# SOIL FACTORS IN THE FAILURE OF EARTHEN DAM STRUCTURES

By

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# SOIL FACTORS IN THE FAILURE OF
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# CHAPTER I

# INTRODUCTION

Since the beginning of time, man has wasted and conserved the natural resources of this earth. One of the most precious resources to mankind has been pure water suitable for human consumption and use. The quest for water has increased over the decades as the demand increased due to a growing population. Man is well aware of the water cycle with its periods of droughts and floods. The need to conserve water for drought periods, and various means of conserving a water supply have been used. The most common means of storing water has been the construction of dams across waterways. These dams have been constructed of various materials from concrete and steel to soil.

The retaining structures or dams of earthen materials vary in size from the massive world record Fort Peck Dam located on the Missouri River in the state of Montana with its 125,628,000 cubic yards of earth and rock fill, and 3.98 mile length with a height of 251 feet; to the small farm pond dams which dot the countryside and average twenty to forty feet in height.

In recent years, various parts of the world have experienced a building boom in terms of small earthen dams for conserving water to meet the needs of small municipalities and to prevent floods along streams and rivers. With the increase in the construction of small earthen dams, the problem of dam failures has appeared, thus creating the need for research and investigation into the causes of these failures.

The objective of this research was to investigate the chemical and mineralogical properties of soil materials from flood control dams that had failed as compared to the normal dam that had not failed.

# CHAPTER II

## LITERATURE REVIEW

The first reported incident in the literature of failures of small earthen dams was made by Volk (1937). The incident occurred in the Cove area in the state of Arizona. The dam failure was due to a reduction in the strength and volume of the soil when the soil was saturated with water. Volk suggested that soil dispersion was important in the failures of the dams. The earthen structures were made up of layers of material existing as saturated or wet layers and unsaturated or dry layers. The water saturated layers occurred below the unsaturated layers. The water saturated layers slumped away from the unsaturated layers and resulted in the formation of a "soil-pipe" or "soil arch."

Volk's concept of dispersive soils in the state of Arizona is not a new concept to soil scientists. For at least forty years, soil scientists have known about dispersive soils, especially the clay fraction, in the state of Arizona (Sherrard *et al*. 1972). The problem in these areas of Arizona, involves a surface layer of highly dispersive clay that is about twelve feet deep in some areas. The clay-soil layer is above a layer of gravel or sandy material. The clay is dispersed by rain water and is carried downward toward the gravel layer by means of various leakage channels. The leakage channels are formed as a result of decaying roots, shrinkage cracks and holes made by burrowing animals. These channels erode very rapidly under natural conditions thus forming the undesirable condition of tunneling, piping and sink holes on or near the soil surface. The surface was eventually eroded to the point that all agricultural activity was stopped and the land was left idle. These types of soils would surely present problems to the dam builder. According to Bell (1968), Carroll (1949), Heede (1971), Richards (1954) and Fletcher and Carroll (1948); the same type of damage in terms of tunneling occurs in other natural clay (soil) deposits.

Peterson and Iverson (1953) studied the failures of three small earthen dams in Canada due to "piping". Their investigation concluded that the failures were due to slumping of the lower water saturated layer of material away from the upper water unsaturated layer, thus leaving a passageway through which the water could flow. The flowing water results in the enlargement of the passageway and the formation of a "soil pipe".

Terzaghi and Peck (1968) define "piping" as follows: The water in a reservoir is discharged by means of an outlet passage. The width and depth of the passage is increased by erosion resulting from the rapidly moving water. The moving water will cause the surface material above the passage to collapse and be carried away by the current. Terzaghi and Peck believe that dam failures due to piping are caused by two entirely different processes. The processes are: (1) subsurface erosion and failure due to "heave". In the subsurface erosion process, the erosion starts near the base of the earthen structure and progresses backward toward the reservoir of water. The failure of the structure occurs when the erosion process has completely eroded a passageway through the base of the dam. (2) The process of "heave", causes the piping failure to be encouraged to develop by a sudden upward movement or rise in the soil near the base of the dam. The failure occurs when the pressure of the seepage water is greater than the weight of the soil. Parker (1963), Parker, Shown and Ratzlaff (1964) and Terzaghi and Peck (1948) define "piping" as a destructive subsurface erosion phenomenon. They report "piping" occurs throughout the world. A majority of the reported cases of "piping" appear to occur in the arid to semi-arid regions of the world. Piping has been classified into three types due to its origin. The types of piping are: (1) desiccation - stress cracks, (2) entrainment and (3) variable permeability subsidence. The variable permeability-subsidence type of piping results in the movement of sand, silt and dispersive clay thru the open pipes which have developed in the embankment of the dam. The desiccation crack type of "piping" is a serious problem along many highways in the western United States. Water enters the cracks at the surface and through erosion of the cracks damage and failure of the structure may result. According to Jumikis (1962), the entrainment type of "piping" is commonly associated with water retaining structures such as dams. This type of "piping" displaces enough material below the surface to result in a collapse of the surface above. The collapse will result in a rapid destruction of the structure.

Sherrard et al. (1963) believed that the principle causes of dam failures are piping and earth slides on the downstream portion of the dam. These researchers explained the phenomenon by the following example: The water which seeps through and under the dam generates or creates the erosion forces which pulls the soil particle along with the current of water. When the forces of erosion are greater than the forces resisting erosion, the soil particle is carried away and piping erosion begins.

Fletcher _et al_. (1954) states that the following five conditions must be present if soil pipes are to occur:

1. Water source
2. Permeability of a subsurface layer is less than the rate of water entering the surface.
3. A highly erodible layer of material must be above the impermeable layer of material.
4. A hydraulic gradient must exist in the highly erodible layer of material.
5. The lateral flowing water must have an outlet.

Downes (1946) applied the term tunneling erosion to the piping failures which occurred on the natural slopes due to percolating rain water. Aitchison (1960) believed that the failures by piping occurred when the percolating rain water dispersed the clay material from the slope. Jennings and Knight (1957) applied the term collapsing structure to the subsidence which occurs in alluvium material. In the more arid regions, alluvium, colluvium and loess are highly susceptible to subsidence when in the saturated state. Poland (1960) reported a lowering of the ground surface by ten to fifteen feet while Hardy (1950) reported a thirteen percent volume decrease caused by this subsidence.

Jumikis (1967) states that dam failures are influenced by climatic conditions and hydrologic conditions. Dam failures may also be caused by man's activity near the dam area. He believes the changes affecting the stability of man-made or natural slopes takes years to bring about a failure in the stability of the slope. He also indicates that the activity of water will cause a rupture of the soil and a failure of the slope. The water adds weight to the soil and decreases the cohesion of the soil resulting in a decrease in the soil shear strength. In unconsolidated soil, water is probably the main cause contributing to the many slides that result in this type of material. Jumikis states that slopes fail in the following ways: (1) slope failure occurs above or through the base of the dam, and (2) a base failure occurs when the surface rupture passes through the embankment and is below the base of the dam.

In recent years, the failure of small earthen dams in Australia has been reported (Sherrard _et al_. 1972). The failure dams are usually less than twenty feet in height and are used to retain water for farm and town use. The capacities of reservoirs range from .1 to 10 million gallons. The dams were crudely built with no drains or filters, and they were compacted by the traffic of the construction equipment, and because of the dry weather the earthen materials used were below optimum moisture content. Recent estimates show that 3,391 earthen dams were built and about 296 or 8.7 percent of the total failed due to piping. Saxena and Tarooqui (1968) report the number of failures and causes of the failures are known only to a few people, while successes are boldly reported.

The investigators of the failures of small earthen dams in Australia reported their findings which have been reviewed by Sherrard et al. (1973).

In summary these investigators found:

1. Certain clays can be classified as dispersive clays because of their highly erodible nature. (The nondispersive clays are used by engineers because of their resistance to erosion).
2. A dispersive or deflocculation process results in the erosion and piping of dispersive clays.
3. The development of piping in dispersive clays is influenced by the following factors: pH, exchangeable sodium percentage (ESP), soil type, and dissolved salts in the reservoir water.
4. As the piping leak develops in the dam embankment the following processes could occur. First, if the flow of water thru the leak is slow and allows the clay to swell and seal the leak off. Second, if the flow of water thru the leak is fairly rapid the leak will not seal off, and a serious piping failure will result.
5. The development of macropores due to inadequate compaction and cracks due to drying may lead to leaks developing in the embankment.
6. If the dam building material contains a large amount of montmorillonite or illite clay the chance of dam failure is increased. If the clay material contains kaolinite (a low-swelling clay) the chance of a dam failure is reduced.

The United States Soil Conservation Service has constructed several thousand small earthen dams for various purposes from flood control to providing water for irrigation and other general uses. The Soil Conservation Service has two main problem areas in the United States. These areas are: (1) Mississippi and (2) Oklahoma (Sherrard et al 1972).

During the past 20 years, in the state of Mississippi, the U.S.

Soil Conservation Service has constructed approximately 400 small earthen dams. Of the 400 earthen dams, three failed due to breaching and approximately 50 have a tunnel erosion problem due to rainfall erosion. These homogeneous dams were constructed mainly for flood control purposes. Sherrard et al. (1972) summarizes the data concerning the dam failures as follows:

1. The failure dams occurred in a small geographic area of north-central Mississippi (100 miles north and south by 30 miles east and west).
2. The soil profile common to this area is composed of a 5 to 30 foot layer of clay material over a very soft easily weathered clay stone.
3. The badly damaged dams in terms of erosion tunnels caused by rainfall erosion were covered with a good protective growth of grass. The grass was planted to provide protection to the dam slopes and prevented gully or sheet erosion from occurring.
4. The climatic conditions common to this region were as follows: 40 to 60 inches of rainfall per year, and hot, dry summer months with extremely heavy rainstorms of short duration.

The Soil Conservation Service has directed the construction of approximately 1500 small earthen dams in the State of Oklahoma. The purpose of the Oklahoma dams was to control flooding. The first filling of these reservoirs was rapid and resulted in the failure of several of the earthen dams. Sherrard *et al.* (1972) summarizes the data concerning the dam failures as follows:

1. The dams range from 22 to 50 feet in height and were built from the clay material weathered from thin bedded shale-sandstone bedrock.
2. The failure dams consisted of highly dispersive types of clay material.
3. With the initial filling of the reservoir, the failure of the structure suggests the possibility that the initial leak must have had its origin in a crack or some other concentrated leakage channel. The compacted embankment of the dam would not allow the water to penetrate at such a rapid rate unless a leakage channel or crack was present.
4. Eleven of the 1500 dams failed and a majority of the failures were located in a small area of southeastern Oklahoma. The climatic, soil, and geological conditions should be very similar in this region of Oklahoma.
5. The 40 to 60 inches of rainfall per year probably resulted in the formation of erosion tunnels located on the slopes and crests of the earthen structures.

# CHAPTER III

## METHODS AND MATERIALS

The soil samples were collected from the various failure dams throughout the United States (Table I and Figures 1 & 2). The United States Soil Conservation Service scientists collected the samples from the following states: Oklahoma, California, Utah, Arkansas and Mississippi. The samples were used in the special dam study conducted by Sherrard (1971).

The samples of soil were placed in plastic bags and the bags were sealed to prevent excess drying and contamination of the samples. The plastic bags were placed in coded paper bags and packed in a wooden box and shipped to Oklahoma State University, Stillwater, Oklahoma by Dr. Sherrard.

A small amount of the sample was removed from the sealed bags and spread on a sheet of Kraft paper. The sample was examined and initial removal of debris was carried out. The debris removed from the sample were plant roots, rocks and man made material such as wire and pieces of plastic.

After the initial removal of debris from the samples, the samples, were placed in Kraft paper bags. The bagged samples were placed in a drying oven until the samples were dried to the required state for grinding..

The dried sample was ground to 20 mesh and then sealed in a

## TABLE I

## LOCATION AND DESCRIPTION OF SOIL SAMPLES USED IN THIS STUDY

| Dam Structure | State | Sample No. | Location and Description |
|---|---|---|---|
| Little Wewoka Creek Site #17 | Okla. | S-1 | Downstream toe at conduit-eroded vertical tunnels |
| Caney Coon Site #2 | Okla. | S-4 | Stream channel wall, 100 ft. downstream from conduit |
| | | S-6 | Left abutment, 100 ft from dam |
| | | S-7.1 | Left abutment, 100 ft from dam |
| | | S-7.2 | Left abutment, 100 ft from dam |
| Leader Middle Clear Boggy #15 | Okla. | S-8 | Downstream slope, near crest, 15 ft right of conduit. Eroded vertical tunnels. |
| | | S-9 | Wall of dischange channel below conduit. |
| Leader Middle Clear Boggy #29 | Okla. | S-11 | Wall of canal between two reservoirs, Severe erosion gullies |
| Upper Clear Boggy #53 | Okla. | S-13 | Downstream slope, 200 ft. right of conduit. No erosion on dam |
| Upper Clear Boggy #50 | Okla. | S-21 | Left wall of breach. Near erosion tunnels. |
| | | S-22 | Left wall of breach. Near erosion tunnel |
| Leader Middle Clear Boggy #33 | Okla. | S-23 | 200 ft. upstream of dam Left valley wall. |
| Owl Creek Site #7 | Okla. | S-26 | Above principal spillway level at lake's edge 100 ft upstream from dam. |
| | | S-27 | Downstream toe at conduit Erosion. |
| Owl Creek Site #13 | Okla. | S-29 | Borrow pit upstream on right side. |
| Cherokee Sandy 8a | Okla. | S-32 | Lake shore just above spillway level 300 ft. upstream on left side. |
| | | S-33 | Near downstream toe. 200 ft to right of breach. |
| | | S-34 | Lake shore. Right side. 300 ft upstream of dam. |
| | | S-36 | Dischange channel wall just down stream from conduit. |

TABLE I "CONTINUED"

| Dam Structure | State | Sample No. | Location and Description |
|---|---|---|---|
| Upper Red Rock Site 42 | Okla. | S-37 | Lake shore. Left side. 100 ft. upstream from dam. |
| Upper Red Rock Site #48 | Okla. | S-40 | Lake shore. Left side. 100 ft. upstream from dam |
| Wister Dam | Okla. | S-42<br>S-43<br>S-44<br>S-45 | Downstream slope. Right half. Above berm. Samples Near Large eroded vertical tunnels. Over 100 ft dam length |
| Stockton Creek Dam | Calif. | S-58 | Downstream slope. Center and mid-height of dam. |
| | | S-59 | Borrow area. Upstream. Left valley wall. |
| | | S-60 | Borrow area. Near Spillway. |
| Millsite Dam | Utah | S-69<br>S-70<br>S-71 | Typical core material Samples appear almost identical |
| Lake Yosemeite | Calif. | S-72<br>S-73 | Downstream slope. Mid-height near conduit. 200 ft apart. Dam with stood leakage many years with no piping. |
| Frogville #2 | Okla. | S-74 | From crest and slopes. Composite of typical lime treated soil. |
| | | S-75 | 200 ft downstream in vicinity of erosion gully. |
| Caney Creek Site #7 | Ark. | S-77 | Blanket on left abutment where had severe eroded vertical tunnel. |
| Hall Reservoir | Ark. | S-78.1<br>S-78.2 | Samples from downstream slope near eroded vertical tunnel. |
| Caney Creek Site #6 | Ark. | S-79 | From wall of large vertical tunnel on downstream slope. |
| Perry Creek Site #3 | Miss. | S-85 | From wall of large vertical tunnel on crest. |
| Big Sand Site #10 | Miss | S-86 | Adjacent large vertical tunnel on downstream slope near top. |
| Big Sand Site #8 | Miss. | S-87 | Upstream slope near crest. |
| | | S-88 | Downstream berm near conduit. |
| | | S-89 | Down stream slope at right end.<br>(all samples from vicinity of vertical tunnels) |

TABLE I "CONTINUED"

| Dam Structure | State | Sample No. | Location and Description |
|---|---|---|---|
| Potacocawa Site #3 | Miss. | S-90 | Downstream slope in bad area of vertical tunnels near conduit. |
| | | S-91 | Upstream slope near vertical tunnels 100 ft. to right of conduit. |
| Baldwin Hills Res. | Calif. | S-92 | Foundation material from right wall of breach. |
| | | S-93 | From a single 12 inch thick layer of the formation |
| | | S-94 | The typical compacted clay reservoir lining taken from the right wall of breach about 20 ft above bottom of reservoir. |

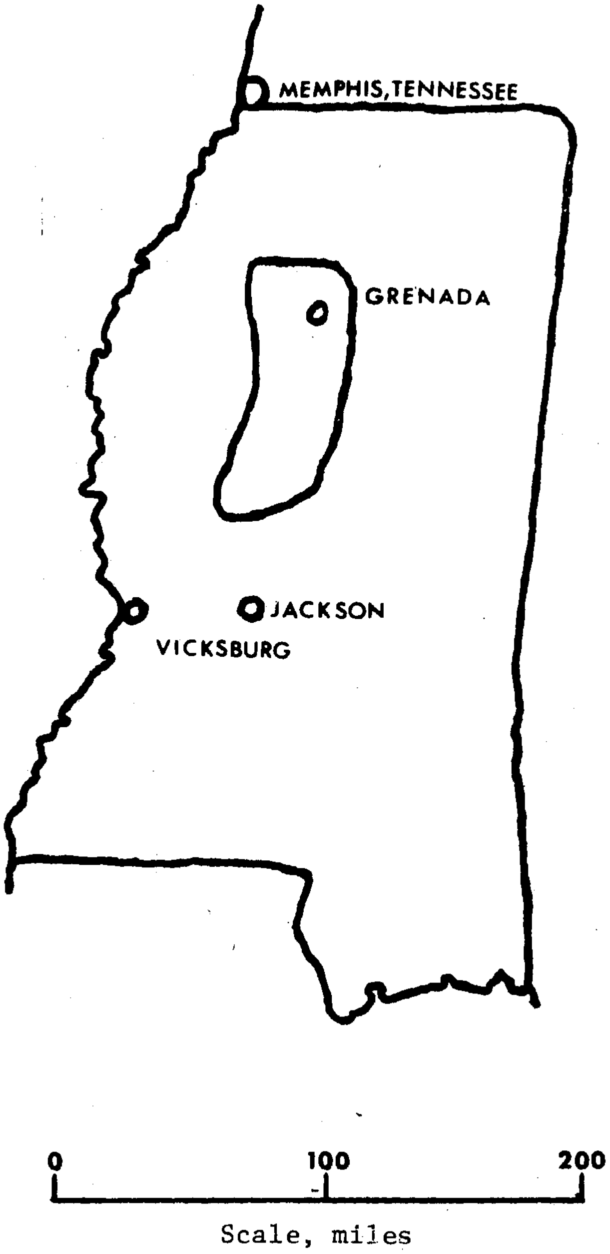
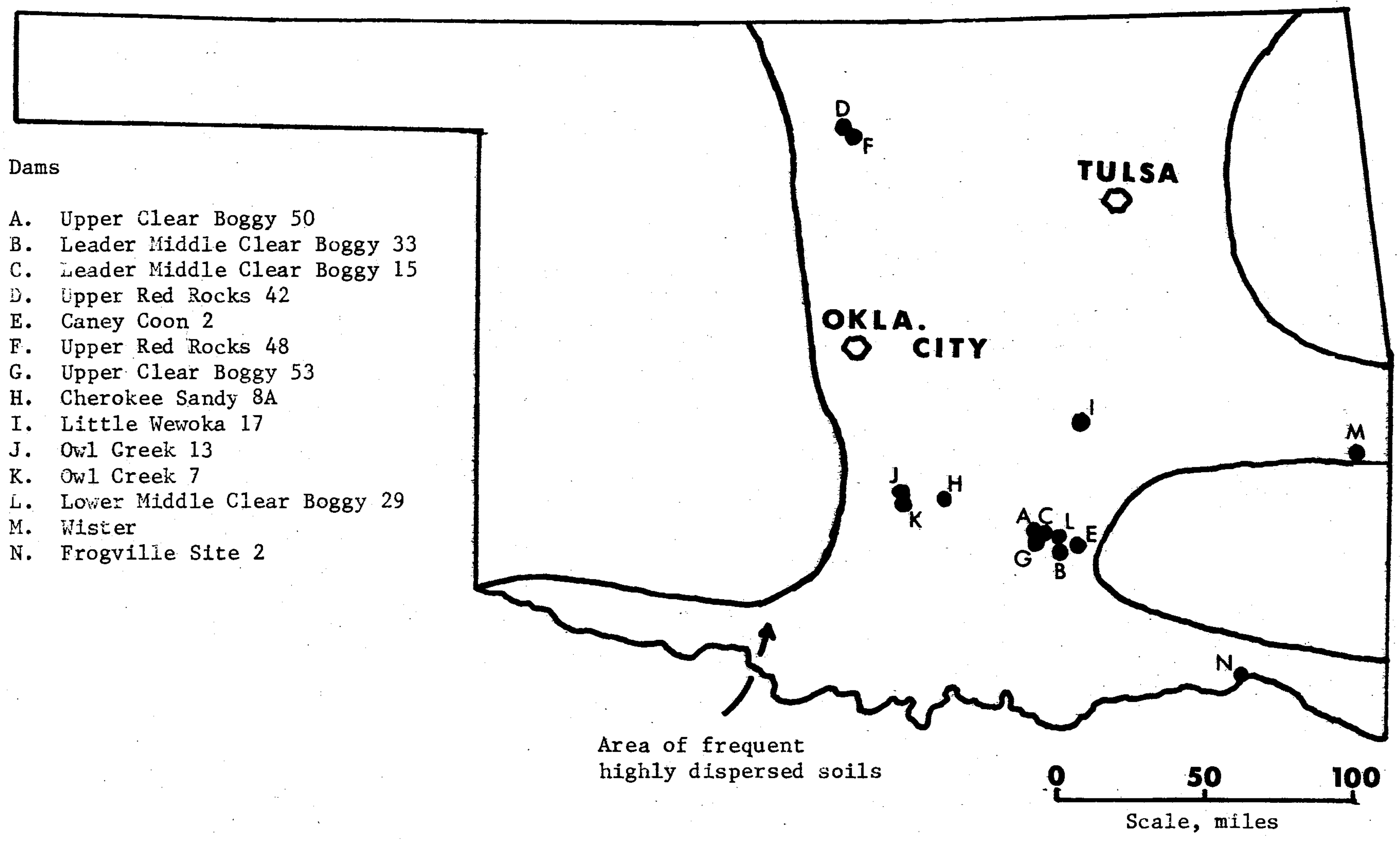


Figure 1. Approximate Geographic Area of Severe Erosion Damage from Rainfall to SCS Flood Control Dams in Mississippi.



Area of frequent highly dispersed soils

Figure 2. Locations of Oklahoma Failed Dams

plastic bag for storage and to prevent contamination.

The samples were prepared for mineralogical and x-ray diffraction analysis. The pretreatments of the samples were as follows:

1. Removal of carbonates and soluble salts
2. Removal of organic matter
3. Removal of free iron oxides

The number of treatments used were minimized to avoid damage to the soil fractions.

### Removal of Carbonates and Soluble Salts

The salts and carbonates in the samples act as flocculating agents and thus makes dispersion of the soil particles different to obtain. The salts and carbonates create an alkaline condition in the soil sample. The alkaline condition must be changed to an acid condition if the removal of organic matter by hydrogen peroxide is to occur. The removal of the soluble components is necessary if adequate x-ray diffraction patterns are to be obtained. The soluble salts can be removed by a water treatment but carbonates are removed by an acid-sodium-acetate solution.

Approximately forty grams of the sample was placed in a centrifuge bottle and pH 5.0 sodium acetate solution was added. The mixture was stirred and placed in a 80°C water bath for at least thirty minutes and stirred during the heating porcess. The centrifuge bottle was removed and allowed to cool, centrifuged at 1500 rpm for five minutes and decanted. If upon the addition of fresh sodium acetate solution to the residue results in effervescense, the process must be repeated and followed by an overnight digestion period. The sample was washed and centrifuged with fresh sodium acetate solution and decanted. Excess sodium acetate was removed by water wash and upon removal of excess salt the residue was stored in water to prevent desiccation (Jackson 1956).

## Removal of Organic Matter

Organic matter has a cementing affect on the soil particles and must be removed to allow dispersion of the soil particles to occur. Organic matter can be removed by several procedures. Troell (1931) used sodium hypobromite to oxidize organic matter. Robinson (1922) used hydrogen peroxide to oxidize soil organic matter. The Robinson method requires the hydrogen peroxide to react in an acid environment if complete oxidation is to occur. The previous treatment to remove carbonates and soluble salts from the sample resulted in the formation of an acid condition which is ideal for the oxidation of organic matter (Jackson 1956).

The washed soil sample was placed in an 80°C water bath and 30% hydrogen peroxide was added slowly to avoid frothing. Oxidation of the organic matter occurred over a period of 4-24 hours. A saturated sodium chloride solution was added to flocculate the clay. The sample was centrifuged, supernatent discarded and the sample was then washed free of excess salts by washing with deionized water by stirring, centrifugation and decanting the supernatent until free of soluble salts.

The iron oxide coatings must be removed to reduce the background count in the x-ray diffraction analysis and to free the clay particle from the cementing effect of the iron oxide. When a copper x-ray target is used the iron oxide coating fluorescence resulting in a decrease in the quality of the diffraction pattern. The iron oxide coatings were removed by using the sodium dithionite-citrate-bicarbonate procedure (Mehra and Jackson 1960). The sodium dithionite reduces the iron, while the sodium citrate acts as a chelating agent for the ferrous and ferric forms of iron while sodium bicarbonate acts as a buffer.

The soil was mixed with the bicarbonate-citrate buffer solution and placed in a water bath. Upon heating the mixture to 75-80$^{o}$C, the sodium dithionite was added slowly to prevent excessive frothing. The mixture was stirred and after fifteen minutes the sample was removed from the bath. The mixture was cooled, centrifuged, supernatent decanted and discarded. The sample was washed again with fresh citrate buffer solution followed by centrifugation, washing and discarding of supernatent.

The residue was dispersed by washing and centrifuging with deionized water. The sand fraction was removed by passing the dispersed material through a 270 mesh sieve. The silt fraction was separated from the clay fraction by a fifteen hour siphoning process which involves the addition, then the extraction of deionized distilled water containing the clay fraction. The sand and silt fractions were saved. The clay fraction was separated into the coarse clay 2-.2μ and the fine clay <.2μ. The separation of the fine and coarse clays was made by using the Sharples supercentrifuge operating at 33,000 rpm with a flow rate of 600 ml/min (Jackson 1956).

Kelly, Dore and Brown (1931) and Hendricks and Fry (1930) were among the first to use x-ray diffraction for the study of soil material.

The use of x-ray diffraction techniques has become a standard research tool in clay mineralogy and soil science. The dispersed or sodium saturated fine and coarse clay fractions were flocculated with one Normal calcium chloride and washed until free of the chloride ion. The calcium saturated clay was applied to a porous ceramic slide. The slide was dried for twenty-four to forty-eight hours in a vaccuum desiccator containing anhydrous calcium chloride. The calcium saturated clay was x-rayed and then the same sample was x-rayed again after being solvated with ethylene glycol. Another portion of the sodium saturated clay was potassium saturated (Jackson 1956) and dried in the desiccator before being x-rayed and then the potassium saturated slide was heated to 500° C for four hours and x-rayed. The calcium saturated, glycol solvated, potassium saturated and potassium saturated heated slides were x-rayed on the General Electric XRD 6 instrument with a Ni-filtered Cμ Kα radiation generated at 30 KVP and 20 ma. The following settings were made and maintained on the General Electric XRD 6 throughout the research work: Counts Per Second (CPS) = 1,000, time constant = 1.0, and range = 50. The General Electric XRD 6 was operated from the lower limit of two degrees 2θ to the upper limit of thirty degrees 2θ.

# CHAPTER IV

## RESULTS AND DISCUSSION

The results from the x-ray diffraction patterns of the clay fractions from the failure dams indicates the following: (see Figures 3-14 and Table II).

The pretreatment to remove soluble salts and carbonates from the samples appears to have been quite successful. The only sample showing any carbonate material on the x-ray diffraction patterns was sample S-9 (fine).

Several of the fine and coarse clay fractions of the various samples from the failure dams contained the following major minerals: montmorillonite, illite, kaolinite and quartz. The results indicate that the dominant clay mineral found in the samples was montmorillonite. Illite clay was sub-dominant and kaolinite was found in lesser amounts.

The failure of the earthen structures is related to the type of clay that is present in the earthen material used in the construction of the structure. The structural units of the montmorillonite are held together very loosely by the weak oxygen-water exchange cation-water-oxygen linkage. This type of structure may cause the clay to expand very readily due to the large variation in water content. According to Russell (1961) isomorphous substitution in the clay mineral structure is responsible for the large amount of exchange. When the montmorillonite is dispersed in water the exchange cations tend to dissocate and the clay particle resembles a large complex anion. The charged clay particles tend to repel one another and the montmorillonite structure appears to swell due to absorption of water. The complete hydration of the exchange cations will result in the greatest number of water molecules on the clay particle. The greater the charge the more swelling will occur for montmorillonites. Conversely the mineral kaolin with very low charge does not swell appreciably.

The clay mineral illite of the hydrous-mica group has a crystal structure of the 2:1 type. The illites are very similar to the montmorillonites in terms of their general structure. However, illite crystals are much less expansive when compared to montmorillonite but are more expansive than kaolinite. The clay mineral kaolinite has 1:1 type of crystal structure. The structure of kaolinite precludes isomorphous substitution and therefore the Cation Exchange Capacity (C.E.C.) is low and upon wetting expansion between the plate-like units does not occur. Kaolinite therefore, shows little or no expansion when dispersed in water.

The structure of the various clay minerals influences the process of swelling which occurs when clay material comes in contact with water. According to Grim (1968), the montmorillonites and illites and other swelling types of clay materials react in the following way when dispersed in water: The clay mineral placed in contact with water will swell due to rapid absorption of water. The absorption of water by the clay material will continue until a point is reached in which the clay-water system becomes a thick pasty mass. When equilibrium between the clay and absorbed water has been reached further addition of water will cause the system to become liquid in terms of flow impedance. In terms of earthen structures, the clay-water solid-state equilibrium could impede the movement of water through the structure and thus stabilize the structure against possible failures. The "ideal" clay-water equilibrium may be influenced by the degree of charge on the clay mineral structure, the chemical composition of the clay material and the amount and nature of the exchangeable cations.

According to Hardy (1926), Grim and Cuthbert (1945) and Low (1961) the water of the clay-water system is held on the clay surface and extends a short distance from the clay surface. The thickness of the water film varies for the various clay minerals. In the case of montmorillonites and illites, the water film is well developed and has the greatest thickness on the basal plane or flat surfaces of the clay minerals. In the case of kaolinite, the irrigular surfaces of the edges provide for a water film around the clay particles, however, only a small quantity of water is held on the basal planes.

The attraction and retention of water by clay minerals is important in the study of the problem of dam failures. Hughes (1950) indicates the montmorillonite displays water retention to a marked degree, while illites to a lesser degree and kaolinite to a very low degree. Low (1961) reported that the attraction of the water to the clay surface was due to the nature of the exchangeable cations. If the exchangeable cations are small or highly charged, the cations will be hydrated and therefore the clay system is hydrated. Walker (1949) believed that the type of exchange on the ion clay surface could influence the amount and arrangement of the water molecules on the charged clay surface. Weigner (1931) believed that the exchange cations are hydrated and the hydrated cations influence the thickness of the water film around the clay particles. Grim (1942) states that sodium saturated montmorillonite expands to a greater degree in the presence of water than calcium saturated montmorillonite. The high swelling sodium montmorillonite is at one end of the extreme, while the low or no swelling kaolinite is at the other end. The swelling properties of the calcium montmorillonite and illites places them between the extremes. According to Nowak and Krueger (1951), salt content of the water which comes into contact with the clay particles also can greatly influence the swelling properties of clays.

The x-ray diffraction patterns obtained in this study are reported in Table II and Figures 3-14. The data presents four clay minerals based on relative diffraction peak intensity. The samples were then grouped according to presence and relative amounts of clay. The five groups are as follows: (1) montmorillonite, illite, kaolinite, quartz; (2) illite, kaolinite, quartz; (3) montmorillonite, kaolinite, quartz; (4) montmorillonite; quartz and (5) minor amounts of montmorillonite; illite, quartz and kaolinite, quartz.

The #1 group of clays found in the soils reported in this study was a mixture of montmorillonite: illite: kaolinite: quartz are: S-1, S-7, S-8, S-11, S-13, S-22, S-23, S-27, S-37, S-42, S-43, S-44, S-69, S-72, S-74, S-75, S-77, S-78.2, S-79, S-85, and S-86. The x-ray diffraction patterns of samples S-23, S-72, and S-75 were also a part of this group. Sample S-23 is reported in Figures 3 and 4 and is representative of this group while the major share of the data concerning this group of soils is reported in Table II. The coarse clay fraction of S-23, Figure 3 contains a moderate amount of vermiculite represented by the 14-15A$^{o}$ peaks resulting from the calcium, ethylene

## TABLE II

## X-RAY DIFFRACTION DATA FOR CLAY FRACTIONS SEPARATED FROM SOILS COLLECTED FROM EARTH FILL DAMS

| Sample No. | Clay Fraction | Ca. sat. 25°C * | Ca. sat. Gly. 25° | K sat. 25°C | K sat. 500°C | Type of Major Mineral |
|---|---|---|---|---|---|---|
| S-1 | Coarse | 10.04 (7) | 10.04 (7) | 10.04 (3) | 10.04 (6) | Illite |
| | | 7.25 (9) | 7.25 (8) | 7.25 (4) | 3.35 (5) | Kaolinite |
| | | 3.59 (5) | 3.59 (5) | 3.59 (3) | | Quartz |
| | | 3.35 (6) | 3.35 (7) | 3.35 (4) | | |
| | Fine | 14.72 (7) | 18.02 (6) | 14.02 (7) | 10.16 (6) | Montmorillonite |
| | | 3.35 (3) | 14.02 (4) | 12.63 (6) | 3.35 (4) | Vermiculite |
| | | | 3.35 (2) | 3.35 (3) | | Quartz |
| S-4 | Coarse | 10.04 (6) | 10.04 (6) | 10.04 (6) | 10.04 (3) | Illite |
| | | 7.25 (5) | 7.25 (6) | 7.25 (5) | 3.35 (6) | Kaolinite |
| | | 3.57 (5) | 3.57 (4) | 3.58 (3) | | Quartz |
| | | 3.35 (5) | 3.35 (6) | 3.35 (5) | | |
| | Fine | 7.25 (5) | 7.25 (4) | 7.25 (3) | | Kaolinite |
| | | 3.32 (3) | 3.32 (5) | 3.32 (3) | | Illite |
| S-6 | Coarse | 10.04 (7) | 10.04 (5) | 10.04 (5) | 10.04 (5) | Illite |
| | | 7.25 (7) | 7.25 (7) | 7.25 (4) | 3.35 (6) | Kaolinite |
| | | 3.58 (4) | 3.58 (4) | 3.58 (3) | | Quartz |
| | | 3.35 (5) | 3.35 (6) | 3.35 (5) | | |
| | Fine | 3.35 (3) | 3.35 (3) | 3.35 (2) | | Quartz |

*100 counts per second = 10. The intensity of diffraction maxima

## TABLE II "CONTINUED"

| Sample No. | Clay Fraction | Ca. sat. $25^\circ$C | Ca. sat. Gly. $25^\circ$ | K sat. $25^\circ$C | K sat. $500^\circ$C | Type of Major Mineral |
|---|---|---|---|---|---|---|
| S-7.1 | Coarse | 7.25 (7) | 7.25 (6) | 7.25 (5) | | Kaolinite |
| | | 3.59 (4) | 3.59 (4) | 3.59 (3) | | Quartz |
| | | 3.35 (5) | 3.35 (4) | 3.35 (4) | 3.35 (5) | |
| | Fine | 3.35 (3) | 3.35 (4) | 3.35 (4) | 3.35 (6) | Quartz |
| S-7.2 | Coarse | 15.22 (12) | 16.98 (14) | 12.62 (4) | 10.04 (5) | Montmorillonite |
| | | 10.04 (5) | 10.04 (5) | 10.04 (5) | 3.35 (5) | Illite |
| | | 7.25 (6) | 7.25 (4) | 7.25 (4) | | Kaolinite |
| | | 3.58 (3) | 3.58 (3) | 3.59 (2) | | Quartz |
| | | 3.35 (5) | 3.35 (4) | 3.35 (4) | | |
| | Fine | 3.35 (2) | 3.35 (2) | 3.35 (2) | 3.35 (3) | Quartz |
| S-8 | Coarse | 14.97 (8) | 15.77 (7) | 10.04 (3) | 10.04 (3) | Illite |
| | | 10.04 (4) | 10.04 (3) | 7.25 (4) | 3.35 (5) | Vermiculite |
| | | 7.25 (5) | 7.25 (4) | 3.59 (2) | | Kaolinite |
| | | 3.59 (2) | 3.59 (2) | 3.35 (4) | | Quartz |
| | | 3.35 (5) | 3.35 (4) | | | |
| | Fine | 15.22 (16) | 17.66 (17) | 12.62 (8) | 10.16 (5) | Montmorillonite |
| | | 3.35 (5) | 3.35 (5) | 3.35 (3) | 3.35 (6) | Quartz |
| S-9 | Coarse | 15.77 (9) | 15.77 (9) | 10.04 (3) | 10.04 (4) | Vermiculite |
| | | 10.27 (2) | 10.04 (2) | 7.25 (4) | 3.35 (6) | Illite |
| | | 7.25 (5) | 7.25 (4) | 3.59 (2) | | Kaolinite |
| | | 3.59 (2) | 3.59 (2) | 3.35 (7) | | Quartz |
| | | 3.35 (8) | 3.35 (7) | | | |
| | Fine | 3.35 (2) | 3.35 (2) | 3.35 (2) | 3.35 (2) | Quartz |
| | | 3.04 (2) | 3.04 (2) | 3.04 (2) | | Calcite |

TABLE II "CONTINUED"

| Sample No. | Clay Fraction | Ca. sat. 25°C | Ca. sat. Gly 25° | K sat. 25°C | K sat. 500°C | Type of Major Mineral |
|---|---|---|---|---|---|---|
| S-11 | Coarse | 15.22 (13) | 15.22 (10) | 15.77 (7) | 3.35 (5) | Vermiculite |
| | | 10.04 (6) | 10.04 (6) | 10.04 (5) | 10.04 (2) | Illite |
| | | 7.25 (6) | 7.25 (6) | 7.25 (5) | | Kaolinite |
| | | 3.59 (2) | 3.59 (2) | 3.59 (2) | | Quartz |
| | | 3.35 (5) | 3.35 (6) | 3.35 (5) | | |
| | Fine | 15.77 (18) | 18.02 (22) | 12.99 (9) | 10.04 (3) | Montmorillonite |
| | | 7.25 (2) | 7.25 (2) | 7.25 (2) | 3.35 (4) | Kaolinite |
| | | 3.35 (4) | 3.35 (4) | 3.35 (2) | | Quartz |
| S-13 | Coarse | 14.72 (5) | 17.66 (6) | 12.99 (4) | 10.04 (3) | Montmorillonite |
| | | 10.04 (2) | 10.04 (2) | 10.04 (2) | 3.35 (5) | Illite |
| | | 7.25 (2) | 7.25 (2) | 7.25 (2) | | Kaolinite |
| | | 3.59 (1) | 3.59 (1) | 3.59 (1) | | Quartz |
| | | 3.35 (4) | 3.35 (5) | 3.34 (4) | | |
| | Fine | 15.77 (12) | 17.67 (15) | 12.62 (8) | 10.04 (4) | Montmorillonite |
| | | 3.35 (4) | 3.35 (4) | 3.35 (3) | 3.35 (4) | Quartz |
| S-21 | Coarse | 10.04 (3) | 10.04 (3) | 10.04 (3) | 10.04 (3) | Illite |
| | | 7.25 (3) | 7.25 (3) | 7.25 (2) | 3.35 (7) | Kaolinite |
| | | 3.59 (2) | 3.59 (2) | 3.59 (2) | | Quartz |
| | | 3.35 (6) | 3.35 (6) | 3.35 (4) | | |
| | Fine | 10.04 (6) | 10.04 (6) | 10.04 (8) | 10.04 (5) | Illite |
| | | 7.25 (4) | 7.25 (4) | 7.25 (3) | 3.35 (4) | Kaolinite |
| | | 3.59 (2) | 3.59 (2) | 3.59 (2) | | Quartz |
| | | 3.35 (5) | 3.35 (6) | 3.35 (4) | | |

TABLE II "CONTINUED"

| Sample No. | Clay Fraction | Ca.sat. 25°C | Ca. sat. Gly. 25° | K sat. 25°C | K sat. 500°C | Type of Major Mineral |
|---|---|---|---|---|---|---|
| S-22 | Coarse | 10.04 (2) | 10.04 (2) | 10.27 (2) | 10.27 (4) | Illite |
| | | 7.25 (2) | 7.25 (2) | 7.25 (2) | 3.35 (8) | Kaolinite |
| | | 3.59 (1) | 3.59 (1) | 3.59 (1) | | Quartz |
| | | 3.35 (5) | 3.35 (5) | 3.35 (5) | | |
| | Fine | 14.72 (14) | 18.39 (23) | 12.62 (6) | 10.04 (7) | Montmorillonite |
| | | 3.35 (4) | 3.35 (4) | 3.35 (2) | 3.35 (2) | Quartz |
| S-23 | Coarse | 14.72 (5) | 14.22 (5) | 14.24 (4) | 10.04 (4) | Vermiculite |
| | | 10.04 (3) | 10.04 (2) | 10.04 (3) | 3.35 (6) | Illite |
| | | 7.25 (3) | 7.25 (3) | 7.25 (3) | | Kaolinite |
| | | 3.59 (1) | 3.59 (2) | 3.59 (2) | | Quartz |
| | | 3.35 (5) | 3.35 (5) | 3.35 (4) | | |
| | Fine | 14.24 (24) | 17.66 (24) | 12.44 (14) | 10.37 (14) | Montmorillonite |
| | | 7.25 (5) | 7.25 (4) | 7.25 (4) | 3.35 (6) | Kaolinite |
| | | 3.59 (3) | 3.59 (2) | 3.59 (2) | | Quartz |
| | | 3.35 (4) | 3.35 (4) | 3.35 (6) | | |
| S-26 | Coarse | 14.72 (13) | 16.98 (14) | 12.62 (6) | 10.04 (4) | Montmorillonite |
| | | 7.25 (2) | 7.25 (2) | 7.25 (1) | 3.35 (5) | Kaolinite |
| | | 3.35 (4) | 3.35 (5) | 3.35 (3) | | Quartz |
| | Fine | 14.22 (29) | 16.98 (27) | 12.62 (12) | 10.27 (3) | Montmorillonite |
| | | 3.35 (2) | 3.35 (3) | 3.35 (2) | 3.35 (4) | Quartz |

TABLE II "CONTINUED"

| Sample No. | Clay Fraction | Ca. sat. 25°C | Ca. sat. Gly. 25° | K sat. 25°C | K sat. 500°C | Type of Major Mineral |
|---|---|---|---|---|---|---|
| S-27 | Coarse | 14.24 (5) | 16.98 (5) | 12.62 (3) | 10.04 (3) | Montmorillonite |
| | | 10.04 (2) | 10.04 (2) | 10.04 (3) | 3.35 (6) | Illite |
| | | 7.25 (3) | 7.25 (2) | 7.25 (3) | | Kaolinite |
| | | 3.59 (2) | 3.59 (1) | 3.59 (2) | | Quartz |
| | | 3.35 (4) | 3.35 (4) | 3.35 (4) | | |
| | Fine | 14.72 (16) | 17.66 (19) | 12.62 (11) | 10.04 (8) | Montmorillonite |
| | | 3.35 (2) | 3.35 (4) | 3.35 (3) | 3.35 (3) | Quartz |
| S-29 | Coarse | 10.04 (3) | 10.04 (3) | 10.04 (4) | 10.04 (3) | Illite |
| | | 7.25 (3) | 7.25 (3) | 7.25 (3) | 3.35 (3) | Kaolinite |
| | | 3.59 (2) | 3.59 (2) | 3.59 (1) | | Quartz |
| | | 3.35 (4) | 3.35 (5) | 3.35 (3) | | |
| | Fine | 10.27 (6) | 10.27 (4) | 10.27 (5) | 10.27 (5) | Illite |
| | | 7.25 (3) | 7.25 (2) | 7.25 (2) | 3.35 (5) | Kaolinite |
| | | 3.35 (4) | 3.35 (4) | 3.35 (3) | | Quartz |
| S-32 | Coarse | 14.24 (7) | 16.98 (4) | 12.62 (3) | 3.35 (1) | Montmorillonite |
| | | 3.35 (1) | 3.35 (1) | 3.35 (1) | | Quartz |
| | Fine | 14.72 (33) | 17.31 (34) | 14.72 (14) | 10.37 (8) | Chlorite (Swelling) |
| S-33 | Coarse | 15.22 (11) | 16.98 (14) | 12.98 (5) | 10.04 (2) | Montmorillonite |
| | | 7.25 (2) | 7.25 (1) | 7.25 (1) | 3.35 (3) | Kaolinite |
| | | 3.35 (3) | 3.35 (4) | 3.35 (3) | | Quartz |
| | Fine | 14.72 (26) | 17.66 (25) | 12.98 (12) | 10.04 (7) | Montmorillonite |
| | | 3.35 (1) | 3.35 (2) | 3.35 (1) | 3.35 (2) | Quartz |

TABLE II "CONTINUED"

| Sample No. | Clay Fraction | Ca. sat. 25°C | Ca. sat. Gly 25° | K sat. 25°C | K sat. 500°C | Type of Major Mineral |
|---|---|---|---|---|---|---|
| S-34 | Coarse | 15.22 (17) | 16.98 (19) | 12.99 (6) | 10.04 (4) | Montmorillonite |
| | | 3.35 (2) | 3.35 (3) | 3.35 (1) | 3.35 (3) | Quartz |
| | Fine | 15.77 (24) | 17.31 (33) | 12.72 (5) | 10.04 (5) | Montmorillonite |
| | | 3.35 (4) | 3.35 (4) | 3.35 (4) | 3.35 (4) | Quartz |
| S-36 | Coarse | 15.22 (25) | 16.98 (25) | 12.80 (12) | 10.04 (5) | Montmorillonite |
| | | 3.35 (2) | 3.35 (3) | 3.35 (3) | 3.35 (4) | Quartz |
| | Fine | 15.77 (28) | 16.98 (32) | 12.98 (8) | 10.04 (4) | Montmorillonite |
| S-37 | Coarse | 14.72 (6) | 16.98 (5) | 12.62 (2) | 10.04 (2) | Illite |
| | | 10.07 (3) | 10.04 (3) | 10.04 (2) | 3.35 (4) | Montmorillonite |
| | | 7.25 (3) | 7.25 (2) | 7.25 (1) | | Kaolinite |
| | | 3.59 (1) | 3.59 (1) | 3.59 (1) | | Quartz |
| | | 3.35 (4) | 3.35 (4) | 3.35 (3) | | |
| | Fine | 14.24 (7) | 17.66 (18) | 12.44 (6) | 10.04 (6) | Montmorillonite |
| | | 7.25 (2) | 7.25 (1) | 7.25 (2) | 3.35 (4) | Kaolinite |
| | | 3.35 (2) | 3.35 (2) | 3.35 (3) | | Quartz |
| S-40 | Coarse | 10.04 (4) | 20.04 (4) | 10.04 (3) | 10.04 (5) | Illite |
| | | 7.25 (3) | 7.25 (2) | 7.25 (2) | 3.35 (4) | Kaolinite |
| | | 3.35 (4) | 3.35 (4) | 3.35 (3) | | Quartz |
| | | 3.14 (4) | | 3.14 (3) | | Feldspar |
| | Fine | 10.04 (8) | 10.04 (7) | 10.04 (8) | 10.04 (10) | Illite |
| | | 3.59 (2) | 3.59 (1) | 3.59 (2) | 3.35 (6) | Kaolinite |
| | | 3.35 (5) | 3.35 (4) | 3.35 (5) | | Quartz |

TABLE II "CONTINUED"

| Sample No. | Clay Fraction | Ca. sat. 25°C | Ca. sat. Gly. 25° | K sat. 25°C | K sat. 500°C | Type of Major Mineral |
|---|---|---|---|---|---|---|
| S-42 | Coarse | 10.04 (3) | 10.04 (3) | 10.04 (3) | 10.04 (4) | Illite |
| | | 7.25 (4) | 7.25 (3) | 7.25 (3) | 3.35 (5) | Kaolinite |
| | | 3.59 (2) | 3.59 (2) | 3.59 (2) | | Quartz |
| | | 3.35 (5) | 3.35 (5) | 3.35 (4) | | |
| | Fine | 14.24 (14) | 17.66 (16) | 14.24 (9) | 10.04 (7) | Montmorillonite |
| | | 7.25 (4) | 15.77 (16) | 12.44 ( 9) | 3.35 (3) | Vermiculite |
| | | 3.59 (3) | 7.25 (3) | 10.27 (7) | | Kaolinite |
| | | 3.35 (3) | 3.59 (2) | 7.25 (3) | | Quartz |
| | | | 3.35 (4) | 3.59 (1) | | |
| | | | | 3.35 (3) | | |
| S-43 | Coarse | 10.04 (2) | 10.04 (2) | 10.04 (3) | 10.04 (3) | Illite |
| | | 7.25 (2) | 7.25 (2) | 7.25 (2) | 3.35 (3) | Kaolinite |
| | | 3.59 (1) | 3.59 (1) | 3.59 (1) | | Quartz |
| | | 3.35 (3) | 3.35 (3) | 3.35 (3) | | |
| | Fine | 14.02 (12) | 17.66 (14) | 12.27 (9) | 10.04 (8) | Montmorillonite |
| | | 7.25 (5) | 7.25 (4) | 7.25 (4) | 3.35 (4) | Kaolinite |
| | | 3.59 (3) | 3.59 (1) | 3.59 (1) | | Quartz |
| | | 3.35 (3) | 3.35 (4) | 3.35 (4) | | |
| S-44 | Coarse | 10.04 (2) | 10.04 (2) | 10.04 (4) | 10.04 (5) | Illite |
| | | 7.25 (3) | 7.25 (3) | 7.25 (3) | 3.35 (5) | Kaolinite |
| | | 3.59 (1) | 3.59 (1) | 3.59 (1) | | Quartz |
| | | 3.35 (4) | 3.35 (4) | 3.35 (4) | | |
| | Fine | 14.72 (13) | 17.31 (14) | 12.27 (6) | 10.04 (2) | Montmorillonite |
| | | 7.25 (4) | 7.25 (4) | 7.25 (2) | 3.35 (3) | Kaolinite |
| | | 3.59 (1) | 3.59 (1) | 3.59 (1) | | Quartz |
| | | 3.35 (4) | 3.35 (4) | 3.35 (2) | | |

TABLE II "CONTINUED"

| Sample No. | Clay Fraction | Ca. sat. 25°C | Ca. sat. Gly. 25° | K sat. 25°C | K sat. 500°C | Type of Major Mineral |
|---|---|---|---|---|---|---|
| S-45 | Coarse | 15.22 (9) | 15.77 (10) | 15.22 (8) | 10.04 (5) | Vermiculite |
| | | 10.27 (5) | 10.04 (4) | 10.27 (4) | 3.35 (3) | Illite |
| | | 7.25 (2) | 7.25 (2) | 7.25 (1) | | Kaolinite |
| | | 3.35 (3) | 3.35 (3) | 3.35 (2) | | Quartz |
| | Fine | 14.72 (4) | 14.24 (4) | 14.24 (4) | 10.04 (3) | Vermiculite |
| | | 10.04 (3) | 10.04 (3) | 10.04 (4) | 3.35 (4) | Illite |
| | | 7.25 (3) | 7.25 (3) | 7.25 (3) | | Kaolinite |
| | | 3.59 (3) | 3.59 (2) | 3.59 (2) | | Quartz |
| | | 3.35 (4) | 3.35 (4) | 3.35 (3) | | |
| S-58 | Coarse | 14.72 (4) | 17.66 (4) | 14.24 (3) | 10.04 (6) | Vermiculite |
| | | 7.25 (2) | 14.24 (3) | 12.42 (4) | 3.35 (5) | Montmorillonite |
| | | 3.35 (3) | 7.25 (2) | 10.04 (6) | | Kaolinite |
| | | | 3.35 (3) | 7.25 (4) | | Quartz |
| | | | | 3.35 (4) | | |
| | Fine | 3.35 (3) | 3.35 (5) | 3.35 (6) | 3.34 (4) | Quartz |
| S-59 | Coarse | 10.04 (5) | 10.04 (4) | 10.04 (4) | 10.04 (3) | Illite |
| | | 7.25 (5) | 7.25 (5) | 7.25 (4) | 3.35 (3) | Kaolinite |
| | | 3.59 (3) | 3.59 (4) | 3.59 (3) | | Quartz |
| | | 3.35 (2) | 3.35 (3) | 3.35 (3) | | |
| | Fine | 10.04 (2) | 10.04 (2) | 10.27 (4) | 10.04 (2) | Illite |
| | | 7.25 (5) | 7.25 (3) | 7.25 (5) | 3.35 (4) | Kaolinite |
| | | 3.59 (1) | 3.57 (1) | 3.57 (2) | | Quartz |
| | | 3.35 (3) | 3.35 (3) | 3.35 (4) | | |

TABLE II "CONTINUED"

| Sample No. | Clay Fraction | Ca. sat. 25°C | Ca. sat. Gly. 25° | K sat. 25°C | K sat. 500°C | Type of Major Mineral |
|---|---|---|---|---|---|---|
| S-60 | Coarse | 10.04 (4) | 10.04 (4) | 10.04 (8) | 10.04 (8) | Illite |
| | | 7.25 (4) | 7.25 (3) | 7.25 (6) | 3.35 (4) | Kaolinite |
| | | 3.59 (2) | 3.59 (1) | 3.59 (3) | | Quartz |
| | | 3.35 (3) | 3.35 (3) | 3.35 (5) | | |
| | Fine | 7.25 (3) | 7.25 (3) | 7.25 (4) | 3.35 (4) | Kaolinite |
| | | 3.35 (4) | 3.35 (3) | 3.35 (7) | | Quartz |
| S-69 | Coarse | 14.02 (2) | 18.39 (5) | 12.27 (4) | 10.04 (3) | Montmorillonite |
| | | 10.04 (2) | 10.04 (2) | 10.04 (3) | 3.35 (4) | Illite |
| | | 7.25 (2) | 7.25 (1) | 7.25 (3) | | Kaolinite |
| | | 3.35 (3) | 3.35 (3) | 3.35 (6) | | Quartz |
| | Fine | 14.27 (4) | 16.98 (6) | 12.44 (4) | 10.04 (2) | Montmorillonite |
| | | 3.35 (5) | 3.35 (5) | 3.35 (7) | 3.35 (3) | Quartz |
| S-70 | Coarse | 10.04 (3) | 10.04 (3) | 10.04 (5) | 10.04 (4) | Illite |
| | | 7.25 (2) | 7.25 (2) | 7.25 (5) | 3.35 (6) | Kaolinite |
| | | 3.35 (4) | 3.35 (5) | 3.35 (7) | | Quartz |
| | Fine | 10.27 (8) | 10.04 (4) | 10.04 (9) | 10.04 (7) | Illite |
| | | 7.25 (1) | 7.25 (1) | 7.25 (2) | 3.35 (4) | Kaolinite |
| | | 3.35 (3) | 3.35 (4) | 3.35 (5) | | Quartz |
| S-71 | Coarse | 10.27 (2) | 10.04 (2) | 10.04 (2) | 10.16 (4) | Illite |
| | | 7.25 (2) | 7.25 (2) | 7.25 (2) | 3.35 (7) | Kaolinite |
| | | 3.35 (5) | 3.35 (4) | 3.35 (3) | | Quartz |
| | Fine | 3.35 (5) | 3.34 (5) | 3.35 (6) | 3.35 (4) | Quartz |

TABLE II "CONTINUED"

| Sample No. | Clay Fraction | Ca. sat. $25^{\circ}$C | Ca. sat. Gly. $25^{\circ}$ | K sat. $25^{\circ}$C | K sat. $500^{\circ}$C | Type of Major Mineral |
|---|---|---|---|---|---|---|
| S-72 | Coarse | 15.22 (16) | 17.66 (18) | 12.62 (14) | 10.04 (6) | Montmorillonite |
| | | 10.04 (5) | 10.27 (5) | 10.04 (10) | 3.32 (3) | Illite |
| | | 7.25 (3) | 7.37 (3) | 7.25 (5) | | Kaolinite |
| | | 3.59 (1) | 3.59 (2) | 3.59 (4) | | Quartz |
| | | 3.35 (2) | 3.35 (3) | 3.35 (5) | | |
| | Fine | 15.22 (23) | 17.66 (26) | 12.80 (18) | 10.04 (2) | Montmorillonite |
| | | 7.25 (3) | 7.25 (3) | 7.25 (3) | 3.35 (2) | Kaolinite |
| | | 3.35 (2) | 3.35 (3) | 3.35 (4) | | Quartz |
| S-73 | Coarse | 15.77 (8) | 17.66 (10) | 12.98 (4) | 3.35 (3) | Montmorillonite |
| | | 3.35 (3) | 3.35 (3) | 3.35 (5) | | Quartz |
| | Fine | 3.35 (7) | 3.35 (7) | 3.35 (9) | 3.35 (5) | Quartz |
| S-74 | Coarse | 15.22 (11) | 17.66 (12) | 12.62 (6) | 10.04 (6) | Montmorillonite |
| | | 10.04 (4) | 10.04 (3) | 10.04 (5) | 3.35 (5) | Illite |
| | | 7.25 (2) | 7.25 (2) | 7.25 (4) | | Kaolinite |
| | | 3.35 (3) | 3.35 (4) | 3.35 (6) | | Quartz |
| | Fine | 15.77 (23) | 17.66 (24) | 12.27 (12) | 10.27 (5) | Montmorillonite |
| | | 3.35 (2) | 3.35 (3) | 3.35 (4) | 3.35 (3) | Quartz |
| S-75 | Coarse | 14.72 (16) | 17.66 (19) | 12.99 (5) | 10.04 (6) | Montmorillonite |
| | | 10.04 (5) | 10.04 (4) | 10.04 (4) | 3.35 (6) | Illite |
| | | 7.13 (4) | 7.13 (3) | 7.13 (6) | | Kaolinite |
| | | 3.59 (2) | 3.59 (1) | 3.59 (3) | | Quartz |
| | | 3.35 (4) | 3.35 (5) | 3.35 (7) | | |
| | Fine | 14.72 (26) | 17.66 (26) | 12.99 (10) | 3.35 (2) | Montmorillonite |
| | | 3.35 (3) | 3.35 (4) | 3.35 (5) | | Quartz |

TABLE II "CONTINUED"

| Sample No. | Clay Fraction | Ca. sat. 25°c | Ca. sat. Gly. 25° | K sat. 25°C | K sat. 500°C | Type of Major Mineral |
|---|---|---|---|---|---|---|
| S-77 | Coarse | 14.72 (8) | 17.66 (8) | 12.62 (5) | 10.04 (5) | Montmorillonite |
| | | 10.04 (4) | 10.04 (3) | 10.04 (6) | 3.35 (5) | Illite |
| | | 7.25 (2) | 7.25 (1) | 7.25 (2) | | Kaolinite |
| | | 3.35 (4) | 3.35 (4) | 3.35 (5) | | Quartz |
| | Fine | 15.22 (20) | 18.39 (24) | 12.99 (12) | 3.35 (2) | Montmorillonite |
| | | 3.35 (4) | 3.35 (4) | 3.35 (6) | | Quartz |
| S-78.1 | Coarse | 15.22 (9) | 17.66 (11) | 12.62 (5) | 10.04 (8) | Montmorillonite |
| | | 10.16 (4) | 10.04 (3) | 10.16 (5) | 3.35 (9) | Illite |
| | | 3.35 (6) | 3.35 (6) | 3.35 (5) | | Quartz |
| | Fine | 14.72 (23) | 17.66 (20) | 12.27 (15) | 10.04 (4) | Montmorillonite |
| | | 3.35 (3) | 3.35 (4) | 3.35 (6) | 3.35 (3) | Quartz |
| S-78.2 | Coarse | 14.72 (12) | 17.66 (13) | 12.62 (7) | 10.04 (4) | Montmorillonite |
| | | 10.04 (3) | 10.04 (3) | 10.04 (6) | 3.35 (4) | Illite |
| | | 7.25 (1) | 7.25 (1) | 7.25 (3) | | Kaolinite |
| | | 3.35 (4) | 3.35 (3) | 3.35 (5) | | Quartz |
| | Fine | 15.49 (24) | 17.66 (25) | 12.62 (5) | 3.35 (2) | Montmorillonite |
| | | 3.35 (3) | 3.35 (4) | 3.35 (3) | | Quartz |
| S-79 | Coarse | 14.72 (9) | 16.98 (9) | 12.62 (8) | 10.04 (7) | Montmorillonite |
| | | 10.04 (4) | 10.04 (3) | 10.04 (8) | 3.35 (7) | Illite |
| | | 7.25 (2) | 7.25 (2) | 7.25 (3) | | Kaolinite |
| | | 3.35 (4) | 3.35 (4) | 3.35 (6) | | Quartz |
| | Fine | 15.22 (24) | 17.66 (26) | 12.62 (8) | 10.04 (2) | Montmorillonite |
| | | 3.35 (4) | 3.35 (4) | 3.35 (4) | 3.35 (2) | Quartz |

TABLE II "CONTINUED"

| Sample No. | Clay Fraction | Ca. sat. 25°C | Ca. sat. Gly. 25° | K sat. 25°C | K sat. 500°C | Type of Major Mineral |
|---|---|---|---|---|---|---|
| S-85 | Coarse | 14.72 (8) | 17.66 (5) | 12.27 (4) | 10.04 (4) | Montmorillonite |
| | | 10.04 (5) | 10.04 (4) | 10.04 (5) | 3.35 (5) | Illite |
| | | 7.25 (3) | 7.25 (1) | 7.25 (2) | | Kaolinite |
| | | 3.59 (1) | 3.59 (1) | 3.59 (1) | | Quartz |
| | | 3.35 (5) | 3.35 (3) | 3.35 (3) | | |
| | Fine | 3.35 (3) | 3.35 (2) | 3.35 (2) | 3.35 (2) | Quartz |
| S-86 | Coarse | 10.04 (4) | 10.04 (2) | 10.04 (3) | 10.04 (2) | Illite |
| | | 7.25 (6) | 7.13 (4) | 7.13 (4) | 3.35 (3) | Kaolinite |
| | | 3.59 (3) | 3.59 (1) | 3.56 (1) | | Quartz |
| | | 3.35 (4) | 3.35 (3) | 3.35 (3) | | |
| | Fine | 15.22 (12) | 16.98 (8) | 12.99 (7) | 10.04 (3) | Montmorillonite |
| | | 7.25 (5) | 7.25 (3) | 7.25 (3) | 3.35 (2) | Kaolinite |
| | | 3.56 (3) | 3.56 (1) | 3.56 (2) | | Quartz |
| | | 3.35 (4) | 3.35 (3) | 3.35 (3) | | |
| S-87 | Coarse | 15.22 (9) | 17.66 (6) | 7.25 (2) | 3.35 (2) | Montmorillonite |
| | | 7.25 (3) | 7.25 (2) | 3.59 (1) | | Kaolinite |
| | | 3.59 (1) | 3.59 (1) | 3.35 (1) | | Quartz |
| | | 3.35 (3) | 3.35 (2) | | | |
| | Fine | 15.22 (11) | 18.39 (9) | 12.27 (3) | 3.35 (3) | Montmorillonite |
| | | 3.35 (4) | 3.35 (3) | 3.35 (3) | | Quartz |

## TABLE II "CONTINUED"

| Sample No. | Clay Fraction | Ca. sat. 25°C | Ca. sat. Gly. 25° | K sat. 25°C | K sat. 500°C | Type of Major Mineral |
|---|---|---|---|---|---|---|
| S-87 | Coarse | 15.22 (9) | 17.66 (6) | 7.25 (2) | 3.35 (2) | Montmorillonite |
| | | 7.25 (3) | 7.25 (2) | 3.59 (1) | | Kaolinite |
| | | 3.59 (1) | 3.59 (1) | 3.35 (1) | | Quartz |
| | | 3.35 (3) | 3.35 (2) | | | |
| | Fine | 15.22 (11) | 18.39 (9) | 12.27 (3) | 3.35 (3) | Montmorillonite |
| | | 3.35 (4) | 3.35 (3) | 3.35 (3) | | Quartz |
| S-88 | Coarse | 14.72 (11) | 17.66 (8) | 12.62 (6) | 3.35 (3) | Montmorillonite |
| | | 7.13 (3) | 7.13 (2) | 7.13 (3) | | Kaolinite |
| | | 3.59 (1) | 3.59 (1) | 3.59 (1) | | Quartz |
| | | 3.35 (5) | 3.35 (3) | 3.35 (3) | | |
| | Fine | 14.72 (12) | 17.66 (13) | 12.62 (10) | 3.35 (3) | Montmorillonite |
| | | 3.35 (2) | 3.35 (2) | 3.35 (2) | | Quartz |
| S-89 | Coarse | 15.22 (10) | 17.66 (13) | 12.99 (5) | 10.27 (4) | Montmorillonite |
| | | 7.13 (4) | 7.13 (3) | 7.13 (3) | 3.35 (3) | Kaolinite |
| | | 3.58 (1) | 3.58 (1) | 3.58 (1) | | Quartz |
| | | 3.35 (3) | 3.35 (3) | 3.35 (2) | | |
| | Fine | 15.77 (15) | 18.39 (18) | 12.62 (5) | 10.04 (3) | Montmorillonite |
| | | 3.35 (3) | 3.35 (1) | 3.35 (1) | 3.35 (2) | Quartz |
| S-90 | Coarse | 15.22 (8) | 15.77 (4) | 10.04 (3) | 10.04 (3) | Vermiculite |
| | | 3.35 (3) | 3.35 (3) | 3.35 (3) | 3.35 (4) | Quartz |
| | Fine | 4.25 (1) | 4.27 (1) | 4.27 (1) | 4.23 (1) | Quartz |
| | | 4.07 (1) | 4.07 (1) | 4.07 (1) | 4.07 (1) | Cristobalite |
| | | 3.35 (3) | 3.35 (2) | 3.35 (2) | 3.35 (2) | Quartz |

TABLE II "CONTINUED"

| Sample No. | Clay Fraction | Ca. sat. 25°C | Ca. sat. Gly. 25° | K sat. 25°C | K sat. 500°C | Type of Major Mineral |
|---|---|---|---|---|---|---|
| S-91 | Coarse | 15.49 (7) | 15.77 (5) | 10.04 (2) | 10.04 (1) | Vermiculite |
| | | 10.04 (3) | 10.04 (2) | 3.35 (3) | 3.35 (3) | Illite |
| | | 3.35 (4) | 3.35 (3) | | | Quartz |
| | Fine | 15.22 (12) | 17.66 (9) | 12.62 (6) | 3.35 (2) | Montmorillonite |
| | | 3.35 (3) | 3.35 (3) | 3.35 (2) | | Quartz |
| S-92 | Coarse | 15.22 (12) | 17.66 (10) | 12.99 (5) | 10.04 (8) | Montmorillonite |
| | | 3.35 (4) | 3.35 (3) | 3.35 (3) | 3.35 (4) | Quartz |
| | Fine | 15.77 (16) | 17.66 (15) | 12.99 (5) | 3.35 (2) | Montmorillonite |
| | | 3.35 (4) | 3.35 (3) | 3.35 (2) | | Quartz |
| S-93 | Coarse | 15.22 (18) | 17.66 (11) | 12.62 (6) | 10.04 (7) | Montmorillonite |
| | | 10.27 (3) | 10.16 (2) | 10.04 (5) | 3.35 (3) | Illite |
| | | 3.35 (3) | 3.35 (3) | 3.35 (3) | | Quartz |
| | Fine | 15.77 (15) | 17.66 (14) | 12.99 (7) | 10.04 (2) | Montmorillonite |
| | | 3.35 (3) | 3.35 (2) | 3.35 (2) | 3.35 (2) | Quartz |
| S-94 | Coarse | 15.22 (12) | 17.66 (9) | 12.99 (2) | 10.04 (2) | Montmorillonite |
| | | 3.35 (3) | 3.35 (2) | 3.35 (2) | 3.35 (3) | Quartz |
| | Fine | 15.22 (5) | 17.66 (6) | 12.99 (2) | 10.04 (2) | Montmorillonite |
| | | 3.35 (3) | 3.35 (3) | 3.35 (3) | 3.35 (3) | Quartz |

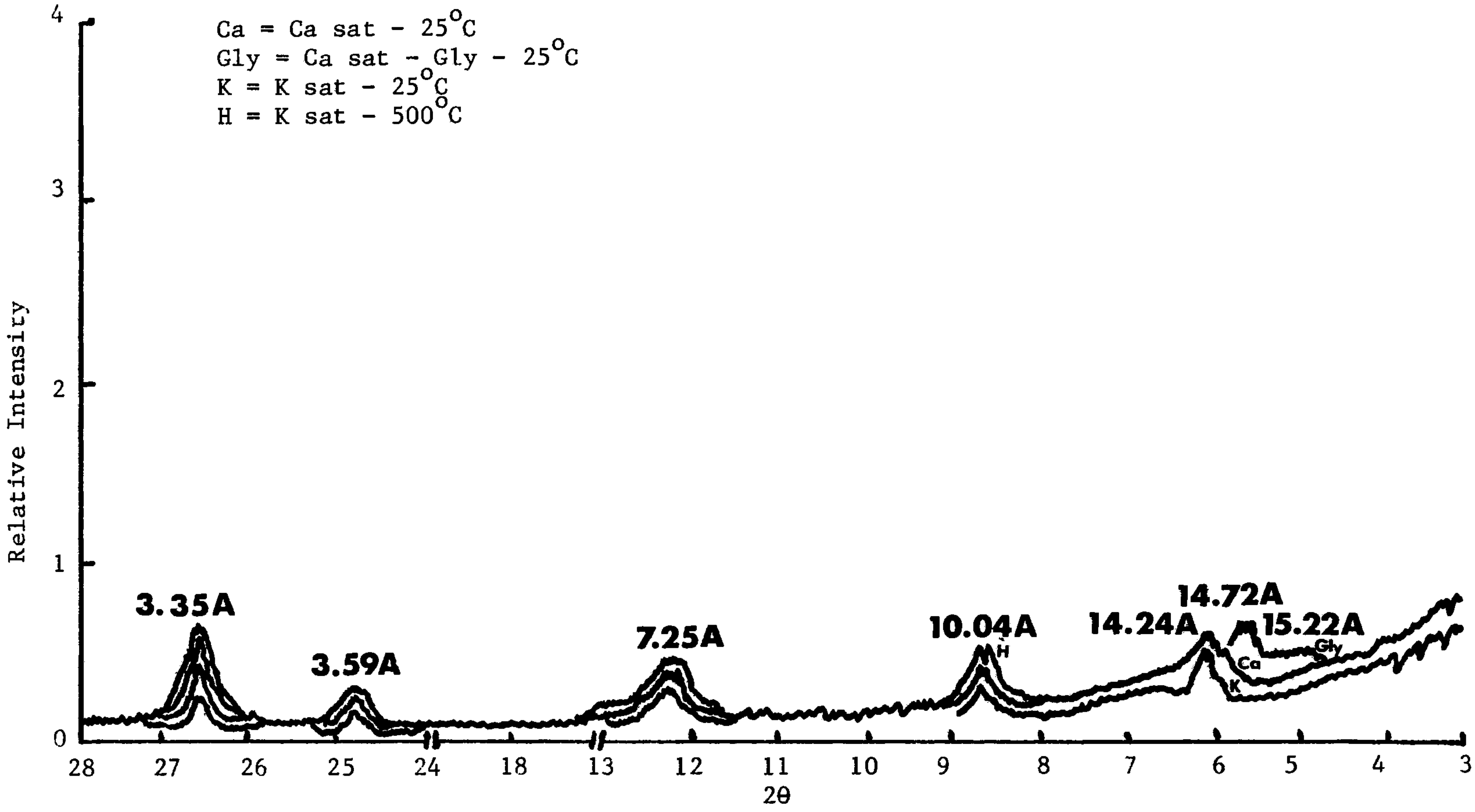


Figure 3. X-ray Diffraction Pattern and d-spacings in Angstroms of the Coarse Clay Fraction of [illegible]-23.

glycol, and potassium treatments. The 10.04A$^{o}$ peak represents illite and collapsed vermiculite due to the 500°C heat treatment. The 7.25A$^{o}$ peaks represent first order kaolinite and second order kaolinite is represented by the 3.59A$^{o}$ peaks. Upon heating, the first and second order kaolinite peaks disappear. Quartz is represented by the 3.35A$^{o}$ peaks, however, the part of the intensity of the quartz diffraction peak is due to the ceramic plate on which the sample is mounted. The fine clay fraction of S-23 (Figure 4) contains a large amount of montmorillonite. The calcium saturated montmorillonite resulted in the 14.24A$^{o}$ spacing of the (oo1). The ethylene glycol treatment caused the calcium saturated montmorillonite to expand to a 17.66A$^{o}$ spacing of the (oo ). Upon potassium saturation, the montmorillonite collapsed to a 12.44A$^{o}$ spacing (oo ). The heating process caused a further collapse of the montmorillonite to a 10.27A$^{o}$ spacing. The first and second order kaolinite is represented by 7.25A$^{o}$ and 3.59A$^{o}$ peaks. The 500°C heating process caused complete destruction of the kaolinite. The 3.35A$^{o}$ spacing represents the mineral quartz. The tabular data for the samples in this group are reported in Table II. Sample S-72 which is a part of Group 1 is represented in Figures 5 and 6. The coarse clay fraction of S-72 (Figure 5) contains a moderate amount of montmorillonite, and illite, and lesser amounts of kaolinite. The fine clay fraction of S-72 (Figure 6) contains a large amount of montmorillonite, first order kaolinite and no second order kaolinite. The montmorillonite spacings are broad and upon heating the 10.04A$^{o}$ spacing almost disappeared, thus indicating amorphous material on the clay surfaces.

Sample S-75, which is a part of Group 1 is from a lime treated dam embankment (Table I) and the x-ray diffraction data is presented in

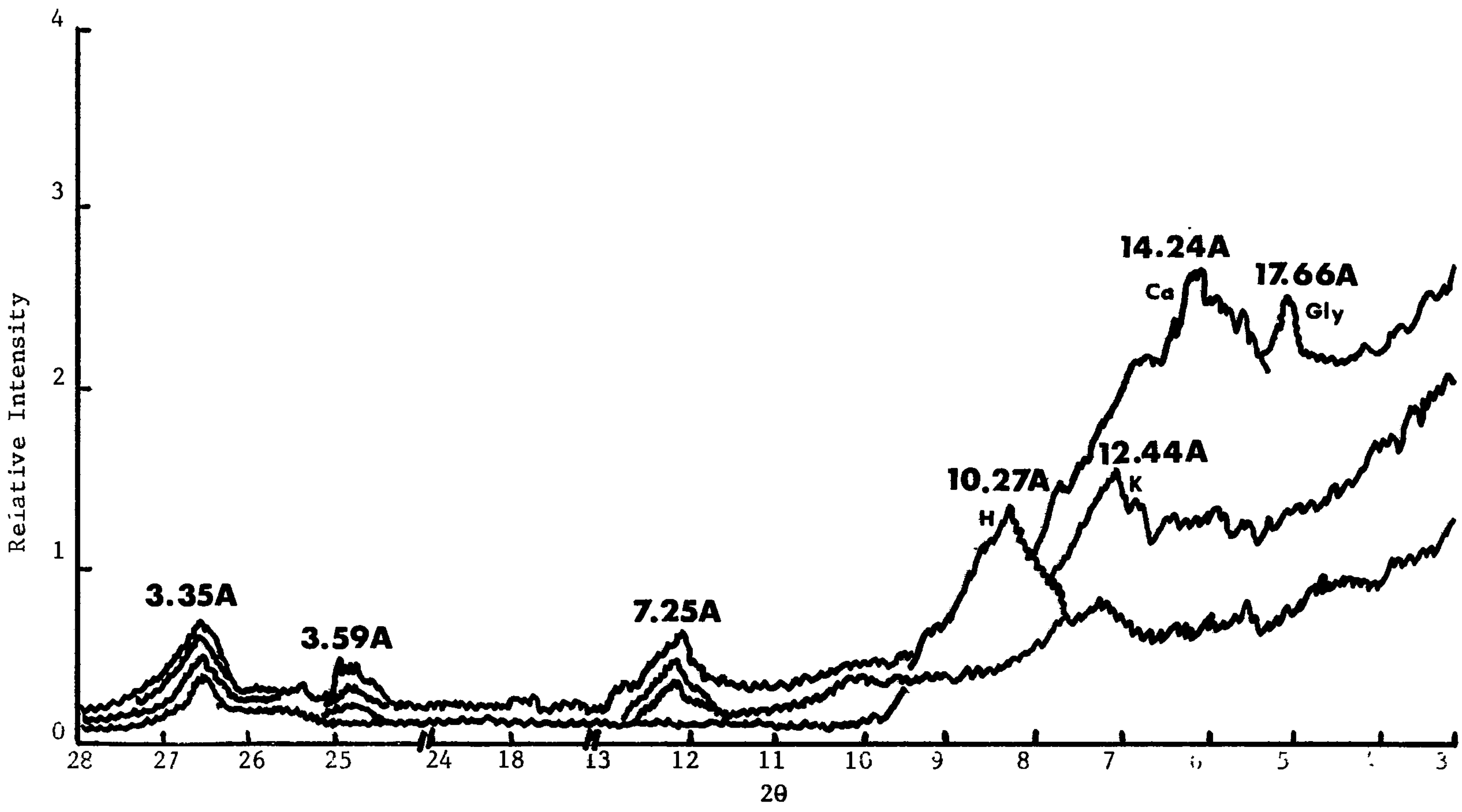


Figure 4. X-ray Diffraction Pattern and d-spacings in Angstroms of the Fine Clay Fraction of S-23.

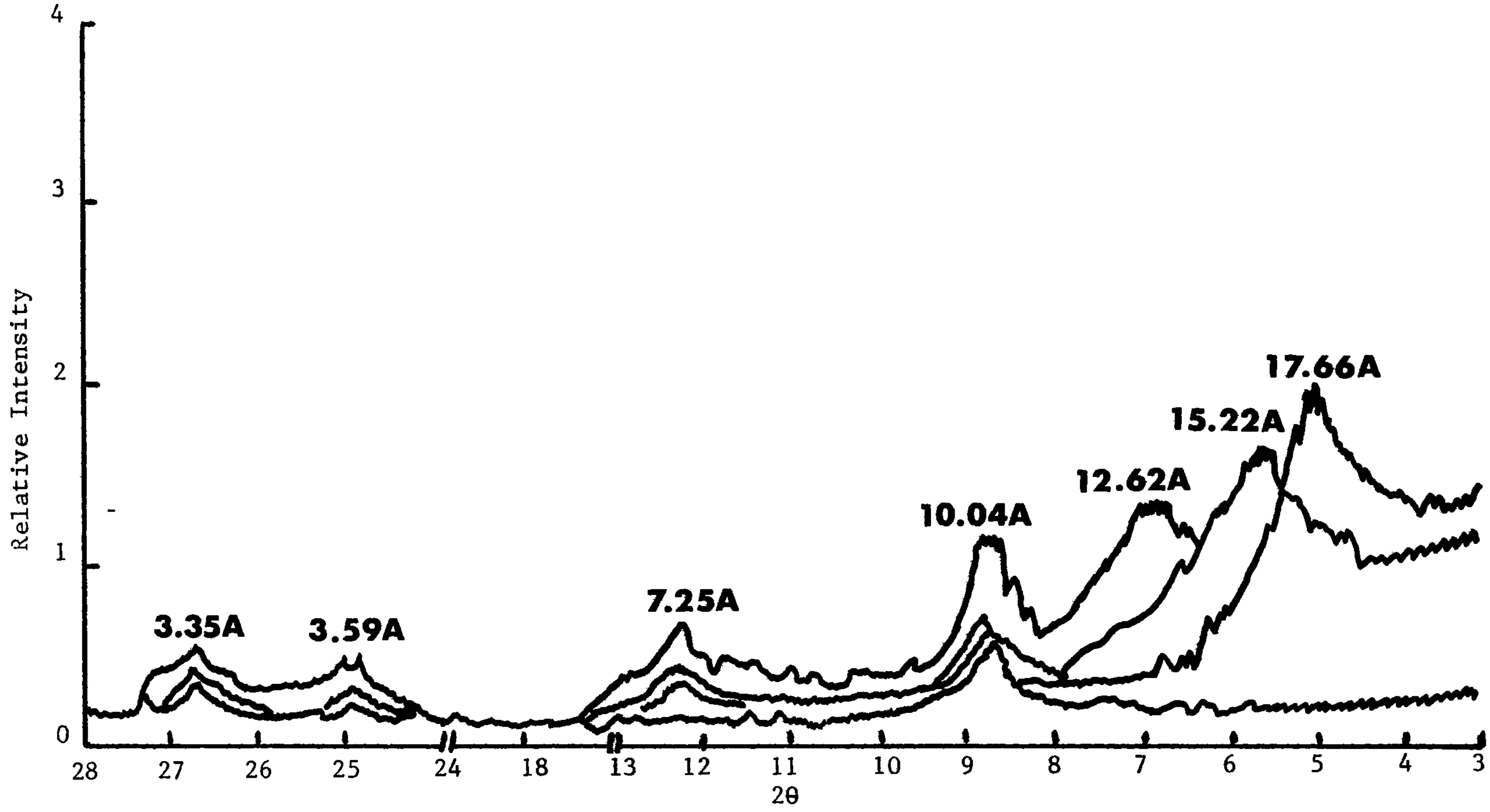


Figure 5', X-ray Diffraction Pattern and d-spacings in Angstroms of the Coarse Clay Fraction of S-72.

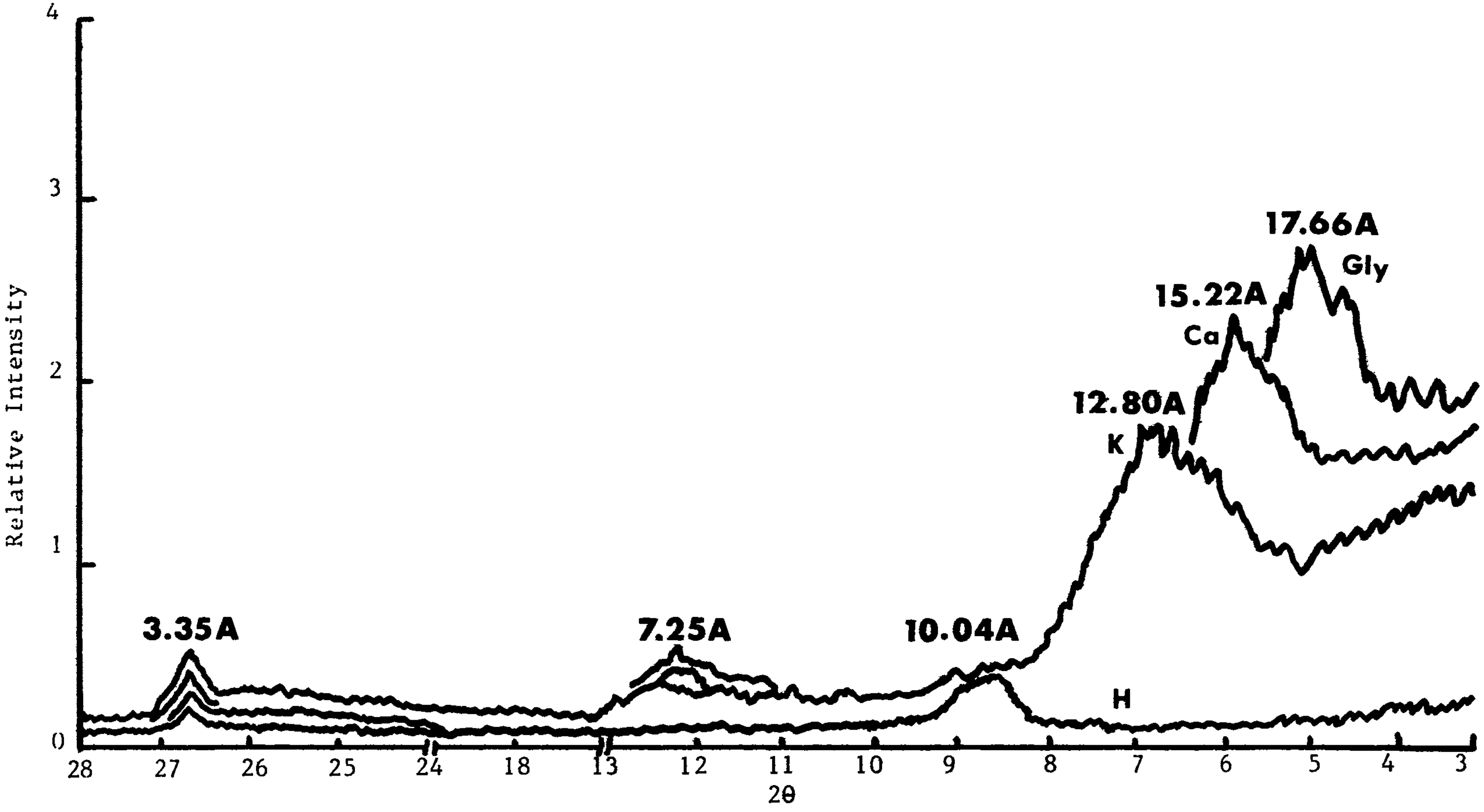


Figure 6. X-ray Diffraction Pattern and d-spacings in Angstroms of the Fine Clay Fraction of S-72

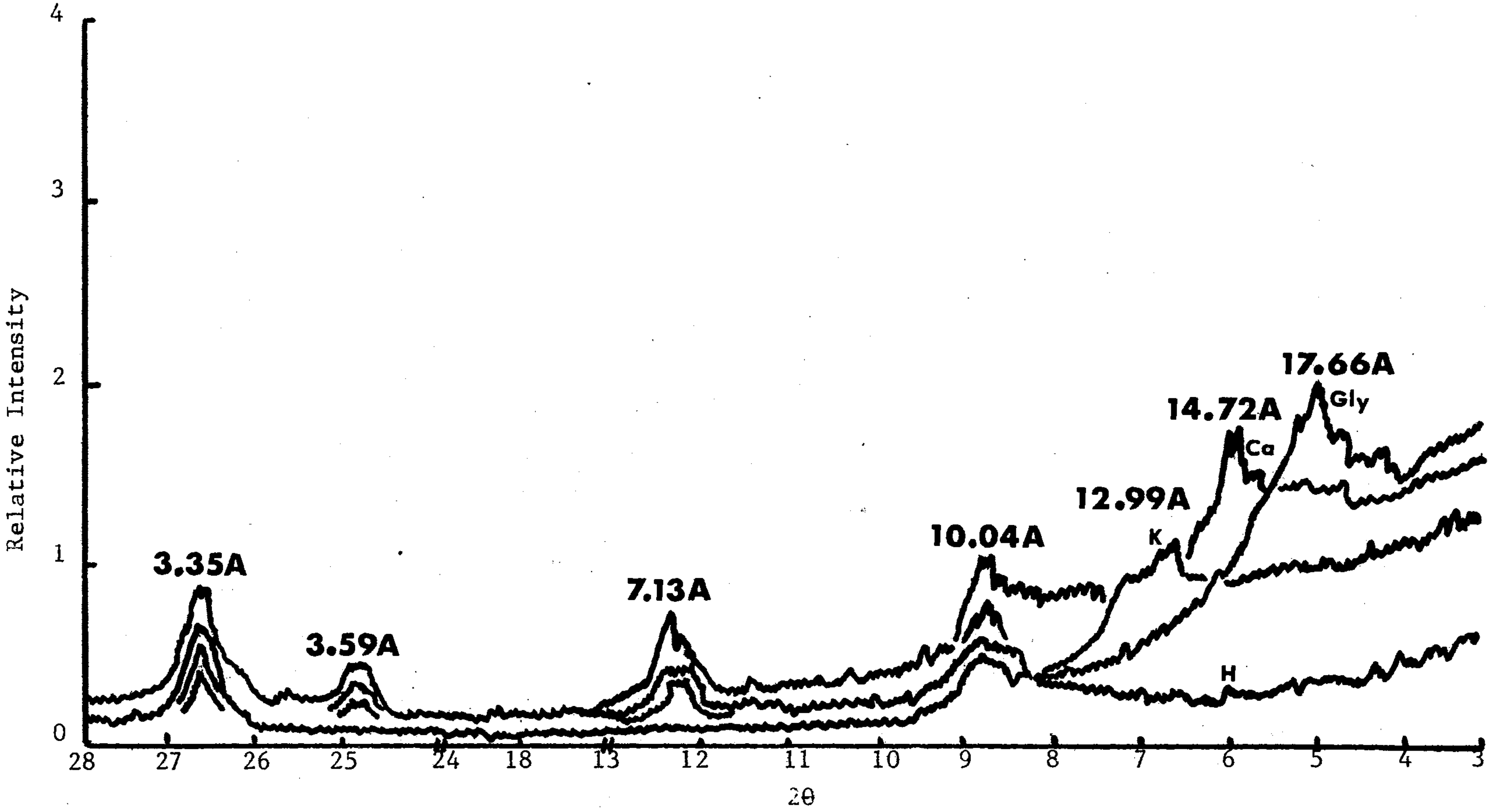


Figure 7. X-ray Diffraction Pattern and d-spacings in Angstroms of the Coarse Clay Fraction of S-75

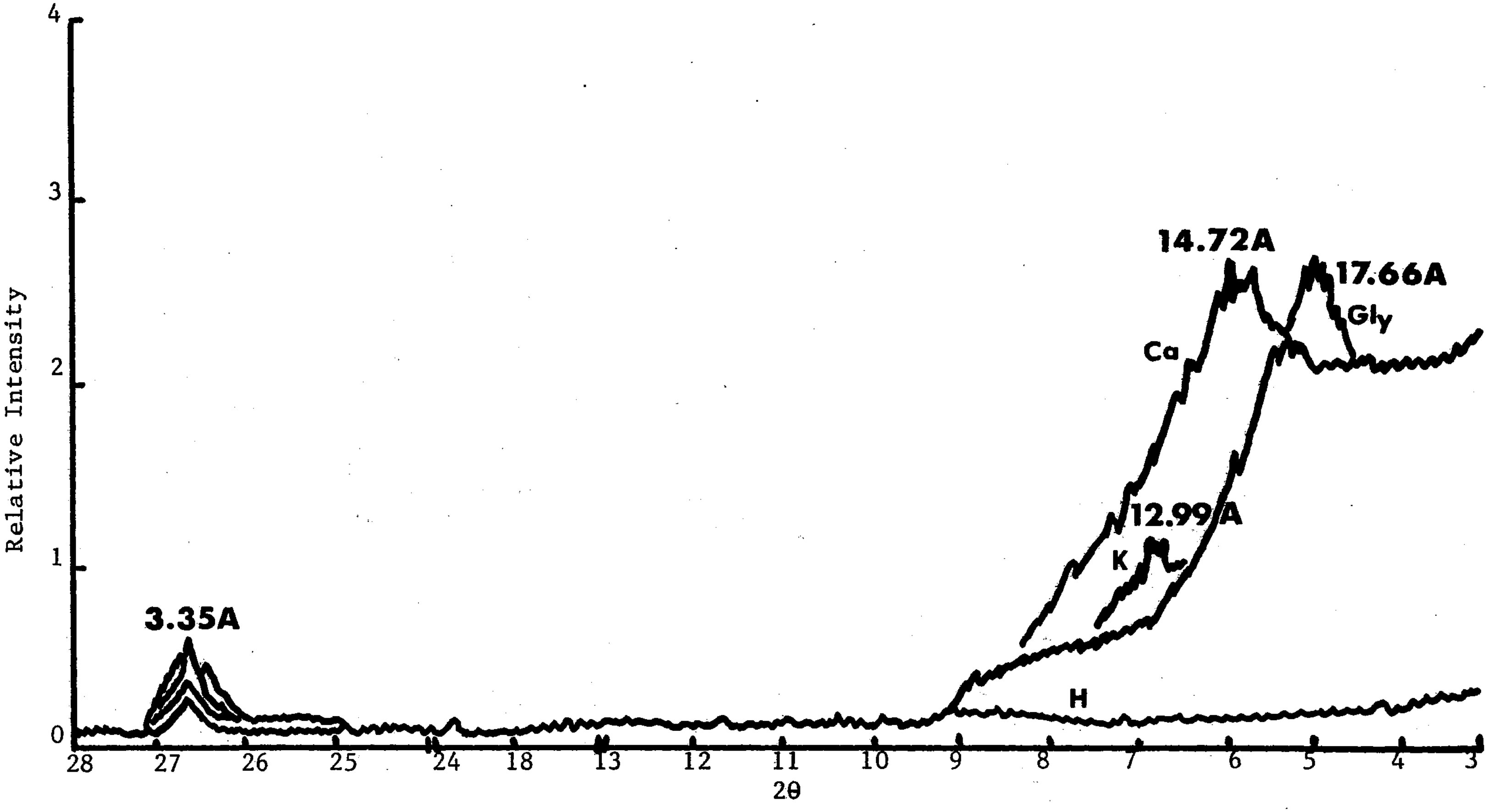


Figure 8. X-ray Diffraction Pattern and d-spacings in Angstroms of the Fine Clay Fraction of S-75.

in Figures 7 and 8. The coarse clay fraction of S-75 (Figure 7) contains a moderate amount of montmorillonite and illite and lesser amounts of kaolinite. The fine clay fraction of S-75 (Figure 8) contains a large amount of montmorillonite and is essentially monomineralic. The montmorillonite spacings are braod and upon heating the montmorillonite collapses completely, thus indicating amorphous material may be present on the clay surfaces.

Those samples were the major clay minerals, Group 2, are illite: kaolinite: quartz are: S-4, S-6, S-9, S-21, S-29, S-40, S-45, S-59, S-60, S-70, and S-71. The x-ray diffraction pattern of sample S-59 is representative of this group (Figure 9 and 10). The coarse clay fraction of S-59 (Figure 9) contains illite and kaolinite and quartz. Upon heating, the kaolinite peaks disappear and the quartz peak is intensified. The fine clay fraction of S-59 (Figure 10) contains illite ($10.04A^{o}$) kaolinite and quartz. The heating process intensified the quartz peak. The remainder of the x-ray diffraction spacings (oo ) and intensities are reported in Table II. Those samples where the major clay minerals, Group 3, are montmorillonite: kaolinite: quartz are: S-26, S-33, S-58, S-87, S-88 and S-89. The x-ray diffraction pattern of sample S-89 is presented in Figures 11 and 12. The coarse clay fraction of S-89 (Figure 11) contains moderate amounts of montmorillonite, lesser amounts of kaolinite and quartz. The fine clay fraction of S-89 (Figure 12) contains moderate amounts of montmorillonite with this clay mineral as the only recognizable clay mineral present and small amounts of quartz. The conformation of the peaks and the presence of a $10.04A^{o}$ peak after heating indicates the presence of amorphous material on clay surfaces. Those samples where

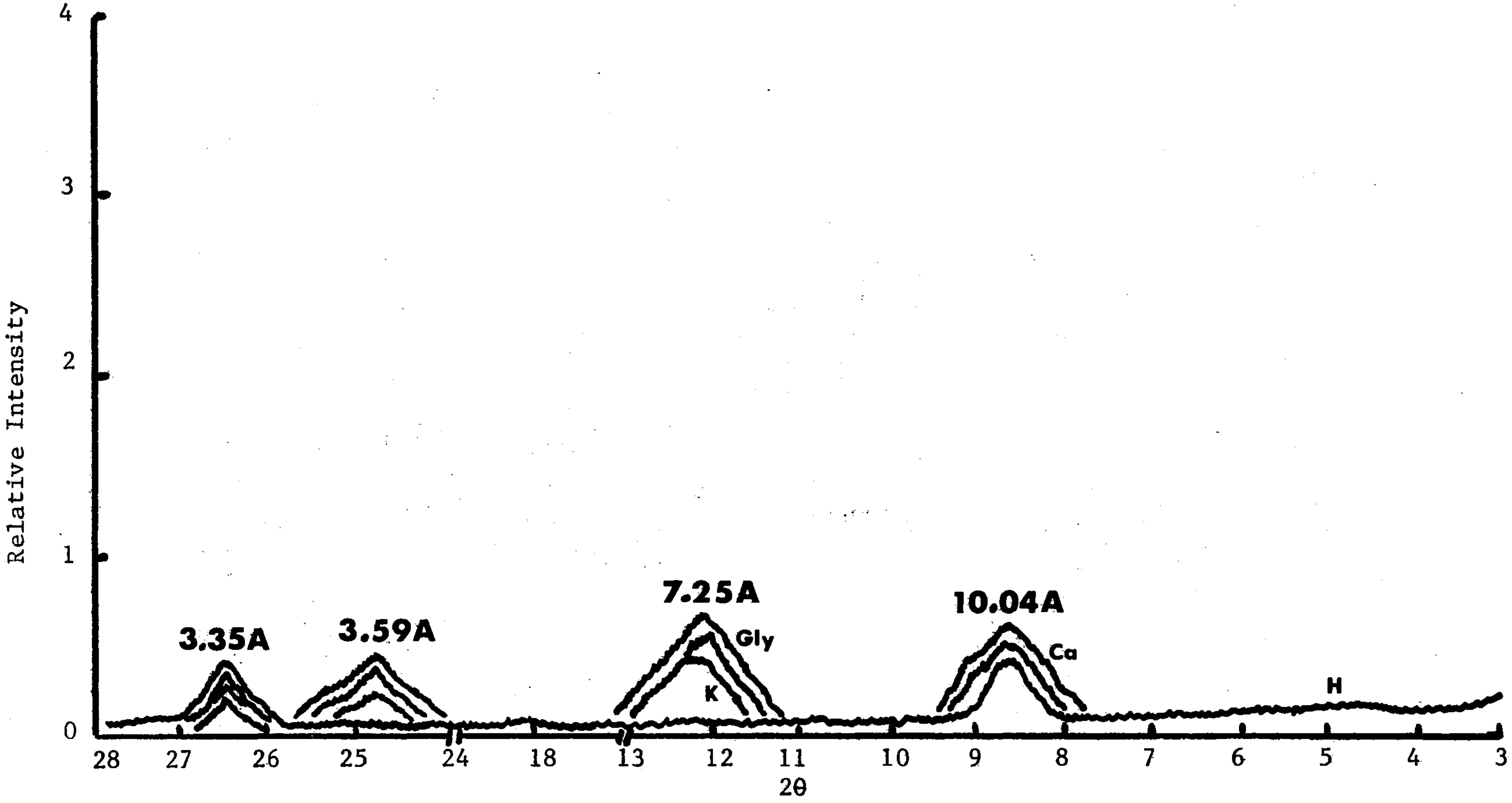


Figure 9. X-ray Diffraction Pattern and d-spacings in Angstroms of the Coarse Clay Fraction of S-59

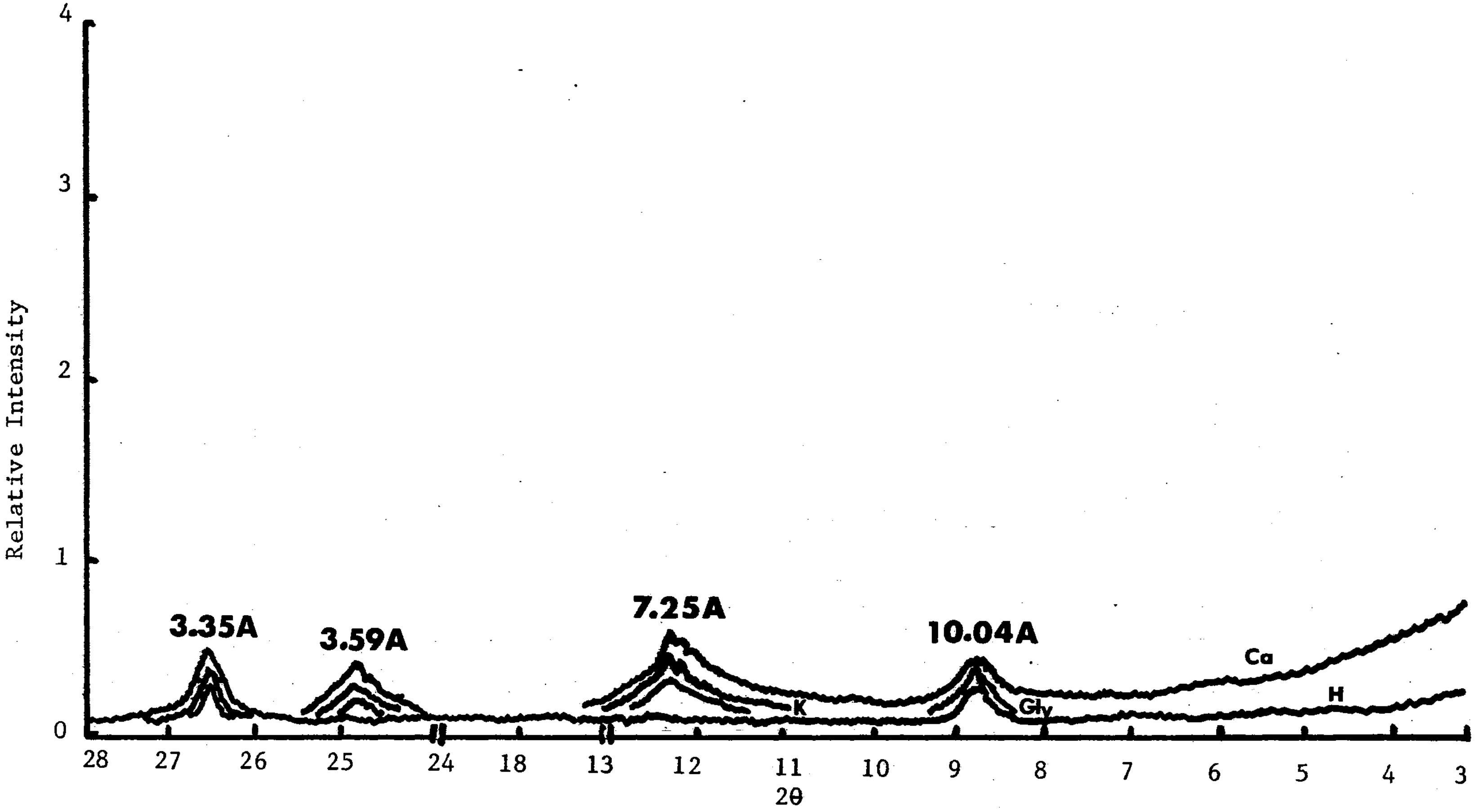


Figure 10. X-ray Diffraction Pattern and d-spacings in Angstroms of the Fine Clay Fraction of S-59.

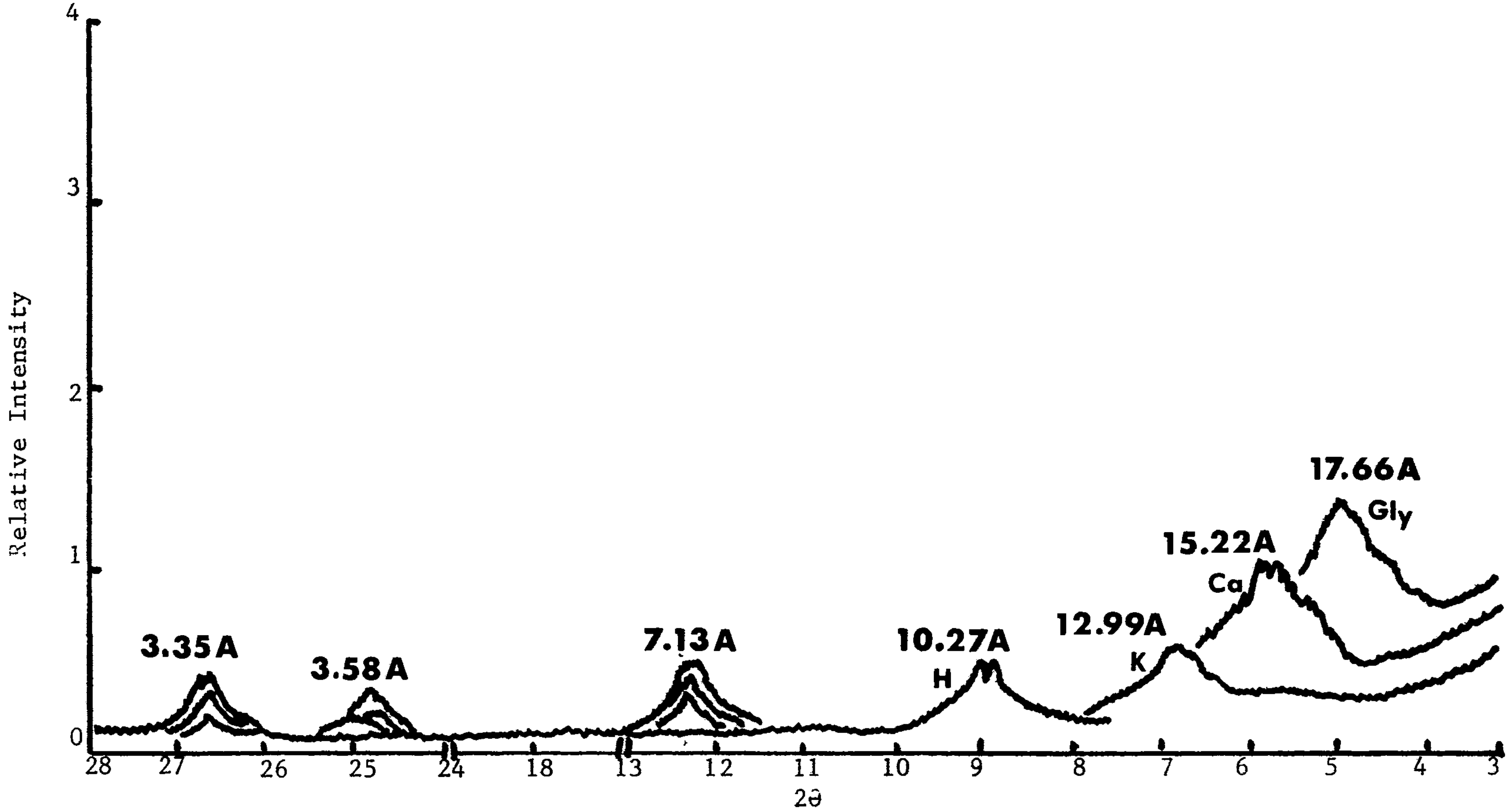


Figure 11. X-ray Diffraction Pattern and d-spacings in Angstroms of the Coarse Clay Fraction of S-89.

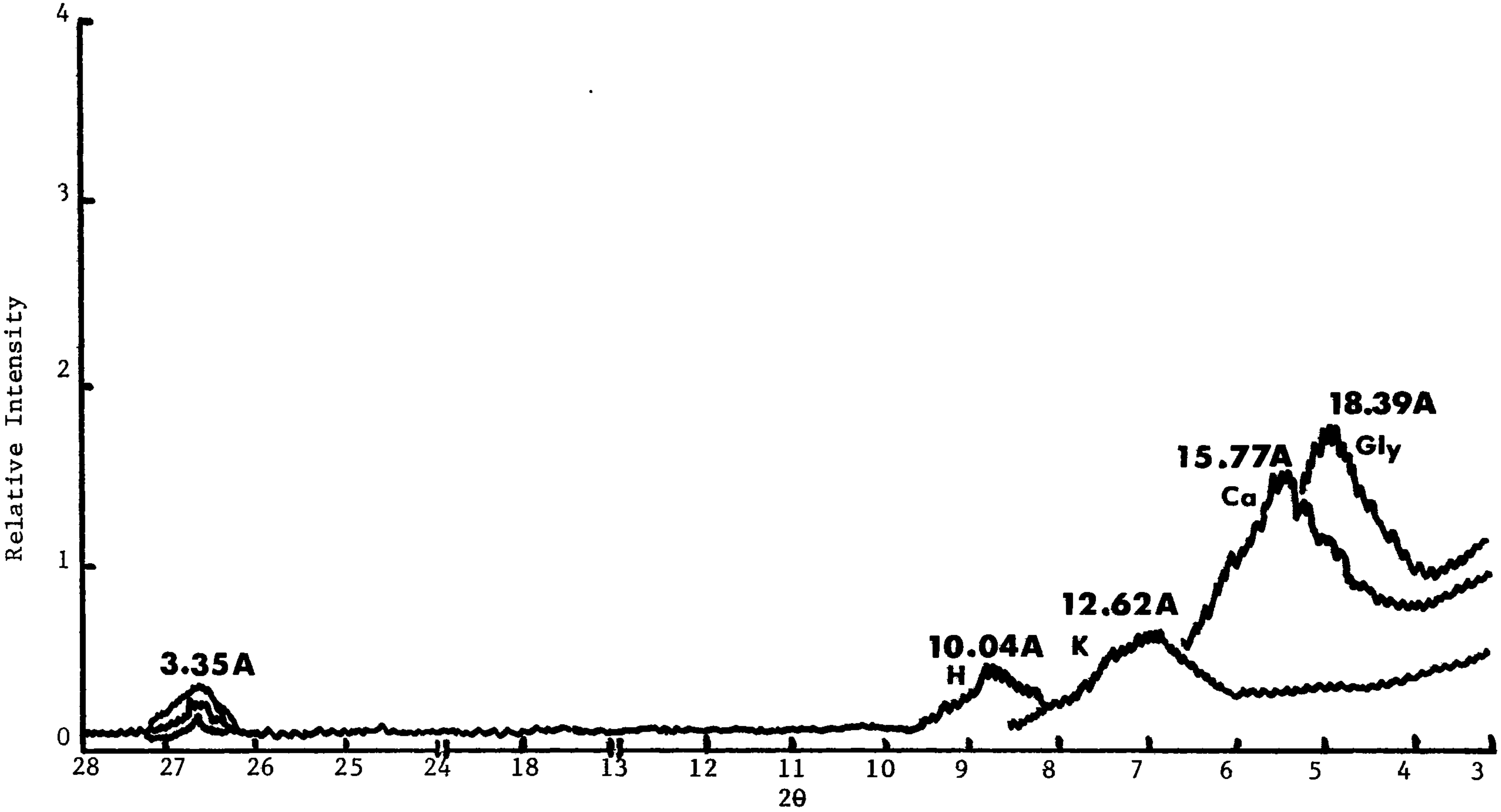


Figure 12. X-ray Diffraction Pattern and d-spacings in Angstroms of the Fine Clay Fraction of S-89.

the major clay minerals, Group 4, are montmorillonite and quartz are: S-32, S-34, S-36, S-73, S-91, S-92, and S-94. The x-ray diffraction pattern of sample S-36 is representative of the group and the x-ray diffraction data for this sample is presented in Figures 13-14. The coarse caly fraction of S-36 (Figure 13) contains a large amount of montmorillonite and moderate amount of quartz (3.35A$^{o}$). The fine clay fraction of S-36 (Figure 14) contains only montmorillonite. Therefore these samples are essentially mono-mineralic in respect to clay minerals particularly in the fine (<,2μ) fraction.

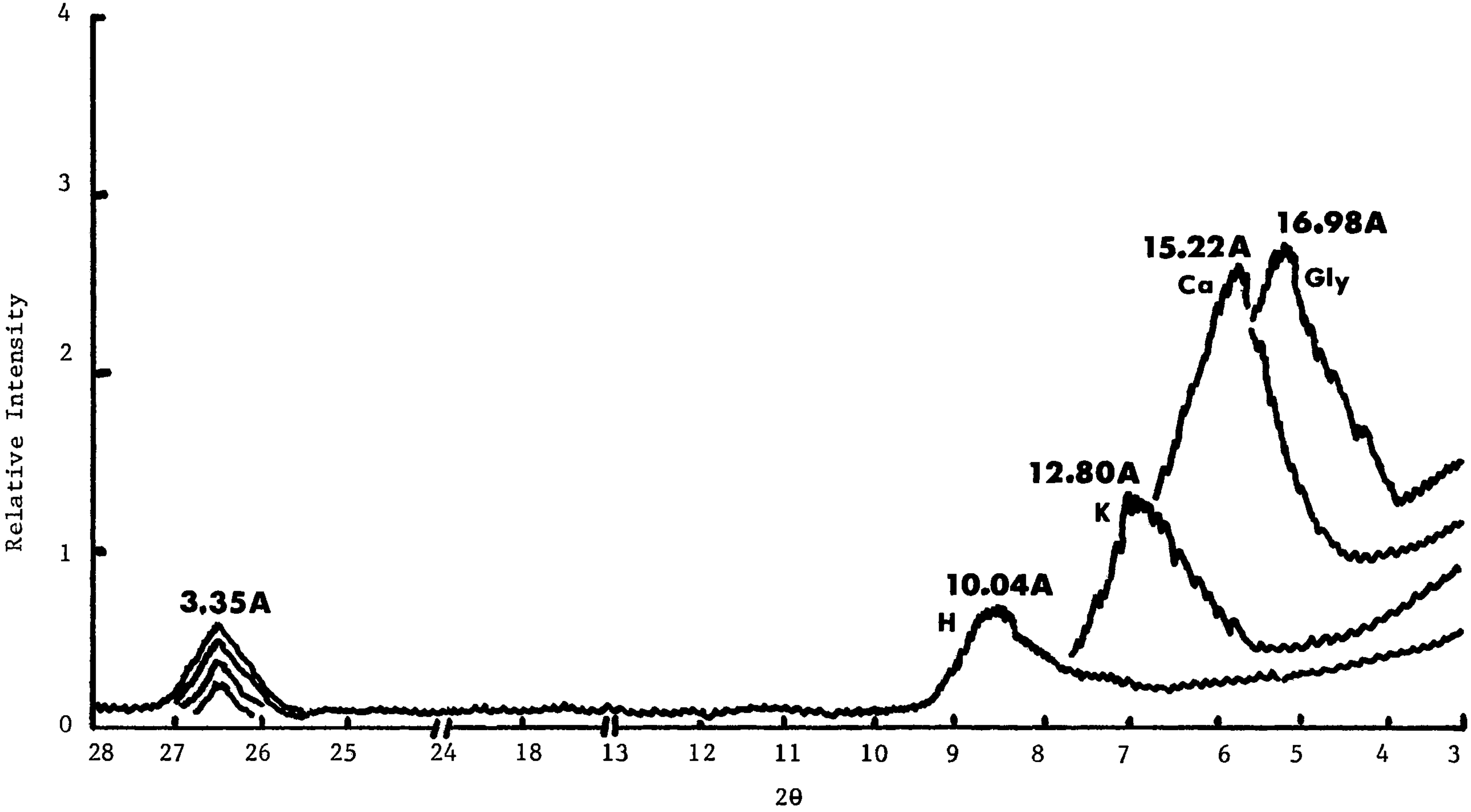


Figure 13. X-ray Diffraction Pattern and d-spacings in Angstroms of the Coarse Clay Fraction of S-36.

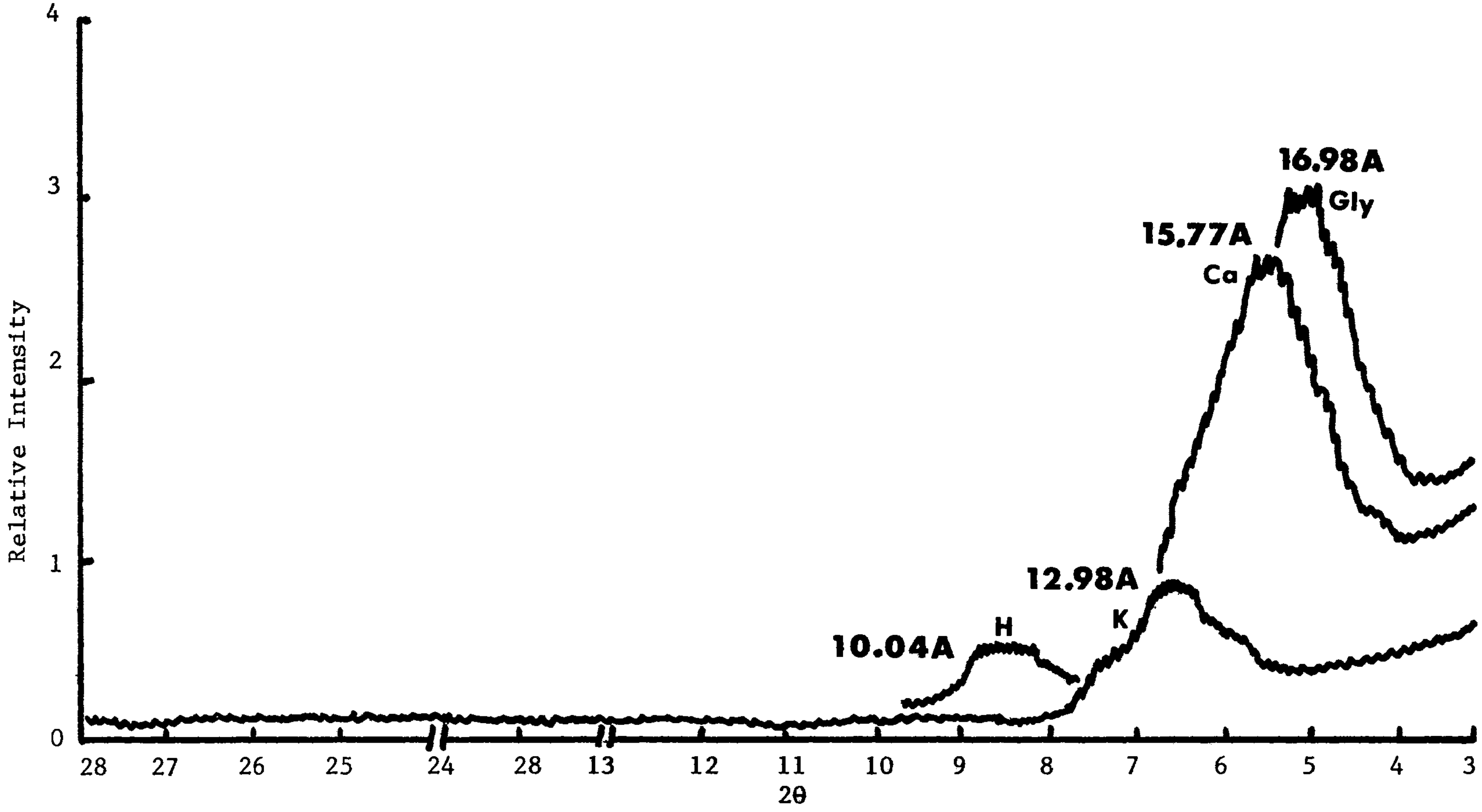


Figure 14. X-ray Diffraction Pattern and d-spacings in Angstroms of the Fine Clay Fraction of S-36.

# CHAPTER V

## SUMMARY

Within the scope of this study several concepts and ideas of various researchers and investigators were reported. The first and one of the most important concepts to be elaborated on is the concept of the clay-water equilibrium and stability of earthen structures. If a clay-water equilibrium is established in an earthen water retaining structure, the equilibrium would be stable and the retaining structure would not fail. If, however, the equilibrium is disturbed, the stabilizing effects would be reduced and possible failure to the structure could occur. Volk (1937) implied that the failure of the earthen water retaining structures was related to the formation of soil pipes and arches. The disturbed clay-water equilibrium could be related to the formation of the soil pipes, tunnels, and in the extreme case, breaches in the retaining structures.

The following possibility could exist between the disturbed equilibrium and the phenomenon of piping. During construction and upon completion of the earthen water retaining structure, a slow drying process could have occurred and resulted in the formation of a water unsaturated upper soil layer and a saturated lower soil layer within the structure. As the reservoir filled with water, the water could have slowly percolated and moved laterally into the lower part of the embankment of the structure. The drying process would have produced surface cracks particularly where high shrink-swell clays were present and this would encourage the movement of water to the lower depths of the embankment. The movement of water would then disturb the established clay-water equilibrium. If the dominant clays are swelling montmorillonite or illite or a mixture of the two, the disturbed equilibrium of the clay-water system could cause the clay particles to absorb water to a point that a high degree of swelling occurs. The high degree of swelling of the clays due to water absorption would result in the clay particles going into suspension, and the clay particles are dispersed, or a liquid phase is established.

The dispersed clay and the additional water would result in the weakening of the shear strength of the soil material. The reduction in the shear strength of the material would result in the weakened saturated material giving way under the overburden. The saturated material slumping away from the unsaturated material would result in the formation of soil pipes and tunnels, or in the extreme case of a complete failure of the structure due to the formation of a structural breach.

The next concept to be considered is the effect of the reservoir water on the failure of the soil water-retaining structures. The reservoir water possesses several properties which could influence the failure of the dam structures. The two main properties are chemical composition and force or movement of the water. The chemical composition of the reservoir water could effect the failure of the dam structure built of soil in the following way. A majority of the failure dams failed when the reservoirs were filled for the first time. The initial filling of these reservoirs was achieved by extremely heavy rains of short duration. The concentration of the soluble salts within the reservoir water was affected by the rain storms. The fresh water from the rain storms resulted in a low concentration of soluble salts in the percolating water which enters the dry embankment of the dam structure. The water film or hull surrounding the clay particles increased in thickness, and the clay mass is weakened by the disassociation of clay particles. The clay particles become dispersed into a clay-water suspension. The dispersed clay particles are easily eroded away when the water is moving with some force, particularly if the concentration of soluble salts is quite low.

The force of movement of the water could affect the magnitude of the failure of the dam structures in the following way. Due to swelling of the clay particles, the disassociated clay particles would become dispersed in a water suspension. If the velocity of the water moving through the dam is reduced, the dispersed clay particles are not carried away by the water. The dispersed clay particles will continue to swell and gradually seal off the leak and check future water movement. This situation would produce minor or non-detectable damage to the earthen structure.

On the other hand, if the velocity of the water through the structure is increased the following two possibilities exist: (1) The velocity of the water might cause only minor detectable damage but yet serious damage could result to the dam structure. The dispersed clay and other fine particles of soil material are carried away and results in the formation of leaks and small soil pipes. If the condition is not detected or left unrepaired, the failure area could slowly progress to the more serious types of damage to the dam structure. (2) The velocity of the water may have reached such force that serious damage to the earthen structure is eminent. The increased velocity of the water could result in a chain reaction. The chain reaction would involve first minor damage caused by the structure being subjected to a severe erosion process. Due to the erosion process, minor leaks would develop into pipes, tunnels, and finally into breaches and major destruction to the dam structure.

Finally, the most important concept is the relationship between the dam failures and the type of clay present in the building material. The x-ray diffraction results reported in this study indicates that montmorillonite and illite type clay material were present to a larger degree than the kaolinite type of clay in the dams which failed. Due to the existing conditions, structure, and other properties of the clays the montmorillonite and illite type of clays encourage the development of failure areas within the dam embankments. The kaolinite type of clay appears to have a stabilizing affect on the structure and this could have possibly reduced the degree of the failure or prevented the formation of the failure areas within the earthen embankment. It should also be pointed out that those dams where the clays are essentially mono-mineralic are probably more subject to failure than those of a mixed mineralogy.

These concepts are applicable to the Oklahoma failure dams. The results indicate that sample S-1 from Little Wewoka Creek Site 17 contained montmorillonite and illite clays, while the samples S-4 S-6 and S-7.1 from Caney Coon Creek Site 2 contained illite and kaolinite clays. The Caney Coon Creek Dam failed from piping tunnels while the Little Wewoka Creek Dam failed from a tunnel developing into a breach. Since both dams contained illite clays, the severity of the failure is probably related to the montmorillonite. The kaolinite clay may have resulted only in the formation of piping tunnels in the Caney Coon Creek Dam which eventually caused failure. The high swelling montmorillonite clay, however, in the Little Wewoka Creek Site #17 dam caused the development of a tunnel and due to the swelling of the clay the tunnel developed into a breach. The swelling of the montmorillonite clay caused a reduction in the shear strength of the soil material and the soil material above the tunnel collapsed, thus the breach was formed.

According to the results reported for Sample S-11, Table I and II, the dominant clays were montmorillonite and illite. The sample was collected from the Leader Middle Clear Boggy Creek Site 29. The dam failed when a small leak developed above the conduit during a period when the water level in the reservoir was high. The leakage was stopped by lowering the water level in the reservoir. When the water level again was high, the high swelling montmorillonite and illite clays encouraged the development of the leak above the conduit. Upon swelling of the montmorillonite and illite, the clay particles were dispersed and carried away by the force of the water. The water level in the reservoir was lowered and the velocity of the flowing water was reduced. The reduced water velocity allowed the montmorillonite and illite clay particles to swell and not be eroded away. Therefore, the swelling clays sealed off the leak and the failure to the structure was slowed or stopped.

These concepts are applicable to the control and lime treated samples S-72 and S-75, respectively. The control sample S-72 was collected from the Lake Yosemite Dam, which had developed minor leaks without resulting in a piping failure. The lime treated sample S-75 was collected from the Frogville Dam Site 2, which was seriously eroded by rainfall during the construction of the embankment. The slopes and crest of the embankment were covered with a lime treated soil up to a depth of twleve inches. After two years, the lime treated dam was in very good condition with only negligible erosion. According to the x-ray diffraction patterns, the control and lime treated samples contain montmorillonite, illite, and kaolinite. The x-ray diffraction patterns of both samples indicates the presence of amorphous material on the surfaces of the montmorillonite clay. The amorphous material appears to control the swelling properties of the clays and reduces the susceptibility of the clays to the forces of erosion.

# CHAPTER VI

# CONCLUSION

The mineralogical properties of the soil material from the flood control dams were studied. The results indicate a strong correlation between the failure of the earthen water-retaining structure (dam) and the presence of montmorillonite or illite or a mixture of the two types of clays. The same correlation of the failure of dam structures to the presence of montmorillonite or illite types of clays was also strongly indicated by James and Wickham (1970).

Since the montmorillonite and illite clay types appears to be the cause of the failure of dam structures, the following measures could be used in trying to solve and prevent the problem to existing structures and structures to be built in the future.

The area selected for the construction site should be subjected to a complete aerial survey. According to Ingles and Wood (1964), the aerial survey would uncover the presence of turbid waters and erosion gullies within the area. The survey provides an excellent means of recognizing the general soil areas which might have a high risk factor in terms of constructing earthen structures which would fail.

The clay mineralogy of the soil material used in the construction of a structure should have the lowest possible percentage of montmorillonite and illite clay types. If the earthen material contains a high percentage of montmorillonite or illite types of clays, the use of the following chemicals to produce a flocculated and stable condition are recommended: calcium hydroxide, calcium sulfate, calcium chloride, ferrous sulphate and aluminum sulfate. The chemicals must be mixed and thoroughly distributed in the soil material. The ferrous sulphate and aluminum sulfate can be applied as sprayed solutions due to their high degree of solubility.

During and after construction of the dam structure, quality control in terms of engineering methods and practices must be maintained at the highest possible level. The establishment of grasses or other natural vegetative covers on the crest and slopes of the embankment must occur as soon as possible.

During the initial filling of the reservoir, the filling process should be watched and given special attention. The rate of water entering the reservoir or retaining area should be at a slow rate, thus minimizing the possibility of a failure to the structure. The dispersive power of the water can be reduced by the addition of soluble salts to the reservoir water and the application of soluble salts to the surfaces of the embankment. The quantities of the soluble salts added to the reservoir water must be given special considerations. In some cases, the quantity of soluble salts needed to be added to the reservoir water would be both uneconomic and probably undesirable in the water. The salts in high concentration are especially undesirable if the water is used for animal and human consumption.

Finally, all failures should be reported and brought to the attention of the proper authorities. Through the frank and open reporting of all failures and successes of water retaining structures built from soil and with a concentrated effect by all, from scientists to construction workers to the general public, the problem of failures of soil dam structures might be solved.

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# APPENDIX

# APPENDIX

## Basic Data of Oklahoma Failure Dams

### Upper Clear Boggy Creek Site 50

The 28 foot structure retains approximately 1,005 acre feet of water. The structure was completed in May 1970 and the initial filling of the reservoir occurred on October 9, 1970. The dam failed on October 15, 1970 due to a vertical wall breach. The breach was well above the foundation and indicated that the failure was confined to the embankment. The vertical breach was 50 feet wide at the crest of the dam. The crest and slopes were in fair condition. The following four factors were cited as possible causes of the dam failure:

(1) Drying cracks.

(2) Differential settlement cracks

(3) Tension cracks due to swelling of clay and shale.

(4) Highly dispersive soils.

### Leader Middle Clear Boggy Creek Site 33

In September 1963, the 23 foot structure was completed and retained 370 acre feet of water. The initial filling of the reservoir occurred during 1964 and the failure of the structure occurred on October 14, 1969 after a rapid reservoir filling on October 13. The failure was brought about by the development of two tunnels at the same time. The tunnels were 90 feet apart and the largest one measured eight feet high by fifteen feet wide. The possible cause of the dam failure has been cited as erosion of the drying cracks due to rainfall. The dam was repaired and since January 1970, the surface of the dam has been in excellent condition due to a lime treatment applied during the fall of 1970. Before the lime treatment, the slopes of the dam were badly eroded with vertical tunnels measuring up to four feet in diameter. After the treatment by lime, the slopes were in excellent condition and the formation of vertical tunnels was reduced.

### Leader Middle Clear Boggy Creek Site 15

The 25 foot structure was completed in June 1965. The initial filling was on May 26, 1965. The dam failed on May 26, 1965 and again on June 1, 1968. The two failure sites were located about 100 feet apart. The formation of an arch-like tunnel three feet high by fifteen feet wide occurred in the 1965 failure. The tunnel extended through the base of the dam. In 1968 the dam failed due to a three foot diameter circular tunnel which passed through the bottom of the dam. The possible causes of the 1965 and 1968 failure have been cited as follows:

1965 failure;

(1) Highly dispersive soil.

(2) Cold and wet weather occurred during the construction period.

(3) No clear cause stated.

1968 failure;

(1) Highly dispersive soil.

(2) Drying or differential settlement cracks.

(3) Piping in the foundation.

### Upper Red Rock Creek Site 42

The 23 foot structure was completed on December 1966 and the initial filling of the reservoir occurred on June 20, 1967 and retained approximately 385 acre feet of water. On June 20, 1971, the dam failed when a small leak was observed at 5 p.m. on June 20, 1971 and within twenty-four hours the reservoir was empty. The leak was located near the discharge end of the conduit. The erosion tunnel was three feet high by six feet wide and was confined to the embankment. The conduit was exposed over a majority of its length and only small sections were in contact with the embankment. The possible cause for the dam failure was cited as a defective concuit due to inadequate bonding of the conduit with the bedding.

### Caney Coon Creek Site 2

An 8,500 acre feet reservoir was created by the 50 foot retaining structure. The dam was completed on November 16, 1964 and initial filling occurred on November 17, 1964. The failure of the structure was due to the formation of two independent piping tunnels. The tunnels were about 125 feet apart and occurred on the downstream toe of the dam. A small six inch diameter leak was observed on October 19, 1964 and occurred along the municipal water supply conduit. The small six inch diameter leak eroded to eighteen inches in diameter in less than one day. On November 20, 1964, the leak was fifteen feet in diameter. A second leak developed on November 20, 1964 and in less than two days the leak had eroded to a hole ten feet in diameter. The possible causes of the dam failure were cited as the following:

(1) Differential settlement cracks

(2) Leaks in the foundation material, which is alluvium

(3) Cracks in the rock abutment.

(4) Highly dispersive soils.

(5) Material compacted dry of optimum.

### Upper Red Rock Creek Site 48

The 22 foot structure was completed on November 2, 1964 and the initial filling of the 394 acre feet reservoir occurred on November 16, 1964. On November 17, 1964, the dam failed when the reservoir was emptied through an erosion tunnel. The erosion tunnel was ten feet in diameter and located near the conduit. The possible causes of the dam failure were not obvious but the material for the embankment and foundation was packed on the dry side of optimum.

### Upper Clear Boggy Creek Site 53

On February 15, 1964, the 26 foot structure was completed and retained 360 acre feet of water. The initial filling was on June 16, 1964 with the failure of the structure occurring on June 18, 1964. Within twenty-four hours after the initial leak, the reservoir was emptied through an erosion tunnel located near the conduit. The erosion tunnel was ten feet in diameter and passed through the embankment. The possible causes of the failure have have been cited as follows:

(1) Differential settlement cracks

(2) Drying Cracks.

(3) Highly dispersive soils.

(4) Compacted layers poorly bonded together.

(5) Material was compacted dry of optimum.

## Cherokee Sandy Creek Site 8A

The 27 foot structure was completed on January 22, 1963 and the structure resulted in the formation of a 633 acre feet reservoir. Initial filling occurred on May 6, 1964. The initial leak developed into tunnel with a final diameter of eight feet. Two days were required before the main volume of the reservoir was discharged through the tunnel. The possible causes of the failure have been cited as the following:

(1) Drying cracks developing during and after construction.

(2) Differential settlement cracks.

(3) Highly dispersive clay.

(4) Difficulty in compacting the clay.

## Little Wewoka Creek Site 17

On May 14, 1960, the forty foot structure was completed and resulted in the formation of a 2,043 acre feet reservoir. The initial filling occurred on May 19, 1960 and on May 21, 1960 the structure failed. The initial leak was about 6 inches in diameter and was sighted at 8:00 a.m. The leak located near the conduit and eroded to a ten foot diameter hole by 12 a.m. noon. By 6 p.m. the reservoir was empty. The tunnel collapsed forming a breach with a width of 47 feet at the crest of the dam. The conduit was at the bottom of the breach. The possible causes of the failure have been cited as follows:

(1) Differential settlement cracks.
(2) Highly dispersive soils.
(3) Reservoir filling very rapidly.

### Owl Creek Site 13

The 24 foot structure retaining 124 acre feet of water was completed on January 6, 1957. The initial filling of the reservoir occurred on May 17, 1957 and the dam failed on May 19, 1957. The failure tunnel with diameter of eighteen feet occurred along the conduit. The full length of the conduit was exposed. The possible causes of the failure were cited as follows:

(1) Differential settlement cracks.
(2) Highly dispersive soils.
(3) Drying cracks.
(4) Inadequate bonding between conduit and bedding.

### Owl Creek Site 7

On March 19, 1957, the 24 foot structure was completed and resulted in the formation of a 205 acre feet reservoir. The initial filling occurred on May 17, 1957 and on May 19, 1957 the dam failed. The erosion tunnel located in the soil on the upstream side had a diameter of four feet. The erosion tunnel on the dam had a diameter of fifteen feet and extended three feet below the conduit. The possible causes of the failure were cited as follows:

(1) Differential settlement.
(2) Drying cracks encouraging piping.
(3) Inadequate bonding between the conduit and the compacted soil.

(4) Cracks in shale encouraging piping.

## Leader Middle Clear Boggy Creek Site 29

The 23 foot retaining structure was completed on September 19, 1962 and resulted in the formation of a 258 acre-feet reservoir. The initial filling occurred during 1963 and the failure of the structure occurred in 1970. A small three inch diameter leak developed about ten to twelve feet above the conduit. The leak developed during a period when the water was at a high level in the reservoir. After a short time, the leak stopped due to a drop in the reservoir level. The possible causes of the failure were not cited because no formal investigation was conducted.

## Wister Dam

In November 1949, the one hundred foot structure was completed and resulted in the formation of a 30,000 acre feet reservoir. The initial filling of the reservoir occurred between January 23 to January 28, 1950 and the failure occurred on January 30, 1950. Heavy rains for a few days raised the water level to a height of 65 feet. On January 30, 1950, a leak broke through the dam below the reservoir level. The reservoir level was lowered and by February 5, 1950 the leaks were nearly stopped. Upon lowering the reservoir level, extensive repairs were made on both slopes. The cause of the failure was cited as a crack in the embankment through which the leak formed. No further investigations were reported and therefore not available.

# VITA

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