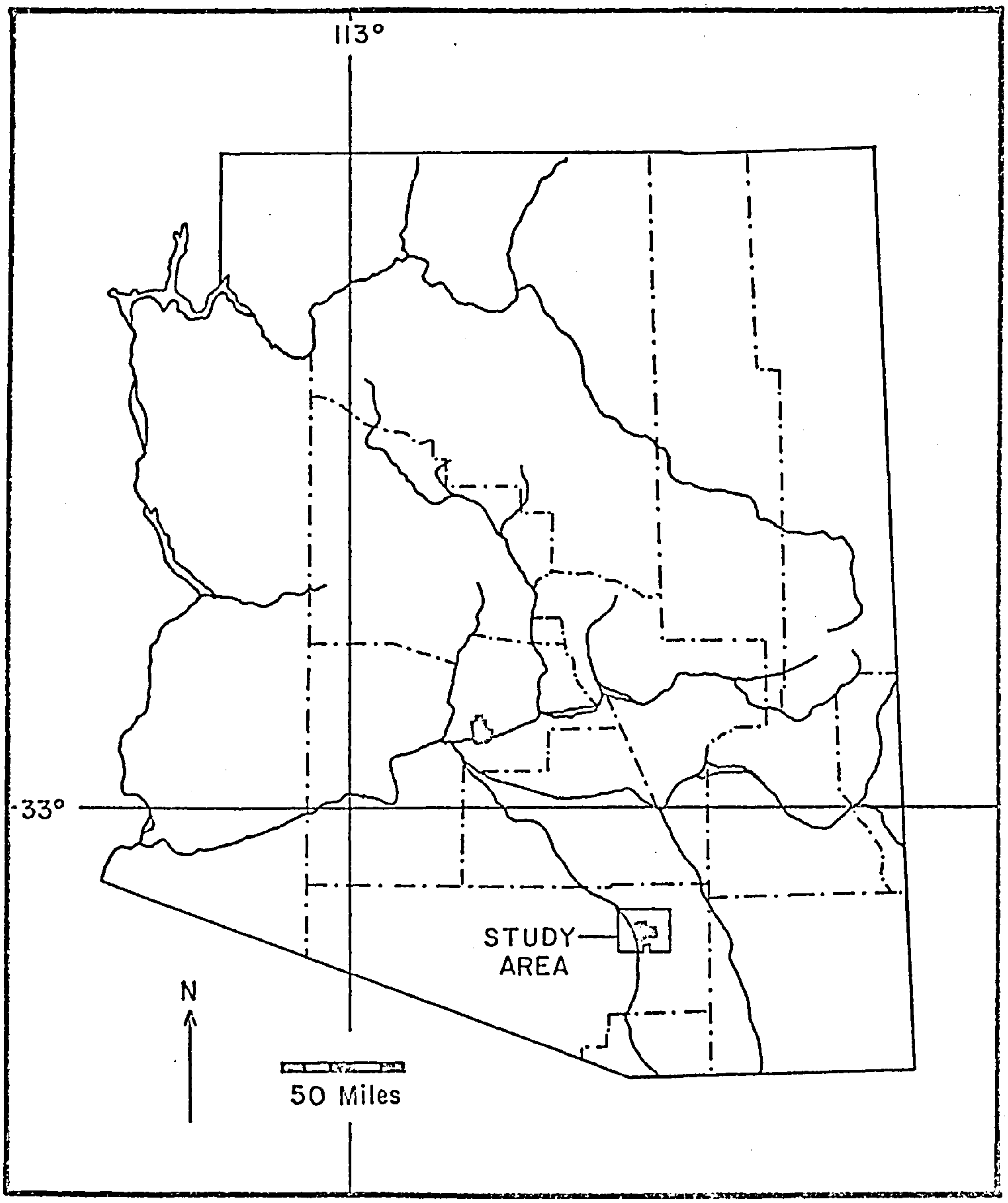


Figure 1. Location of Study Area.

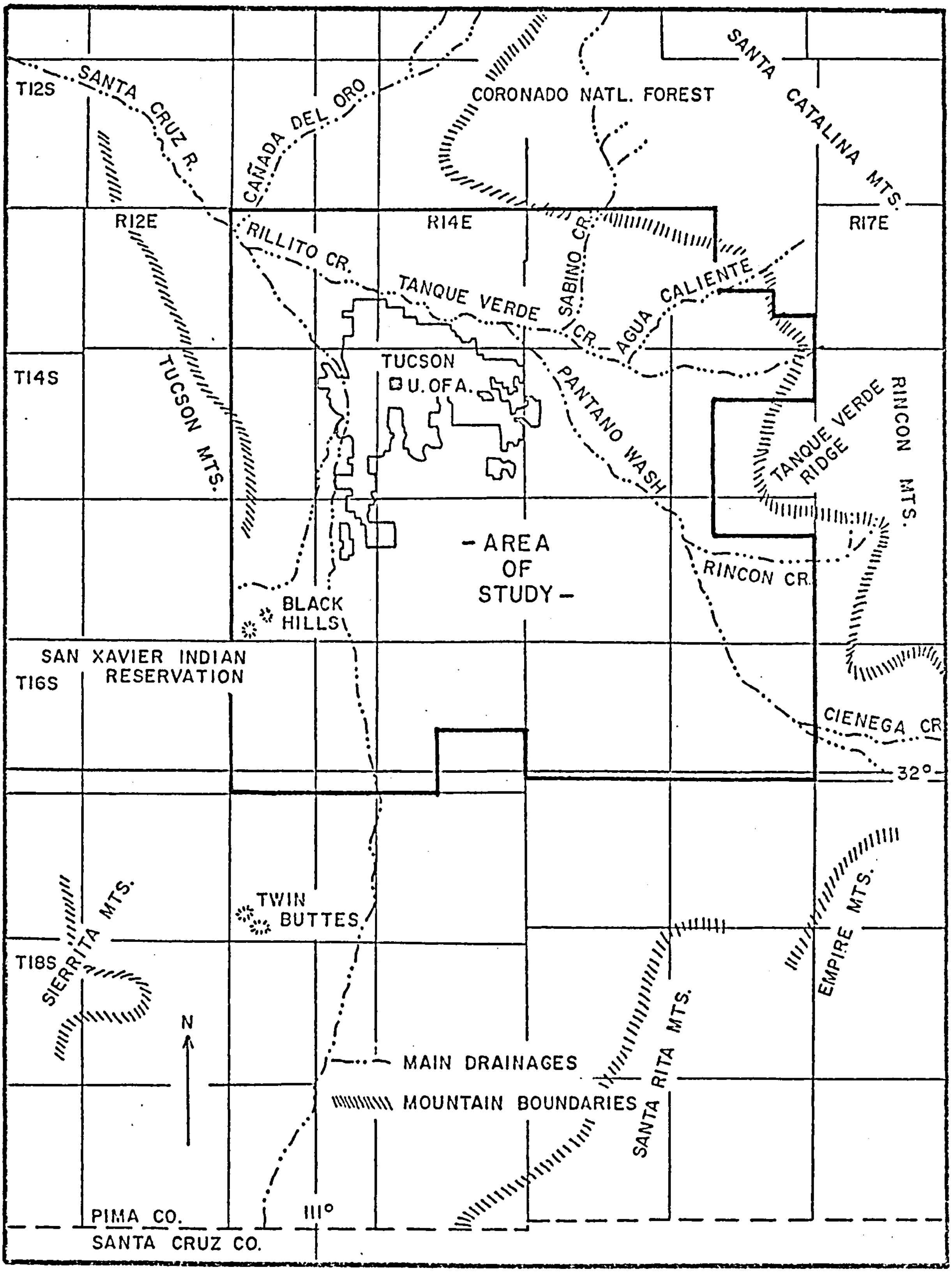


Figure 2. Location and Geography of Study Area.

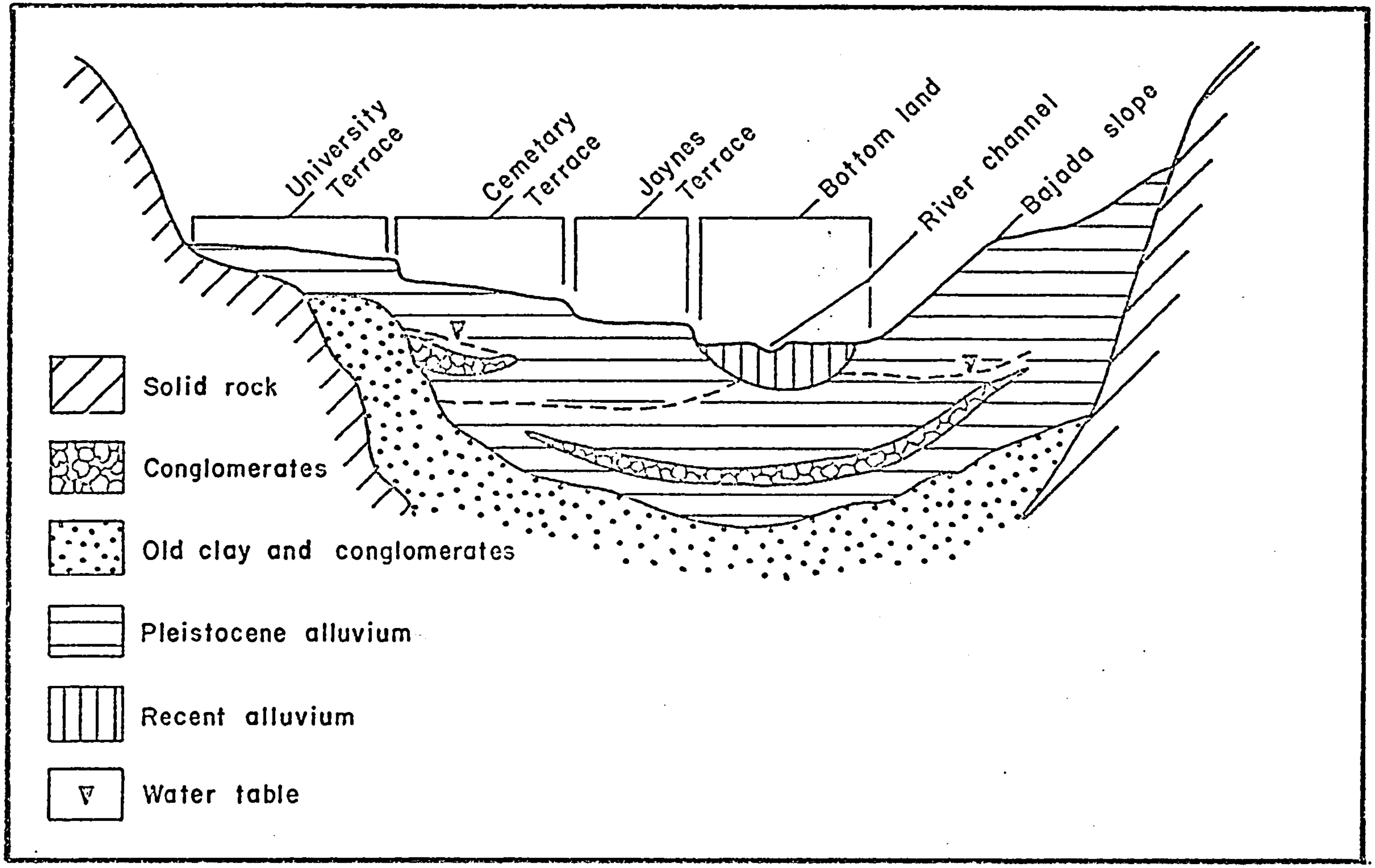


Figure 3. Generalized Cross Section of a Typical Arizona Basin-and-Range Valley and its Relationship to Terraces in the Tucson Basin. (Schwalen and Shaw 1957)

runoff from storm precipitation. The main drainage stream is the Santa Cruz River which flows north along the western edge of the basin. The Santa Cruz is fed by the Rillito Creek to the north which has two main tributaries, the Tanque Verde Creek to the northeast and Pantano Wash to the east. The Tanque Verde is fed by Sabino Canyon Creek and Agua Caliente to its north and the Pantano Wash by Rincon Creek and Cienega Creek to its east and southeast. Just to the north of where the Rillito feeds into the Santa Cruz River, Canada del Oro, flowing to the southwest out of the Santa Catalina Mountains, enters the Santa Cruz. The Santa Cruz River flows northwest out of the Tucson Basin at Cortaro entering the Gila River drainage system at Maricopa.

The average July temperatures range from 75° to 85°F and from 40° to 50°F in January. Yearly extremes range from 6° to 115°F. Because of the low rainfall and high temperatures, the climate is very dry which results in the evapotranspiration of from 90 to 95 percent of the precipitation falling in the area.

Geologic History

Information on the Paleozoic and Precambrian history of the Tucson Basin region is sketchy, but the following general comments can be made based on information taken from Lindeke and Pajaczkowski (1970), Crossley (1969), Jackson (1969), Kidwai (1957), Wilson (1962), and Peirce (1972). Sometime during the Precambrian, there were granitic intrusions into schist. Toward the end of this period, some volcanic flows occurred. During the Paleozoic era, sea encroachment and marine deposition occurred several times followed by large-scale earth movements and deep erosion; and crustal movements and associated igneous activity occurred with the intrusion of magmas. This crustal instability may have been related to the Nevadan Orogeny which resulted in the uplifting of the Cordilleran Geosynclinal Belt to the west.

Final sea encroachment and marine deposition probably occurred during the early Cretaceous Period. During the late Cretaceous, there was deposition of continental and volcanic material followed by regional folding and faulting. Large amounts of lavas, tuffs, and ash were deposited during the regional tectonic activity.

The temperature dropped after the Paleocene Epoch and the Rocky Mountain Orogeny died out during the early Oligocene. During the late Oligocene to early Miocene, the Sierra Nevadas began to rise, changing the climate of the region from sub-humid to semi-arid by mid-Miocene.

During the late Oligocene-early Miocene, the sedimentary beds (Rillito Formation) were being deposited which presently outcrop in the mountain foothills and as part of the mountain blocks (Minetta Formation). These have been identified as the Rillito Formation to the north (Kidwai, Tinaja beds of Davidson), the Pantano beds to the east, and the Minetta Formation on the east side of the Rincon Mountains. The basin and range orogeny occurred during the mid-Tertiary with accompanying deposition of large amounts of lava and tuff.

The exact time when the uplifting of the Santa Catalina, Tanque Verde, and Rincon Mountains began is not known, however, it is generally believed that this occurred no earlier than the earliest Tertiary, but no later than the earliest Pliocene. This was preceded by pedimentation.

From late Miocene through the early Pliocene, large scale earth movements and associated volcanism occurred which outlined the present structure of the basin and range and may have continued intermittently to the present with a second earth moving phase occurring during the Pleistocene. The volcanic flows blocked the ancestral drainage of the basin during the mid-Pliocene. Block faulting separated the mountains and the valleys with deposition in the Santa Cruz Trough occurring from material washed down from the mountains. Sand, silt, and gravel was deposited unconformably on the Rillito beds. During the late Pliocene through early Pleistocene, uniform sands and silts were deposited, and there is some indication that lakes were present at this time.

During the ice advances of the Pleistocene Epoch, Arizona's climate was cold and dry. Very low temperatures and frost action during the early Pleistocene resulted in rapid weathering of the basin and range topography with severe erosion and gullying creating gorges and terraces through Quaternary time. The Quaternary terrace deposits were laid down disconformably over alluvial basin-fill deposits. The ancestral drainage began to flow again, the sediment supply increased, flooding occurred, and the maximum height of the basin fill was reached.

The University Terrace (Figure 4, in pocket) is the oldest and highest terrace and represents the top of the original valley fill. The next oldest is the Cemetary Terrace which was carved by the Rillito Creek when it was flowing further to the south from its present location. Filling by ancestral Rillito formed this terrace. The Jaynes Terrace is the youngest and was cut and formed in the deeper fill as the Rillito Creek migrated to the north. The youngest and lowest level is the Bottomland consisting of recently deposited sediments. Lindeke and Pajaczkowski (1970) states that "each terrace lies in a trench excavated in older materials [by migrating, laterally meandering streams]. These terraces can be distinguished from each other . . . by changes in slope of land surface or by vague differences in age of sediments and by some peculiar geomorphic distinguishing characteristics--amount and depth of caliche, compactness" (p. 3).

Aggradation and degradation caused by alternate erosion and partial filling, forming the present bottomlands and flood plains, occurred throughout the Recent Epoch and continues to occur today. The alternating erosion and deposition can be attributed mostly to changes in elevation and, in part, to climatic changes.

A degradation environment, superimposed on the normally occurring erosion, exists at the present which was believed to be brought about by unlimited, uncontrolled overgrazing of cattle and ground water withdrawal during Tucson's early growth period which, resulted in the removal of most of the grasses and topsoil which had been resisting erosion in the past.

Table 1 is a schematic representation of the Tucson Basin's general geologic history and its relationship to the geologic history of the State of Arizona.

Table 1. Schematic of the General Geologic History of the Tucson Basin.

ERAS	PERIODS & EPOCHS		TIME IN MIL. YRS.	GEOLOGIC HISTORY OF THE TUCSON BASIN	GENERAL ROCK UNIT CORRELATION (JACKSON, 1969)	MAJOR GEOLOGIC EVENTS EFFECTING ARIZONA (WILSON, 1962)
CENEZOIC	QUATERNARY	RECENT	.001	DEGRADATIONAL ENVIRONMENT DUE TO OVER GRAZING ALTERNATE AGGRADATION & DEGRADATION	ALLUVIAL DEPOSITS, BASALT	
		PLEISTOCENE	1	ANCESTRAL DRAINAGE FLOWED AGAIN--SEDIMENT SUPPLY INCREASED, FLOODING, BASIN FILL REACHED MAXIMUM TERRACES FORMED RAPID WEATHERING--EROSION & GULLYING--GORGES CREATED DEPOSITION OF UNIFORM SANDS & SILTS (POSSIBLY SOME LAKE BEDS)		VOLCANISM AND MINOR FAULTING
	TERTIARY	PLIOCENE		SAND, SILT, & GRAVEL UNCONFORMABLY COVER RILLITO BEDS DRAINAGE BLOCKED, BLOCK FAULTING DEPOSITION IN SANTA CRUZ TROUGH	GILA CONGLOMERATE	
		MIOCENE	12	LARGE SCALE EARTH MOVEMENTS & ASSOCIATED VOLCANISM (BASIN & RANGE OUTLINED) BASIN & RANGE OROGENY--DEPOSITION OF LAVA & TUFF EROSION & DEPOSITION OF THICK SEDIMENTS (RILLITO & PANTANO FMS.)		BASIN & RANGE OROGENY;
		OLIGOCENE	23	DEPOSITION OF SEDIMENTARY (RILLITO) BEDS	VOLCANICS WHITETAIL CGL.--PANTANO FM.	TRANSITION ZONE AND PLATEAU UPLIFT VOLCANISM
		EOCENE				
		PALEOCENE	70	COVERING OF CONGLOMERATE BY LAVA FLOWS CONGLOMERATE DEPOSITION UPLIFT & EROSION--BLOCKING OUT OF BASIN & RANGE	ANDESITES & RHYOLITES	GRANITIC INTRUSIONS
MESOZOIC	CRETACEOUS	LATE		DEPOSITION OF LARGE AMOUNTS OF VOLCANIC LAVAS, TUFFS, & ASH REGIONAL FOLDING AND FAULTING DEPOSITION OF VOLCANIC & CONTINENTAL SEDIMENTS	LOCAL SEDIMENTARY FORMATIONS PINKARD FM.	LARAMIDE REVOLUTION
		EARLY	135	SEA ENCROACHMENT & MARINE DEPOSITION	BISBEE GROUP LOCAL VOLCANICS	
	JURASSIC		180	CRUSTAL INSTABILITY ASSOCIATED WITH THE UPLIFT OF THE CORDILLERAN GEOSYNCLINAL BELT	LOCAL VOLCANICS	NEVADAN REVOLUTION VOLCANISM GRANITIC INTRUSIONS
	TRIASSIC		220	SEA ENCROACHMENT SEA ENCROACHMENT--CRUSTAL MOVEMENTS, INTRUSIVE MAGMAS, METAMORPHISM	LOCAL RED BEDS LOCAL VOLCANICS	MOGOLLON HIGHLANDS IN CENTRAL ARIZONA
PALEOZOIC	PERMIAN		270		RAINVALLEY FM.; CONCHA LS. SHERRER FM.; EPITHAT DOL.; COLINA LS.	GENERAL UPLIFT
	PENNSYLVANIAN		320		EARP FM. HORQUILLA LS. BLACK PRINCE LS.	
	MISSISSIPPIAN		350	(? UPLIFT OR DOMING OF THE SANTA CATALINA, TANQUE VERDE, & RINCON MOUNTAINS, AND PEDIMENTATION ALONG MOUNTAIN SLOPES ?)	PARADISE FM. ESCABROSA LS. MARTIN FM.	UPLIFT IN CENTRAL ARIZONA
	DEVONIAN		400			
	SILURIAN			LARGE SCALE EARTH MOVEMENT & DEEP EROSION } EXACT TIME OF OCCURRENCE UNKNOWN	EL PASO LS.	GENERAL UPLIFT
	ORDOVICIAN		490			
	CAMBRIAN		600	SEA ENCROACHMENT & MARINE DEPOSITION } EXACT TIME OF OCCURRENCE UNKNOWN	ABRIGO FM. BOLSA QTZ.	
YOUNGER PRECAMBRIAN			1600	SOME VOLCANIC FLOWS SCHISTS & GRANITES ERODED & COVERED BY SEDIMENTS	TROY QTZ. APACHE GROUP	GRAND CANYON DISTURBANCE DIABASIC INTRUSIONS
OLDER PRECAMBRIAN			2000+	INTRUSION OF SCHISTS BY GRANITE	PINAL SCHIST GRANITE GNEISS	MAZATZAL REVOLUTION; GRANITIC INTRUSIONS

General Basin Geology

The following general comments can be made based on information taken from Kidwai (1957), Davidson (1970), Strietz (1962), and Pashley (1966). Precambrian to late Tertiary intrusive igneous and metamorphic rocks, in particular granodioritic gneiss and granite, siliceous to mafic schist, and several types of siliceous and felsic intrusives, make up the Santa Catalina, Tortolita, and Rincon Mountains. The Sierrita, Empire, and Santa Rita Mountains contain Paleozoic to Mesozoic sedimentary, metamorphic, and intrusive igneous rocks. Andesitic to rhyolitic volcanic flows, tuff, and agglomerate and interbedded conglomerate and sandstone comprise the Mesozoic to middle Tertiary volcanic and sedimentary rocks of the Tucson, Black, and Sierrita Mountains. Late Tertiary volcanic rocks also exist in Black Mountain.

The sedimentary rocks in the basin consist of the Pantano Formation which is overlain by the Tinaja beds which underlie the Fort Lowell Formation. The Pantano Formation (Rillito I of Pashley) is Oligocene in age. It consists, within the basin, of a few hundred to about 1,000 feet of reddish-brown silty sandstone to well cemented gravel with minor volcanic flow and tuff beds. The Pantano contains little Catalina Gneiss, no less than 30 percent sand and gravel, and 10 percent or more larger detritus. The lower part of the formation contains mudstone and the upper part contains gypsiferous mudstone along with mudflow-landslide breccia and large individual block landslides.

The Tinaja beds (Rillito II and III of Pashley) are Miocene (?) in age. These beds lie unconformably on the Pantano Formation and are from less than 100 to over 2,000 feet thick grading from sandy gravel at the perimeter of the basin to gypsiferous mudstone, clay, and silt in the center of the basin which is either a lacustrine or playa deposit. The coarser material ranges from grey to reddish brown and generally contains from 30 to 90 percent of material coarser than silt and from 5 to 50 percent of material coarser than sand. The Tinaja beds contain granitic, volcanic, and sedimentary rock fragments. The amount of Catalina Gneiss fragments increases toward the top of the beds. The upper Tinaja beds and the lower Fort Lowell Formation contain coarse grained material that may be interpreted as a combined beach and sand dune deposit that could indicate the existence of a buried playa.

The Fort Lowell Formation is a locally derived sedimentary deposit, underlying most of the Tucson Basin, and outcropping in the Santa Catalina and Rincon Mountain foothills. It lies unconformably on top of the Tinaja beds (Rillito Surface of Pashley) and is Pliocene to middle Pleistocene in age. Most of the Formation is 300 to 400 feet thick. Both the Tinaja beds and the Fort Lowell Formation are relatively flat lying with the contact between the two being indistinct due to the probable reworking of the Tinaja beds which was later deposited as part of the Fort Lowell Formation. The University terrace is the top of the formation with thick, dense caliche underlying the surface. The Fort Lowell Formation grades from silty gravel along the basin perimeter to silty sand and silty clay in the center of the basin. The grain size distribution is similar to and coarser than the Tinaja beds and is loosely packed to weakly cemented. The color ranges from dark to light reddish brown. Volcanic, sedimentary, and granitic fragments are present in a matrix of sand and montmorillonite clay. Catalina Gneiss fragments are also abundant along with landslide and mudflow detritus.

The surficial deposits, overlying most of the older deposits, consists of alluvial fan, sheet flow, stream channel, and flood plain sands, silts, and gravels and range from 5 to 100 feet thick. Lake beds are evidenced by thin, local, and randomly distributed clay beds and thick silt deposits. The chief cause of deposition is the loss of stream competence "due to a flattening of gradients or depletion of transporting medium by evaporation and infiltration" (Strietz 1962, p. 36). Strietz (1962) relates the type of sediments to different phases of flooding:

1. Sandy clay phase--flash floods, broad sheet wash and general flood conditions.
2. Coarse conglomerates (perimeter)--headward flood deposition or alluvial fan apex deposition.
3. Well sorted sand and gravel--channel deposits, constant streamflow between floods or emplaced after floods.
4. Clay units--laid down during periods of quiet water, overflow areas or enclosed ponds.

Therefore, the valley fill depositional environment was fluvial. Kidwai (1957) stated that the interfingering of clays, silts, sands, and gravels depended on the location and type of medium of transportation and deposition. The location shifted which produced fluctuations in the type, and the vertical and horizontal distribution of, the sediments that were deposited. These deposits comprise the terraces and bottomland discussed in this chapter under Geologic History. The contact of these deposits with the Fort Lowell Formation will be in all probability gradational. The deposits to the west, south, and east contain more silt than the deposits to the north. The older deposits are more densely packed than the loosely packed, non-cemented stream deposits and the material composition is the same as the surrounding mountains. The weathered yellow-brown gneiss fragments help distinguish the surficial deposits from underlying older deposits.

The structure seen on the geologic map (Figure 5, in pocket) is the result of an interpretation by Davidson from drill-core samples and abrupt changes in the coarse sediment content.* All the faults are interpreted as being vertical. The oldest fault trends northwest from Tucson to Rillito with a displacement of 5,000 feet or more. A slightly younger fault system (late Oligocene to early Miocene) includes the north trending fault at the basin's center, and the northeast trending probable fault cross-cutting the eastern part of the basin and the fault parallel to Rillito Creek. Displacements range from 600 to 2,000 feet. The youngest fault system consists mainly of northeast trending faults, many of which are inferred to cross the

---

*For a complete discussion Davidson's (May 1970) interpretation, refer to his U.S.G.S. open file report, Geohydrology and Water Resources of the Tucson Basin, Arizona, pp. 101-112.

basin from the Tucson Mountains to the Santa Catalina Mountains. The offset is believed to be less than 500 feet. The change of the drainage from a basin-confined system to a flow-through system may be explained by an uplift of as much as 1,000 feet to the south of the basin. The faults are believed to have formed in response to a series of basin depressions with respect to the surrounding mountains.

CHAPTER 3

GEOLOGIC FACTORS

In any area, the use of proper engineering and construction techniques can overcome any geologic factor present, which is a nuisance or threatens the existence of a structure. However, if these factors are overlooked or forgotten, they can become a hazard to property values and lives after the structure is completed. For example, the flood which washes away homes and businesses, and in some cases their inhabitants. Or the earthquake, which reduces a highway overpass to a pile of rubble. The cost of repairing the geologically related damage is always greater than the cost of correcting the problem at the outset of construction. The problem is recognizing, evaluating, and reckoning with each of the geologic factors in the planning stage of development.

Some of these factors are nature-induced, some are man-induced, and many fall into both categories. The geologic factors in the Tucson Basin include collapsing and expanding soils; flooding and associated aggradation and degradation; piping; deep subsidence; earthquakes; caliche; and landslides, mudslides, and creep. Each will be discussed separately, first to discuss the general theory and characteristics, and then to determine if and how they affect the Tucson Basin.

Collapsing and Expanding Soils

"A collapsing soil is defined as a soil which undergoes appreciable loss of volume due to a major readjustment of the soil fabric upon wetting or upon the application of a boundary force. A boundary force may or may not be required to induce collapse" (Anderson 1968, p. 2).

Sultan (1969, 1971b) states that the genesis of a collapsing soil varies widely from wind blown deposits to alluvial, and even colluvial deposits. They all have two properties in common, that of being highly porous and geologically young in age.

Anderson believes that the origin is relatively unimportant and that the soil structure is the governing factor. Figure 6 illustrates Anderson's interpretation. In Figure 6 (a) hard grains are separated by spaces in which clay particles have been concentrated by the action of capillary forces when dessication of the soil occurred. He theorized that some soils in a semi-arid climate "were deposited and dessicated, rapidly buried, and never saturated again" (Anderson 1968, p. 8). A curved air-water interface exists between unsaturated soil grains drawing and holding them together by the creation of tension forces. The clay particles possess a negative charge and are affected by electrostatic forces, not body contact forces. The electrostatic forces include repulsion, which produces the maximum separation of clay particles, and attraction, which causes flocculation of clay particles, that is the forming of clumps or packets. This combination of forces results in some consolidation of the clay which, when combined with a

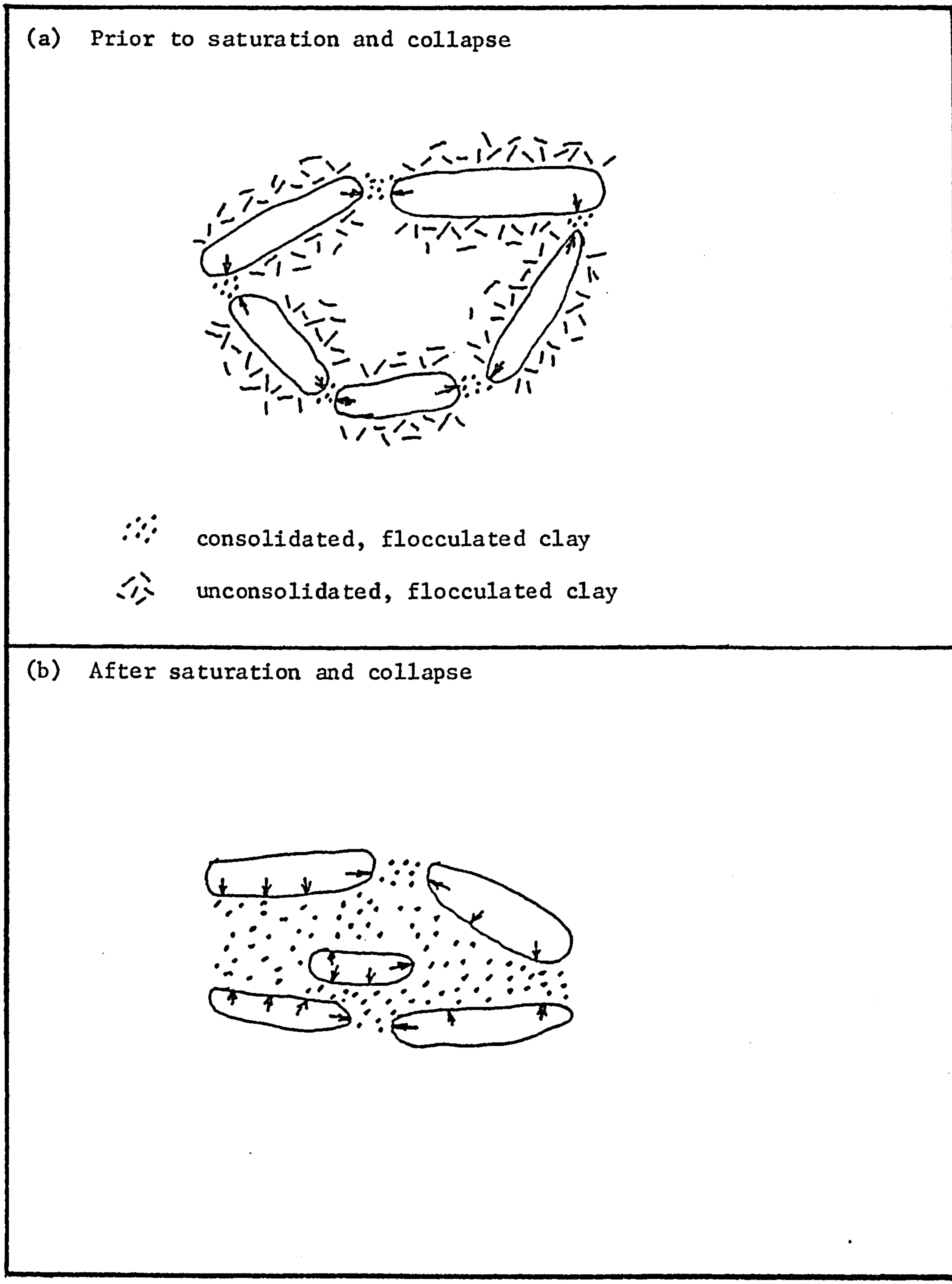


Figure 6. Structure of a Collapsing Soil. (Anderson 1968)

cementing agent, such as calcium carbonate, form a "glue," or bond, holding the hard, unweathered grains together. In Figure 6 (b), the air-water interfaces and tension forces are removed by saturation of the soil. "Collapse occurs when the magnitude of shear stresses exceeds the shear strength of the clay bridges at a given moisture content. Soil grains roll and translate past each other to assume a new state of equilibrium under the applied stresses at a lower porosity. . . ." (Anderson 1968, p. 16). The original equilibrium of the bridges was determined by the largest intergranular pressure and the greatest moisture content that the clay bridges had experienced prior to collapse, that is, during its unsaturated state.

Figure 7 represents the different soil structures that would occur at different moisture contents.

> Point A . . . represents a soils of a low water content and a flocculated structure . . . . Strong concentration of electrolytes (salts) causes the presence of the flocculated structure. Point B. represents a soil of higher water content and an increase in the double layer's thickness. This causes the clay particles to orient due to the repulsive forces which are caused by water content increase. Therefore, packets of particles are formed. Point C. represents a soil of very high water content which will cause a complete repulsion between the soil particles. This case is called the dispersed (weakest) soil (Abdullatif 1969, p. 26).

All soil particles carry a net positive or net negative electrical charge, of which only negative charges have been measured (Lambe and Whitman 1969). In an attempt to neutralize its net charge, a soil particle will attract ions, for example, sodium ions.

> If the individual clay particles are now dropped into water, both the mineral surfaces and the exchangeable ions pick up water, i.e., hydrate. Upon hydration, the sodium ion grows about sevenfold. . . . Actually, the exchangeable ions with

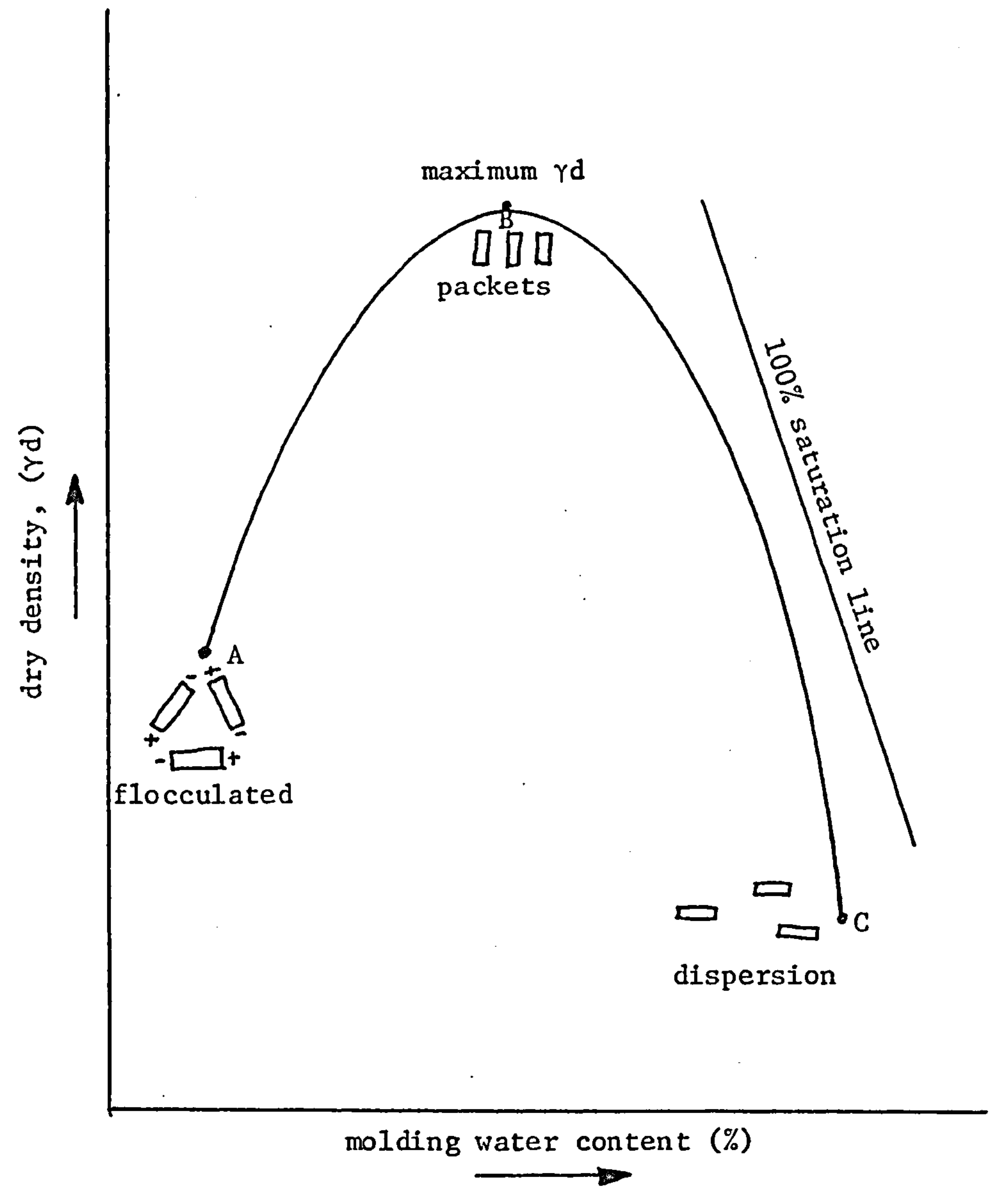


Figure 7. Soil Structure due to the Increase in Water Content. (Abdullatif 1969)

> their shells of water move away from the mineral surfaces to positions of equilibrium. The ions are attracted to the mineral surface to satisfy the negative charge existing within the surface; they also desire to move away from each other because of their thermal energies; the actual positions they occupy are comprimises between these two types of forces. Thus when the individual particles are dropped into water the ions move away from the surfaces to form what is termed a double layer. . . . The double-layer thickness is thus the distance from the surface required to neutralize the net charge on the particle. . . . (Lambe and Whitman 1969, pp. 56-57).

The thickness of the double layer is dependent on the type of exchangeable ion present. For example, if the sodium ions are replaced by calcium ions the thickness of the double layer is reduced.

Flocculation is due to the neutralization of charges thus collapsing the double layer thickness and allowing the particles to approach one another. Figure 7 is an over-simplification and does not take into account the pH and nature of the anionic and cationic species, the concentration of salts, or the type of clay species present. Actually, a clay-water system can be dispersed at a low viscosity, flocculated at a high viscosity, or flocculated at a low viscosity given the same solids content. For a more complete discussion of this topic, see Lambe and Whitman (1969).

The mechanism of collapse is still a debatable topic, additional information being required. Sultan (1971b) describes seven types of behavior during collapse.

1. Some soils collapse instantaneously upon increasing their degree of saturation by wetting . . .
2. Some soils collapse upon dewatering . . .
3. Some soils have not collapsed upon wetting but have actually swelled . . . and upon the application of external load have substantially collapsed . . . attributed to presence of highly swelling clay minerals, e.g. montmorillonoid.

4. Some loessal soils have shown increased amount and rate of collapse upon increasing the applied loads.
5. Some dry granular wind-blown sands have shown a decrease in the rate of subsidence as the applied load was increased.
6. Some soils have not recovered any of their collapsed volume with time.
7. Some soils have recovered some of their collapsed volume with time, even while sustaining the load that caused collapse (pp. 3 and 4).

Vibrational effects have a definite impact on collapsing soils. Abu-Obeid (1970) confirmed that the application of a pulsating load on sand produced a settlement which is greater than that produced by a static load. "When the granular structure is disturbed by dynamic forces, the material consistently compacts leading to an increase in the relative density, soil resistance to penetration and bearing capacity" (p. 5). The dynamic forces disrupt and readjust the soil structure resulting in rapid consolidation. If these forces are stopped, the rate of consolidation, due only to static forces, will be suddenly and severely reduced or stopped. The rate of consolidation will return to its original rate if the vibrations are again placed in effect (Figure 8).

A number of other terms have been used to describe a collapsing soil-type condition. One term that is receiving wide acceptance is near-surface subsidence. Bull (1964, 1970, 1972a, 1972b) goes into great detail discussing the effects of irrigation water on near-surface subsidence in southern California. For a complete discussion of this topic, refer to the reference list. Bull's definition of near-surface subsidence is practically identical with the definition of a collapsing soil.

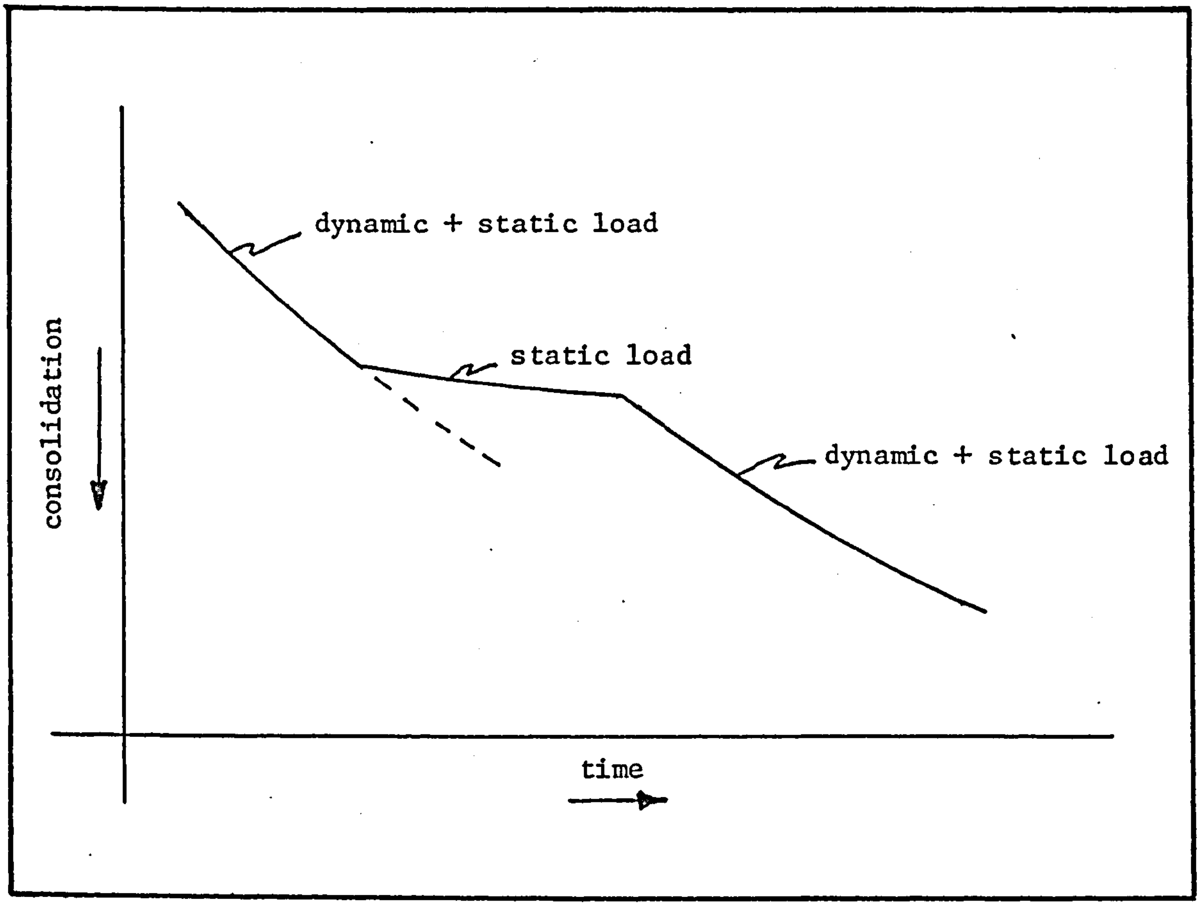


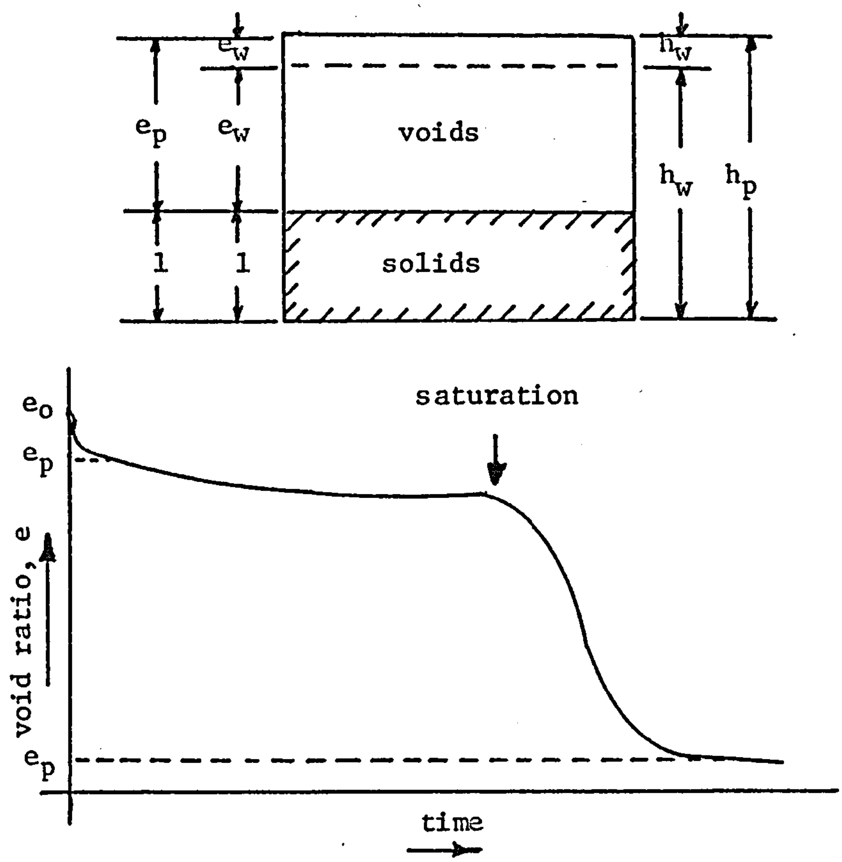
Figure 8. Changes in the Rate of Consolidation due to the Application of a Dynamic Load. (Abu-Obeid 1970)

> Near-surface subsidence results from the compaction of deposits by an overburden load as the clay bond supporting the voids is weakened by water percolating through the deposits for the first time since burial. The amount of compaction due to wetting is dependent mainly on the overburden load, natural moisture conditions, and the type and amount of clay in the deposits (1972a, p. 244).

A number of methods have been advanced for determining a soil's potential for collapse. Sultan (1971b) lists twelve such methods, two of which are the most useful. The first is Denisov's Oedometer Test (Figure 9). Briefly, as an external load is applied to an unsaturated sample, the void ratio, with time, drops from its natural value (e_o) to a new value (e_p) where normal consolidation has essentially ceased. Then upon saturating the sample, further consolidation occurs dropping the void ratio to e_w which is the result of the collapse of the soil structure. Figure 10 shows how the change in volume with saturation is effected by various magnitudes of stress (load).

The second method is the Double Consolidometer Technique by Jennings and Knight (Figure 11). Here, one consolidation test is run under natural moisture conditions and another under saturated conditions. The results of the two are then superimposed to indicate the effects of saturation, stresses, and loss of cementation. Figure 11 is self explanatory.

Additional criteria have been developed for collapsing soils (Anderson 1968). A collapsing potential may be indicated if a soil exhibits a low natural density (70 to 90 pcf); a porosity greater than 40 percent; a low natural moisture content (less than the saturated moisture content); the presence of soluble salts, calcium carbonate, or



Coefficient of subsidence due to wetting,

$$R_w = \frac{h_p - h_w}{h_p} = \frac{(e_p - e_w)}{(1 - e_p)}$$

Where h_p = sample height under pressure "p"
h_w = sample height after wetting, under pressure "p"
e_p = void ratio under pressure "p"
e_w = void ratio after wetting, under pressure "p"

$$R_p = \frac{(e_o - e_p)}{(1 + e_o)} \qquad R_t = \frac{(e_o - e_w)}{(1 + e_o)}$$

Where R_p = coefficient of subsidence due to loading
R_t = coefficient of total subsidence
e_o = natural "in situ" void ratio

Figure 9. Denisov's Oedometer Test. (Sultan 1971b)

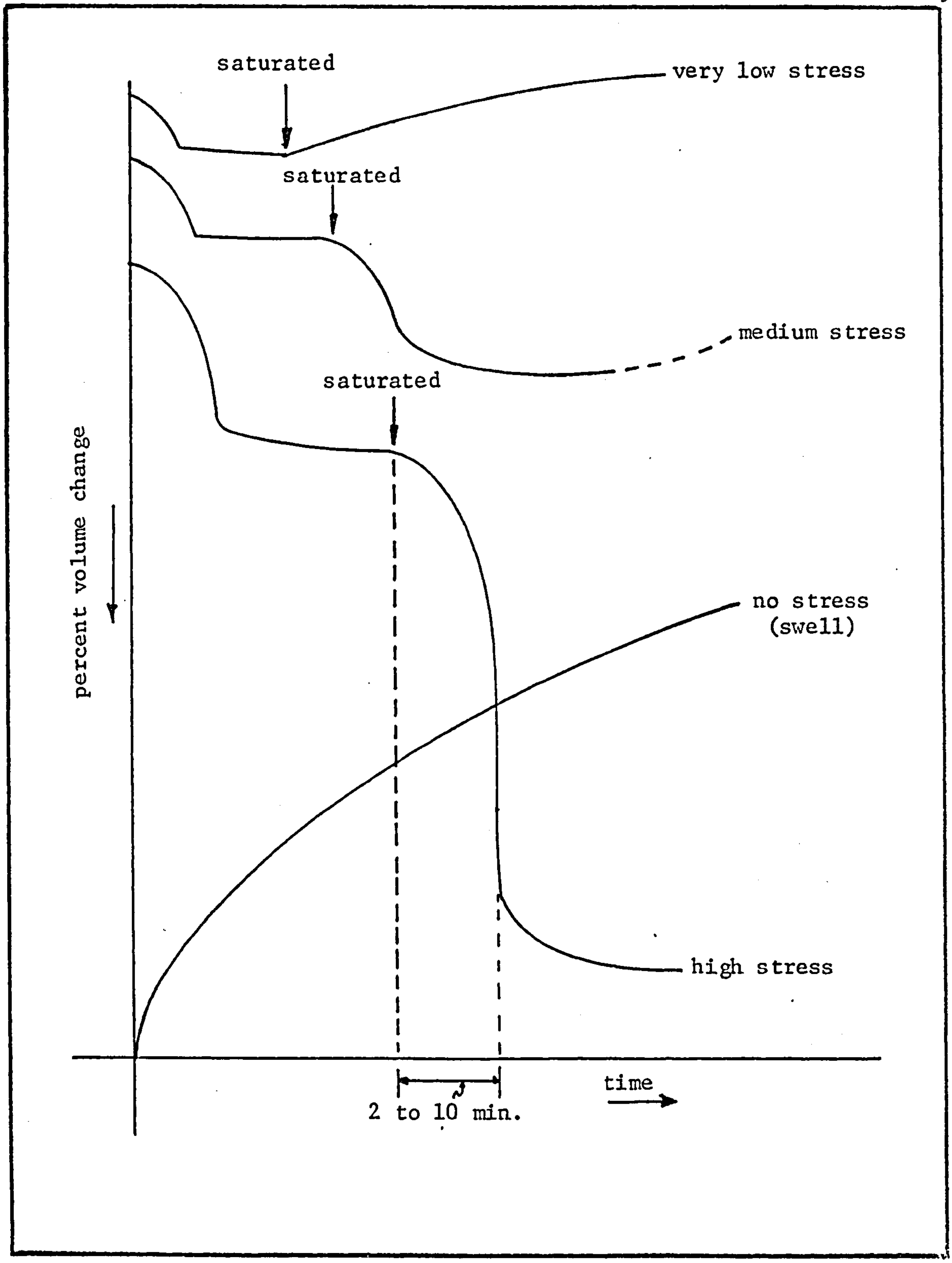


Figure 10. General Effect of Various Stress Magnitudes on Collapsing Soils. (Sultan 1971a)

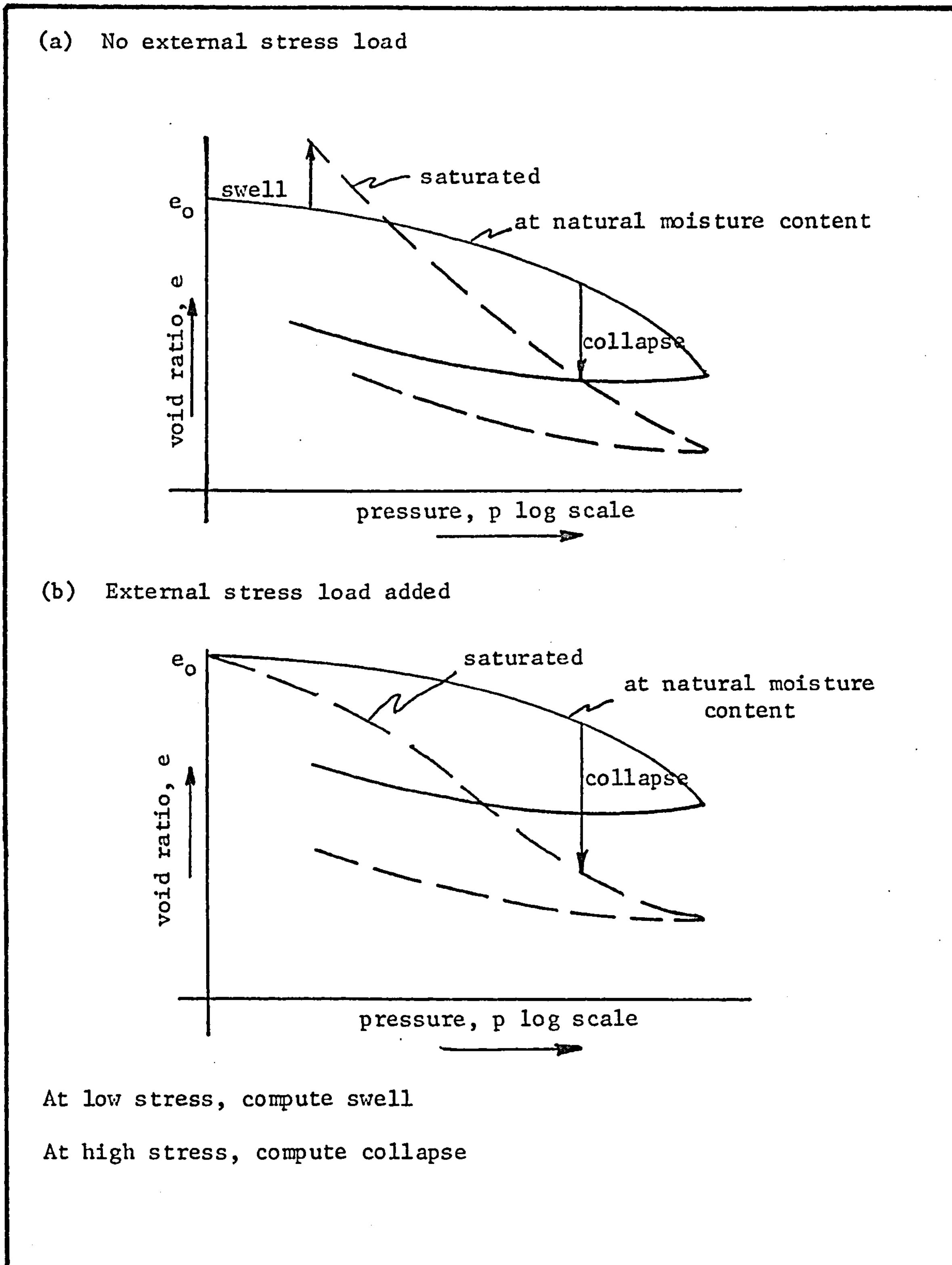


Figure 11. Double Consolidometer Technique by Jennings and Knight. (Sultan 1971b)

gypsum; an optimum clay content of about 15 percent depending on the clay mineralogy; and/or a natural moisture content which is less than the liquid limit. Generally, poorly sorted sands with greater than 15 percent fines (SM) can be considered to exhibit potential collapsing characteristics.

Past studies (Anderson 1968, Sultan 1969, Abdullatif 1969, Abu-Obeid 1970, Lacy 1964, and Crossley 1969) support the definite occurrence of collapsing soils throughout the Tucson Basin. As an example, a break in a gas line in a dry cleaning establishment was attributed, by Lacy, to collapsing soils which resulted in an explosion and one death. Crossley's study of foundations in small buildings indicates that the intensity of failures can be directly related to collapsing soils (Figure 12, in pocket). The intensity classification is based on a percentage, that is, the number of failures to the density of buildings. The factors influencing the damage include the age of the buildings, the construction materials used, the type of foundation, and the soils and geologic parameters. The classification can be described as follows:

Light Intensity: noticeable but minor building cracking. Adobe--cracks around door and window sills, brick--hairline cracks in mortar. One or two cracks in three of the outside walls, minor plaster cracks. Less than one half of the structure shows damage.

Moderate Intensity: more than one half of the structure shows damage. Same characteristics as light intensity but more severe.

Strong Intensity: all of the structure is damaged. Adobe--cracks run from ground to roof, brick--cracks cross bricks and cause displacement in mortar. Doors and windows are warped, floors are flexed, plaster and tiles are broken and displaced, yield cracks show in the roof with leaks, and pipes may be bent or broken.

Laboratory consolidation tests (Sultan 1971b) resulted in an increase in volume loss in saturated samples, obtained from the Silvercroft Subdivision, of from 6 to 11 percent. Assuming 10 feet of collapsing soils, as a simplified example, the amount of additional settlement could range anywhere from a few inches to greater than one foot which can produce considerable structural damage, particularly if the settlement is not uniform throughout the entire structure.

The collapsing soils in the Tucson area are, in all probability, alluvial in origin, being deposited by water on the flood plains and alluvial fans and during mudflows and floods. It is believed that the soils were then dessicated, rapidly buried, and never resaturated. The extent and location of collapsing soils and potentially hazardous areas has never been adequately delineated. Studies do indicate, however, the tremendous variability in lateral extent of collapsing soils. While one area may have a high potential for collapse, within a few feet of travel, this potential could drop quickly. Therefore, the necessity of testing for collapse, when any construction or development is being considered, becomes mandatory since, collapsing soils are probably the greatest single geologic impediment existing in the basin. There also exists the possibility of swelling in areas where weathered volcanic tuff has accumulated.

Flooding and Associated Aggradation and Degradation

A flood can be defined as an overflow or inundation that comes from a river or other body of water and causes or threatens damage (Langbein and Iseri 1960). It may also be defined as any relatively high stream flow overtopping the natural or artificial banks in any reach of a stream. The extent and magnitude of damage created by a flood varies with the volume of stream flow and the location of the overtopping of the stream's banks. Obviously, the way the floodplain is used in relation to the density of population and the extent of industry or agriculture will determine the magnitude of damage a flood might incur.

Man's occupancy of the flood plain, by encroachment and urban sprawl, only acts to support the problem of increased flood damages and loss of life through flood waters and sediment erosion and deposition. Accompanying increased urbanization is an increase in the impervious surface area (roads, parking lots, roofs), the provision of storm sewers, and, in some cases, the channelization of streams. This reduces the amount of infiltration, increasing the volume of direct runoff which, results in increased flood peak sizes.

The mean annual flood is that volume of water carried by a particular stream at a projected time interval of once every 2.3 years. Rivers construct channels that will support flows which are somewhat less than the mean annual flood. This is known as the bankfill stage, which is the stage at which a stream just overflows its natural banks. The time interval for bankfill is once every 1.5 or 2.0 years. As an area changes from rural to urban, the time interval for bankfill stage could drop to 0.25 years (Leopold 1968). This means that the area could experience flooding once every three months given a consistent pattern of rainfall (Tanenbaum 1972).

Tucson is located in a semi-arid environment with an ephemeral drainage system that only flows as a result of the direct runoff from precipitation. Precipitation consists of convective, high intensity storms in the late summer months and cyclonic storms during the winter months and averages 10.9 inches per year. Large floods effecting the entire basin can be expected to occur when the winter rains are combined with a quick snow melt. The summer rains produce localized flooding conditions with most of the storms resulting in flash floods of varying magnitudes. As an indication of the conditions existing, the following data for the Rillito Creek (Grove 1962) is provided:

9,000 cfs constitutes flooding.

12,000 cfs can occupy the flood plain.

30,000 cfs is the 50 year flood, occupying the maximum flood plain area.

85,000 can be expected to eventually occur.

As of 1970:

9,000 cfs occurred 12 times.

13,000 cfs occurred 5+ times.

30,000 cfs occurred 2+ times.

The flood plains, due to their aesthetic and open space value, are considered dynamic growth areas. In the Rillito Creek area, the 1970 population is expected to double by 1980.

Feeding the basin's major drainage channels is a dense network of tributary rills and washes which can also exhibit flooding, providing a definite hazard to development. Already, residential structures have encroached on some of these "mini" floodplains.

The Tucson Basin is a geologically young region and erosional and depositional processes are still very active in the area. It can be observed, qualitatively, that, during flooding, the basin's drainage system carries large amounts of sediment ranging from automobile size boulders to fine silts and clays. However, there are no sediment load data for the Tucson Basin. This sediment transport is a definite hazard to development in the area.

Figure 4 (in pocket) delineates the areas prone to flooding as mapped by the U. S. Geological Survey in Tucson and by Morrison (1971). The magnitude of the flood in the indicated area is that volume which has a 1 in 100 chance of occurring. Since this study has yet to be completed, much of the data for the basin is not yet available.

Another related factor is the aggradation and degradation of the stream channels with associated gullying and bank erosion which may, in some cases, be promoted by the existence of a piping potential (to be discussed later). This can occur, due to undermining of the banks, during flows which are less than flood stage. Measurements taken from 1936 U. S. Department of Agriculture and 1967 Highway Department air photos show that, for certain reaches of the Santa Cruz River south of the City limits, average channel widening has occurred to the extent of 14 feet per year over a 31 year period (see Figures 13, 14, 15, and Table 2). The maximum amount of widening measured was 1,875 feet over 31 years and 148 feet of channel filling being the minimum width change. The absence of data and yearly photo coverage makes it impossible to determine the amount of erosion occurring in a single year or as a result of a single storm. However, 3 feet of widening in spots along the Rillito Creek was recorded during a single storm during the winter of 1965. In Figure 14, SM indicates some areas where stream meandering has occurred. In Figure 15, the Santa Cruz flowed along the channel indicated by Q_1 in 1936. By 1967, the channel had apparently filled shifting the flow to the channel indicated by Q_2. These data are only an example of the process of bank erosion that exists in the basin.

Piping

"Piping is a unique form of soil erosion that acts on the subsoils through the removal of soil particles in tube-like channels to a free or escape exit. This type of erosion usually results, in its final stages, in the caving in of the surface soils causing the initiation of gully erosion" (Massanat 1972, p. 2).

Piping is largely controlled by fractures including surficial dessication cracks in the soil and alluvium, joint systems in rocks, and large scale fracture patterns in alluvium produced by tectonism or differential settlement. The direct effects of man (roads, railroads, diversion dams and ditches, flood control banks, etc.), cattle trails,

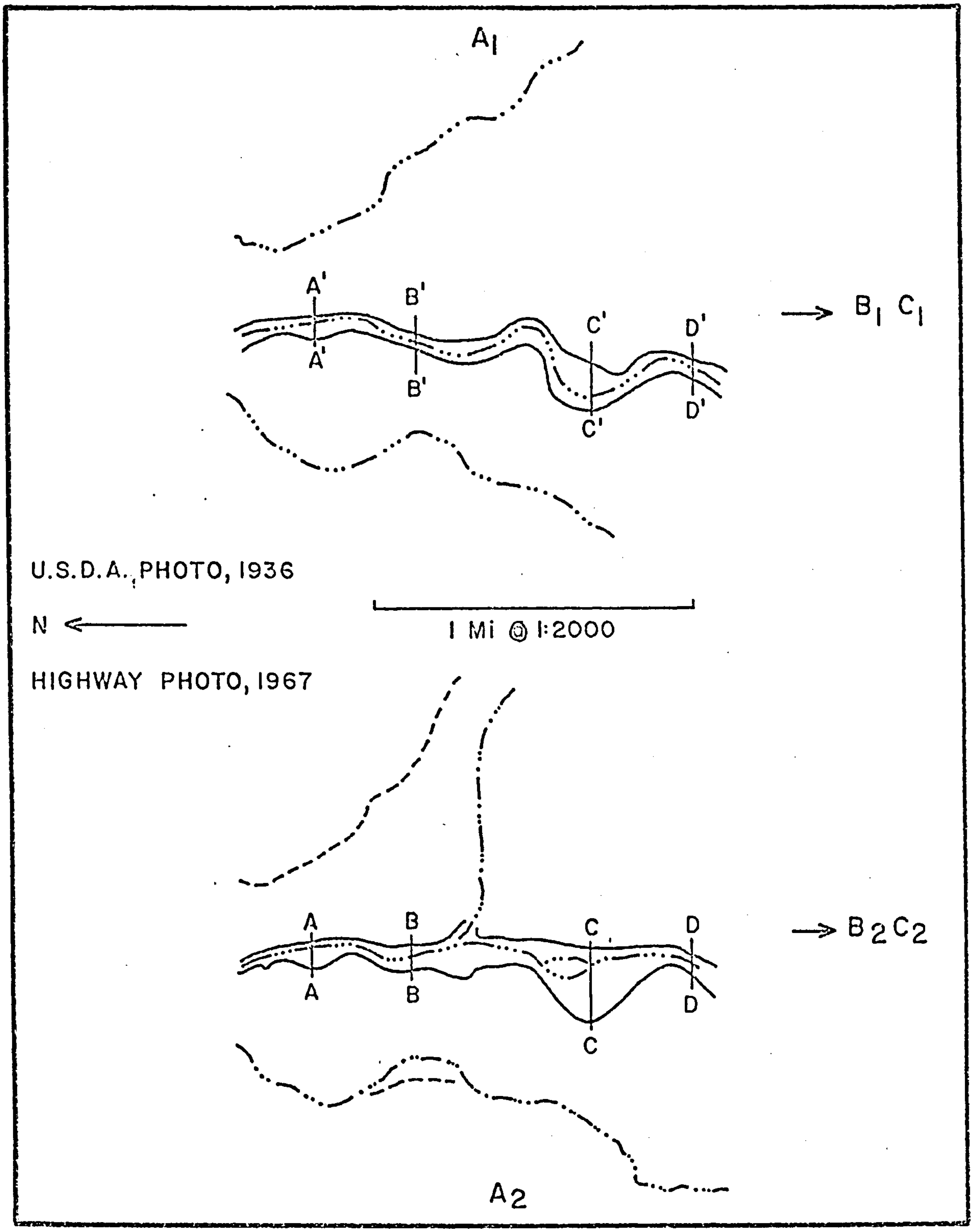


Figure 13. Channel Widening along the Santa Cruz River--Section A.

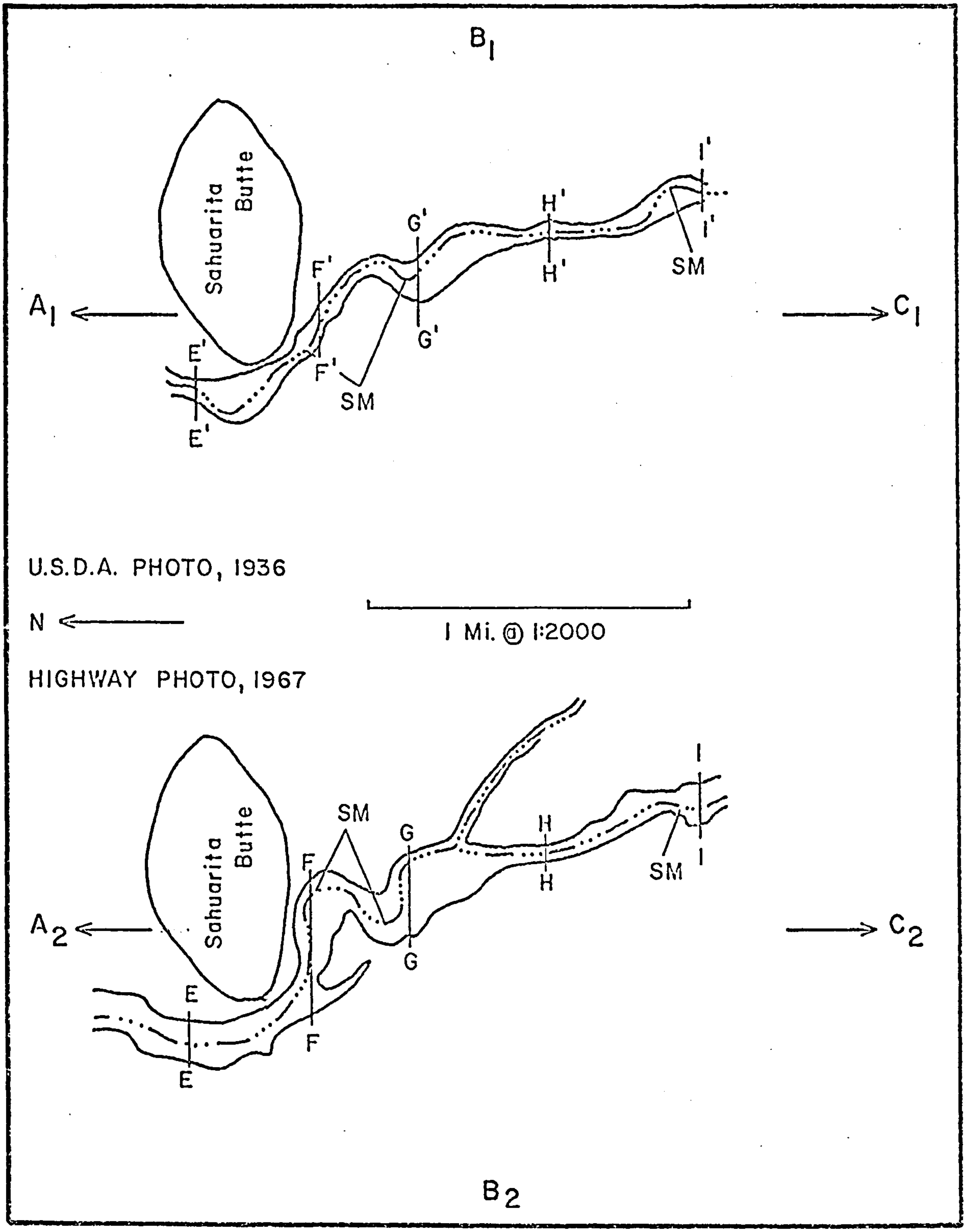


Figure 14. Channel Widening along the Santa Cruz River--Section B.

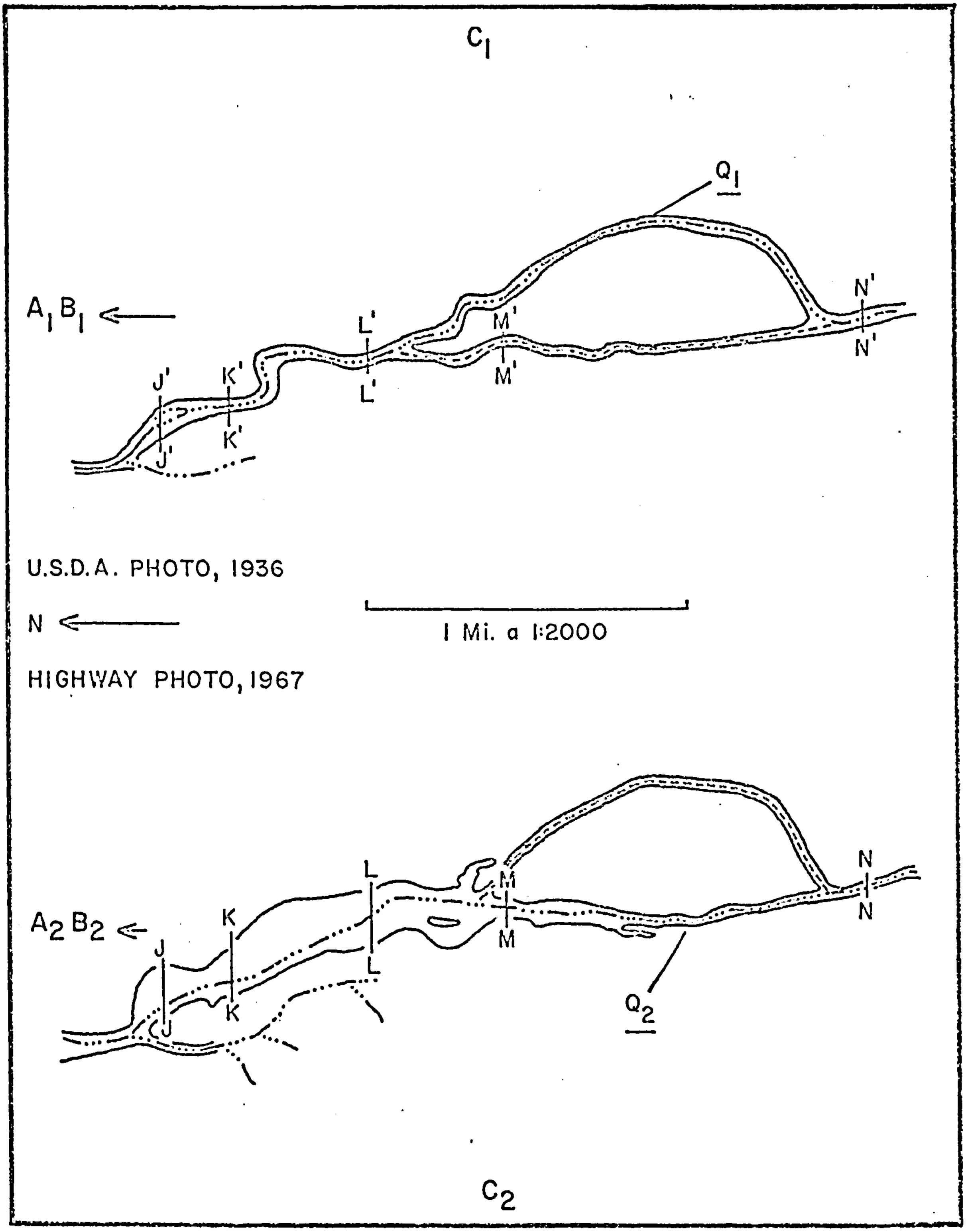


Figure 15. Channel Widening along the Santa Cruz River--Section C.

Table 2. Channel Widening along the Santa Cruz River from 1936 to 1967.

Location	Width of Channel (feet)		Change in Channel Width (ft)	Width Change (ft/yr)
	1936	1967		
A	394.8	542.9	148.1	4.78
B	296.1	444.2	148.0	4.78
C	641.6	1283.1	641.5	20.69
D	246.8	246.8	0	0
E	444.2	839.0	394.8	12.73
F	789.6	2664.9	1875.3	60.49
G	888.3	1727.2	839.0	27.06
H	394.8	246.8	-148.0	-4.77
I	296.1	740.2	444.2	14.33
J	542.8	1184.4	641.6	20.70
K	345.4	888.3	542.9	17.51
L	197.4	839.0	641.6	20.70
M	197.4	246.8	49.4	1.59
N	246.8	148.0	-98.8	-3.19

Average width change = 437.1 feet = 14.1 feet/year
Maximum width change = 1875 feet
Minimum width change = -148 feet

Negative number indicates channel filling
Positive number indicates bank erosion

and vehicle ruts can result in initiating piping. Climatic changes can initiate piping, e.g., a drought that kills the vegetation followed by severe storm erosion. Animal burrows and deep roots also increase the possibility of the occurrence of piping. Any type of erodible soil, under the influence of steep gradients and the erosive force of water, is susceptible to piping. Soils exhibiting collapsing characteristics are particularly susceptible.

Jones (1968) discusses the sequence of formation and destruction of a typical pipe system.

1. Formation of a steep-banked channel in cohesive but erodible sediments in a fan or valley segment, which previously lacked a distinct drainage channel.
2. Increased velocity of water flow in fractures and subsurface channels leading to the new channel because of the steepened gradient.
3. The formation of pipes by enlargement of the fractures by erosion to such extent that they cannot be closed by swelling.
4. Collapse of segments of the pipe, and gradual extension of the pipe system as the base level is lowered further from the original channel.
5. Growth of the pipe system toward the steeper parts of the catchment where runoff is more concentrated. This causes isolation of some parts of the pipe system from runoff from the upper part of the catchment.
6. Flow of concentrated runoff into a small portion of the inlets and rapid upslope extension of these inlets by headcut.
7. Gradual collapse of pipes and enlargement of collapse areas by bank caving, thus producing an arroyo system with some isolated pipe remnants.
8. Collapse of all pipes to form an integrated arroyo system, with long profiles indistinguishable from arroyos formed by headcut advance.
9. Slow modification of the plan of the arroyo system by channel meander, bank collapse, and soil creep (pp. 146 and 147).

Large scale piping can be expected in the Santa Cruz River flood plain south of Tucson. Small scale piping has been observed (Jones 1968) in the banks of the Rillito Creek and Tanque Verde Wash. Presently, piping offers no real problem, save for channel embankment erosion. However, if deep subsidence occurs, with resultant surface and near-surface cracking, piping can become a problem as water begins to drain through the cracks.

Deep Subsidence

Subsidence is the vertical sinking of part of the earth's crust with little or no horizontal displacement. Subsidence can be attributed to numerous causes (Davidson 1970, Peterson 1962, Platt 1963, Lofgren and Klausing 1969, and Bull and Miller 1972) including:

1. Subsidence due to the compaction of aquifer systems caused by a reduction of fluid pressures.
2. Subsidence due to the hydrocompaction of moisture deficient surficial deposits caused by wetting (near-surface subsidence, collapsing soils).
3. Subsidence due to the oxidation and compaction of organic materials as a result of drainage and cultivation.
4. Subsidence due to oil and gas withdrawl and underground mining.
5. Tectonic movement causing structural downwarping.
6. General consolidation and compaction of surface material due to increased overburden loads.
7. Natural and artificial vibrations at or near the land surface.
8. Soil compaction or swelling due to irrigation.
9. Drying and shrinking of soils.

10. Subsidence or slumping of ground over a cavity.

11. Settlement of structures due to deterioration of foundation materials.

Of the eleven mentioned causes, the first is the most likely cause of much of the deep subsidence in the Southwest that is contemporaneous with man. Lofgren and Klausing (1969) best summarize the theory of deep subsidence from which the following quote is taken:

> Under natural conditions, unconsolidated deposits are generally in equilibrium with their overburden load. An increase in grain-to-grain stress, however, due to either surficial loading or a change in ground-water levels, causes a corresponding strain or compaction of the deposits, which is related to their physical and chemical properties; the magnitude of the increased stress; possibly the type and rate of stress applied; and the stress history, that is, whether the increased stress is being applied for the first time or has been attained or exceeded previously.
>
> Depending on the nature of the deposits, compaction may be (1) largely elastic, in which case stress and strain are proportional, independent of time, and reversible, or (2) principally nonelastic, in which case the granular structure is rearranged in such a way that the volume is permanently decreased. In general, if the deposits are coarse-grained sand and gravel, the compaction will be small, chiefly elastic, and thus reversible, whereas if they contain fine-grained clayey beds, the compaction will be much greater, chiefly inelastic, and thus permanent. In either type of compaction, subsidence of the land surface is due to one-directional compression of the deposits (p. 64).

There are three types of stresses involved in deep subsidence:

1. Gravitational Stress--due to overburden; downward grain to grain distribution.

2. Hydrostatic Stress--weight of interstitial water; transmitted downward through the water.

3. Dynamic Seepage Stress--viscous drag on grains by downward vertical movement of water.

The effective stress is the combination of the gravitational and hydrostatic stresses. The dynamic seepage stress is a neutral stress which has no compaction effect.

Terzaghi's theory of consolidation is an effective means of describing the compaction of fine grained deposits. Basically, by increasing the overburden load on a bed of fine grained material, the additional stress applied is carried, initially, by the interstitial water which may be forced to drain out transferring the stress to the grains. Due to this drainage, the intergranular stress increases with a corresponding decrease in the void ratio. The rate of compaction depends on the rate of water drainage, which in fine grained materials is slow as compared to coarse grained material where the drainage is rapid with a corresponding rapid increase in effective stress and compaction.

There are two ways in which the change in the water level changes the effective stress (Lofgren and Klausing 1969):

1. A reduction in the water table reduces the bouyant support of the grains in the drained region changing the gravitational stress which is transmitted to all underlying deposits. The effective unit weight of a dewatered material is greater than the submerged unit weight. The loss of bouyant support, therefore, increases the unit weight of the material and therefore, the overburden load and the effective stress.

2. A seepage stress, that is additive to the gravitational stress, can be produced in confined or semi-confined beds by a change in the position of the water table and/or piezometric surface.

If the artesian head remains unchanged, a rise in the water table reduces effective stresses in the unconfined parts of the aquifer system but increases the effective stress in the confined parts, due to the increased downward seepage stress. A decline in the water table, on the other hand, increases downward seepage stresses in the saturated part of the unconfined aquifer system, but decreases the effective stress in the confined beds. A decline in piezometric head in a confined aquifer system, however, has no effect on stresses in an overlying unconfined system, but increases the stress in the confined beds. The magnitude of the change in effective stress is nearly twice as great for a given head change in a confined system as for the same head change in an unconfined system (Lofgren and Klausing 1969, p. 99).

Lofgren and Klausing found that, for unconfined aquifers, the effective stress increases or decreases 0.6 foot* for each 1 foot fall or rise of the water table, respectively. This is dependent on the porosity. For an unconfined aquifer, the effective stress increases 0.4 foot for a 1 foot rise in the water table and 1 foot for a 1 foot decline in the piezometric surface.

The compressibility depends on the range and rate of stress change, the grain size, the clay mineralogy, and the geochemistry of the pore water. Subsidence is due to the net change in thickness of the combined beds of a complex aquifer system. Fast draining coarse grained sediments may compact in a few minutes, whereas, slow draining

---

*One foot of drawdown is approximately equal to 0.43 psi, therefore, effective stress = 0.6 x 0.43 = 0.26 psi/ft.

fine grained sediments may take years or even centuries to fully compact. Some beds may even expand elastically due to reduced stresses brought on by a rising water table, which would be important to know if recharge of an aquifer system is being considered. The amount of subsidence depends on the change in the effective stress, the compressibility of the deposits, the thickness of the compacting beds, and the time rate of compaction. These are not simple relationships and are difficult to analyze.

Lofgren and Klausing (1969) list four criteria for predicting subsidence:

1. Where little or no increase in effective stress has occurred, no compaction is expected.
2. Where increased effective stress has caused measurable subsidence, further increases in effective stress will cause continued subsidence.
3. Delayed/or "lag" compaction of slow-draining beds may represent a major part of the ultimate subsidence at a location. Such compaction, and related subsidence, may continue for many months or years after water levels become stabilized at a lower level.
4. In areas where both subsidence and water-level decline have been observed for a sufficiently long period to establish a long-term relationship, the ratio between these two parameters can be projected into the future as far as the projected water-level trend justifies. This relationship does not take into account residual "lag" effects; thus minimum values of subsidence are determined by this means. Where water levels have declined and then partially recovered, the subsidence to head-decline ratio has little significance until water levels return to their former low levels (pp. 92 and 93).

It is believed, but not yet proven, that deep subsidence has occurred in the Tucson Basin as a direct result of ground-water withdrawal. Figure 16 (in pocket) shows the present depth to ground water and ground-water level contours for the basin as provided by the

University of Arizona's Agricultural Engineering Department. Figure 17 (in pocket) shows the changes in ground-water level for the periods of 1968 to 1971 and 1947 to 1971, also provided by the Agricultural Engineering Department.

In Tucson, the amount of deep subsidence is not known. However, in Eloy, Arizona, about 45 miles north of Tucson, there has been subsidence of more than 7.5 feet with a corresponding water-level decline of about 200 feet.

Davidson (1970) feels that subsidence will occur as ground water withdrawal and water level declines continue and that, although there have been little or no detrimental effects due to subsidence at the present time, the effects can be expected to increase in severity by 1985 if the withdrawal at the present rate continues. Davidson also states that T. 14 S., R. 14 E. and along the Santa Cruz River south of the City limits are the areas expected to have the greatest potential land subsidence. He estimates this potential to be 1 or 2 feet based on past pumpage data. He goes on to say that the aquifer in the area of the Tucson International Airport (T. 15 S., R. 14 E.) contains the most clay and substantial amounts of withdrawable water. Therefore, this area is most susceptible and significant land subsidence can be expected as a result of substantial ground water withdrawal. Differential subsidence may also occur along fault traces in the basin where sediment on either side vary in clay content and degree of cementation. The Santa Cruz Fault (see Figure 5, in pocket) is most susceptible.

Davidson's estimate of the amount of subsidence is purely speculative in nature, since none of the necessary data exists about the physical characteristics of the underlying beds required to make an estimate, which was discussed earlier in this section. The existance of silt and clay lenses in the upper gravel surface, and low permeability lake beds below, add to the potential for deep subsidence in the Tucson Basin. Leveling data gathered by the U. S. Coast and Geodetic Survey, between 1907 and 1952 (Lindeke and Pajaczkowski 1970), though insufficient to delineate the actual shape of subsiding areas, does indicate that the basin has subsided approximately 4.5 inches. Fissures or "linears" have been observed in aerial photographs, but it is debatable whether or not they can be directly attributed to deep subsidence.

Referring to the ground-water level change map of the Tucson Basin (Figure 17, in pocket), water-level depressions of up to 35 feet, for the period from 1968 to 1971, occur along the Rillito Creek, Rincon Creek, and along the west side of the Santa Cruz River. For the period from 1947 to 1971, depressions of up to 125 feet occur in these same areas with similar cones of depression southwest of Davis Monthan Air Force Base and in the vicinity of South Wilmot Avenue and East 22nd Street.

Although there is no existing correlation, it should be safe to say that future deep subsidence is probable in these areas, particularly those underlain by a cone of water table depression, if the ground-water table continues to decline. Continued ground-water depletion, due to heavy pumping by the City of Tucson, the farms, and the mines, is expected to continue indefinitely.

Earthquakes

An earthquake may be defined as a "perceptible trembling to violent shaking of the ground produced by the sudden displacement of rocks below the earth's surface" (Howell 1966, p. 19 of the Supplement). The theory of earthquakes is beyond the scope of this thesis.

A major shock was recorded in March 1947, in October 1952, and again on August 7, 1966 which were felt strongly in the Tucson area. On May 4, 1887, an earthquake occurred in northern Sonora, Mexico, which was of sufficient strength to cause buildings in downtown Tucson to sway, and raised huge clouds of dust in the Santa Catalina Mountains. Large blocks of rock gave way and tumbled into the canyons. The Tucson Magnetic Observatory records about 20 minor tremors per month called "Tucson locals," but it is not known if the epicenters are located in the basin (Crossley 1969).

The U. S. Coast and Geodetic Survey (National Oceanic and Atmospheric Administration) has divided the United States into four seismic risk zones (International Conference of Building Officials 1964). Zones 0 are areas where there is no reasonable expectancy of earthquake damage. Minor damage can be expected in Zone 1, moderate damage in Zone 2, and destructive earthquakes in Zone 3. The Tucson Basin falls into Zone 2.

Although the faults in the Tucson Basin and surrounding mountains are considered inactive, the possibility of an occasional earthquake should not be ruled out.

Caliche

Caliche is a hard, more or less massive carbonate layer, on or near the surface of the ground with the possible existance of a laminar, dense, indurated cap at the top of the caliche profile (Cooley 1966). Figure 18 is an example of a general caliche profile.

Cooley summarizes seven theories for the deposition of caliche:

1. Deposition in extensive shallow lakes by algae and inorganic processes.
2. Deposition in small disconnected lakes and ponds by physical and/or organic processes.
3. Deposition along streams, especially intermittent streams by physical and/or organic processes.
4. Deposition by rising artesian waters, either at the water table or at the surface.
5. Deposition by capillary rise of water from the water table, especially under conditions of high water table or a rising water table brought about by aggradation.
6. Deposition in the B zone by surface waters following saturation of the soil zone.
7. Various combinations of the above.

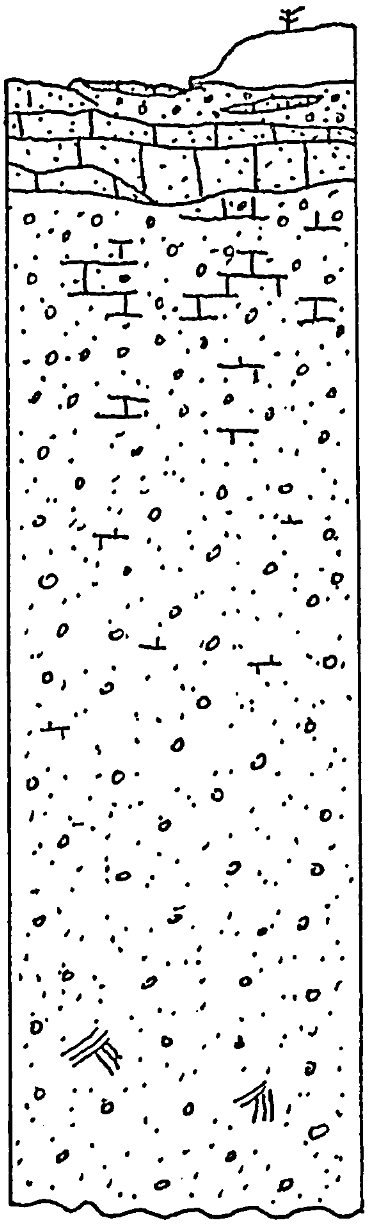


Figure 18. Generalized Caliche Profile. (Cooley 1966)

Caliche, in Arizona, is believed to have formed in the following manner:

1. Caliche . . . was formed by solution, transportation, and precipitation of calcium carbonate.
2. Water when charged with carbon dioxide dissolves calcium carbonate and forms calcium bicarbonate. The calcium bicarbonate is carried in solution and is precipitated as a calcium carbonate, or caliche, where the water is evaporated or when there is a decrease in pressure which drives off CO_2.
3. Caliche strata may be formed beneath the surface of a soil either by the evaporation of descending surface water, or by the evaporation of ascending ground water.
4. Caliche may be formed in a soil by means of plant roots. Plants growing upon the surface absorb soil water for transpiration purposes, and the calcium carbonate that is dissolved in the soil solution is precipitated as caliche.
5. As long as they are permeable to water, caliche strata will move downward in a soil as fast as erosion removes the upper surface.
6. Caliche is probably formed upon the surface of a soil by the evaporation of surface or flood water. The formation under such conditions is hastened by the presence of algae and other water plants (Cooley 1966, pp. 9 and 10).

Cooley also classifies caliche according to its physical characteristics in the following manner:

1. Very strongly indurated: material extremely hard, has unconfined strength range from 3000-8000 psi, difficult to break with a hammer and difficult to score with a knife.
2. Strongly indurated: material is very hard, has unconfined compressive strength from 750-4000 psi, breaks readily with a hammer, but is difficult to remove from the horizon and can be scored with a knife.
3. Moderately indurated: hard, compressive strength from 150-750 psi, readily removed from the horizon, breaks easily with a hammer, and scores easily with a knife.
4. Slightly indurated: not very hard, compressive strength less than 150 psi, easily removed from the horizon, easily broken with a hammer.
5. Non-indurated: soft to hard, slakes in water, compressive strength between 0-800 psi but most are less than 25 psi, may be easy or hard to remove from the horizon, readily broken with a hammer, and easily scored with a knife (pp. 11 and 12).

The most favorable places for the deposition of highly indurated caliche, in the Tucson Basin, are in areas where there is little erosion or deposition. The sources of the calcium carbonate are the basalts of the mountains to the west and the Paleozoic limestones to the east. Some of the cementing materials may come from the gneiss in the Santa Catalina and Rincon Mountains. "The dense caps probably form at the surface. The rest of the caliche profile represents in place cementation of sand and gravel. The depth and amount of cementation is probably related to the original permeability of the sediments" (Cooley 1966, p. 61).

It has been determined (Cooley 1966, Lacy 1964, and Crossley 1969) that the University Terrace contains the hardest caliche, the Cemetary Terrace contains soft caliche, the Jaynes Terrace has a limey subsoil, and the bottomland contains no caliche due to extensive downward flushing. The caliche layers may range from 0 to 60 feet thick and can be located 200 feet below the ground surface.

It is believed that the caliche layer, due to its hardness, acts as a bedrock and should reduce the intensity of foundation fractures. Crossley (1969) found that the caliche is in no way related to foundation failures since some of the areas of highest intensity have the thickest caliche and some of the areas of lowest intensity have no caliche.

Caliche is mainly a nuisance since the harder and thicker it is, the greater the cost of excavation due to the need for heavier equipment. Caliche can be considered a hazard if a structure undergoes differential settlement when only a portion of the foundation is constructed over caliche. From 6th Avenue to the west and Benson Highway north to 17th Street, the non-aggregate caliche is difficult to excavate. This hard caliche may underlie softer material to the north and east in the Jaynes Terrace and is difficult to disaggregate due to reworked, cemented, rounded fragments of caliche which has undergone case hardening up to 5 feet thick. The caliche in the Sentinel Peak ("A" Mountain) area is even more difficult to disaggregate.

Generally, the variability of caliche is intense and can change from highly indurated to non-indurated with a few feet of travel. A general caliche distribution map is provided in Figure 12 (in pocket).

Landslides, Mudslides, and Creep

A landslide is defined as "the perceptible downward sliding or falling of a relatively dry mass of earth, rock, or mixture of the two" (Howell 1966, p. 163). This definition can be broadened to include wet materials and artificial fills. The driving force is gravity inducing the falling, sliding, and flowing of earth masses and materials. The theory of mass movement is complex and beyond the scope of this report.

On the west side of the Tucson Mountains, a classic example of a mudslide exists. The area lends itself to slides and creep because of the presence of shale and clay overlying the bedrock, a situation that may exist on the east slope of the Tucson Mountains due to the weathering of basalts. However, in most of the Tucson Basin, this problem does not appear to exist. The bedrock is directly overlain by coarse alluvium with a low, flat relief. Roadcuts in the foothills area indicate that the alluvium has sufficient cementation and strength to enable it to stand at high angles, in some cases in excess of 60 degrees. This, along with the absence of saturation of the alluvium and an apparent absence of any extensive soil development or presence of fine sediments along the rock-alluvium interface, seems to reduce the probability that landslides, mudslides, and creep will occur under natural conditions in the basin perimeter area. The low, level topography and the thick alluvial cover eliminates the possibility of this type of earth movement occurring in the central portion of the basin. The preceeding conclusions are totally qualitative in nature and the reader should be aware that any interference with nature, for example a cut and fill operation, might induce movement in the natural or fill materials.

CHAPTER 4

SOIL STUDY

To date, the only official soils map for the Tucson Basin is the map produced by the U. S. Department of Agriculture and the University of Arizona Agricultural Experiment Station in 1931, which was based on an agricultural soil classification system. Dr. W. C. Lacy, of the University of Arizona's Department of Mining and Geological Engineering, provided a Unified Soil Classification for the various agricultural soil formations, which is the basis of the soil type map provided in Figure 19 (in pocket).

Field Work

Surface soil samples were obtained throughout the Tucson Basin (see Figure 19). Of the 76 samples taken, 31 were obtain for the purpose of checking Lacy's classifications and the remaining 45 were taken at easy access points throughout the unmapped area to determine if any additional soil types were present and to update the known information.

Laboratory Work

For the purpose of classifying the samples, the grain size distribution and Atterberg limits for each sample were determined, including the liquid limit, the plastic limit, and the plasticity index. Taylor (1948) defines these limits as follows (see Table 3):

Table 3. Relationship of Atterberg Limits to the Physical State of a Soil.

Liquid State		
	Liquid Limit, LL	
Plastic State		Plasticity Index, PI
	Plastic Limit, PL	
Semi-solid State		
	Shrinkage Limit, SL	
Solid State		

(After Taylor 1948)

> The liquid limit . . . is the water content at which a clay is practically liquid but possesses a certain small shearing strength. . . . The plastic limit . . . is the smallest water content at which a soil is plastic, . . . the sample . . . , when rolled into a thread, . . . will start to crumble rather than . . . distort plastically. . . . The range of water contents between the liquid and plastic limits . . . is called the plasticity index. . .(pp. 27, 28, and 65).

The standard methods for preparing these tests were used as outlined in Lambe (1951) with one major variation. Rather than washing the sample through a #200 A.S.T.M. Standard sieve prior to final sieving, the entire sample was sieved dry for the sake of expediency. In order to check the validity of this method, three samples were taken from each of sample locations 25, 72, and 75 which are representative of the soil types present in the basin. Each sample was split in half. The first half of the sample was tested using the standard acceptable method of washing the material through the #200 sieve. The remaining half of the sample was sieved entirely dry. The results can be seen in Figures A27, A28, and A29. In general, the results show that for poorly graded sands with from 0 percent to about 40 percent fines, that is, material passing through the #200 sieve, the dry method did not produce any significant change in the general classification of the soil. However, for silts and clays, the difference is significant due to the clodding of silt and clay size particles which retain sufficient strength preventing any breakdown by physical means, that is, with the use of a mortar and pestle.

After several selected samples were tested for natural moisture content, no further tests of this kind were run. The four month drought in the Southwest produced moisture contents that were less than

10 percent of the normal moisture contents, therefore, the determination of moisture contents, under these conditions, were meaningless.

Eight samples were tested by running three liquid limit tests for each, in order to check the validity of a one point liquid limit test by the use of a set of correction factors (see Table 4) as provided by Beebe (1972). Since the correction factors were found to be accurate, the remaining samples were tested with a single liquid limit test per sample.

The plasticity index is reported as zero when the plastic limit is greater than or equal to the liquid limit. When running the liquid limit test, if the two sample halves joined together in 25 blows or less, and additional water was required to perform the plastic limit test, the sample was considered to be non-plastic and the plasticity index recorded as zero without determining the plastic and liquid limits.

The samples were classified according to the Unified Soil Classification System (Corps of Engineers 1967). The details of this system can be obtained from the reference and most any soil mechanics text book or laboratory manual. The plasticity of the sample was classified according to Table 5.

Results

The results of the laboratory tests are presented in the Appendix, Figures A1 through A29. Because of the type of sieve analysis used and the poor correlation with Lacy's classification, a dual classification is presented in the soil type map (see Figure 19, in pocket) where the first classification is based on the laboratory results

Table 4. Correction Factors for a One Point Liquid Limit Test.

Number of Blows	Correction Factor
20	0.974
21	0.979
22	0.985
23	0.990
24	0.995
25	1.000
26	1.005
27	1.009
28	1.014
29	1.018
30	1.022

Courtesy of Gary Beebe 1972.

Table 5. Classification of Soil Plasticity.

Plasticity Index (%)	Soil Plasticity
0 - 3	non-plastic
4 - 8	slightly plastic
9 - 30	medium plastic
30 or more	highly plastic

LL - PL = PI where LL = Liquid Limit

PL = Plastic Limit

PI = Plasticity Index

If PL is equal to or greater than LL, then PI = 0.

Sowers and Sowers 1951.

and the second classification, in brackets, is Lacy's. The classification of sample 72 was determined from the sample that was washed through the #200 sieve (Figure A28).

In general, the surface soils in the Tucson Basin are alluvial in origin and range from a poor to well sorted sand and gravel with less than 5 percent fines to a medium plastic inorganic silt. The majority of the soils are poorly sorted sand with about 11 to 25 percent non-plastic to slightly plastic fines. No determination of collapsing potential was made. Figure 19 indicates the extensive lateral variability of surface soils.

The Office of Arid Lands, The University of Arizona, in cooperation with the Soil Conservation Service, is presently engaged in preparing a soils map of the Pantano Wash area using remote sensing methods. Using similar methods, Roger Morrison of the U. S. Geological Survey, Denver, Colorado, is preparing a soils map of the entire basin. Another soils map, which would include the soil's collapsing potential, is expected when Frank Anderson completes his doctorate dissertation. When this information is published, many of the unanswered questions about the soils in the Tucson Basin should be answered.

CHAPTER 5

SAND AND GRAVEL

The quantity of sand and gravel in the Tucson Basin is undetermined and the physical quality is highly variable. Claude Seal, production engineer for San Xavier Rock and Gravel Company, stated that there are no problems when the sand is combined with cement (1972). No neutralization process is required and there are no apparent excavation problems.

Williams (1967) lists the following technical problems in obtaining sand and gravel:

1. Thin nature of gravel beds--large area--only 8 to 10 feet thick.
2. Caliche layers may obstruct mining.
3. Volume of coarse aggregate is only about 1/4 of the total volume.
4. Waste elimination complicates the operation.
5. Low rock content overburden is a problem but is mined because of the high value of rock.
6. Dikes are necessary to prevent stream recharge of pits with fine grained sediments and debris.
7. Short hauls required for redi-mix concrete because of faster setting due to higher air temperatures. Hence, aggregate must be hauled further and stored closer to batching plants.
8. Water shortages could hinder processing techniques.

Most of the material is screened and washed. Williams summarizes the processing method as follows:

Step 1. Pit run material hauled to feeder hopper.

Step 2. Conveyed to scalping screen--vibrating double deck screen--to eliminate silty material.

Step 3. Passes to small crusher--middlings bypass and fines are discarded. Some +6 to +7 inch material is separated for rip rap.

Step 4. Combined with middlings.

Step 5. Conveyed to vibrating wet screen--fines used for mortar sand, middlings used as concrete sand.

Step 6. Oversize material is washed.

Step 7. Sizes separated in wet vibrating screen--two sizes: -3/8 inch and +3/8 inch to -1 1/2 inch.

Step 8. Small cone crusher used for further crushing of oversized materials.

Step 9. Log washer used to break apart weak caliche cemented aggregate particles.

Table 6 lists the major mineral aggregate operators and the location of their pits. Figure 5 (in pocket) shows the approximate location of some of these pits.

Nearly all of the Tucson Basin is a potential source of sand, however, the most important source of the gravel necessary for construction is along the basin's water courses (particularly along Pantano Wash) which must be reserved and protected in light of the extensive

Table 6. Mineral Aggregate Operators and Location of Pits in the Tucson Basin.

Operator	Location
Acme Sand and Gravel	SE1/4 SE1/4 sec17, T14S, R15E
Builder's Rock and Sand Co.	NW1/4 MW1/4 sec17, T13S, R13E
Columbia Sand and Gravel Co., Inc.	NE1/4 NW1/4 sec18, T15S, R16E
Columbia Sand and Gravel Co., Inc.	W1/2 NE1/4 sec27, T13S, R14E
Desert Sand and Gravel	SE1/4 SE1/4 sec33, T12S, R15E
Oro Rock and Sand Co.	NW1/4 sec1, T12S, R15E
Riverside Rock and Sand	SE1/4 NW1/4 sec23, T14S, R13E
San Xavier Rock and Gravel Co.	NW1/4 sec14, T15S, R13E
San Xavier Rock and Gravel Co.	NW1/4 sec21, T14S, R15E
San Xavier Rock and Gravel Co.	NW1/4 sec34, T15S, R14E
San Xavier Rock and Gravel Co.	NW1/4 sec23, T14S, R13E
Tucson Rock and Sand Co.	NW1/4 sec8, T14S, R15E
Tucson Rock and Sand Co.	N1/2 sec34, T14S, R15E
Tucson Sand and Soil, Inc.	NW1/4 SW1/4 sec15,T13S, R13E
Wilmot Sand and Gravel	NW1/4 sec6, T14S, R15E

From Williams 1967.

development predicted for two reasons: to assure that there are ample construction materials available and to avoid locating a building site on top of the reserves. If this is not done, the cost of construction will rise due to the necessity of hauling sand and gravel from greater distances at higher costs.

CHAPTER 6

GEOLOGICAL ENGINEERING FACTOR MAP

A geological engineering factor map is prepared by taking each geologic parameter and mapping their locations, overlaying one upon the other. This way, the areas with the most problems will show up as the ones having the most dense pattern, that is, the highest number of different individual symbols if each factor is considered to be of equal weight. This means that these areas are affected by the highest number of geologic factors, and therefore, present the most problems when construction or development is being planned.

An attempt to prepare such a map, using the data accumulated in this thesis, was frustrated by the lack of detailed information. This exemplifies the fact that a great deal more research is necessary in the Tucson Basin.

However, using the information that was available, a reasonable facsimile of a geological engineering factor map was prepared to illustrate the technique and to tie together the assimilated information (Figure 20, in pocket). Four major divisions were designated on this map. The first is a combination of collapsing soils, earthquakes, and piping. Collapsing soils are not a hazard within the water courses or higher up in the foothills of the surrounding mountains, but they can occur almost anywhere else. Earthquakes can occur throughout the entire basin, but the magnitude of the potential hazard varies with the subsurface geology, which has never been adequately studied in this respect. Piping has the most potential along the major and minor water courses but not enough information is available to map the piping potential.

The next major division mapped is the potential deep subsidence. The entire basin bounded by the contact between the desert pediment surface in the foothills and the thick alluvium in the central portion of the basin will undergo deep subsidence of varying magnitudes as ground water depletion continues (see Figure 3). This boundary is sometimes referred to as the "hinge line" (Platt 1963). Areas expected to undergo the most subsidence were chosen from Figure 17 (in pocket) and were designated as those areas with a change in water level of over 50 feet over the last 25 years and areas underlain by cones of water table depression, particularly over the last few years. This choice of boundaries can only be made as an educated guess since no quantitative data is available pertaining to the physical and chemical properties of the subsurface alluvium.

The third major division is the areas that are prone to flooding. Half of the data is available from the U. S. Geological Survey in Tucson. Additional data was obtained from Morrison's (1971) work. This does not include the complete lack of data for the "mini" flood plains. There is also no information about the quantity, quality, and the potential hazards of the sediment load carried by the major and minor streams in the basin. The factor map indicates some flooding along the major streams which the U.S.G.S. has yet to include in its study, hence, no boundaries are provided for these streams.

The final major division is the distribution of caliche which acts as a nuisance to construction. The hardest, most dense indurated caliche is known to exist in the University and Cemetery Terraces which are the areas shown on the map along with the areas deliniated by Morrison (1971). The boundaries of this caliche are limited because of the lack of data throughout the rest of the basin.

To summarize, the geological engineering factor map indicates that the Rillito Creek area, where it borders the City of Tucson, and along the Santa Cruz River, are the areas occupied by the most geologic impediments. This high impediment intensity is followed by the area along the Pantano Wash. The map shows that the southeast portion of the basin contains the least number of geologic parameters; but this is probably due to the lack of sufficient information from this area. All boundaries on the map are inferred.

CHAPTER 7

SUMMARY AND CONCLUSIONS

The Tucson Basin (Figure 21), like any other area, is faced with numerous geologically-induced problems. In this report, these problems have been referred to as geologic hazards and impediments because of the dangers and problems they pose. The potential effects these parameters have in the Tucson Basin can be summarized as follows:

1. Collapsing and Expanding Soils: The sudden and excessive settlement of a soil due to the destruction of its open fabric by saturation and external loading, can destroy the foundation of a building, along with its value, and in some cases may even be hazardous to life (Figures 22 and 23). The collapsing potential of a soil can be determined through field and laboratory tests. Collapsing soils are widespread and highly variable in lateral extent throughout the Tucson Basin. They are particularly prevalent on the flood plains and alluvial fans where it is believed that these soils, after deposition, were dessicated, rapidly buried, and never resaturated. The extent and variability of these soils has yet to be determined, therefore, whenever development is being considered, it becomes necessary to test for collapsing soils since they represent the most widespread and therefore greatest single geologic impediment in the basin.

Figure 21. The Tucson Basin Looking South.

The Tucson Mountains are to the right and the Santa Catalina Mountains are to the left.

Figure 22. Wall Fracturing due to Collapsing Soils, North Fontana Avenue Just North of Grant Road.

Figure 23. Building Fractures due to Collapsing Soils, North Fontana Avenue Just North of Grant Road.

2. Flooding and Associated Aggradation and Degradation: Flooding, as a result of direct precipitation, will continue to threaten lives and property as urbanization continues and encroaches on the major and "mini" flood plains (Figures 24 and 25). Associated with flooding is the danger of severe bank erosion which can produce channel widening at an average rate of nearly 14 feet per year and as much as 3 feet in a single storm (Figures 26 and 27).
3. Piping: Piping is a potential problem in the Tucson Basin (Figure 28). Minor piping is known to exist in the banks of the Rillito Creek and Tanque Verde Wash. Extensive piping is predicted along the Santa Cruz River. Collapsing soils are particularly susceptible to piping. Piping not only creates its own erosion, but enhances the possibility of severe bank erosion during flooding.
4. Deep Subsidence: Deep subsidence has not been a problem in the Tucson Basin to date. However, if ground-water withdrawals and excessive depletion continue at the present or accelerated rates, subsidence can become an extensive, real problem in the near future, possibly as early as 1985. Deep subsidence can be expected to occur along the major water courses and in areas underlain by a cone of water table depression.
5. Earthquakes: The Tucson Basin is located in an area which can expect moderate damage due to earthquakes. The basin has a history of moderate and minor shocks, hence, whenever

Figure 24. Homes Located in a Wash North of Roller Coaster Road.

Figure 25. House Located in a Wash North of Orange Grove Road and East of First Avenue.

Figure 26. Pantano Wash Flood, August 1971, near Craycroft Avenue. (Photo by R. D. Call)

Figure 27. Bank Erosion during the Pantano Wash Flood. (Photo by R. D. Call)

development is being planned, the possibility of an occasional earthquake in the future should be considered.

6. Caliche: Caliche is widespread throughout the Tucson Basin and is highly variable in strength ranging from a non-indurated limey subsoil to a case hardened, indurated cap rock (Figure 29). It is primarily a nuisance where it may raise the cost of excavation due to the need for heavier equipment. Its extent, depth, hardness, and thickness should be determined in any area where development is being considered.

7. Landslides, Mudslides, and Creep: Earth movement of this type is not a problem in the Tucson Basin due to the low lying, thick coarse alluvium overlying the bedrock, the absence of saturation of the alluvium, and the presence of sufficient cementation and strength to enable the alluvium to stand at high angles, in some cases in excess of 60 degrees (Figure 30). However, in the case of cut and fill operations man can create earth moving problems.

Virtually no section of the Tucson Basin is entirely free from geologic factors which will affect man and, in some cases, man himself has created or enhanced particular "geologic impediments." The general parameters summarized must be considered and evaluated whenever development or construction is being planned. An environmental and geological engineering study is needed to evaluate the full extent of the geologically-induced impediments present.

Figure 28. Piping in the Marana, Arizona Area Just North of the Study Area.

Figure 29. Caliche (Note Hand Shovel) in a Road Cut along Sweet Water Drive.

Figure 30. Road Cut along Orange Grove Road Just East of Oracle Road.

CHAPTER 8

RECOMMENDATIONS FOR FURTHER RESEARCH

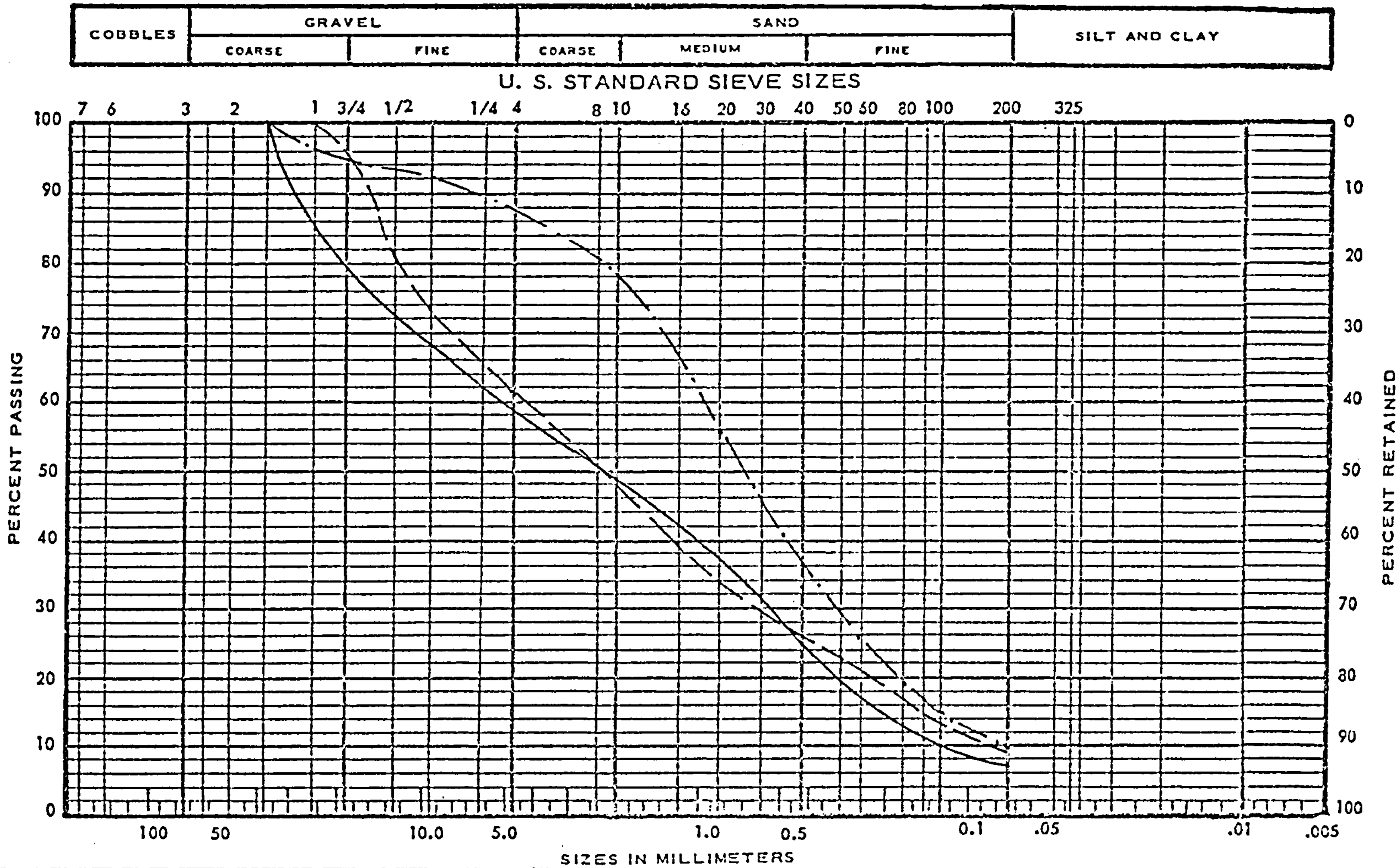
This thesis, if anything, shows how little we know about the geological engineering parameters and problems in the Tucson Basin. In order that the existing information be updated and the voids, created by the lack of information, be filled, the following recommendations for further research are made:

1. An accurate soils map should be prepared based on an engineering and genetic classification. The location of callapsing soils and the range of collapsing intensity and potential should be determined along with an estimate of the amount of normal consolidation which can be expected due to loading of small structures.
2. An accurate drainage and flood potential map, including the main water courses and small washes and rills, should be prepared by the use of field studies and aerial photography.
3. The piping potential and known piping areas should be delineated and mapped.
4. An extensive study of stream sediment transport should be conducted including the bed load, siltation, aggradation and degradation, gullying and bank erosion, and the meandering and shifting of stream locations.

5. Attempts should be made at the quantitative delineation of deep subsidence potential.
6. A quantitative study should be conducted of the probability of landslides, mudslides, and creep and possible effects if an area is disturbed by construction.
7. A study should be conducted of the effect of siesmic shocks on the basin fill and bedrock.
8. Caliche should be mapped according to its physical characteristics, location, thickness, and depth.
9. An attempt should be made to map the subsurface and to produce accurate cross-sections of the basin fill deposits.
10. The engineering properties of the bedrock units in the Tucson Basin should be determined and mapped.
11. The influence of man on geologic hazard parameters should be evaluated.

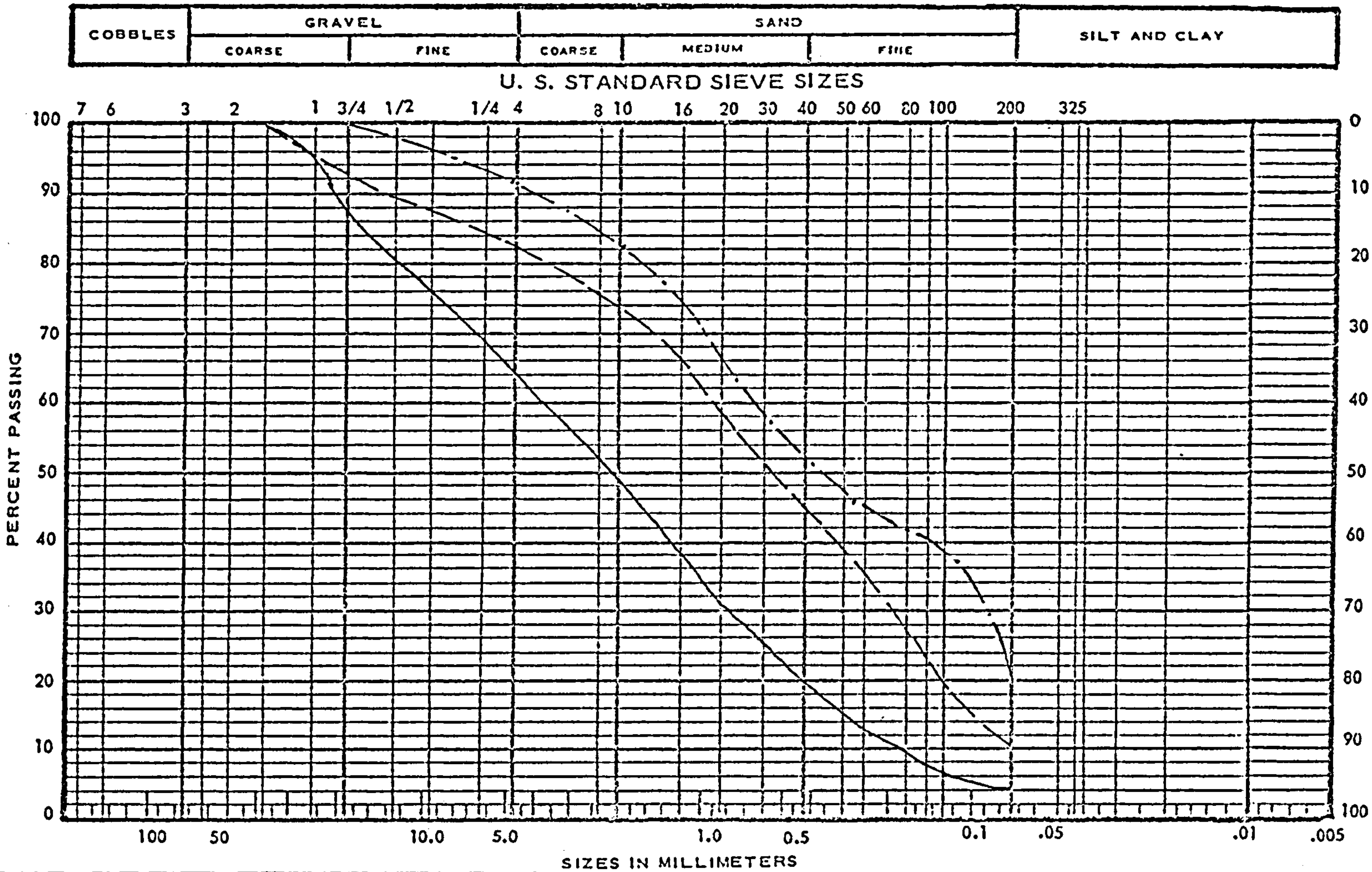
APPENDIX A

LABORATORY SOILS DATA



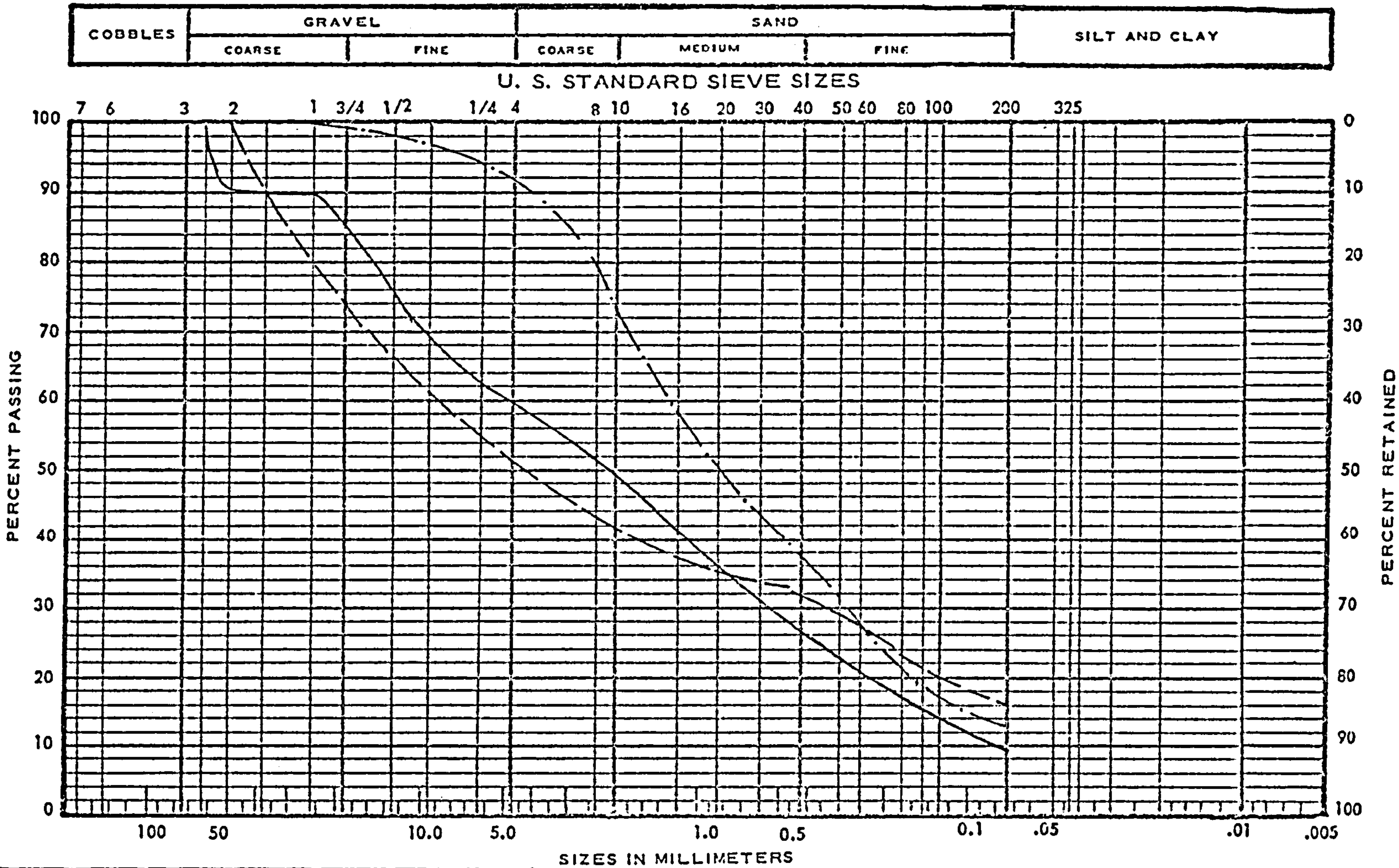
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
1	———	33	20	13	Poorly graded sand w/7% medium plastic fines (SP-SM)
2	— — —	26	21	5	Poorly graded sand w/10% slightly plastic fines (SP-SM)
16	—— · ——	20	13	7	Poorly graded sand w/9% slightly plastic fines (SP-SM)

Figure A1. Laboratory Soil Data for Samples 1, 2, and 16.



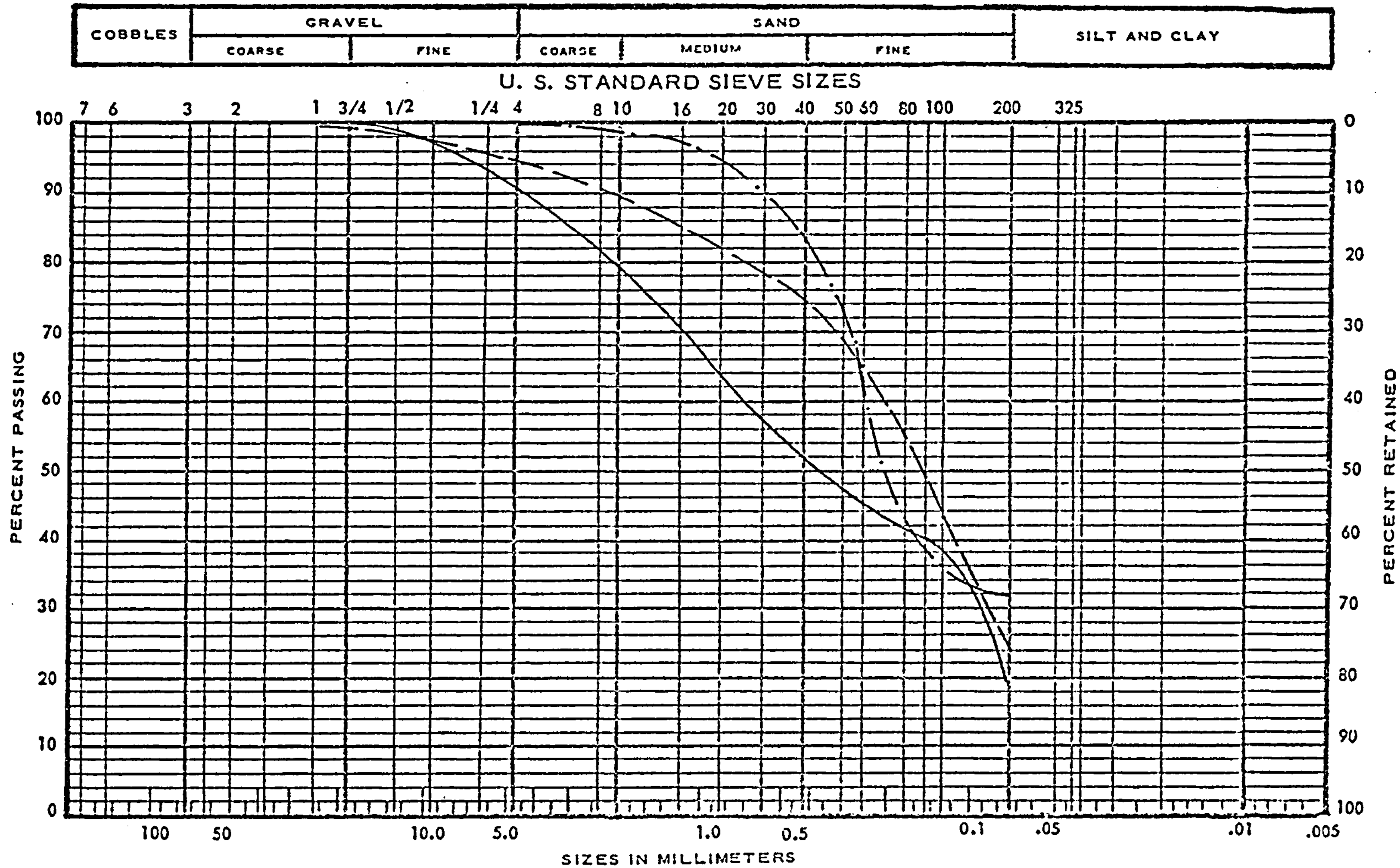
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
3	————	---	---	---	Poorly graded sand w/4% non-plastic fines (SP)
4	— — —	---	---	0	Poorly graded sand w/11% non-plastic fines (SP-SM)
11	—·—·—	20	24	0	Poorly graded sand w/20% non-plastic fines (SM)

Figure A2. Laboratory Soil Data for Samples 3, 4, and 11.



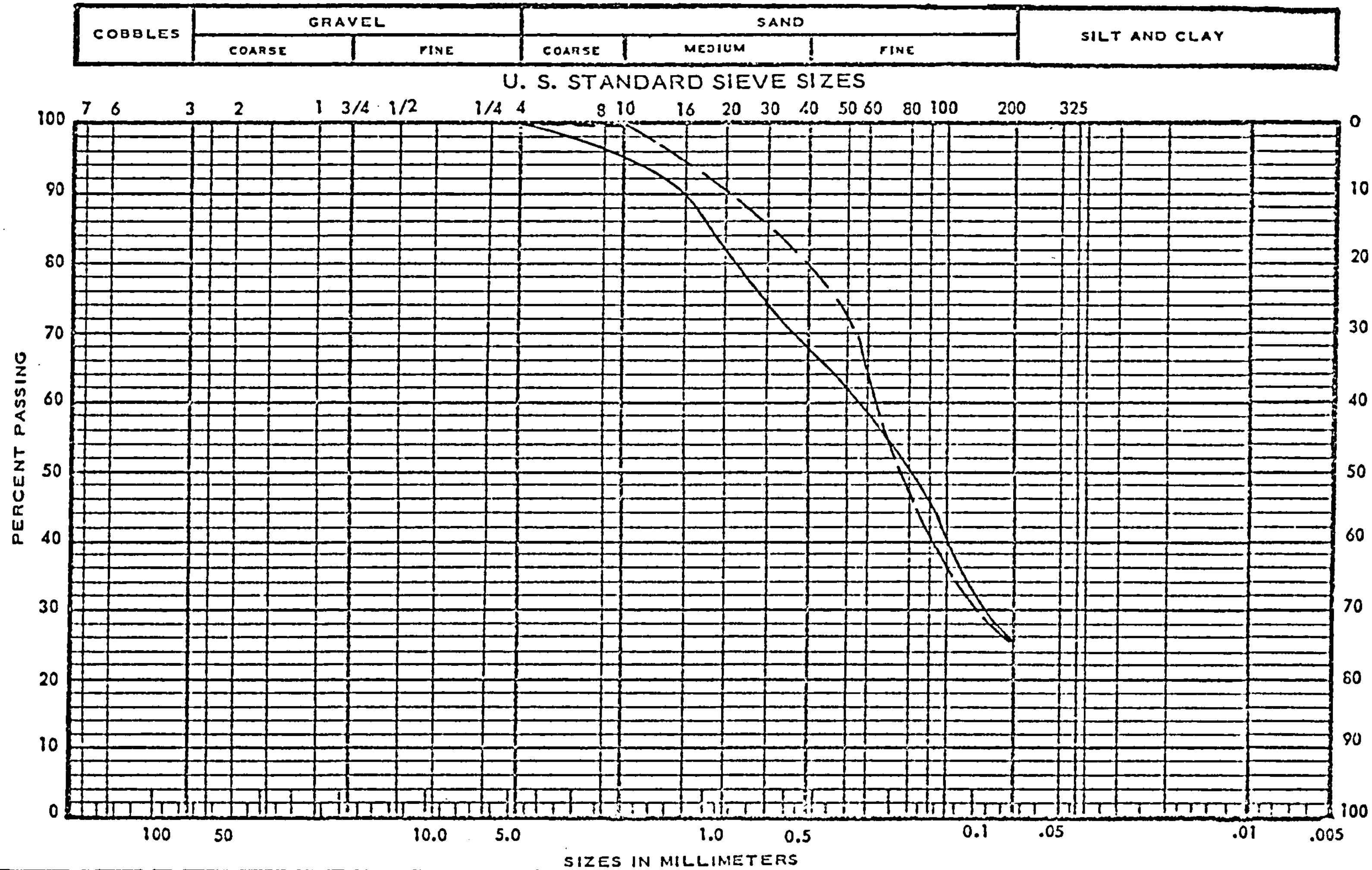
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
5	———	---	---	0	Poorly graded sand w/9% non-plastic fines (SP-SM)
6	— — —	28	15	13	Poorly graded gravel w/16% medium plastic fines (GC)
39	—·—·—	---	---	0	Poorly graded sand w/13% non-plastic fines (SM)

Figure A3. Laboratory Soil Data for Samples 5, 6, and 39.



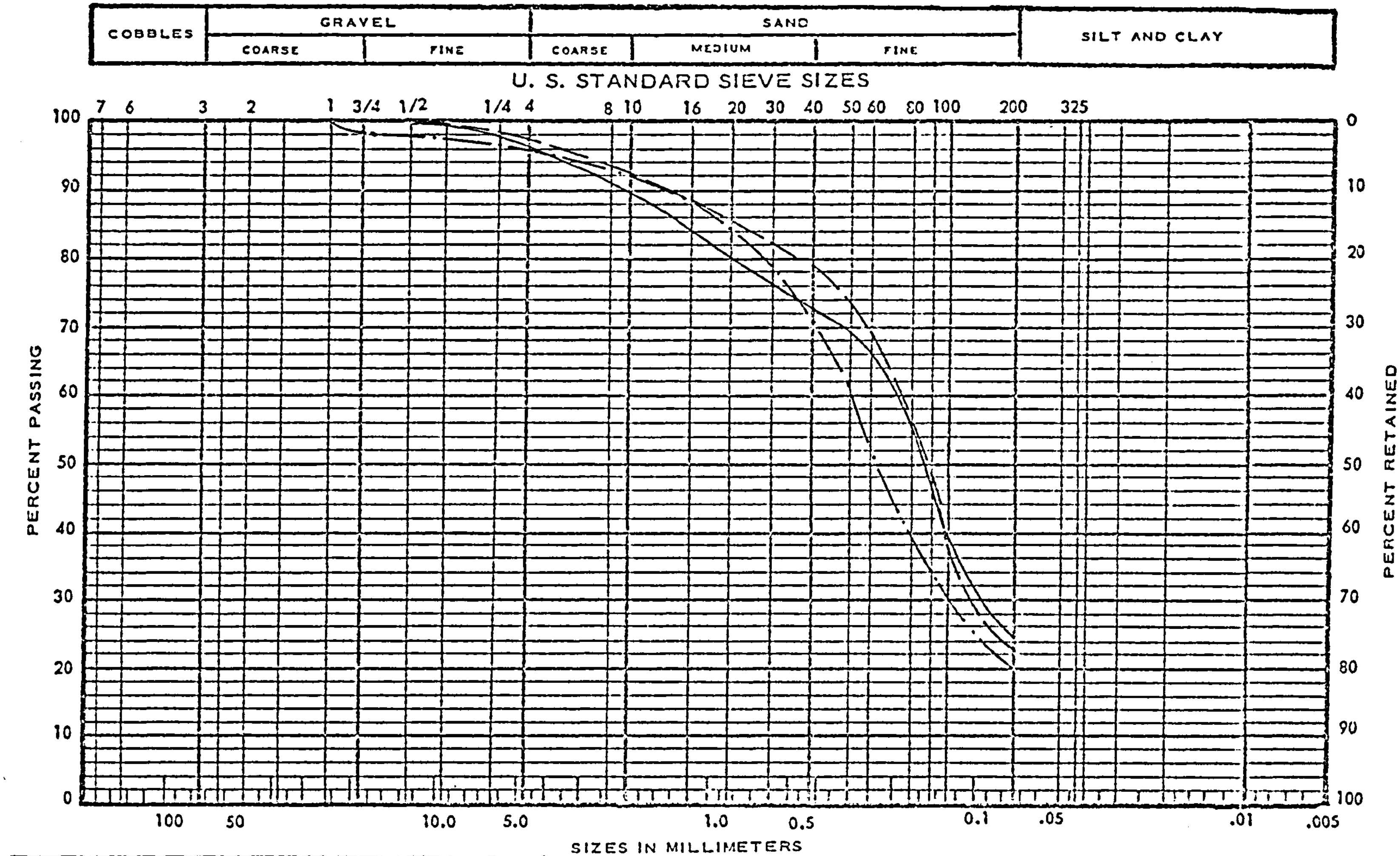
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
12	————	29	19	10	Poorly graded sand w/19% medium plastic fines (SC)
13	— — —	26	25	1	Poorly graded sand w/24% non-plastic fines (SM)
74	—·—·—	33	33	0	Poorly graded sand w/32% non-plastic fines (SM)

Figure A4. Laboratory Soil Data for Samples 12, 13, and 74.



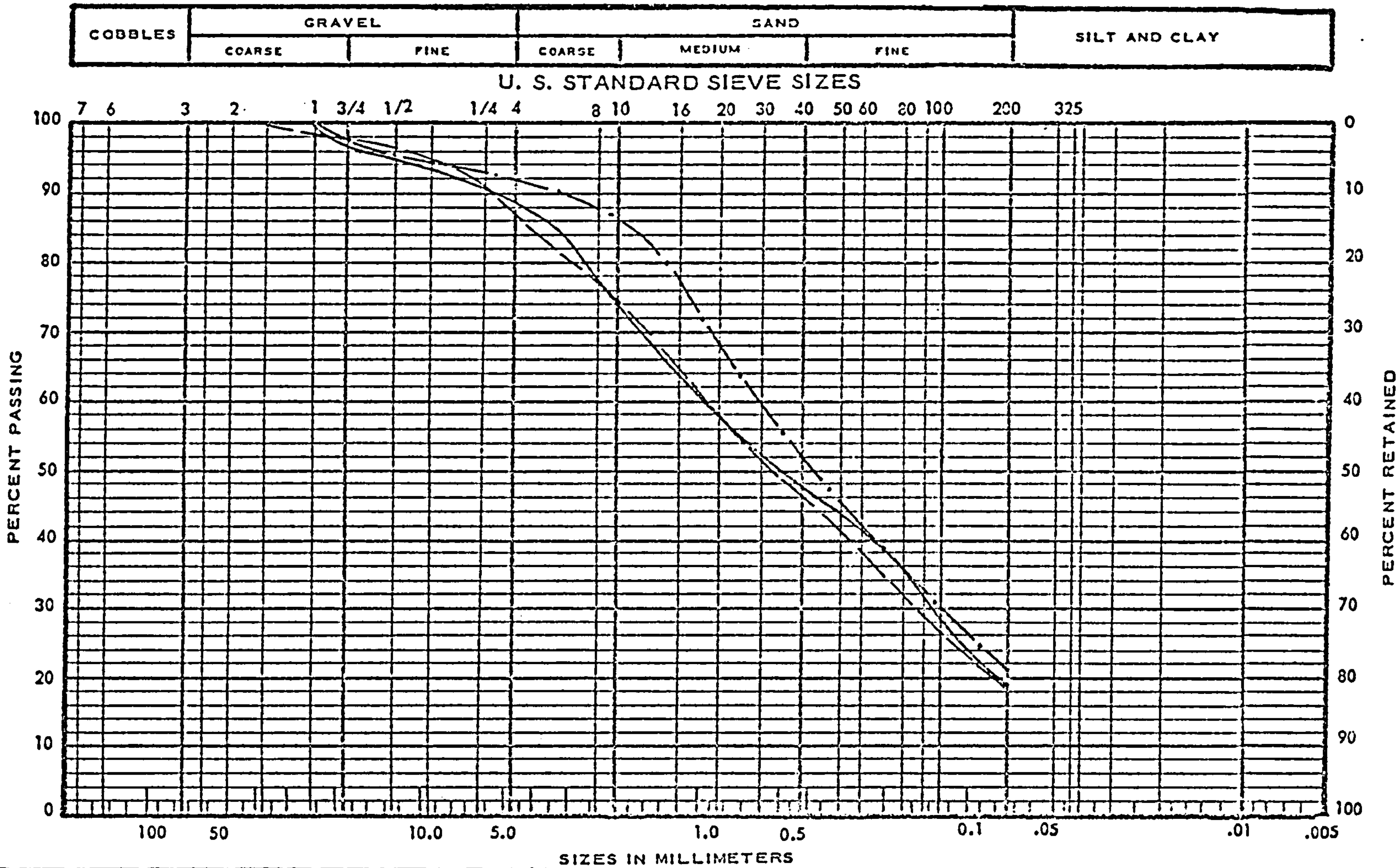
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
14	————	28	21	7	Poorly graded sand w/26% slightly plastic fines (SM-SC)
15	— — —	29	26	3	Poorly graded sand w/26% non-plastic fines (SM)

Figure A5. Laboratory Soil Data for Samples 14 and 15.



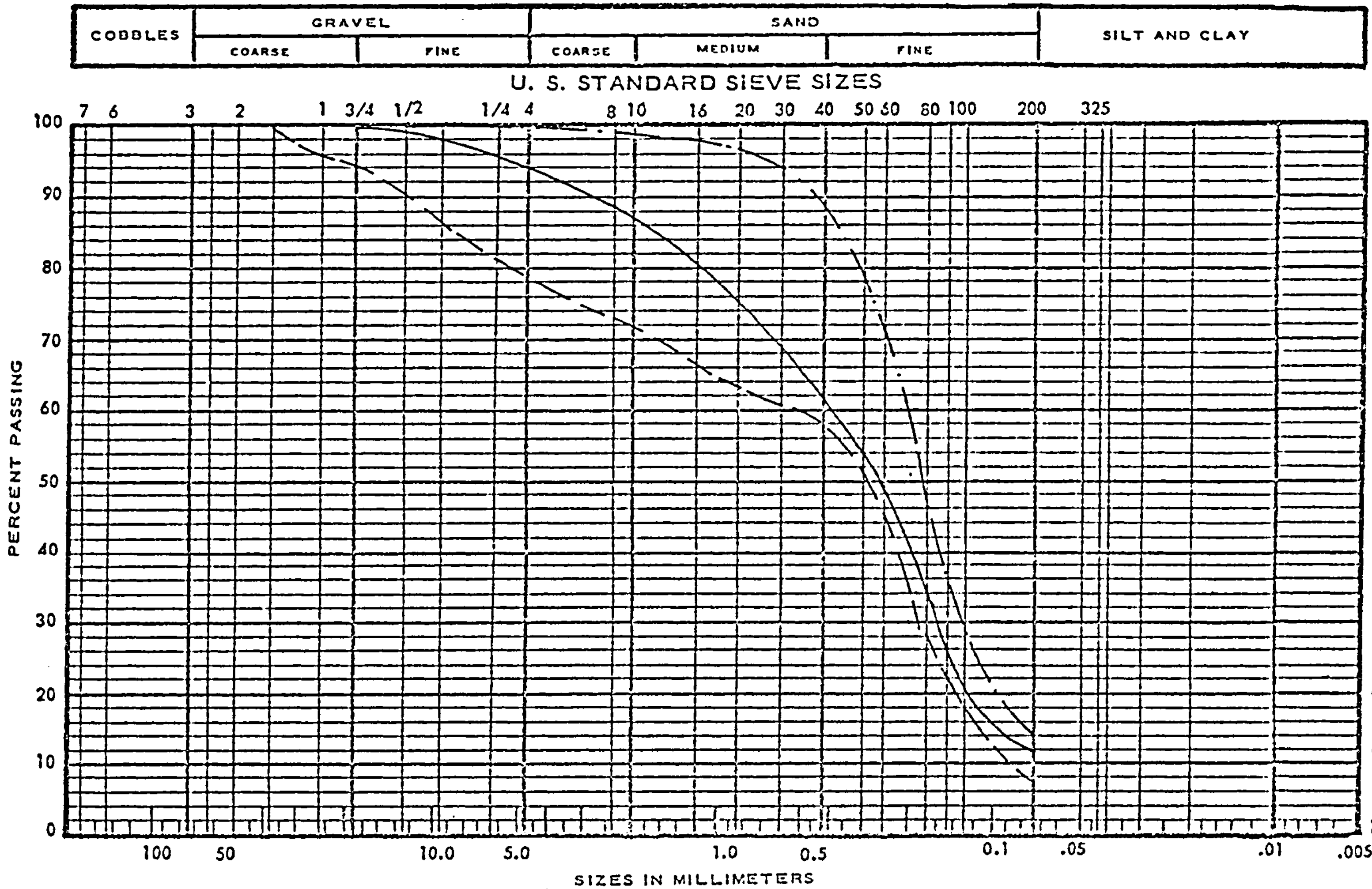
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
21	————	21	24	0	Poorly graded sand w/25% non-plastic fines (SM)
22	— — —	22	22	0	Poorly graded sand w/22% non-plastic fines (SM)
31	—·—·—	---	---	0	Poorly graded sand w/20% non-plastic fines (SM)

Figure A6. Laboratory Soil Data for Samples 21, 22, and 31.



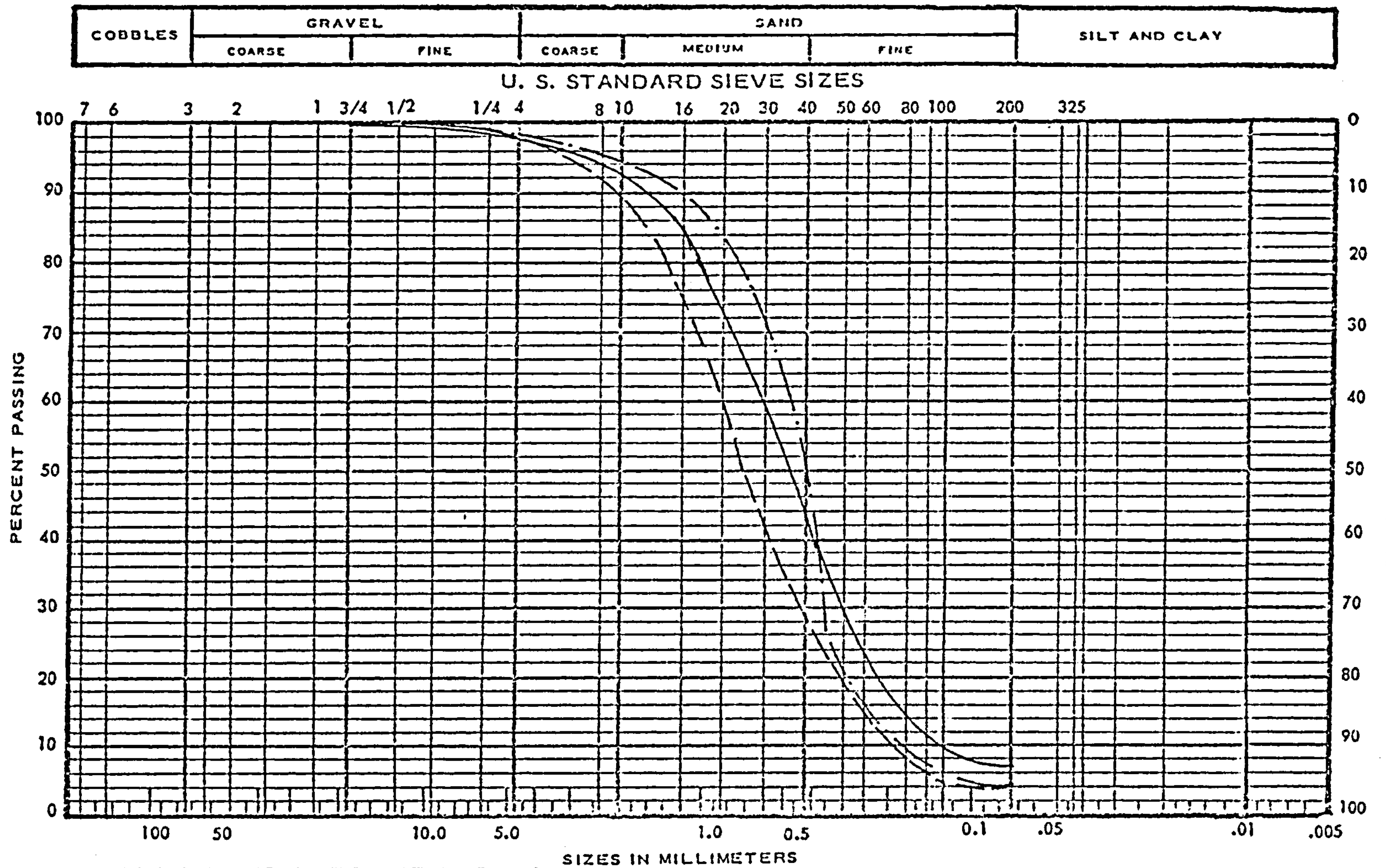
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
23	————	19	18	1	Poorly graded sand w/19% non-plastic fines (SC)
24	— — —	25	20	5	Poorly graded sand w/19% slightly plastic fines (SM-SC)
29	—·—·—	28	20	8	Poorly graded sand w/21% slightly plastic fines (SC)

Figure A7. Laboratory Soil Data for Samples 23, 24, and 29.



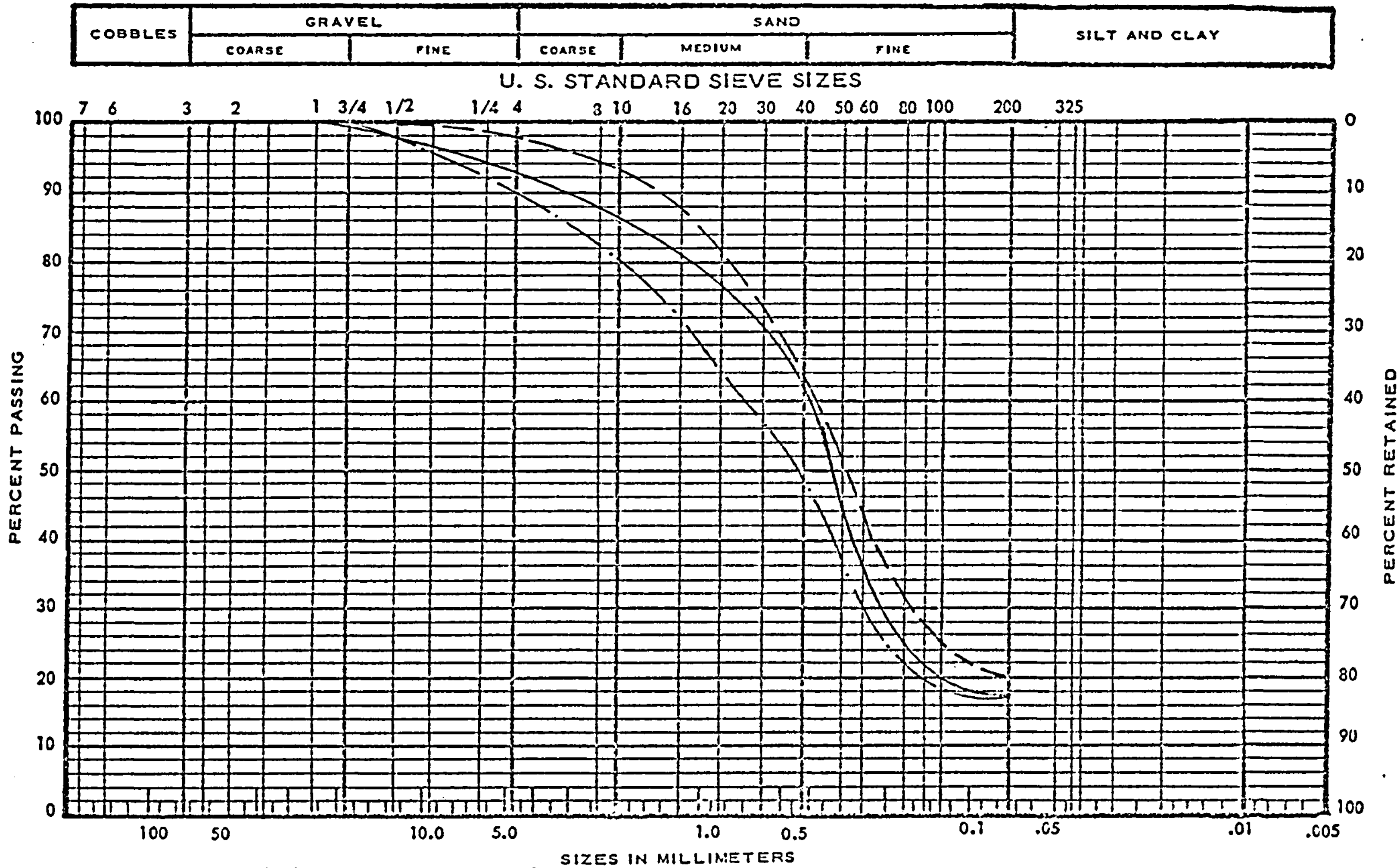
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
25	———————	---	---	0	Poorly graded sand w/11% non-plastic fines (SP-SM)
26	— — — —	---	---	0	Poorly graded sand w/7% non-plastic fines (SP-SM)
30	—·—·—	---	---	0	Poorly graded sand w/15% non-plastic fines (SM)

Figure A8. Laboratory Soil Data for Samples 25, 26, and 30.



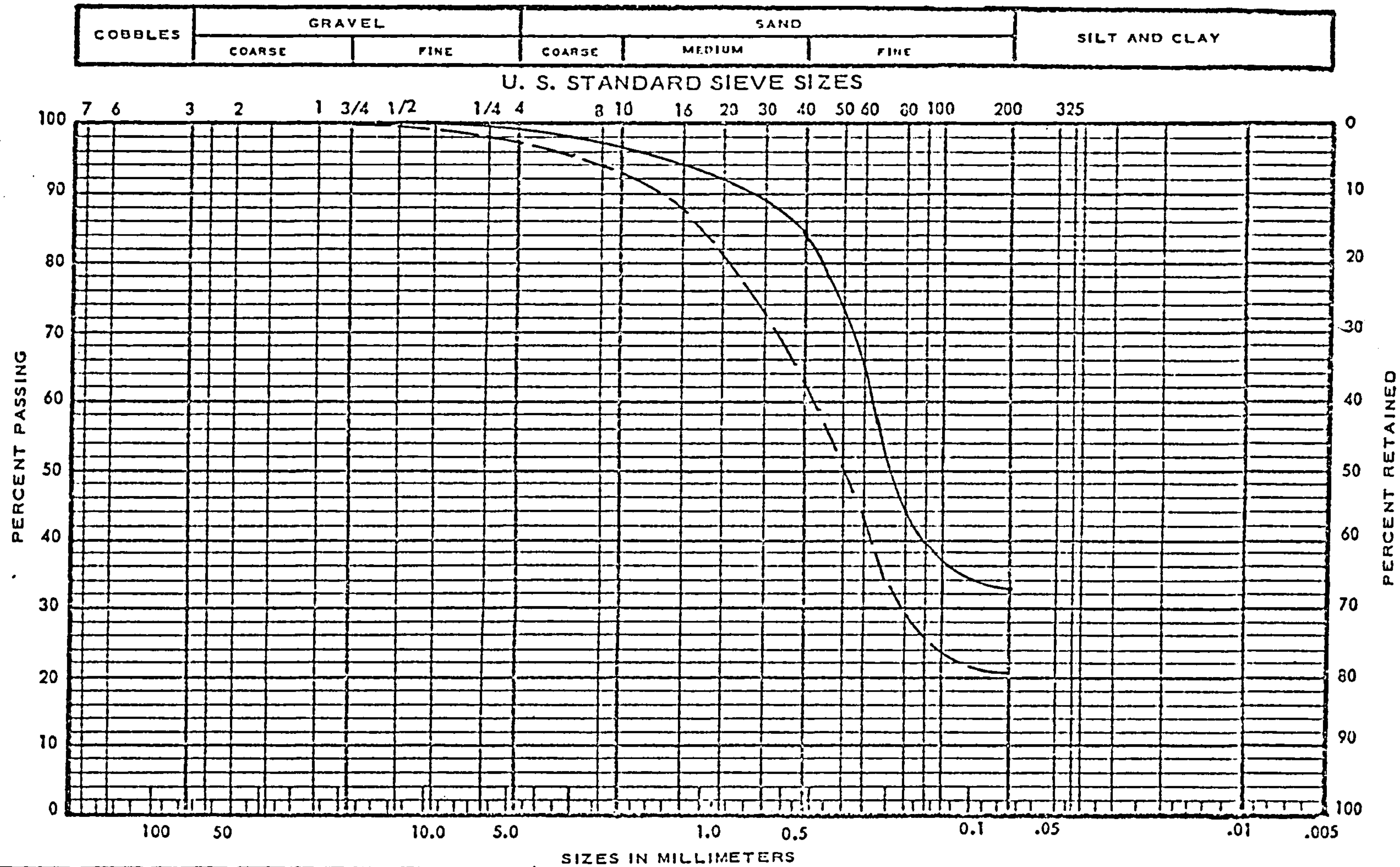
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
32	———	---	---	0	Poorly graded sand w/7% non-plastic fines (SP-SM)
33	— — —	---	---	---	Poorly graded sand w/4% non-plastic fines (SP)
75	—·—·—	---	---	---	Poorly graded sand w/4% non-plastic fines (SP)

Figure A9. Laboratory Soil Data for Samples 32, 33, and 75.



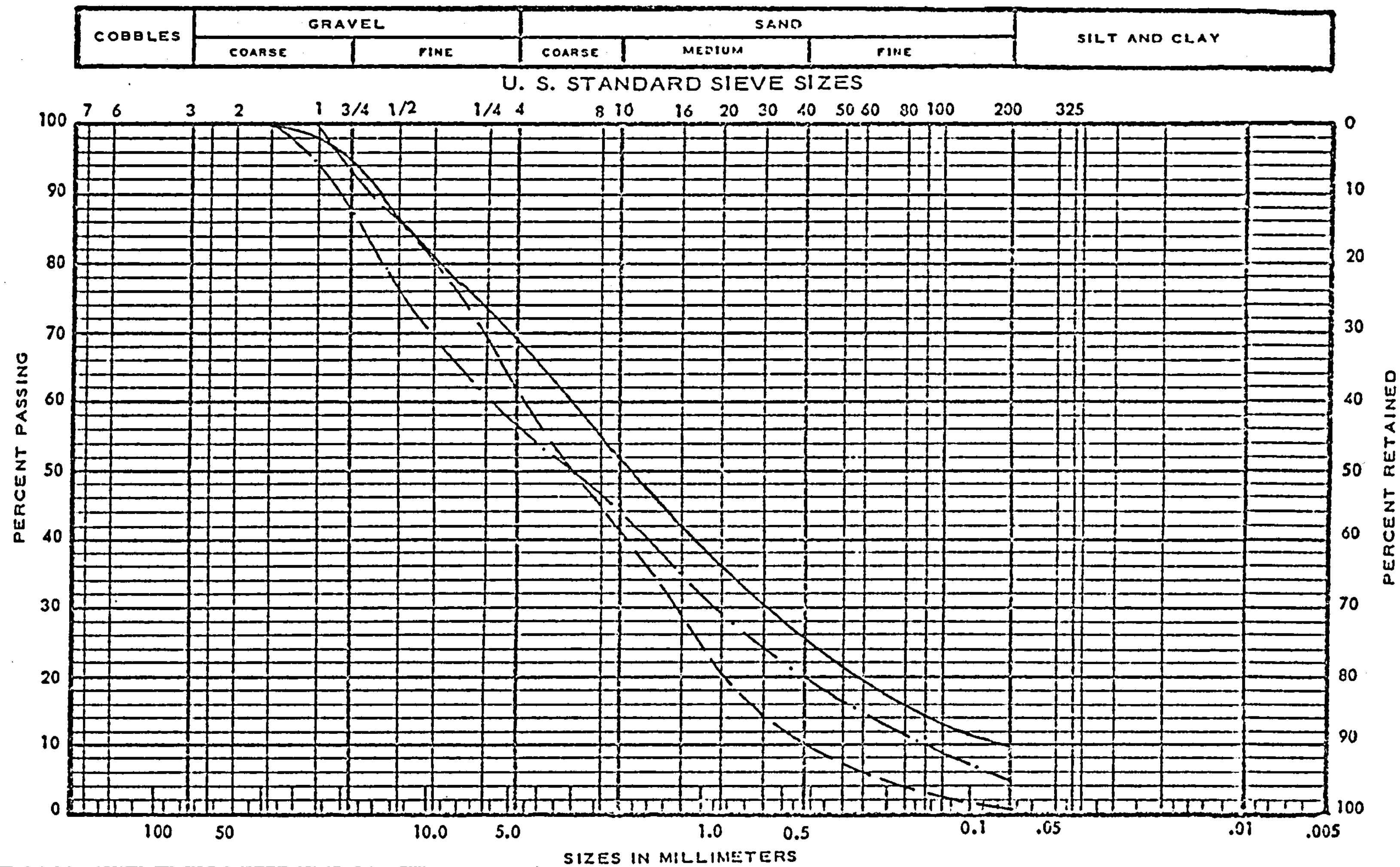
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
63	————	---	---	0	Poorly graded sand w/18% non-plastic fines (SM)
64	— — —	19	15	4	Poorly graded sand w/20% slightly plastic fines (SM-SC)
76	—·—·—	---	---	0	Poorly graded sand w/17% non-plastic fines (SM)

Figure A10. Laboratory Soil Data for Samples 63, 64, and 76.



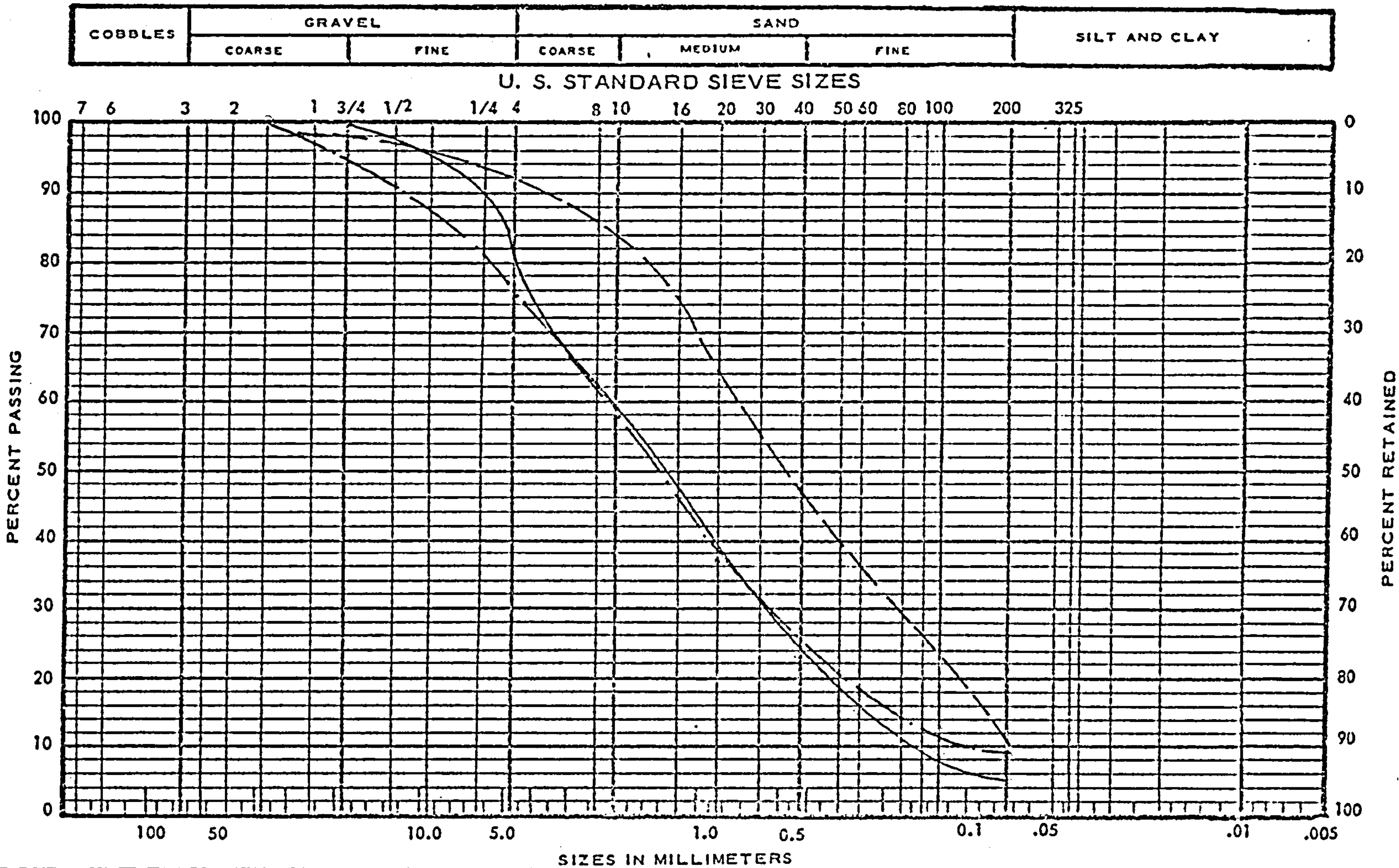
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
72	———————	32	24	8	Poorly graded sand w/33% slightly plastic fines (SM)
73	— — — —	34	26	8	Poorly graded sand w/20% slightly plastic fines (SM)

Figure A11. Laboratory Soil Data for Samples 72 and 73.



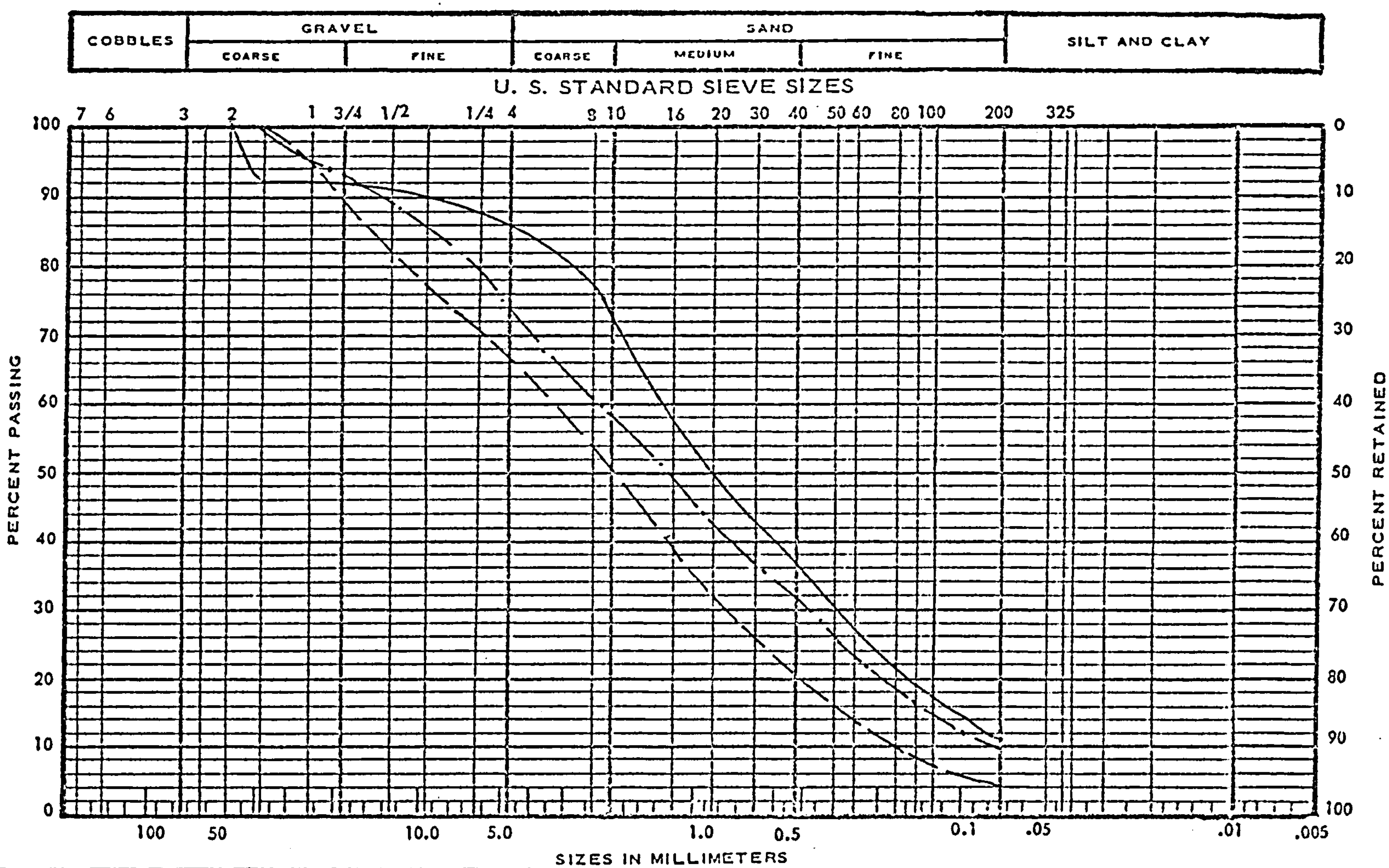
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
7	———————	25	16	9	Poorly graded sand w/9% medium plastic fines (SP-SC)
8	— — —	---	---	---	Poorly graded sand w/2% non-plastic fines (SP)
9	—·—·—	---	---	---	Poorly graded sand w/6% non-plastic fines (SP-SM)

Figure A12. Laboratory Soil Data for Samples 7, 8, and 9.



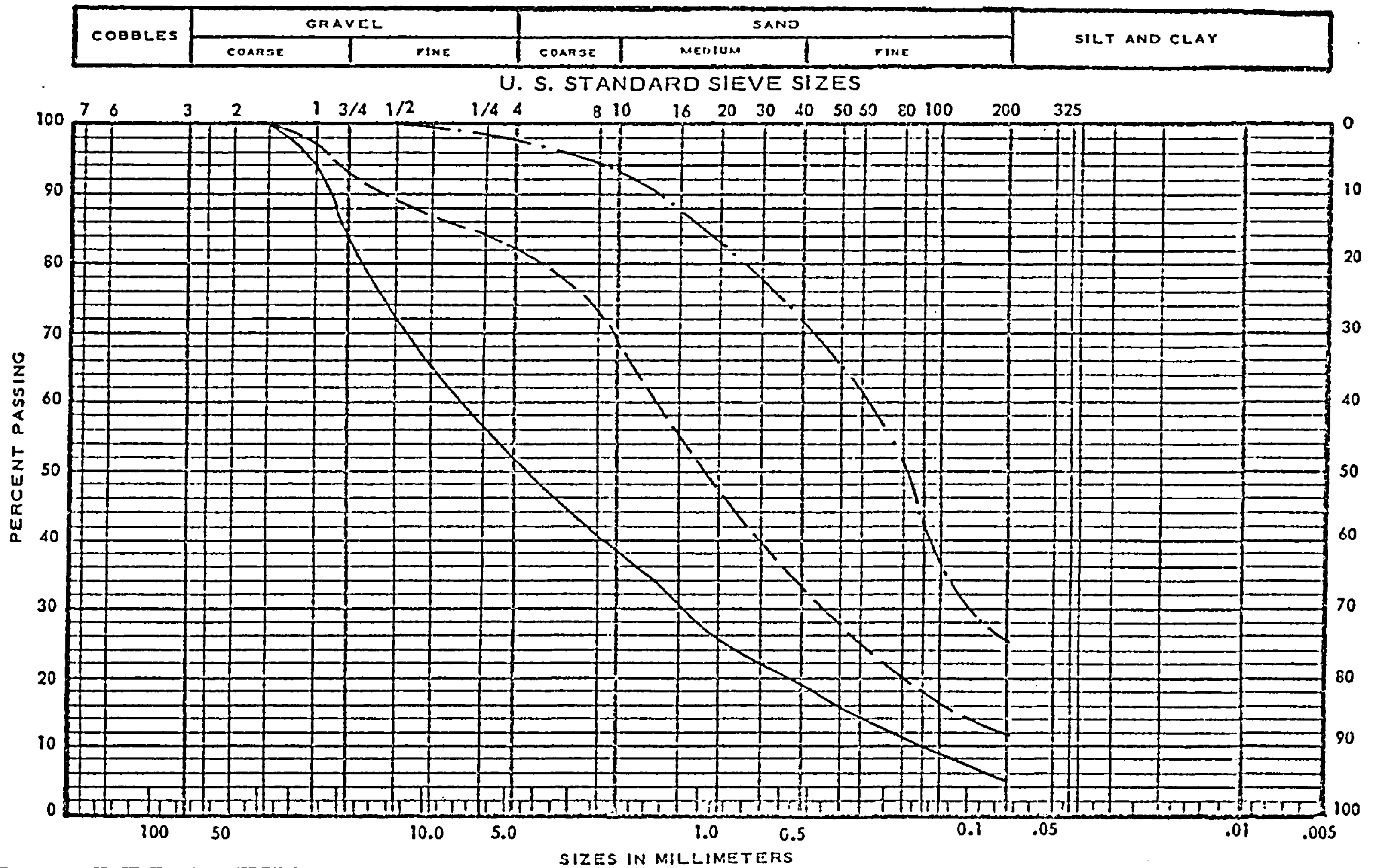
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
10	————	---	---	---	Poorly graded sand w/5% non-plastic fines (SP)
17	— —— —	---	---	0	Poorly graded sand w/11% non-plastic fines (SP-SM)
18	—·—·—	---	---	0	Poorly graded sand w/9% non-plastic fines (SP-SM)

Figure A13. Laboratory Soil Data for Samples 10, 17, and 18.



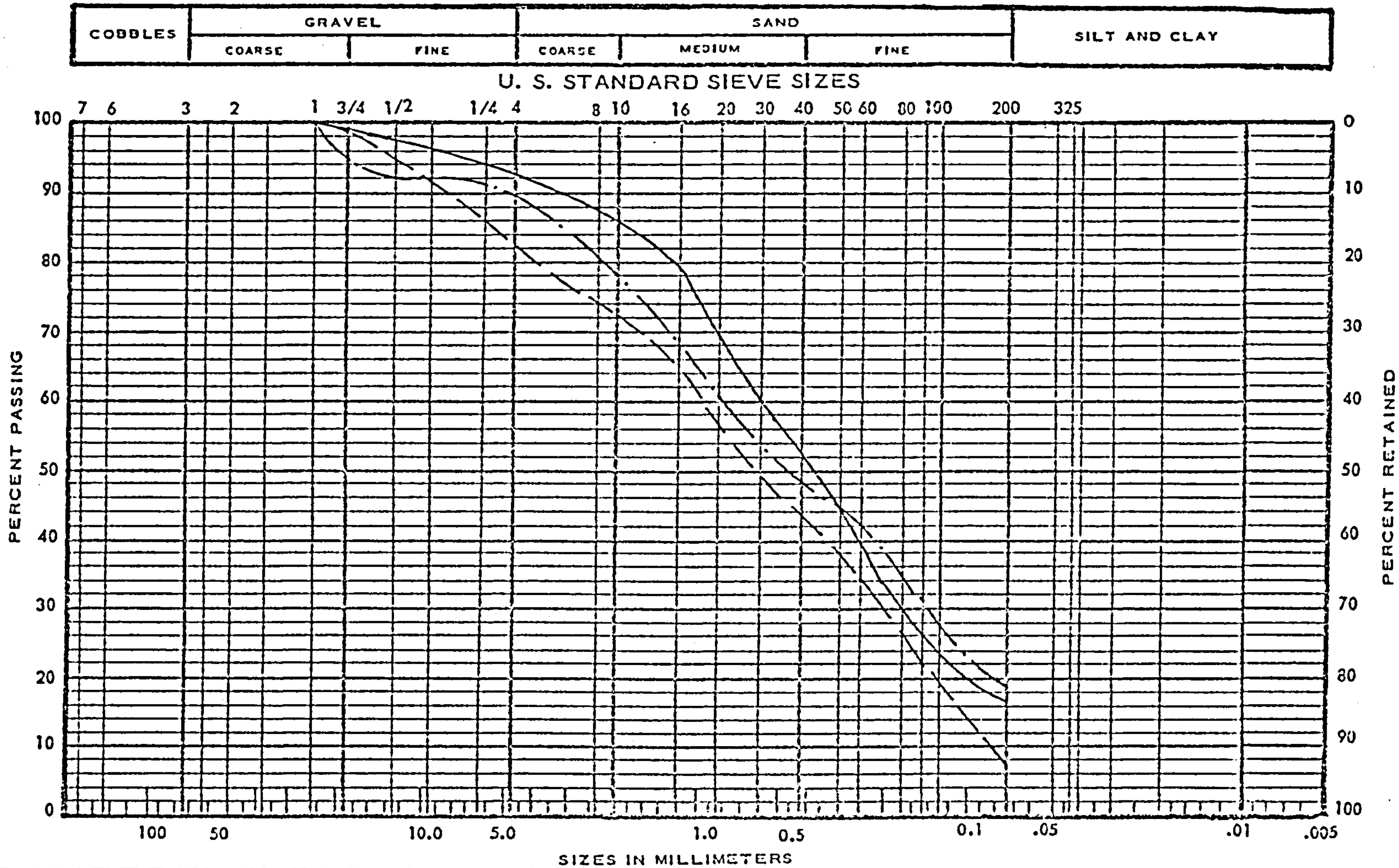
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
19	———————	23	16	7	Poorly graded sand w/12% slightly plastic fines (SP-SM-SC)
20	— — —	---	---	---	Poorly graded sand w/47% non-plastic fines (SP)
27	—·—·—	26	22	4	Poorly graded sand w/11% slightly plastic fines (SP-SM)

Figure A14. Laboratory Soil Data for Samples 19, 20, and 27.



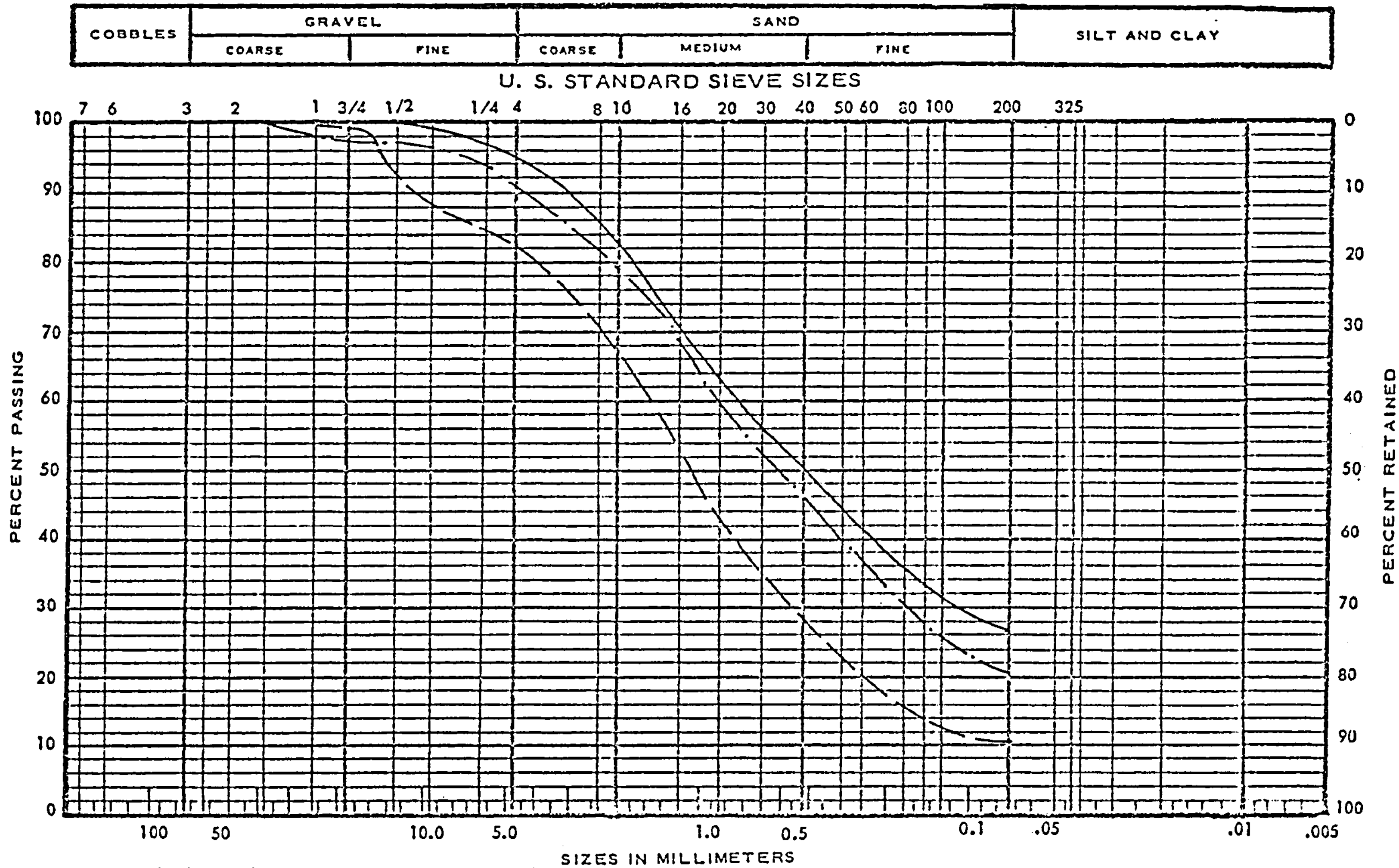
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
28	————	---	---	---	Poorly graded gravel w/6% non-plastic fines (GP-GM)
34	— — —	---	---	0	Poorly graded sand w/12% non-plastic fines (SP-SM)
35	—·—·—	---	---	0	Poorly graded sand w/25% non-plastic fines (SM)

Figure A15. Laboratory Soil Data for Samples 28, 34, and 35.



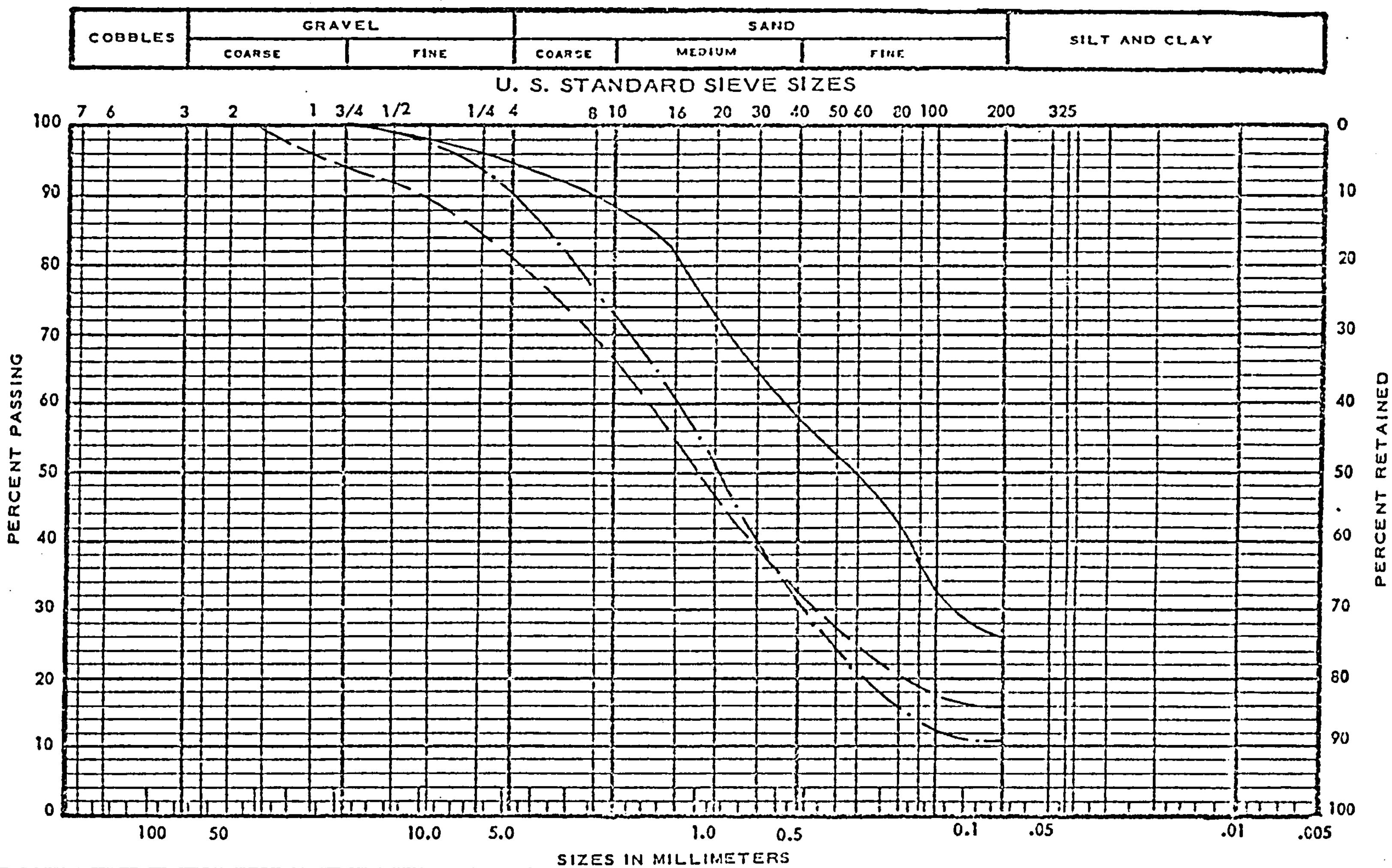
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
36	————	---	---	0	Poorly graded sand w/18% non-plastic fines (SM)
37	— — —	---	---	0	Poorly graded sand w/7% non-plastic fines (SP-SM)
38	—·—·—	---	---	0	Poorly graded sand w/20% non-plastic fines (SM)

Figure A16. Laboratory Soil Data for Samples 36, 37, and 38.



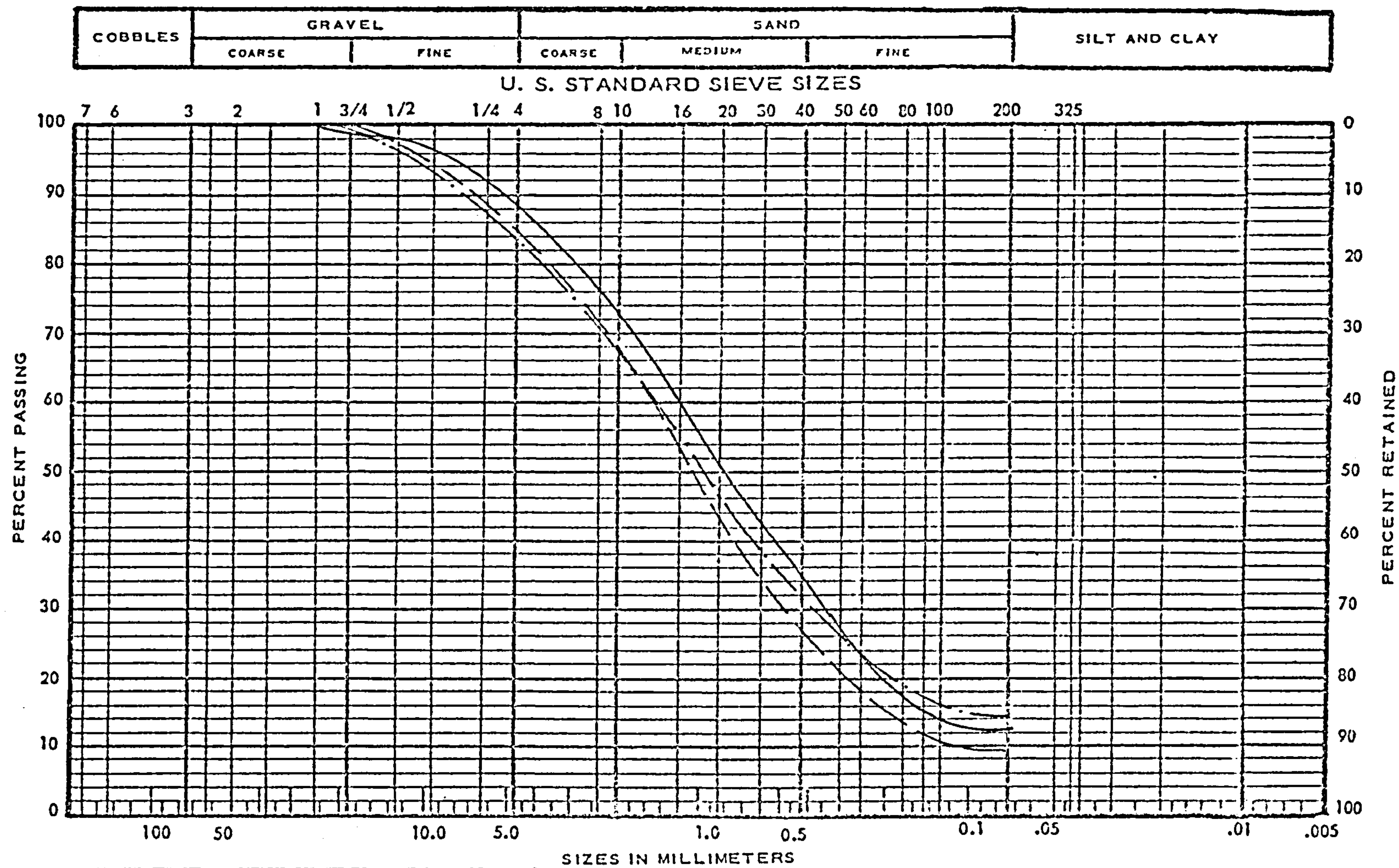
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
40	———————	23	20	3	Poorly graded sand w/26% non-plastic fines (SM)
41	— — —	---	---	0	Poorly graded sand w/11% non-plastic fines (SP-SM)
42	—·—·—	22	18	4	Poorly graded sand w/21% slightly plastic fines (SM-SC)

Figure A17. Laboratory Soil Data for Samples 40, 41, and 42.



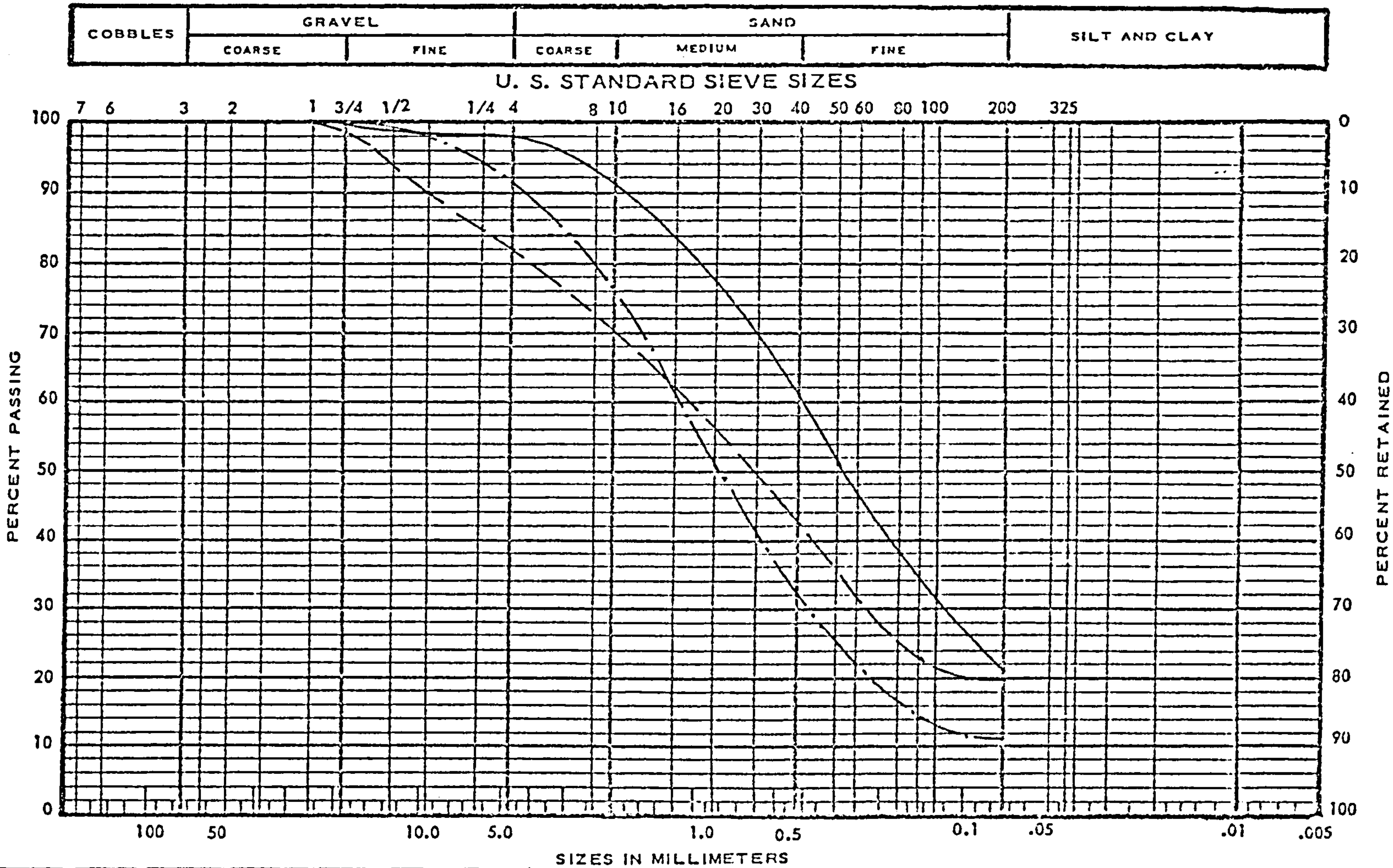
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
43	————	22	26	0	Poorly graded sand w/26% non-plastic fines (SM)
44	— — —	19	15	4	Poorly graded sand w/16% slightly plastic fines (SM-SC)
45	—·—·—	27	18	9	Poorly graded sand w/11% medium plastic fines (SP-SC)

Figure A18. Laboratory Soil Data for Samples 43, 44, and 45.



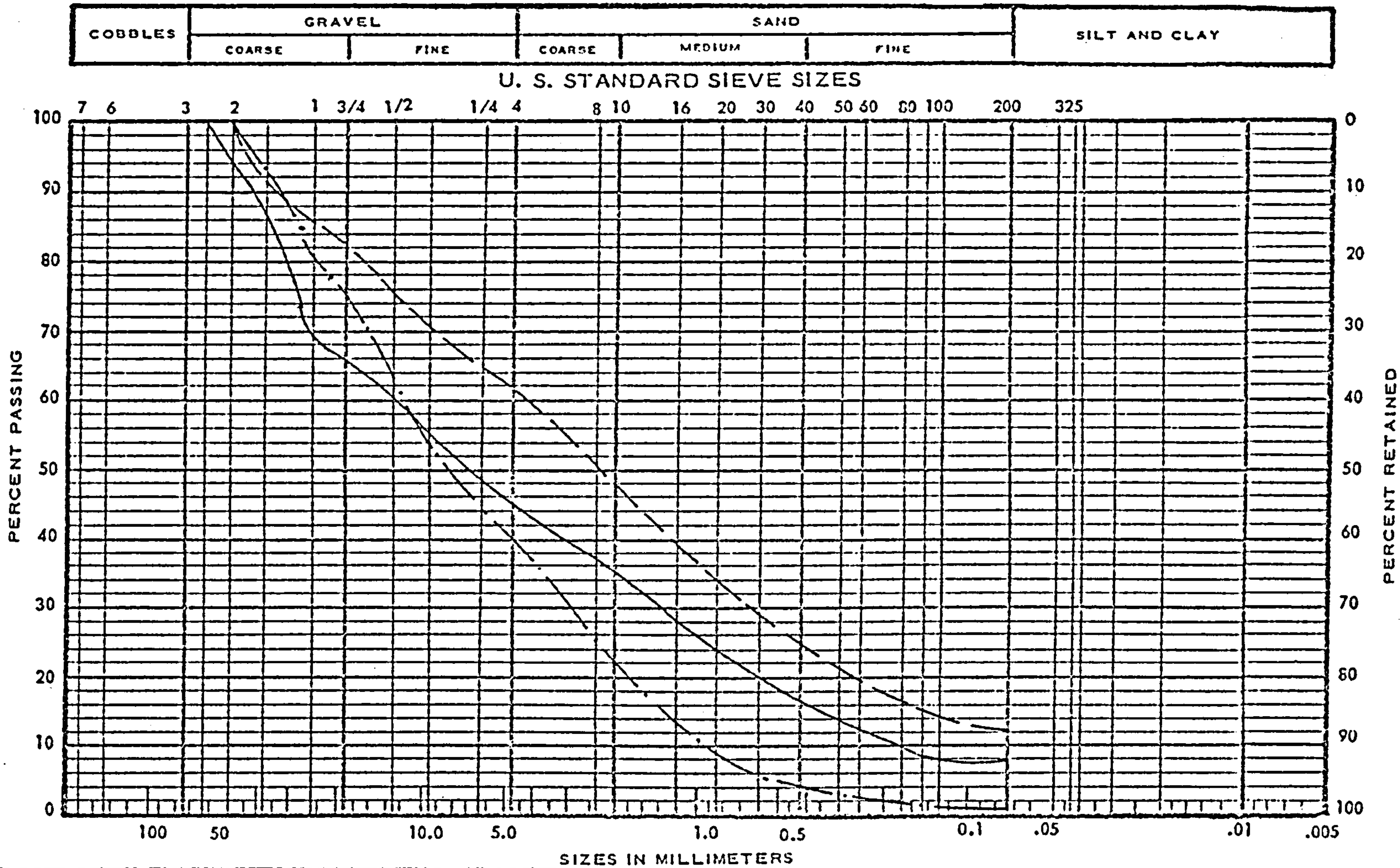
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
46	———————	29	12	17	Poorly graded sand w/14% medium plastic fines (SC)
47	— — — —	---	---	0	Poorly graded sand w/10% non-plastic fines (SP-SM)
48	—·—·—	24	18	6	Poorly graded sand w/14% slightly plastic fines (SM-SC)

Figure A19. Laboratory Soil Data for Samples 46, 47, and 48.



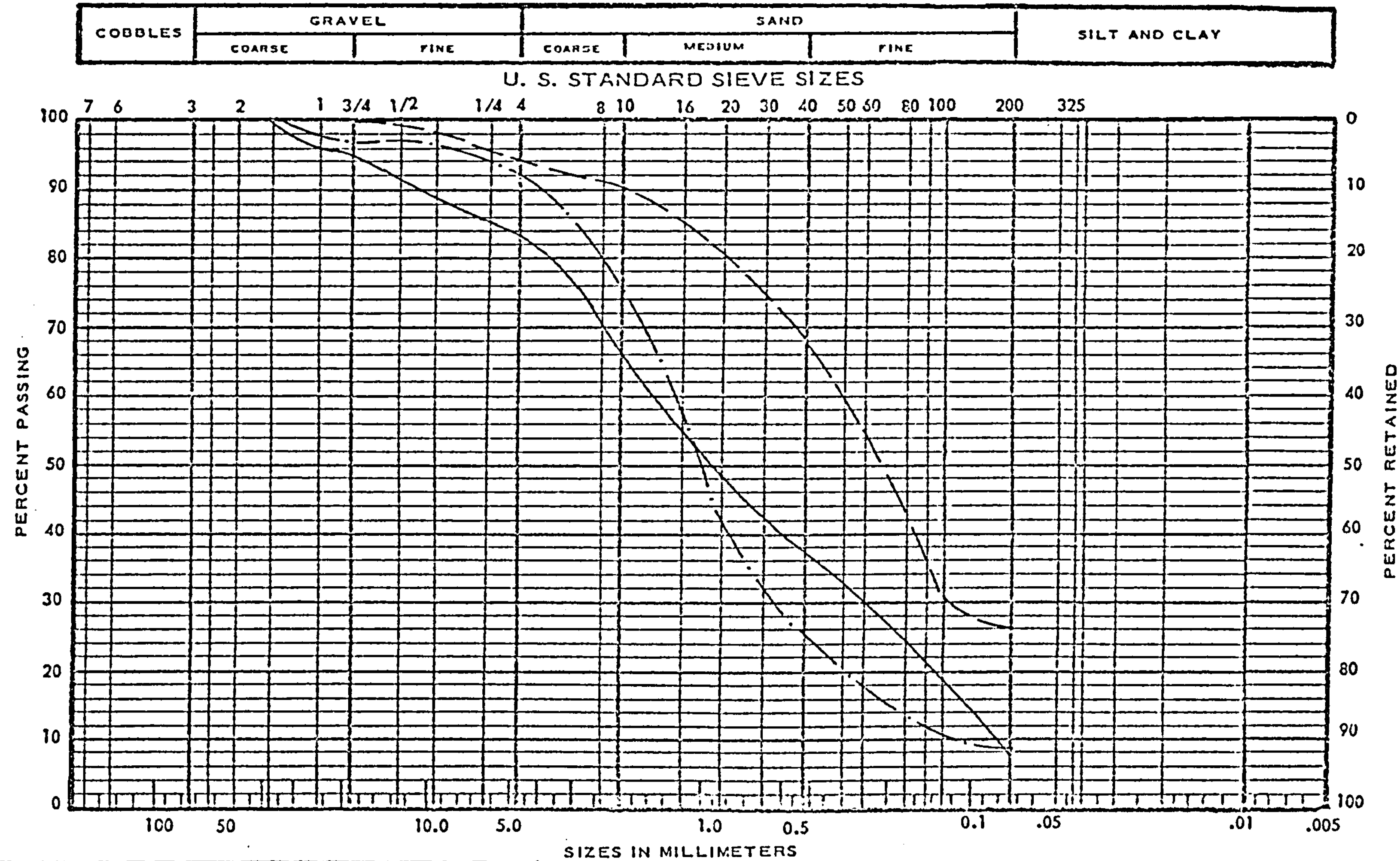
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
49	————	---	---	0	Poorly graded sand w/21% non-plastic fines (SM)
50	— — —	---	---	0	Poorly graded sand w/20% non-plastic fines (SM)
51	—·—·—	24	16	8	Poorly graded sand w/12% slightly plastic fines (SP-SC)

Figure A20. Laboratory Soil Data for Samples 49, 50, and 51.



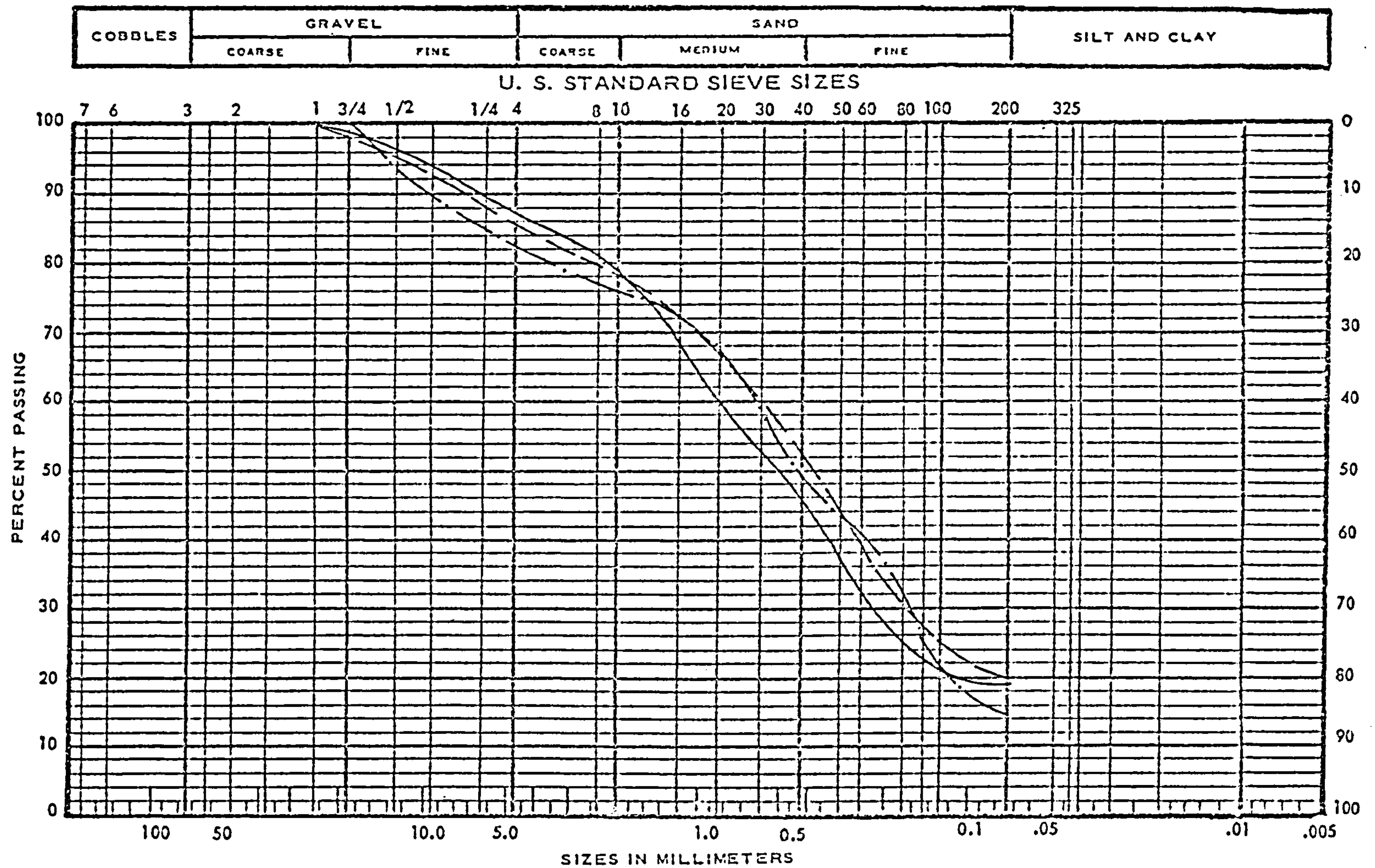
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
52	————	---	---	0	Poorly graded gravel w/8% non-plastic fines (GP-GM)
53	— — —	---	---	0	Poorly graded sand w/12% non-plastic fines (SM)
54	—· —·—	---	---	---	Poorly graded gravel w/1% non-plastic fines (GP)

Figure A21. Laboratory Soil Data for Samples 52, 53, and 54.



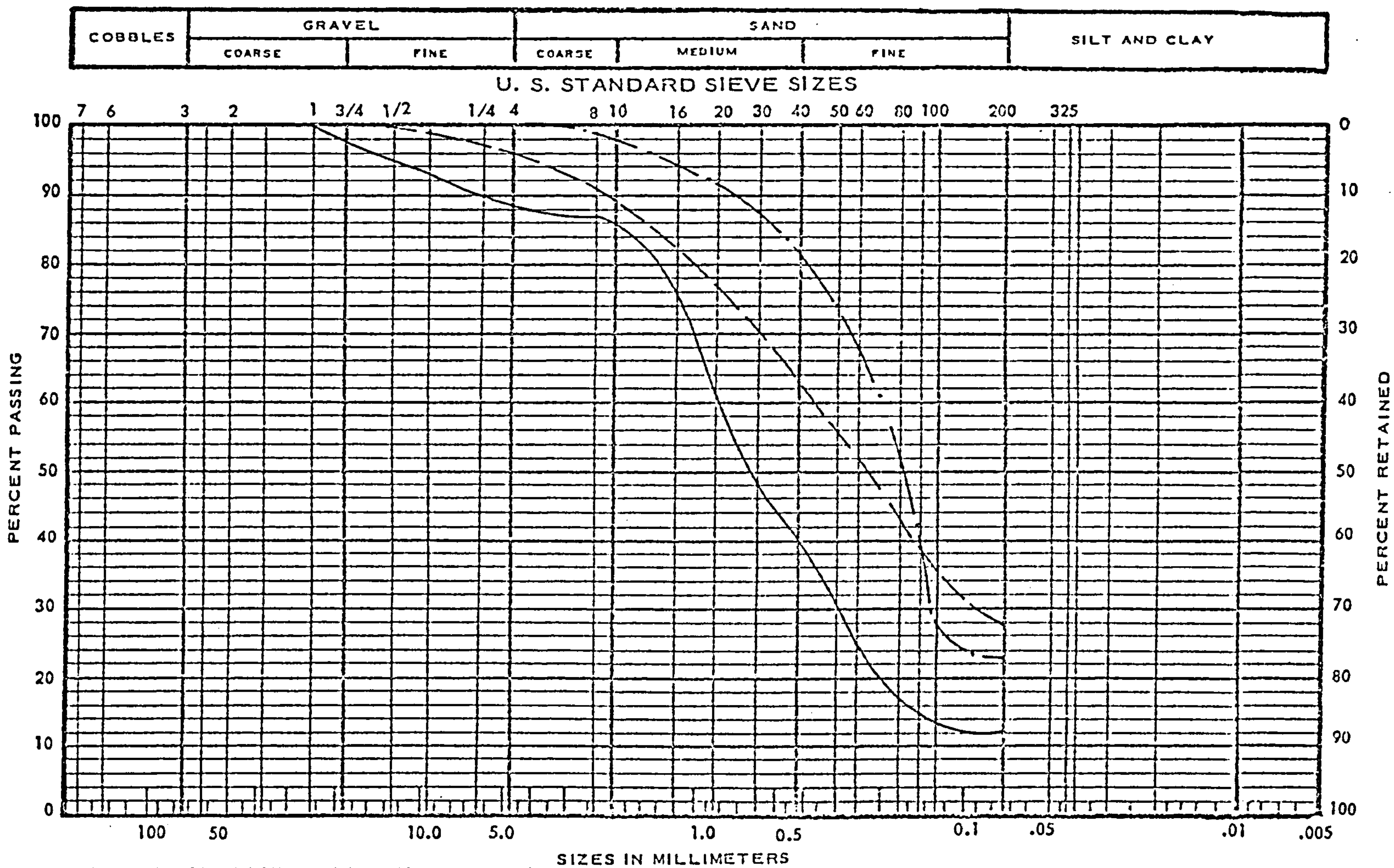
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
55	————	---	---	0	Poorly graded sand w/9% non-plastic fines (SP-SM)
56	— — —	---	---	0	Poorly graded sand w/26% non-plastic fines (SM)
57	—·—·—	23	16	7	Poorly graded sand w/9% slightly plastic fines (SP-SC)

Figure A22. Laboratory Soil Data for Samples 55, 56, and 57.



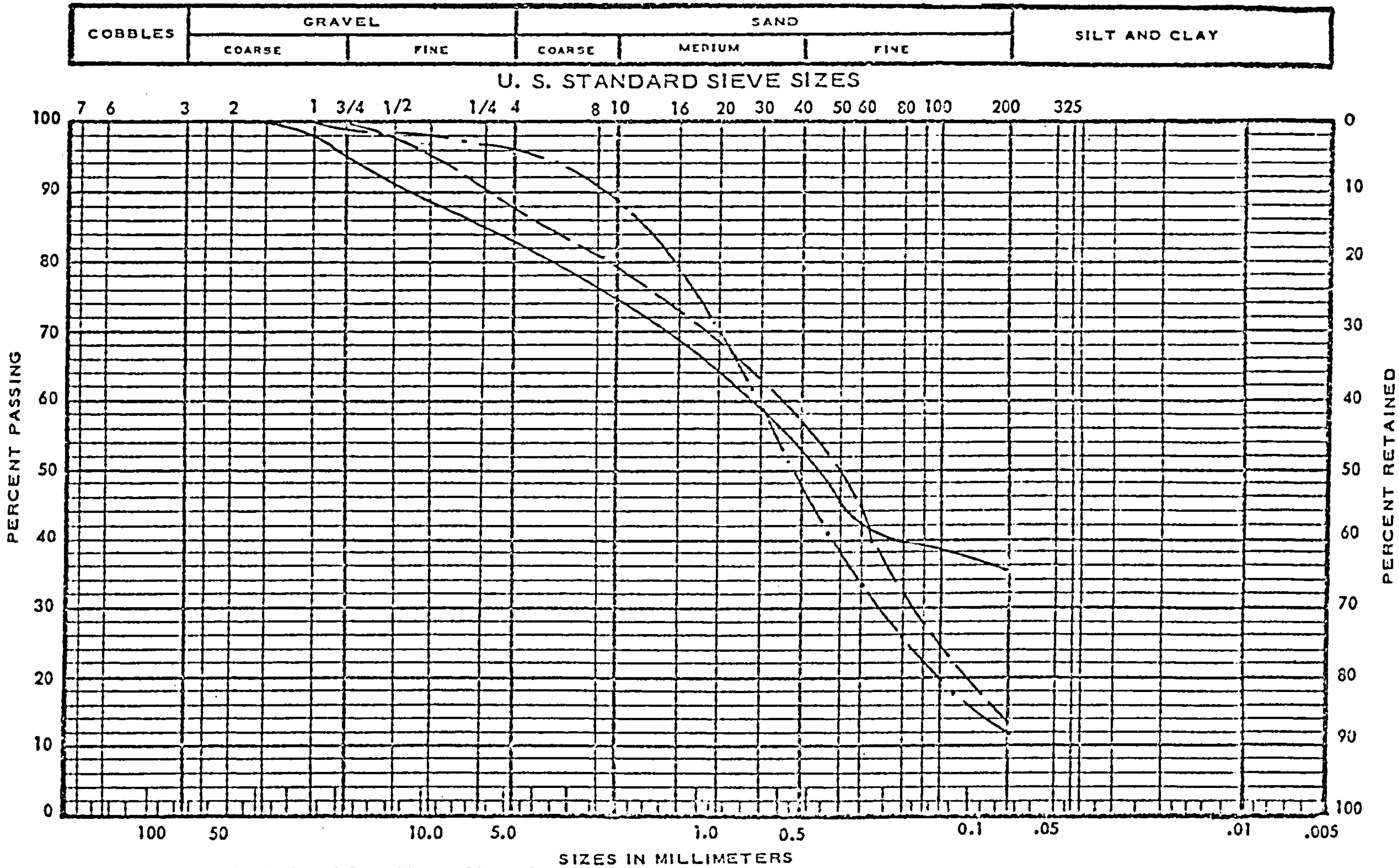
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
58	————	21	18	3	Poorly graded sand w/20% non-plastic fines (SM)
59	— — —	21	21	0	Poorly graded sand w/20% non-plastic fines (SM)
60	—·—·—	---	---	0	Poorly graded sand w/14% non-plastic fines (SM)

Figure A23. Laboratory Soil Data for Samples 58, 59, and 60.



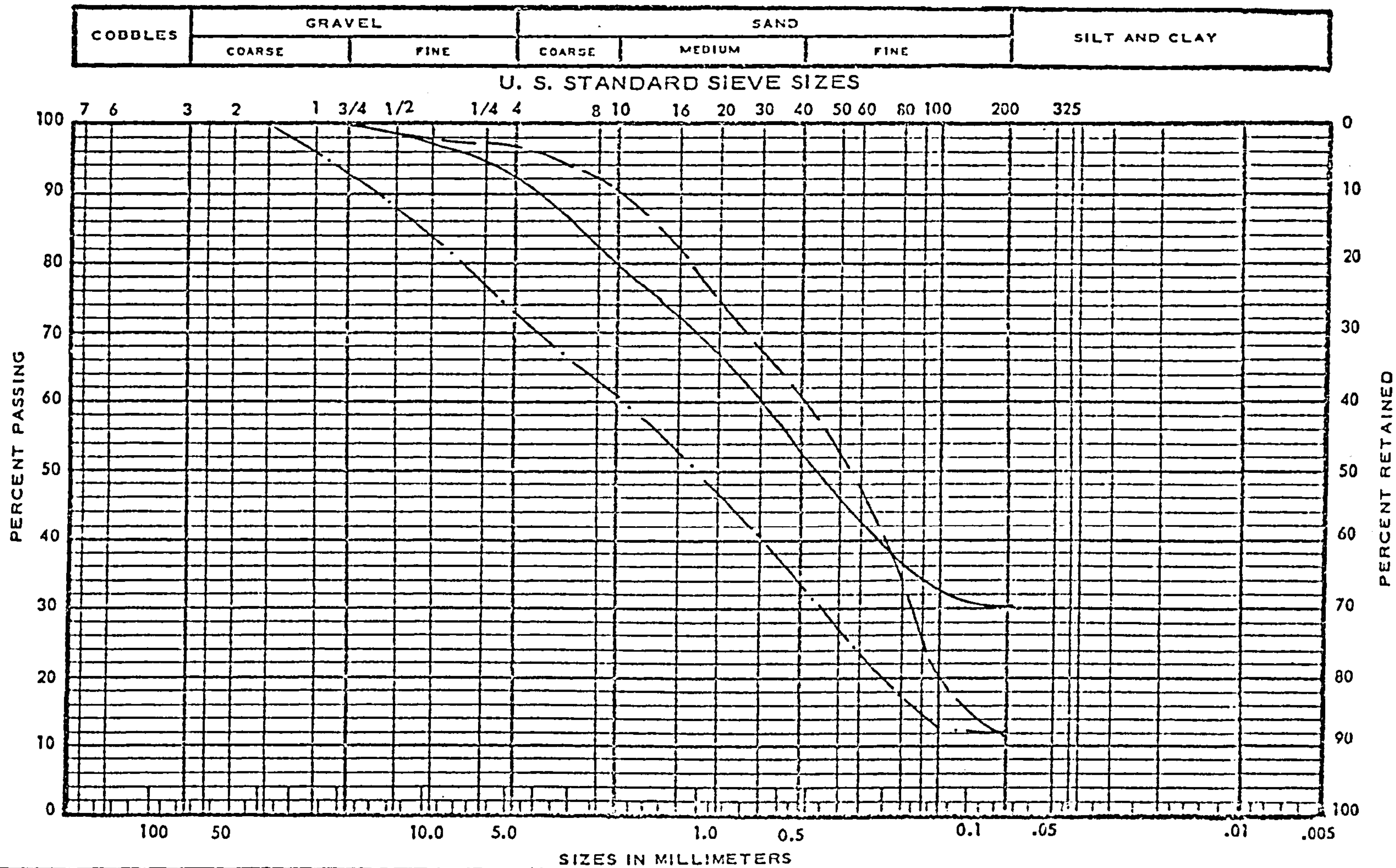
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
61	————	---	---	0	Poorly graded sand w/13% non-plastic fines (SM)
62	— — —	23	18	5	Poorly graded sand w/27% slightly plastic fines (SM)
65	—·—·—	23	17	6	Poorly graded sand w/23% slightly plastic fines (SM-SC)

Figure A24. Laboratory Soil Data for Samples 61, 62, and 65.



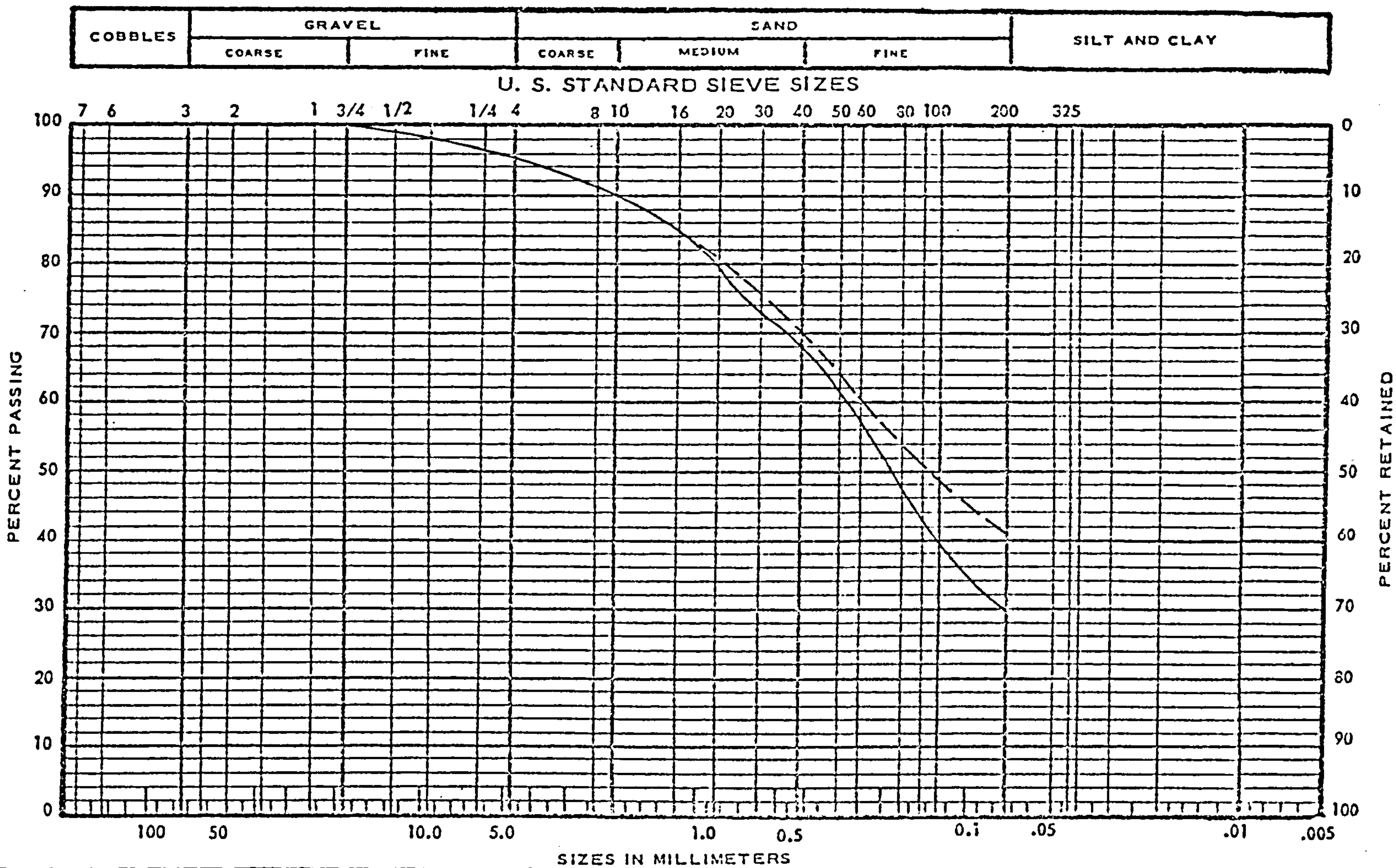
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
66	————	---	---	0	Poorly graded sand w/25% non-plastic fines (SM)
67	— — —	---	---	0	Poorly graded sand w/23% non-plastic fines (SM)
68	—·—·—	20	14	6	Poorly graded sand w/12% slightly plastic fines (SP-SM-SC)

Figure A25. Laboratory Soil Data for Samples 66, 67, and 68.



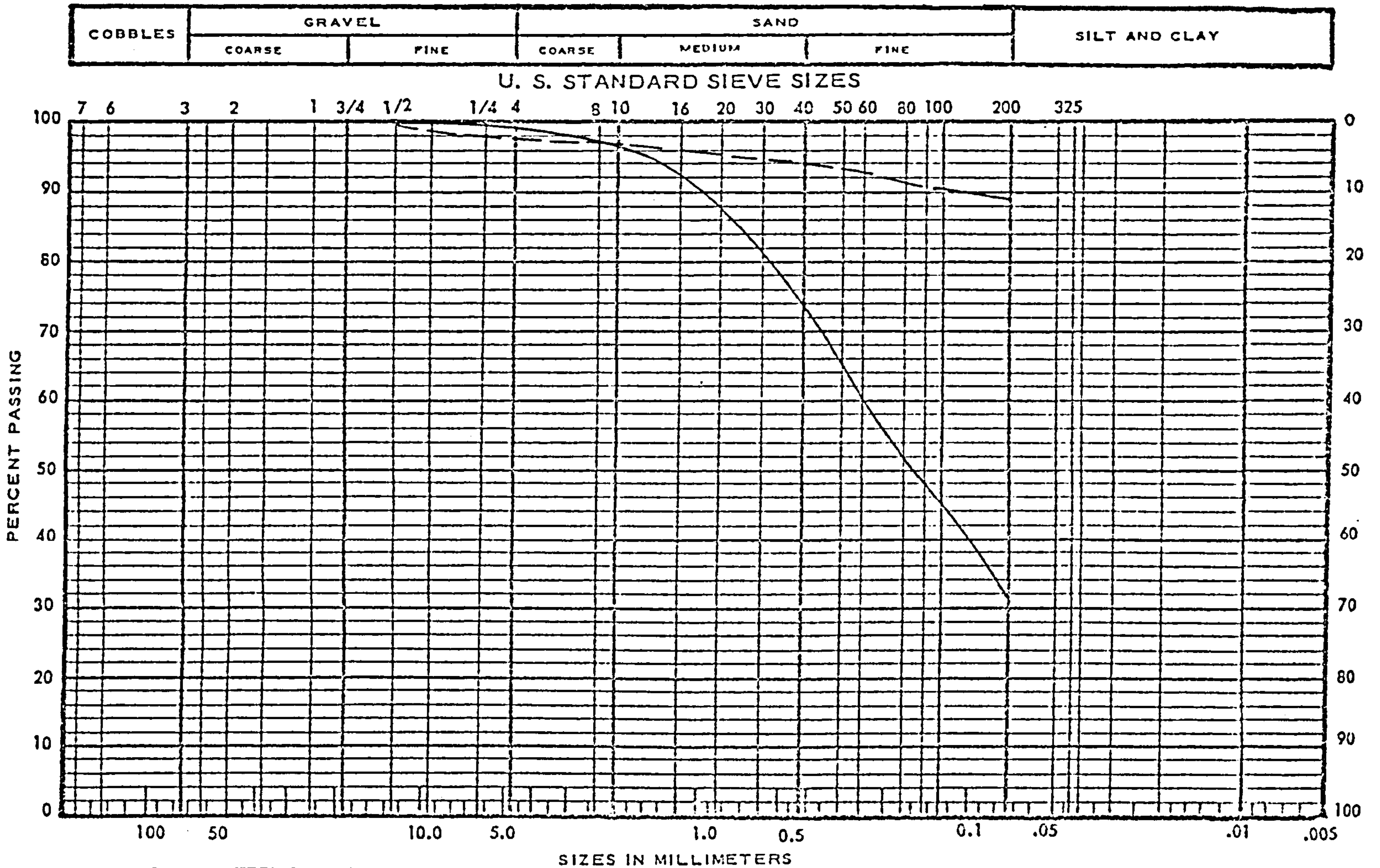
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
69	————————	24	22	2	Poorly graded sand w/30% non-plastic fines (SM)
70	—— —— ——	---	---	0	Poorly graded sand w/11% non-plastic fines (SP-SM)
71	——·——·——	27	23	4	Poorly graded sand w/13% slightly plastic fines (SM)

Figure A26. Laboratory Soil Data for Samples 69, 70, and 71.



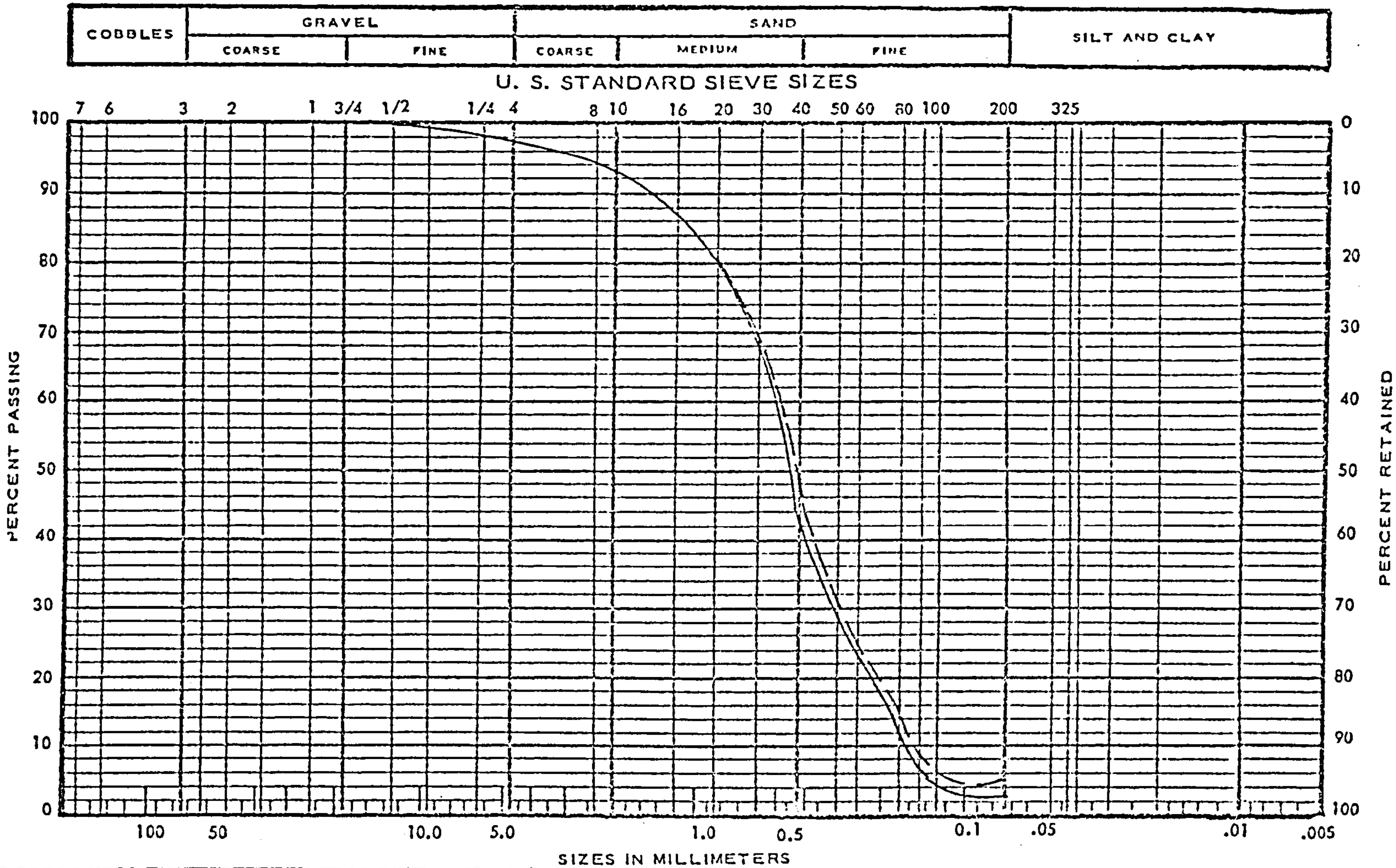
SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
25 Dry	————	---	---	---	Poorly graded sand with 30% non-plastic fines (SM)
25 Washed	— — —	---	---	---	Poorly graded sand w/42% non-plastic fines (SM)

Figure A27. Laboratory Soil Data for Samples 25 Dry and 25 Washed.



SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
72 Dry	————	---	---	---	Poorly graded sand w/32% slightly plastic fines (SM)
72 Washed	— — —	---	---	---	Slightly plastic inorganic silt (ML)

Figure A28. Laboratory Soil Data for Samples 72 Dry and 72 Washed.



SAMPLE NO.	SYMBOL	LL	PL	PI	CLASSIFICATION
75 Dry	————	---	---	---	Poorly graded sand w/2% non-plastic fines (SP)
75 Washed	— — —	---	---	---	Poorly graded sand w/4% non-plastic fines (SP)

Figure A29. Laboratory Soil Data for Samples 75 Dry and 75 Washed.

LIST OF REFERENCES

Abdullatif, A. Abdullatif. 1969. "Physical Testing of Engineering Properties of Collapsing Soils in the City of Tucson, Arizona," Master's Thesis, The University of Arizona, 135 pp.

Abu-Obeid, Hamid A. 1970. "Dynamic Testing of Desert Soils," Master's Thesis, The University of Arizona, 78 pp.

Agricultural Engineering Department. 1971. Ground-water maps. The University of Arizona.

Anderson, Frank J. 1968. "Collapsing Soils and Their Basic Parameters in the Area of Tucson, Arizona," Master's Thesis, The University of Arizona, 104 pp.

Beebe, Gary. 1972. Southern California Testing Laboratory, Inc., 6280 Riverdale, San Diego, California (with permission).

Bull, William B. 1964. "Alluvial Fans and Near-Surface Subsidence in Western Fresno County, California," U.S.G.S. Professional Papers 437-A, 72 pp.

Bull, William B. 1970. Prehistoric Near-Surface Subsidence Cracks in Western Fresno County, California, U.S.G.S. Open File Report, 255 pp. (with permission).

Bull, William B. 1972a. Land Subsidence Due to Ground-Water Withdrawal in the Los Banos-Kettleman City Area, California, Part 2: "Subsidence and compaction of deposits," U.S.G.S. Open File Report, 164 pp. (with permission).

Bull, William B. 1972b. Land Subsidence Due to Ground-Water Withdrawal in the Los Banos-Kettleman City Area, California, Part 3: "Interrelations of water-level change, change in aquifer-system thickness, and subsidence," U.S.G.S. Open File Report, 202 pp. (with permission).

Bull, William B. and Raymond E. Miller. 1972. Land Subsidence Due to Ground-Water Withdrawal in the Los Banos-Kettleman City Area, California, Part 1: "Changes in the hydrologic environment conductive to subsidence," U.S.G.S. Open File Report, 164 pp. (with permission).

Cooley, Donald B. 1966. "Geologic Environment and Engineering Properties of Caliche in the Tucson Area, Tucson, Arizona," Master's Thesis, The University of Arizona, 96 pp.

Corps of Engineers. May 1967. The Unified Soil Classification System, Technical Memorandum No. 3-357, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Crossley, Robert W. 1969. "A Geologic Investigation of Foundation Failures in Small Buildings in Tucson, Arizona," Master's Thesis, The University of Arizona, 58 pp.

Davidson, Edward S. May 1970. Geohydrology and Water Resources of the Tucson Basin, Arizona, U.S.G.S. Open File Report, 228 pp. (with permission).

Grove, George T. 1962. "Rillito Creek Flood Plain Study," City-County Planning Department, Tucson, Pima County, Arizona.

Howell, A. V. 1966. Glossary of Geology and Related Sciences, American Geological Institute, Washington, D.C.

International Conference of Building Officials. 1964. Uniform Building Code, Vol. I, Pasadena, California.

Jackson, Henry M. 1969. Mineral and Water Resources of Arizona, Arizona Bureau of Mines Bulletin 180, 638 pp.

Jones, Neil O. 1968. "The Development of Piping Erosion," Doctorate Dissertation, The University of Arizona, 163 pp.

Kidwai, Zamir U. 1957. "The Relationship of Ground Water to Alluvium in the Tucson Area, Arizona," Master's Thesis, The University of Arizona, 55 pp.

Lacy, Willard C. March 1964. "Geologic Causes of Foundation Failures in the Area of Tucson, Arizona," Society of Mining Engineers, Transactions, pp. 40-44.

Lambe, T. W. 1951. Soil Testing for Engineers, John Wiley and Sons, Inc., New York, N.Y.

Lambe, T. W. and R. V. Whitman. 1969. Soil Mechanics, John Wiley and Sons, Inc., New York, N.Y.

Langbein, W. B. and Kathleen T. Iseri. 1960. "General Introduction and Hydrologic Definitions: Manual of Hydrology: Part 1, General Surface-Water Techniques," U.S.G.S. Water Supply Paper 1541-A, pp. 1-30.

Leopold, Luna B. 1968. "Hydrology for Urban Land Planning--A Guidebook of the Hydrologic Effects of Urban Land Use," U.S.G.S. Circular 554, 18 pp.

Lindeke, Bruce and Milada Pajaczkowski. 1970. "Subsidence in the Tucson Basin," Geological Engineering 206 Report, The University of Arizona, 23 pp. (unpublished).

Lofgren, B. E. and R. L. Klausing. 1969. "Land Subsidence Due to Ground-Water Withdrawal, Tulare-Wasco Area, California," U.S.G.S. Professional Paper 437-B, 101 pp.

Massanat, Yousef M. 1972. "Evaluation of Factors Contributing to Piping Erosion Near Benson, Cochise County, Arizona," Master's Thesis, The University of Arizona, 73 pp.

Morrison, Roger. 1971. "Photointerpretative Geologic-Terrain Mapping and its Application to Land Use Planning in Tucson Metropolitan Area," Applied Remote Sensing of Earth Resources in Arizona, Proc. 2nd ARETS Symp., The University of Arizona, Tucson, Arizona, pp. 199-205.

Pashley, Emil F. 1966. "Structure and Stratigraphy of the Central, Northern, and Eastern Parts of the Tucson Basin, Arizona," Doctorate Dissertation, The University of Arizona, 273 pp.

Peirce, Wes. July 12, 1972. Arizona Bureau of Mines (personal communication).

Peterson, Dennis E. 1962. "Earth Fissuring in the Picacho Area, Pinal County, Arizona," Master's Thesis, The University of Arizona, 35 pp.

Platt, Wallace S. 1963. "Land-Surface Subsidence in the Tucson Area," Master's Thesis, The University of Arizona, 38 pp.

Schwalen, H. C. and R. J. Shaw. 1957. Water in the Santa Cruz Valley, Bulletin 208, Agricultural Experiment Station, The University of Arizona, p. 6 (with permission).

Seal, Claude. 1972. Production Engineer, San Xavier Rock and Sand Co., 1000 W. Valencia Road, Tucson, Arizona (personal communication).

Sowers, G. F. and G. W. Sowers. 1951. Introductory Soil Mechanics and Foundations, 2nd Ed., Macmillan Co., New York, N.Y., p. 111.

Strietz, Robert. 1962. "Subsurface Stratigraphy and Hydrology of the Rillito Creek-Tanque Verde Wash Area, Tucson, Arizona," Master's Thesis, The University of Arizona, 60 pp.

Sultan, Hassan A. August 1969. "Foundation Failures on Collapsing Soils in the Tucson, Arizona Area," Second Conference on Expansive and Collapsing Soils, Texas A&M University, 20 pp.

Sultan, Hassan A. 1971a. "Soil Subsidence, Collapsing Soils," Outline of Personal Notes (unpublished, with permission).

Sultan, Hassan A. 1971b. "Some Engineering Aspects of Collapsing Soils," Prepared for Presentation at Highway Research Board Annual Meeting, 25 pp. (unpublished, with permission).

Tanenbaum, Ronald J. 1972. "Flood-Urbanization Interface," Department of Mining and Geological Engineering, College of Mines, The University of Arizona, 50 pp. (unpublished).

Taylor, Donald W. 1948. Fundamentals of Soil Mechanics, John Wiley and Sons, Inc., New York, N.Y., 700 pp.

Williams, Frank E. 1967. Urbanization and the Mineral Aggregate Industry, Tucson, Arizona Area, U.S.B.M. Information Circular 8318, 23 pp.

Wilson, Eldred D. 1962. A Resume of the Geology of Arizona, Arizona Bureau of Mines Bulletin 171, 140 pp.

7 pieces
in box

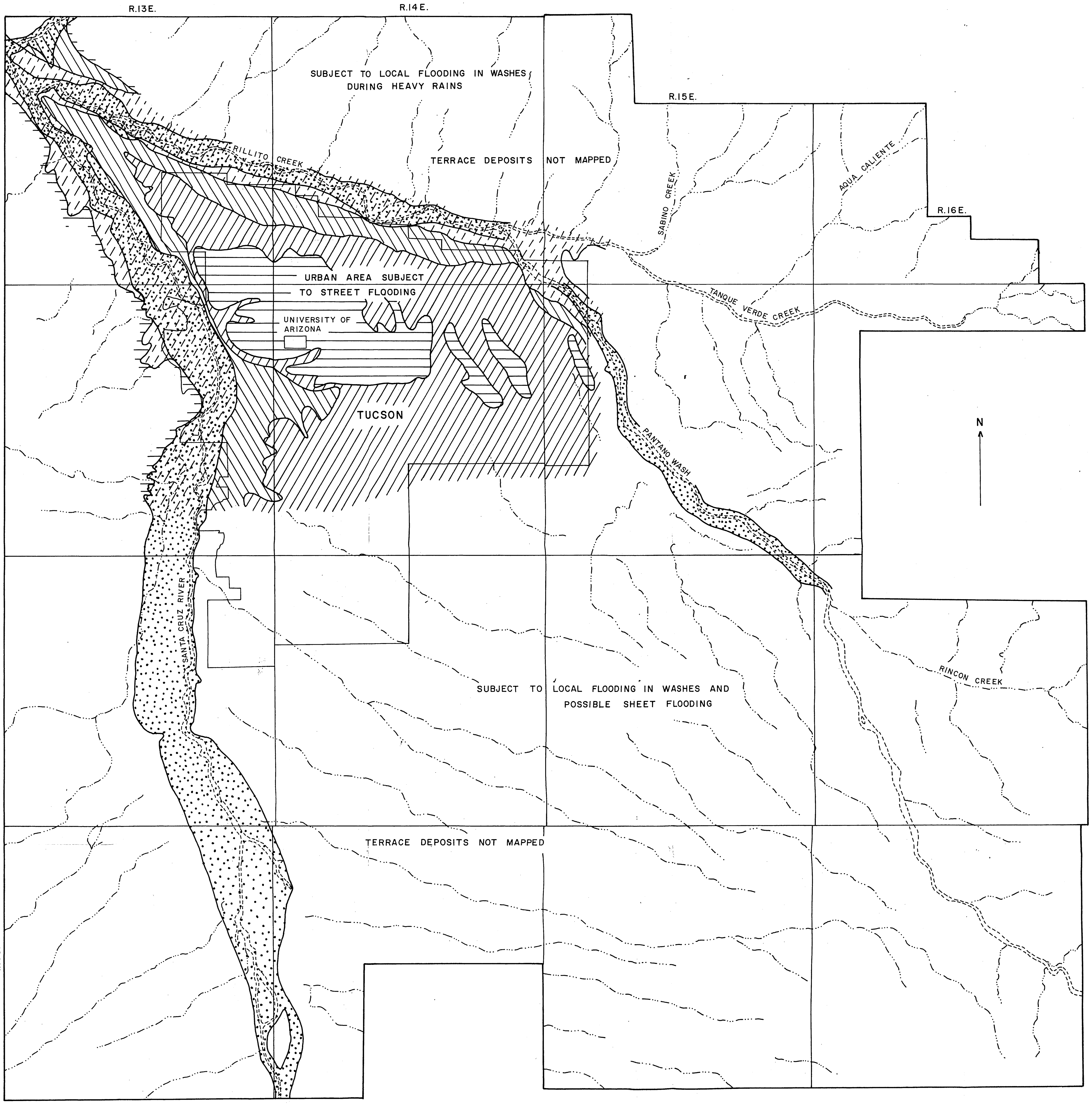


FIGURE 4

FLOOD INUNDATION AND TERRACES IN THE TUCSON BASIN PIMA COUNTY, ARIZONA

RONALD J. TANENBAUM
1972

SCALE 1:62500

0 1 2 3 4
MILES

EXPLANATION

UNIVERSITY TERRACE

CEMETARY TERRACE

JAYNES TERRACE

Note: Terrace information from Cooley, 1966.

BOTTOM LAND

AREAS HAVING A 1 TO 100 CHANCE OF BEING INUNDATED BY FLOODING.

Note: Flood inundation areas based on U.S.G.S. flood prone maps as of 1970. (Does not take into account present or forecasted control facilities. Research is still being carried out by the U.S.G.S. in the areas where the data is not available. Additional data was taken from Morrison, 1971.

C.F. Shakel

R. J. TANENBAUM
GEOLOGICAL ENGINEERING, THESIS
1972

1972 # 398 cop 2 Tannenbaum

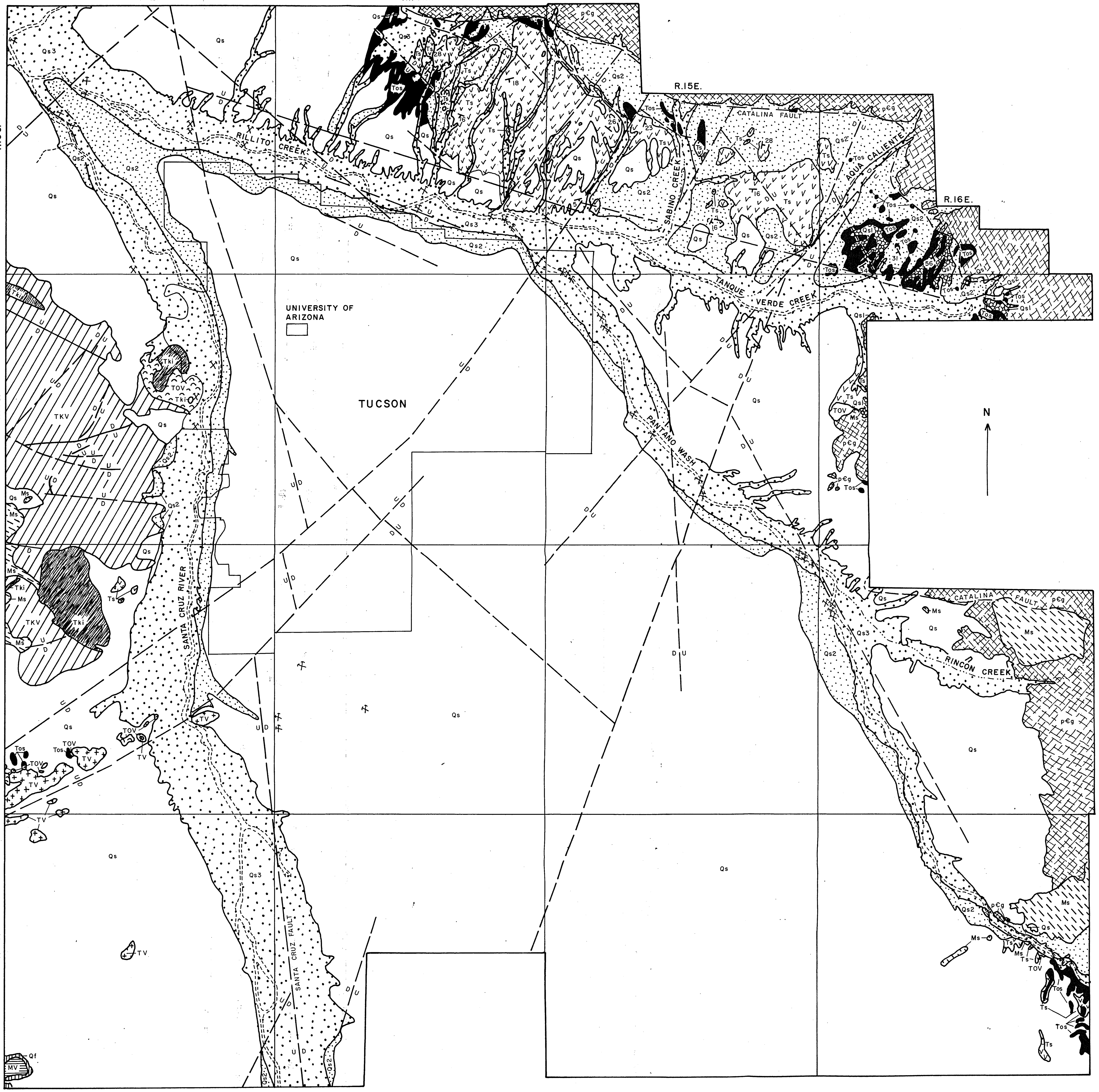


FIGURE 5
GEOLOGY OF THE TUCSON BASIN PIMA COUNTY, ARIZONA

RONALD J. TANENBAUM
1972

SCALE 1:62500

0 1 2 3 4
MILES

EXPLANATION

SEDIMENTARY ROCKS

HOLOCENE

- **Qs3** — Stream and flood-plain alluvial deposits. Underlie stream channels and flood plains; gravel and gravelly sand to sandy silt.
- **Qs2** — Youngest terrace deposits. Underlie the Jaynes Terrace; gravel and gravelly sand.

PLEISTOCENE

- **Qsl** — Intermediate terrace deposits. Underlie Cemetery Terrace; gravel and gravelly sand.
- **Qs** — Alluvial deposits undifferentiated. Underlie the oldest University or Intermediate Cemetary Terraces; include alluvial deposits of the Cemetary Terrace or younger deposits which overlie the Ft. Lowell Fm.; include outcrops of the Ft. Lowell Fm. in the foothills of the Santa Catalina Mts.; Gravel and gravelly sand to sandy silt.

UNCONFORMITY

- **Qf** — Fort Lowell Formation. Gravelly to clayey silt.

MIOCENE and PLIOCENE

UNCONFORMITY

- **Ts** — Tinaja Beds. Gravel and conglomerate to gypsiferous clayey silt and mudstone; includes basaltic andesite flows and dacite tuff.

OLIGOCENE

UNCONFORMITY

- **Tos** — Pantano Formation. Conglomerate sandstone, mudstone and gypsiferous mudstone; includes tuff beds and interbedded volcanic flows.

UPPER CRETACEOUS, PALEOCENE & EOCENE

UNCONFORMITY

- **Ms** — Sedimentary rocks undifferentiated. Conglomerates, sandstone, mudstone, shale and some limestone; interbedded volcanic flows, tuffs and agglomerate tuff; includes limestone and quartzite of Paleozoic age.

UNCONFORMITY

- **p€t** — Quartzite. Does not outcrop in study area.

Approximate gravel pit locations.

IGNEOUS AND METAMORPHIC ROCKS

TERTIARY

- **TV** — Flows and tuff. Basaltic andesite, dacite, some interbedded conglomerate and sandstone.
- **Ti** — Intrusive necks and dikes. Dacite and andesite. Does not outcrop in study area.

UNCONFORMITY

- **TOV** — Flows, tuff, agglomerate, and volcanic breccia. Basaltic andesite to rhyolite; rhyodacite and some interbedded conglomerate, sandstone and siltstone.

CRETACEOUS and TERTIARY

UNCONFORMITY

- **TKV** — Welded tuff, breccia, flows, tuff and interbedded sedimentary rocks. Andesite to dacite, rhyodacite, conglomerate, sandstone, gray shale, and siltstone.
- **Tki** — Intrusive plugs. Quartz monzonite, quartz latite porphyry, diorite and granodiorite.

MESOZOIC and PALEOZOIC

UNCONFORMITY

- **MV** — Flows, welded tuff, agglomeratic tuff, and volcanic breccia, interbedded sedimentary rocks. Rhyolite, latite, rhyodacite, dacite and and andesite; minor interbedded conglomerate, sandstone, quartzite and mudstone.
- **Mi** — Intrusive plugs. Granite and monzonite. Does not outcrop in study area.

PRECAMBRIAN

UNCONFORMITY

- **p€g** — Intrusive and metamorphic rocks. Granite, granite gneiss and schist.

HIGH ANGLE FAULT

- U/D — Probable location
- U/D — Inferred location

LOW ANGLE FAULT

- 21 — dip
- 17 — Strike and dip of beds

NOTE: From E. S. Davidson's Geohydrologic Map, 1970 (with permission). Gravel pit data from Williams, 1967.

C. F. Shakel

R. J. TANENBAUM
GEOLOGICAL ENGINEERING, THESIS
1972

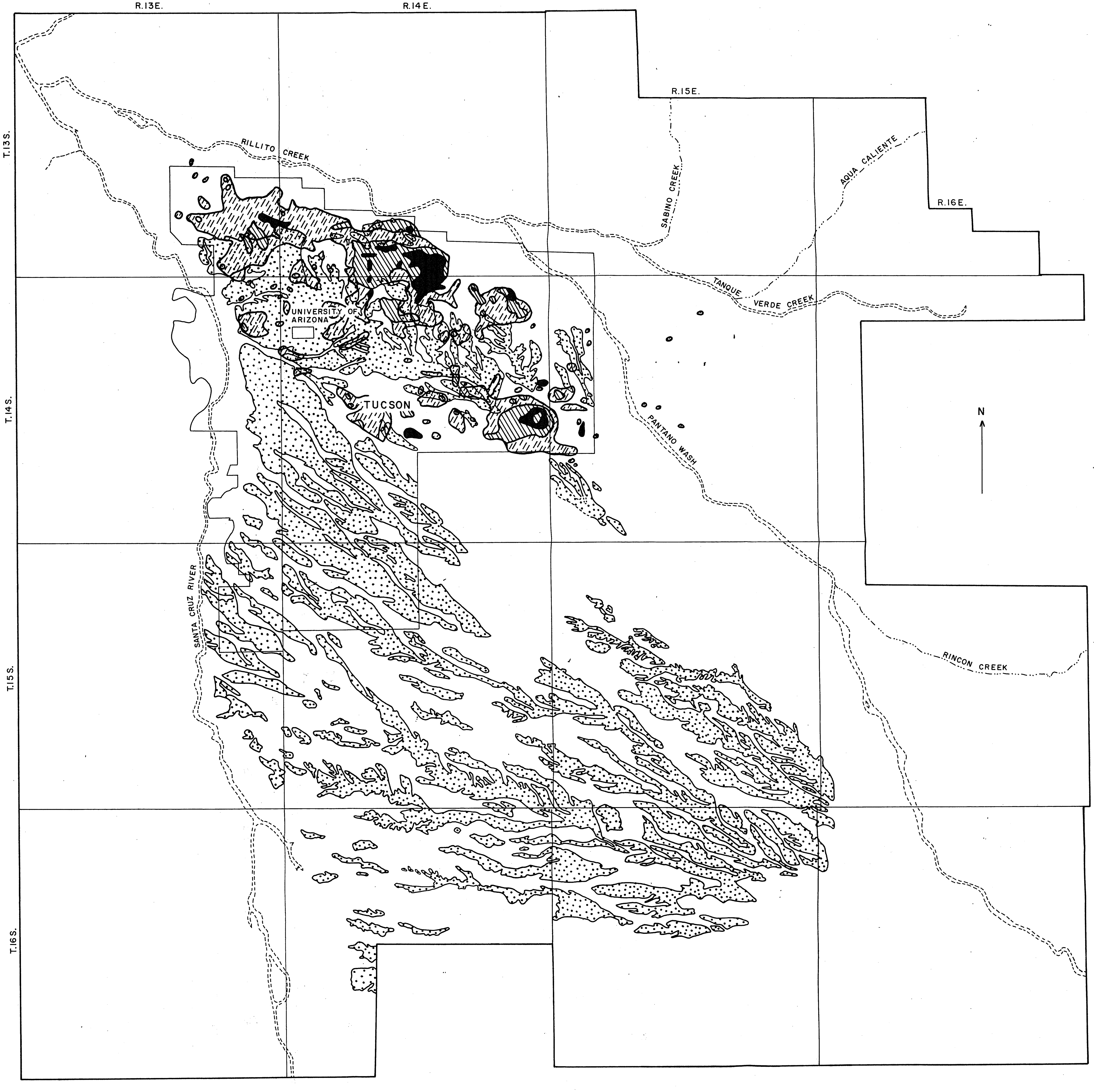


FIGURE 12

CALICHE DISTRIBUTION AND FOUNDATION FAILURE INTENSITIES IN THE TUCSON BASIN PIMA COUNTY, ARIZONA

RONALD J. TANENBAUM
1972

N

SCALE 1:62500

0 1 2 3 4
MILES

EXPLANATION

CALICHE DISTRIBUTION

SURFACE AND NEAR-SURFACE CALICHE

Note: After Cooley, 1965.

FOUNDATION FAILURE INTENSITY

LIGHT INTENSITY

MODERATE INTENSITY

STRONG INTENSITY

Note: After Crossley, 1968.

C. F. Shakel

R. J. TANENBAUM
GEOLOGICAL ENGINEERING, THESIS
1972

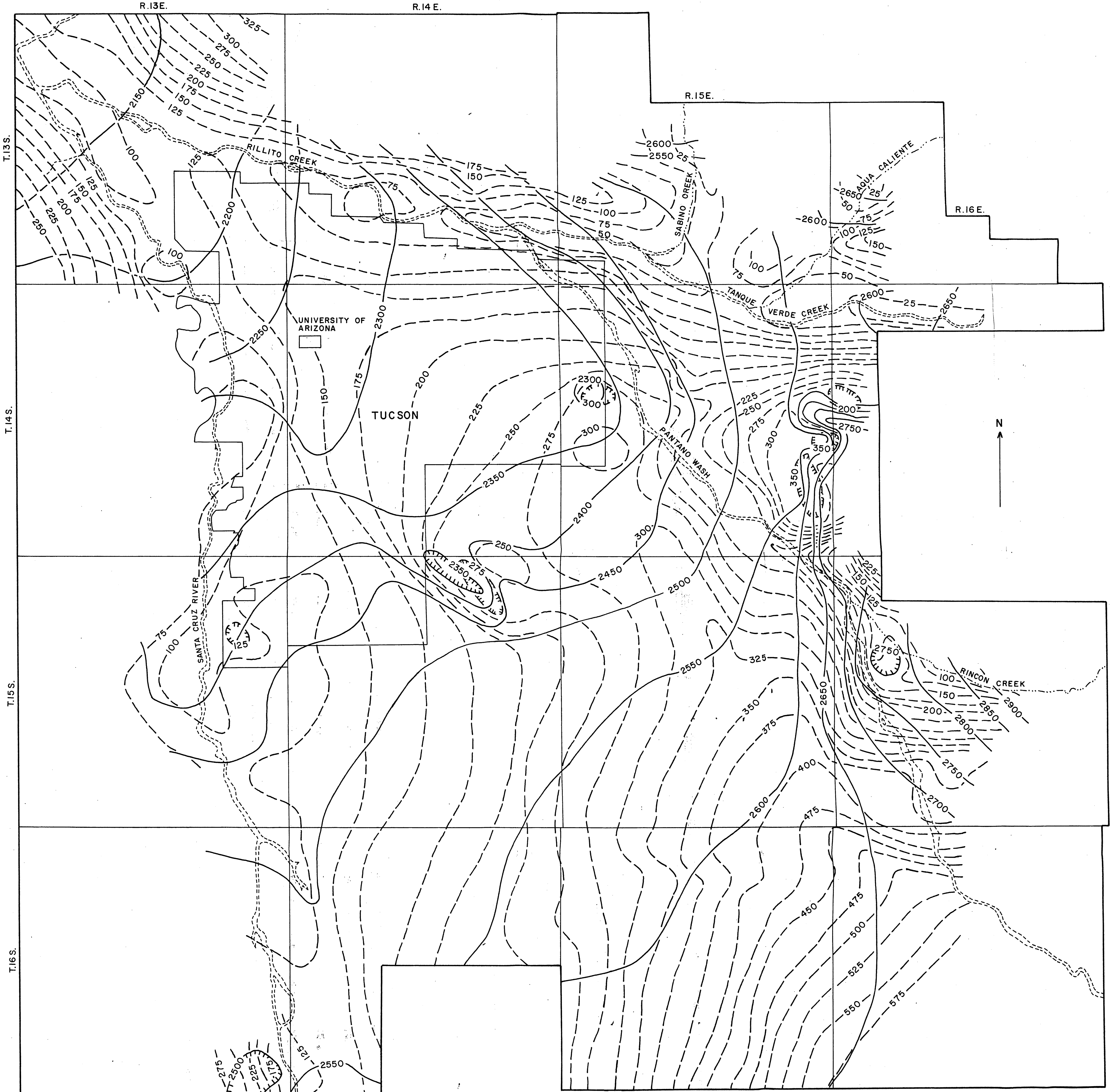


FIGURE 16

1971, GROUND-WATER LEVEL CONTOURS AND DEPTH TO WATER IN THE TUCSON BASIN PIMA COUNTY, ARIZONA

RONALD J. TANENBAUM
1972

SCALE 1:62500

0 1 2 3 4
MILES

EXPLANATION

—2550— GROUND-WATER CONTOURS
50 Foot Intervals
Elevations Above Mean Sea Level

— —25— LINES OF EQUAL DEPTH
25 Foot Intervals

Note: From maps prepared by the Agricultural Engineering Department, University of Arizona, 1971

C.F. Shakel

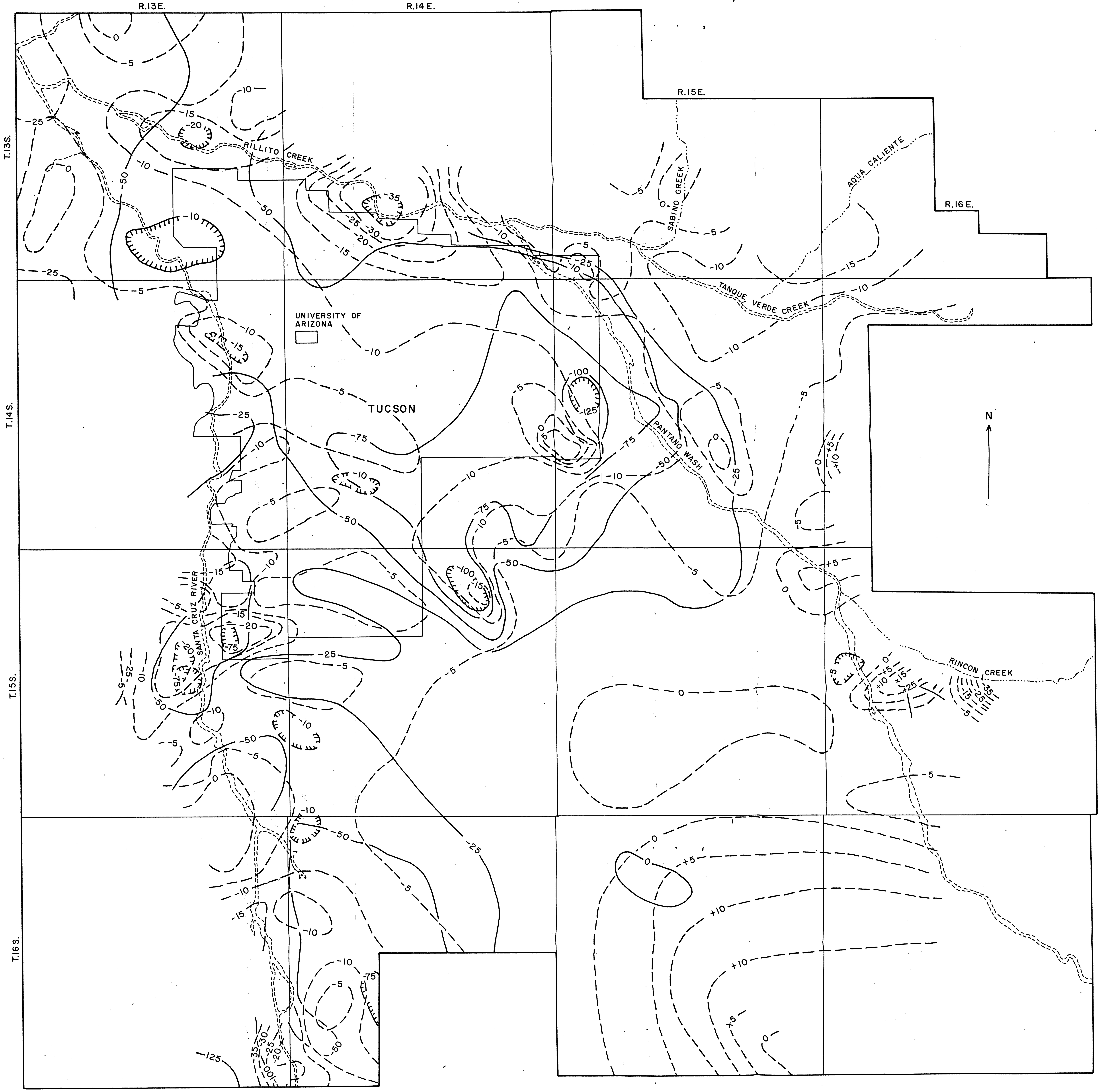


FIGURE 17

CHANGES IN DEPTH TO GROUND WATER IN THE TUCSON BASIN PIMA COUNTY, ARIZONA

RONALD J. TANENBAUM
1972

SCALE 1:62500

0 1 2 3 4
MILES

N

EXPLANATION

—25— LINES OF EQUAL CHANGE
25 Foot Intervals
1947-1971

--5-- LINES OF EQUAL CHANGE
5 Foot Intervals
1968-1971

Note: From maps prepared by the Agricultural Engineering Department, University of Arizona, 1971

C.F. Shakel

R. J. TANENBAUM
GEOLOGICAL ENGINEERING, THESIS
1972

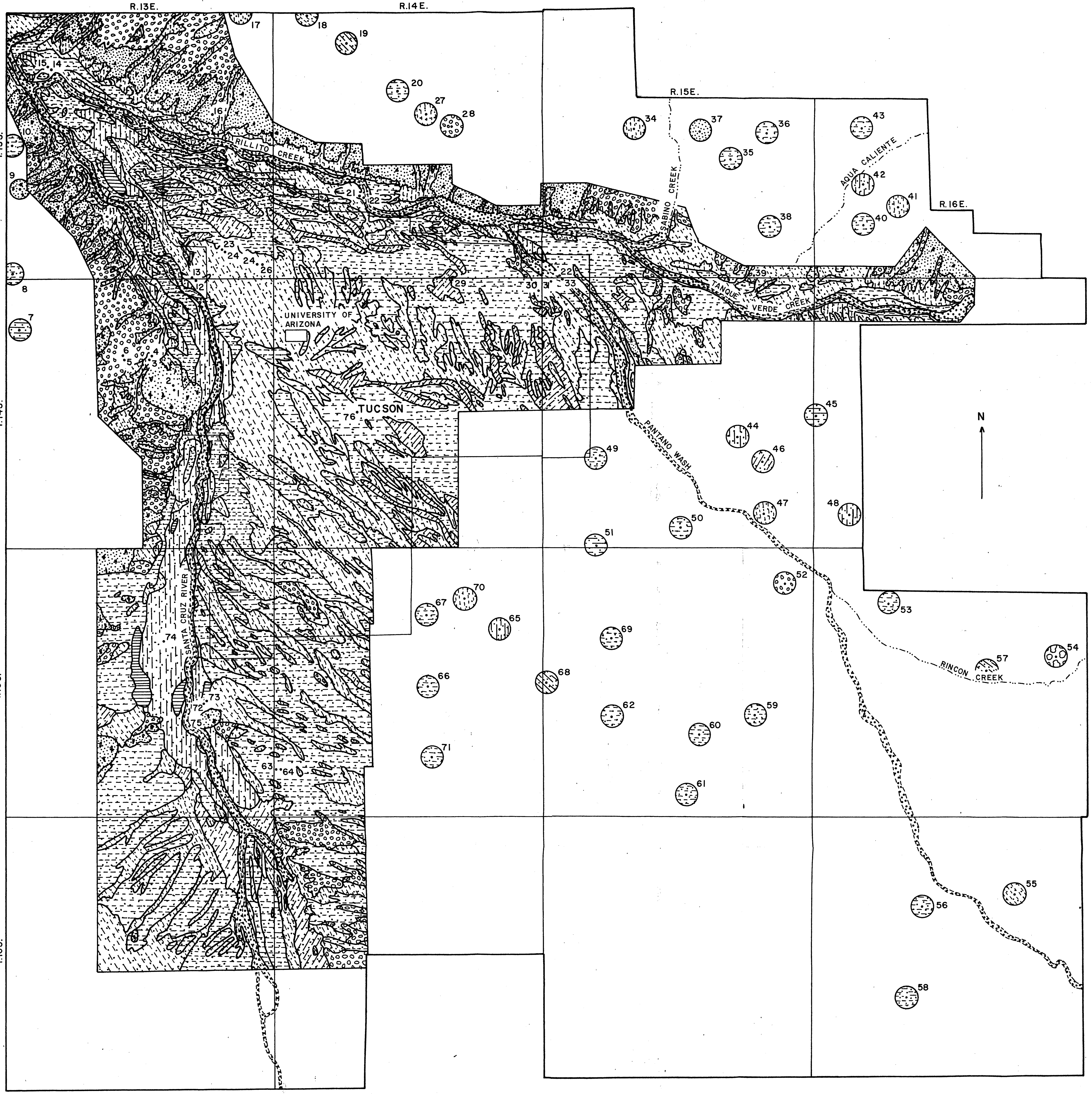


FIGURE 19
GENERAL SOIL TYPES IN THE TUCSON BASIN PIMA COUNTY, ARIZONA

RONALD J. TANENBAUM
1972

N

SCALE 1:62500

0 1 2 3 4
MILES

EXPLANATION

- Poorly graded gravel with about 1% non-plastic fines; decomposed rock (GP)
- Poorly graded gravel with about 13% non-plastic fines; alluvium (GP-GM), [GC]
- Poorly graded sand with about 7% slightly plastic fines and scattered cobbles (SP-SM) [Rough broken & stoney land]
- Poorly graded sand with about 5% non-plastic fines; some gravel lenses; riverwash (SP) [GP Riverwash]

– – – – –

- Poorly graded sand with about 8% non-plastic fines; alluvium (SP-SM) [SM]
- Poorly graded sand with about 11% non-plastic fines; stream deposits (SP-SM) [SW]
- Poor graded sand with about 22% non-plastic fines; alluvium (SM) [SP], [ML-CL]

– – – – –

- Poorly graded sand with about 12% slightly plastic fines; alluvium (SP-SM-SC)
- Poorly graded sand with about 20% slightly plastic fines; alluvium (SC) [CL]
- Poorly graded sand with about 25% slightly plastic fines; flood plain deposits (SM-SC) [MH, OH ML-CL], [ML]
- Poorly graded sand with about 9% medium plastic fines; alluvium (SP-SC)
- Slightly plastic inorganic silt; flood plain deposits (ML) [CH]

2 Soil type in the vicinity of the sample location

NOTE: The first classification was determined from the laboratory tests of the field samples. The classification in brackets is derived from data taken from a 1931 U.S.D.A. Soils Map and data collected by W. C. Lacy, Dept. of Mining and Geological Engineering, Univ. of Arizona.
This map should not be used for the location of a particular soil and is only meant to indicate the variety of soils present in the basin.

C.F. Shakel

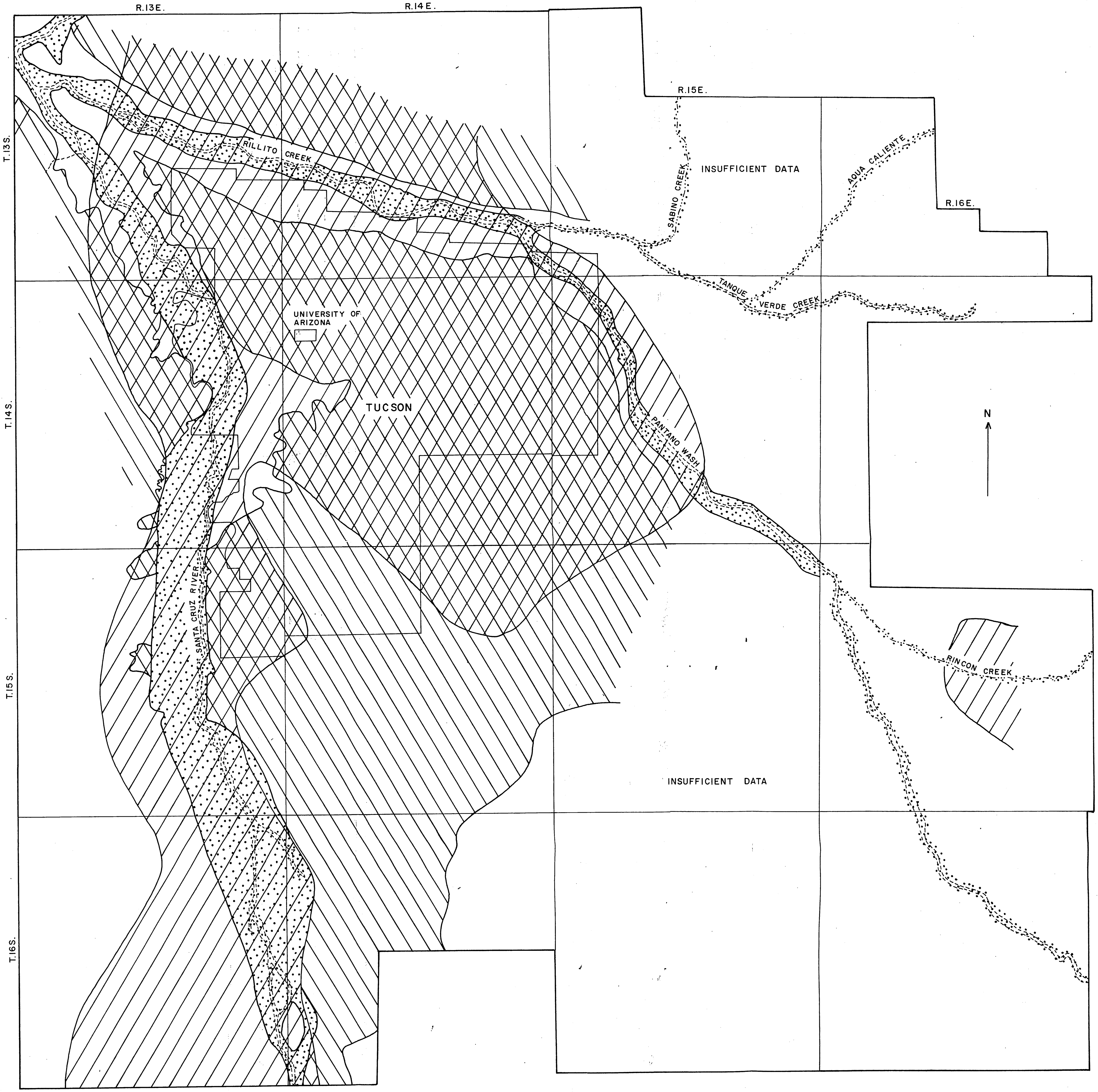


FIGURE 20
GEOLOGICAL ENGINEERING FACTORS IN THE TUCSON BASIN PIMA COUNTY, ARIZONA

RONALD J. TANENBAUM
1972

SCALE 1:62500

0 1 2 3 4
MILES

EXPLANATION

The central portion of the basin is affected by collapsing soils of varying potential. Earthquakes are influential throughout the entire basin depending on the basin geology. Based on the existing information, the piping potential cannot be delineated.

Areas expected to undergo deep subsidence under the influence of ground-water withdrawals and cones of water depression.

Areas affected by caliche as a nuisance.

Areas prone to flooding.

NOTE: All boundaries are inferred.

C.F. Shakel

R. J. TANENBAUM
GEOLOGICAL ENGINEERING, THESIS
1972