TEXTURE AND MINERALOGY OF THE UPPER CAMBRIAN WELGE SANDSTONE, CENTRAL MINERAL REGION, TEXAS

A Thesis

By

James Edward Hooks

Submitted to the Graduate School of the
Agricultural and Mechanical College of Texas in
partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

August 1961

Major Subject Geology

TEXTURE AND MINERALOGY OF THE UPPER CAMBRIAN WELGE SANDSTONE, CENTRAL MINERAL REGION, TEXAS

A Thesis

By

James Edward Hooks

Approved as to style and content by:

Karl J. Koenig
(Chairman of Committee)

(Head of Department)

August 1961

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

LIST OF PLATES

ACKNOWLEDGMENTS

The writer gratefully acknowledges the cooperation and assistance of the following members of the faculty of the Department of Geology and Geophysics, Agricultural and Mechanical College of Texas: Dr. Karl J. Koenig supervised the investigation; Dr. Travis J. Parker helped familiarize the writer with the Central Mineral region and added constructive suggestions during the preparation of the manuscript; Dr. Horace R. Blank aided with the petrographic study and also added constructive suggestions during the preparation of the manuscript.

The writer also acknowledges Dr. V. E. Barnes of the Bureau of Economic Geology, University of Texas, for his assistance in selecting stratigraphic sections of Welge sandstone to be sampled. Dr. John F. Burst of the Shell Development Company kindly assisted with the classification of the Welge glauconite. Mr. William C. Elsik, a fellow graduate student, assisted in collecting samples at three sections.

The final manuscript was typed by Mrs. Gladys Byer, to whom the writer expresses his appreciation.

ABSTRACT

The Welge sandstone is the basal member of the Upper Cambrian Wilberns formation. Its entire outcrop area is within the Central Mineral region of Texas. Textural and mineralogical characteristics were determined from outcrop samples collected at ten sections throughout the Central Mineral region. These were combined with field observations to provide a means of interpreting the environmental conditions and the direction of the source area with respect to the location of the ten sections during the time of Welge deposition.

The Welge sandstone is characterized by both areal and vertical homogeneity of sedimentary parameters, grain size, roundness, nature and percentage of heavy minerals, and percent by weight of heavy mineral content. The most conspicuous variation is the transition from almost pure quartz sandstone in the western part of the Central Mineral region to a glauconitic and calcareous quartz sandstone in the extreme eastern portion of the area. This variation and the overall homogeneity are interpreted as characteristics that would have been impressed on sediments deposited by a sea transgressing rapidly from east to west over a stable platform with very low relief on the platform and in the area to the west of the platform.

Glauconite in the Welge sandstone possesses X-ray diffraction properties that indicate an ordered monomineralic crystal lattice. It is classified as group one ordered glauconite.

INTRODUCTION

Statement of Objectives

The principal objectives of this study were:

1) to determine the textural and mineralogical properties of the Welge sandstone at ten stratigraphic sections distributed throughout its entire area of exposure in the Central Mineral region, Texas;
2) to compare the textural and mineralogical properties from each of the ten sections;
3) to interpret the environmental conditions and direction of the source area during the time of Welge deposition on the basis of data obtained in this investigation.

Location and Size of Area

The Central Mineral region of Texas is located in the central part of the state and includes all or part of the following counties: Mason, Llano, Burnet, Blanco, Gillespie, McCulloch, and San Saba. It is roughly circular in outline with a diameter from east to west of 80 miles and a slightly shorter north-south diameter. This area is frequently referred to in the literature as the Llano uplift. Because the Llano uplift refers to a regional structural feature that has the same approximate geographic limits as the Central Mineral region, the two terms will be used synonomously in this paper when referring to the area of study.

The entire outcrop area of the Welge sandstone is located in the Central Mineral region. However, wells drilled in counties adjacent to the Central Mineral region have penetrated sections of rocks that are correlated with the surface sections of the Welge (Barnes, *et al*, 1959). The subsurface sections of Welge have been traced only a short distance from the outcrop on the north, east, and south sides of the area. This is in part due to a lack of wells that are deep enough to penetrate the Welge. Northwest of the area of surface exposure, the subsurface Welge equivalent has been recognized as far as Nolan County.

Names and Locations of Welge Sections

Ten stratigraphic sections of Welge sandstone from different areas of surface exposure distributed around the Central Mineral region were chosen for this investigation. The location of these sections is shown in Figure 1. The sections sampled were each given a number and a name. The names were, for the most part, recommended by Barnes (1960, personal communication).

Section 1 is named the Mason section and is located on Garfield Street within the city limits of Mason, Mason County, Texas.

Section 2 is named the Squaw Creek section and is located in a bluff along Squaw Creek 0.25 mile north of the Mason-Gillespie county line in Mason County, Texas. This is the type locality of the Welge sandstone (Bridge, Barnes, and Cloud, 1947). A view of the bluff formed by the Welge sandstone is shown on Plate 1 (A).

Section 3 is named the Streeter section and is located 2.75 miles west of Streeter, Mason County, Texas, 0.25 mile south of U.S. Highway 377.

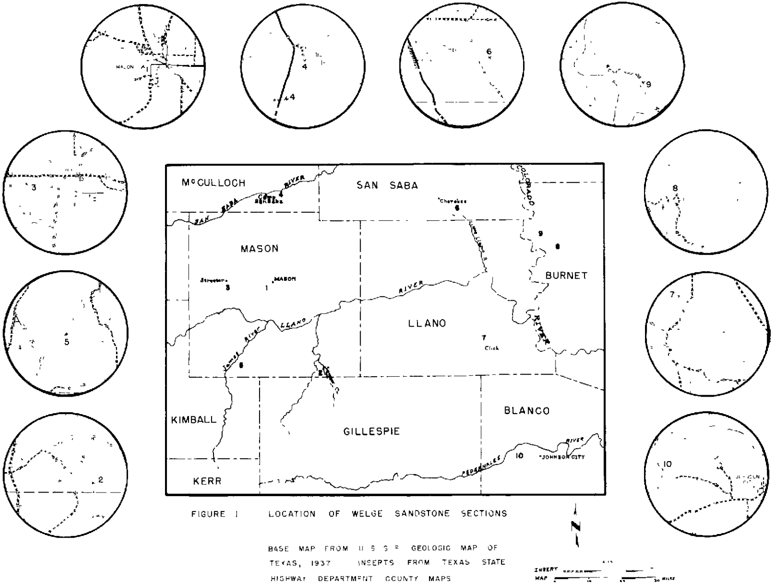


FIGURE 1 LOCATION OF WELGE SANDSTONE SECTIONS

BASE MAP FROM U. S. G. S. GEOLOGIC MAP OF TEXAS, 1937 INSERTS FROM TEXAS STATE HIGHWAY DEPARTMENT COUNTY MAPS

Section 4 is named the Brook-Katemcy Ranch section and is located at Camp San Saba in McCulloch County, Texas. This is a composite section with the lower 16 feet located south of the cemetery at Camp San Saba, and the upper eight feet located on the Katemcy Ranch road 2.7 miles south of Camp San Saba.

Section 5 is named the Upstream James River section and is located along the James River, 2.8 miles east of a private airfield in southwestern Mason County, Texas.

Section 6 is named the Little Llano River section and is located 4.25 miles southeast of Cherokee, San Saba County, Texas. A picture of Cedar Point, from which the samples of section 6 were collected, is shown on Plate 1 (B).

Section 7 is named the East Canyon section and is located in the Riley Mountains 2 miles north of Click, Llano County, Texas.

Section 8 is named the Morgan Creek section and is located near the mouth of the South Fork of Morgan Creek on the eastern side of Lake Buchanan, Burnet County, Texas.

Section 9 is named the Beaver-Silver Creek section and is located near the junction of Beaver and Silver creeks on the eastern side of Lake Buchanan, Burnet County, Texas.

Section 10 is named the Klett-Walker section and is located along the Pedernales River five miles west-northwest of Johnson City, Blanco County, Texas.

It is possible to drive on either public paved roads or private ranch roads to within 0.5 mile of each section.

Previous Investigations

Comstock (1889) published the first detailed investigation of the Central Mineral region. Previous work had been of a reconnaissance nature. Comstock introduced the terms Hickory series and Riley series as names for the Lower Paleozoic rocks of the region. The rock units have been redefined and resubdivided since Comstock's report but the names Hickory and Riley are still used for Upper Cambrian rock units. Comstock also introduced the term Katemcy series but this name has been dropped from usage.

Paige (1911, 1912) named the Wilberns formation from Wilberns Glen along the Little Llano River in northern Llano County, Texas. The base of the Wilberns, as defined by Paige, is well marked by the top of a glauconitic sandstone which is the upper member of the underlying formation. The importance of this boundary has stood the test of time well because it has been recognized in all investigations that followed Paige's work.

Bridge and Barnes (1941) recognized as early as 1941 that the Wilberns formation is divisible into members and that the basal member is a sandstone. Barnes (1944) and Cloud, Barnes, and Bridge (1945) published papers in which the Wilberns formation was divided into various members, but it was not until 1947 (Bridge, Barnes, and Cloud, 1947) that these members were properly named and defined in the literature. In the 1947 publication the Welge sandstone member was named by Barnes from the Welge land surveys in Gillespie County, Texas.

A correlation chart showing the changes in stratigraphic subdivisions and nomenclature from Comstock's (1889) original subdivisions to the latest subdivision by Barnes et al (1959) is presented as Figure 2. Some uncertainty exists as to the exact position of the horizontal lines separating the various rock units of the earliest investigators. Therefore, when reading the chart, it should be kept in mind that some lines may need to be shifted slightly to show equivalency.

The need for a regional analysis of the Welge sandstone to determine its texture and mineralogy becomes apparent when one searches the literature for information pertaining to this member. The limited data concerning the Welge have consisted of observations made by field geologists and published in the form of geologic maps, measured sections, and field descriptions. The lack of information is in part due to the relatively short time that has elapsed since the unit was named.

Barnes, Bridge, and Cloud (see bibliography) have been the major contributors to the literature of the Welge sandstone member. Wilson (1949) described the Upper Cambrian trilobites from the Welge. Wollman (1952) also described the fauna from the basal Welge sandstone.

Daugherty (1959) compared the texture and mineralogy of the Lion Mountain and Welge sandstones in southern Mason County, Texas. Daugherty's study was the first investigation of this type on these two sedimentary units. It adequately illustrated that differences do exist between the sedimentary parameters of the Lion Mountain and Welge sandstones in the area of study. However, the sedimentary parameters and mineralogy determined for the Welge sandstone, because of the small number of Welge samples analyzed (3 per section) and the localized area of study, are not sufficient for a regional interpretation.

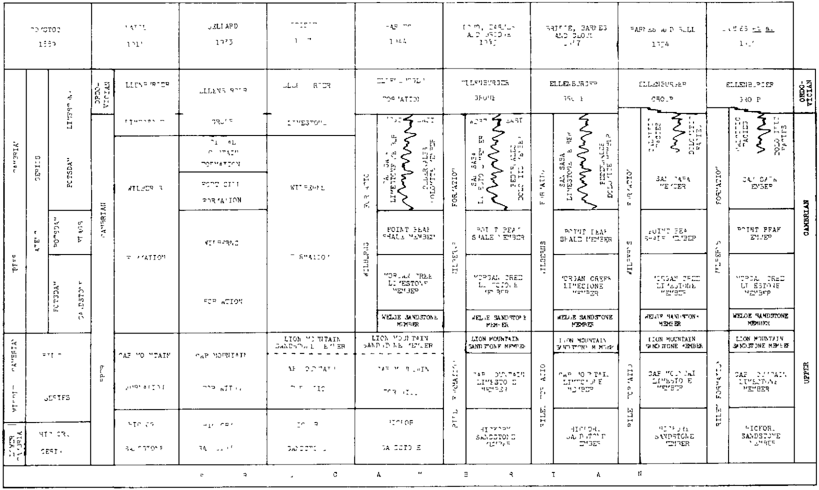


FIGURE 2. CORRELATION CHART OF UPPER CAMBRIAN ROCKS IN THE CENTRAL MINERAL REGION, TEXAS.

STRATIGRAPHY

General Statement

The two Upper Cambrian formations, the Riley and Wilberns, constitute the oldest unmetamorphosed rocks in the Central Mineral region. The presently recognized subdivisions of these two formations may be seen in Figure 2.

The Riley formation has an average thickness of 695 feet, (Barnes and Bell, 1954) and is composed of the Hickory sandstone, Cap Mountain limestone, and Lion Mountain sandstone members named from oldest to youngest. The lower Hickory consists chiefly of light colored to brown quartz sandstones that contain feldspar grains at some exposures. The upper portion of the unit is characteristically composed of deep-red sandstone. The Hickory grades into the Cap Mountain limestone member. This member consists of sandy, silty, and glauconitic limestones. The boundary between the Cap Mountain member and the overlying Lion Mountain sandstone member is gradational and is placed at the lowest occurrence of large quantities of terrigenous material. The Lion Mountain member is characteristically green because of the abundance of glauconite. It is composed of arenaceous limestone with lenses of light-gray limestone containing many fragments of trilobites in the lower part and glauconitic quartz sandstones with minor amounts of siltstone and shale in the upper part.

The Wilberns formation is composed of the Welge sandstone, Morgan Creek limestone, Point Peak, and San Saba members named from oldest to youngest. The Wilberns has an average thickness of 550 feet (Barnes and Bell, 1954). The Welge sandstone is a medium-grained, quartz sandstone that is transitional vertically into the Morgan Creek limestone member. The Morgan Creek is a coarsely granular, glauconitic limestone that has a distinctive maroon color at the base. This limestone grades into the overlying Point Peak member which consists of calcareous siltstones and shales, intraformational conglomerates, and stromatolitic bioherms. The contact between the Point Peak and San Saba members is usually placed at the first appearance of a yellowish-tinged, gray limestone or dolomite. The San Saba member is typically composed of limestone in the western part of the Central Mineral region and dolomite in the eastern part.

A more detailed discussion of the stratigraphy of the Upper Cambrain rocks of the Central Mineral region is found in a report by Barnes _et al_ (1959, p. 25-34).

Welge Sandstone Member

Lithology. The Welge sandstone is typically a brown-yellow, massive, medium-grained, well-sorted, rounded, sparingly to non-glauconitic, non-calcareous, friable to only slightly friable, quartz sandstone. The sections in the western part of the Central Mineral region are composed almost entirely of what is described as typical Welge sandstone. Toward the eastern part of the area the sections exhibit a more variable lithology than do those to the west. The eastern sections are composed of white to yellow-brown to green, massive to thin-bedded, fossiliferous, fine- to medium-grained, glauconitic to sparingly glauconitic, calcareous to non-calcareous, quartz sandstone.

Good exposures of Welge sandstone sparkle on a bright sunny day. This is caused by secondary overgrowths on some of the quartz grains.

<u>Thickness</u>. The thicknesses of the ten stratigraphic sections of Welge sampled for this investigation varied from 12 feet to 25 feet. Their average thickness is 20 feet. Barnes and Bell (1954) stated that the thickness of the Welge ranges from 11 feet to 28 feet in the Central Mineral region, with an average thickness of 20 feet.

Sections on the west and north sides of the area (sections 1 to 6) are consistently thicker than the sections on the east and southeast sides of the area (sections 7 to 10). The average thickness of sections 1 to 6 is 23 feet while the average thickness of sections 7 to 10 is only 15 feet.

<u>Geologic contacts</u>. The Welge sandstone member of the Wilberns formation overlies the Lion Mountain sandstone member of the Riley formation. The boundary between the two members is believed to be a disconformable surface in parts of the area of study. Evidence seen in the field by this writer that is indicative of a disconformity between the Welge and Lion Mountain sandstones is the slight irregularity of the contact. The presence of glauconite in the Lion Mountain sandstone and its absence in the Welge in the western part of the area is further evidence for a disconformity. The sharp contrast between the green color of the Lion Mountain member and the brown-yellow color of the Welge member caused by the difference in composition makes the irregular surface plainly visible where the sections are well exposed.

In sections 1 to 6 the contact is very easily recognized because of the difference in color of the two members. In section 7 the contact is covered and an arbitrary contact was placed at an abrupt change in the slope of the ground. The Welge is more resistant to erosion than the underlying Lion Mountain and therefore its outcrop has a steeper slope than that of the Lion Mountain. A good illustration of the change in slope between these two members is shown in Plate 1 (B).

At sections 8 and 9 there is no apparent field evidence of a disconformity between the Lion Mountain and Welge sandstones. In these sections the Welge member contains glauconite, which is a characteristic constituent of the underlying Lion Mountain member, and color difference cannot be used to locate the contact between these two units. Barnes (Barnes _et al_, 1959) noted that the disconformity so well observed in the western part of the area may not be present in the eastern part of the area. In sections 8 and 9 the Lion Mountain-Welge contact is apparently a conformable one. Barnes (1956, p. 48) stated that fossils provided the most reliable means of locating the contact in the Morgan Creek area. The Wilberns formation is characterized by the presence of trilobites belonging to the _Elvinia_ fauna, whereas the Riley formation does not contain this fauna.

During the field work at sections 8 and 9 this writer made use of contacts picked by Barnes (1956) on the basis of fossil evidence. These contacts were marked by Barnes in the field with yellow paint. It is believed that an accurate contact was picked by correlating beds over the short distances (less than 0.5 mile from section 8 and 3 miles from section 9) from the section measured by Barnes (1956, p. 48) to sections 8 and 9 sampled for this report. It was noted that the Welge in sections 8 and 9 is more resistant to weathering than the underlying Lion Mountain sandstone and the contact is approximately marked by a slight change in slope.

The basal bed of Welge sandstone at section 10 is less well-sorted than is typical of the Welge. It contains fine to very-coarse material. There is no other physical evidence of the contact, except a slight change in slope.

The Welge sandstone is overlain by the Morgan Creek limestone in all parts of the Central Mineral region. The contact between these two members is transitional within a short stratigraphic interval. Barnes (Barnes et al, 1959, p. 46-47) implied that this boundary is the most reliable horizon marker in the Upper Cambrian rocks of the Llano region and in adjacent subsurface areas.

In every section sampled for this study the Welge-Morgan Creek contact was picked at the first appearance of a maroon-colored arenaceous limestone. The presence of this easily recognizable contact and horizon marker greatly facilitated the field work.

Glauconite. The writer views the presence of glauconite in some sections of Welge sandstone and its absence in other sections as indicative of an environmental change and a valuable paleogeographic indicator. The typically non-glauconitic sections (1 to 6) occur in the western part of the area, and sections in the eastern part of the area (7 to 10) contain varying amounts of glauconite ranging up to an estimated 25 percent in some beds. A discussion of the mode of occurrence, physical limits of formation, and classification of glauconite will be presented as a basis on which further statements concerning the Welge glauconite may be made.

Glauconite is a hydrous, iron-alumino silicate substance that occurs in marine sedimentary rocks of all ages from Cambrian to Recent.

It is most commonly found in limestones and sandstones, particularly in calcareous sandstones. The typical form of glauconite is rounded, prolate to semi-spheroidal, green pellets, although it is not uncommonly found as compact masses without regular outlines. Both types of occurrence of glauconite are present in the Welge sandstone. The pelletal form of glauconite is commonly associated with those beds that have a calcareous cement. Beds containing glauconite in compact form without definite outline are represented by samples 8-2, 8-5, 9-2, and 9-4. These beds are glauconitic sandstones composed of an estimated 25 percent glauconite and 75 percent quartz.

Numerous theories have been proposed to explain the origin of glauconite. According to Burst (1958a, p. 482), these include: conversion of fecal pellets, conversion of foraminiferal cavity fillings, alteration of biotite booklets, and agglomeration of clay pellets on the sea floor. The scope of the present study is not so broad as to include an investigation of the origin of glauconite. The primary concern is to determine what, if any, environmental and paleogeographic interpretations can be made based on the knowledge of the type of glauconite present in the Welge sandstone and the physical limits of glauconite formation as discussed by Cloud (1955).

Glauconite is believed to form in a semi-oxidizing to semi-reducing environment (Burst, 1958a, p. 482). The evidence for this belief is the restricted range of ferric-ferrous ratios in glauconites. Burst believed that this ratio reflects the ability of the environment to reduce or oxidize a system. The presence of glauconite associated with fossils of a normal benthonic fauna, such as occur in the Welge sandstone, is explainable by assuming that the overall oxidizing conditions of a normal marine environment are not sufficient to overcome the local reducing conditions created by decaying organic material. The accuracy of the above assumption is in part dependent on other physical criteria for glauconite formation, namely water depth and turbulence.

Based on observations of presently forming glauconite, Cloud (1955, p. 488) concluded that 10 to 400 fathoms is the most common range of water depths in which glauconite forms, and that the "upper part" of this range seems more favorable for its formation. As pointed out by Cloud, the probable depths in which glauconite originates are shallow in terms of modern oceanic depths, but in terms of Paleozoic platform seas they are relatively deep.

It has been stated that glauconite is commonly found in sandstones. This does not imply that all the glauconite formed in these sandstones. Although glauconite is an authigenic mineral, the rounded and abraided appearance of some of the pellets suggests that they may have been transported and redeposited in locales which are not conducive to the genesis of glauconite. The glauconite that occurs as compact masses without regular outlines undoubtedly has not been transported. The association of terrigenous sand grains, glauconite which has not been transported, and very little of anything else suggests an environment in which turbulence was sufficient to prevent the deposition of silts, clays, and carbonate muds, but was not as great as in those areas where pure quartz sand was deposited. Turbulent conditions would be necessary for the water to be oxygenated sufficiently to produce an oxidizing environment, but, as noted above, the turbulence probably was not sufficient to completely destroy the reducing environment created by decaying organic material.

The average thickness of the four Welge sections (7 to 10) containing glauconite is 15 feet while the non-glauconitic sections have an average thickness of 23 feet. This fact apparently supports the observation by Cloud (1955, p. 490), that glauconite is presently forming in areas of decreased sediment influx.

On the basis of x-ray powder-diffractogram characteristics Burst (1958a,b) was able to subdivide all glauconite into four mineralogical classes designated as: ordered glauconite, disordered glauconite, interlayered glauconite, and mixed-mineral glauconite. These results led Burst to conclude that glauconite is used both as a morphological and a mineralogical term. Any small, rounded, green pellet or earthy material qualifies morphologically for the term glauconite, but only those in the ordered glauconite group possess structural properties which characterize the mineral glauconite.

Burst (1958b, p. 32), compared glauconite pellets associated with four unconformities in the Gulf Coast Focene series with pellets from conformable strata of the same age and found a better regulated mineralogy in the form of "crystal-stacking regularity" in the pellets from the unconformable series of strata. Burst probably did not intend, however, that this should be used as a criterion for recognizing unconformities. As will be seen, the Welge glauconite exhibits a high order of crystal-stacking regularity.

FIELD PROCEDURES

Selection of Sections

Each of ten stratigraphic sections of Welge sandstone used in this investigation was selected on the basis of location in the Central Mineral region, quality of exposure, and accessibility. The most important consideration was the geographic location of the section, in as much as it was desired to obtain sections distributed over the entire area of outcrop of the Welge sandstone. Within a specified area an attempt was made to locate the section that offered the best exposure of the unit. This was usually a difficult task because the Welge typically supports a dense vegetation. The banks of streams and road cuts invaribly provided the best sections.

Measurement of Sections

A Brunton compass and Jacob's staff divided into half-foot intervals were used to measure the thickness of each section and to determine the stratigraphic position of each sample. The strike and dip of the beds were first determined with the compass. The distinctly bedded Morgan Creek limestone provided better surfaces on which to determine strike and dip than did the massive Welge sandstone. It was possible to measure stratigraphic thickness with the desired accuracy by sighting through the compass in a direction perpendicular to the strike of the beds when the clinometer in the compass was set to correspond to the dip. The number of feet of section measured in this manner corresponds to the position of the compass on the Jacob's staff. A complete section may be measured by moving the Jacob's staff after each sighting to the point on which the last sighting was made.

Collection of Samples

A total of seventy-six samples of Welge sandstone were collected for this study. At each of the ten section localities shown in Figure 1 a vertical series of spot samples was collected.

Each of the seventy-six spot samples was given a dual number designation based on the section at which it was collected and the stratigraphic position of the sample above the base of the Welge. For example, samples 6-1 and 6-7 were both collected at section 6. Sample 6-1 was the first sample collected above the Welge-Lion Mountain contact and sample 6-7 was the seventh sample collected above the base of the Welge.

An attempt was made to collect fresh samples containing as little weathered material as possible. The stratigraphic position of each spot sample was largely determined by the degree of difficulty of obtaining fresh samples, however, the attempt to collect a representative vertical distribution also influenced the stratigraphic position at which the samples were taken.

LABORATORY PROCEDURES

Initial Sample Treatment

Primary Disaggregation. Silica and iron oxide are the most common cementing materials in the Welge sandstone, however, the quantity of these two cementing agents is not sufficient to indurate the Welge to such an extent that it is not adaptable to a mechanical analysis. Some samples were less friable than others. The increased induration of these samples may have been due to the presence of secondary silica cement in the form of overgrowths on some grains. Most samples were friable enough to be disaggregated by rubbing a small piece of the sample between two wooden boards.

The samples that were cemented with authigenic calcite were placed in dilute 2.4 N (1:5) hydrochloric acid for primary disaggregation. This treatment was sufficient to destroy any calcareous material.

Sample Splitting. The samples that were disaggregated by rubbing between two boards were passed through a Jones sample splitter to obtain an analytical sample weighing approximately 150 grams. The samples cemented with calcite were not split because only enough of the field sample was treated to produce the desired size of analytical sample.

Secondary Disaggregation. An examination with a binocular microscope of grains that had been disaggregated by rubbing between two boards revealed that some very small grains were still present in aggregate form and that most grains were partly coated with iron oxide material.

After having collected samples from ten different sections of Welge sandstone, the writer was aware of the apparently small difference in grain size that exists throughout the outcrop area of the sandstone. In order to detect even the slightest variation in grain size it seemed necessary to disaggregate the grains as completely as possible. For this reason a secondary disaggregation process was undertaken to increase the accuracy of the mechanical analysis and thereby to make smaller variations in grain size more meaningful. The secondary disaggregation also helped prepare the grains for petrographic study as will be discussed later.

The secondary disaggregation process consisted of placing each weighed analytical sample in a 600 milliliter beaker and covering it with 200 milliliters of dilute 2.4 N (1:5) hydrochloric acid. The sample was heated to the boiling point and allowed to boil gently until the iron stain had been completely removed from the grains. During the boiling a reducing agent, solid oxalic acid, was added to the sample as the supernatent liquid reached a yellow color. This served to reduce the iron from the ferric to the ferrous state, so that it went into solution more readily. After the above treatment the grains were free from any surficial coating and sufficiently disaggregated to proceed with the mechanical analysis.

Mechanical Analysis

<u>Separation of Silt-Clay Fraction from Sand Fraction</u>. Upon completion of the final disaggregation process the beaker was removed from the heat and filled with tap water. The sample was stirred thoroughly with a rubber-tipped glass stirring rod and allowed to stand for approximately five minutes after stirring had stopped. According to Wadell's

formula, based on the settling velocities of particles (Krumbein and Pettijohn, 1938, p. 111), five minutes is a sufficient time to allow all sand-size particles (1/16 to 2.0 mm) to settle to the bottom of the beaker. After five minutes the liquid was decanted from the beaker into a funnel lined with a tared filter paper, and the beaker was refilled with tap water and stirred again. This process was repeated until there was no trace of acidity in the beaker and the water was completely free of suspended matter after standing for five minutes. When this stage was reached, distilled water was used instead of tap water and the process of stirring and decanting was repeated three times.

The sample was then placed in an oven to dry at a temperature of less than 100°C. The filter paper containing the silt and clay particles was also placed in the oven to dry.

<u>Sieve Analysis of Sand Fraction</u>. The part of the analytical sample containing sand-size particles (1/16 to 2.0 mm), after having been completely dried and allowed to cool in a desicator, was weighed to the nearest 0.01 gram. This fraction of the sample was placed in a nest of 11 U.S. Standard mesh screens and a pan. The exact size of the screen openings and the corresponding phi values and Wentworth grades are presented in Table 1.

A Tyler Ro-Tap machine equipped with a timer was used to shake the sample in the nest of screens for 20 minutes. The contents of each screen and the pan were removed and weighed. The weight was recorded and the screen contents were retained for the petrographic study.

Table 1: Size of Openings in Screens Used in This Study With Corresponding Wentworth Grades and Phi Values.

U.S. Standard Sieve No.	Screen Opening (in mm.)	Phi Value (ϕ= $-\log_2$ of opening)	Wentworth Grade (of material retained)
10	2.00	-1.0	Granule
14	1.41	-0.5	Very Coarse Sand
18	1.00	0	Very Coarse Sand
25	0.71	0.5	Coarse Sand
35	0.50	1.0	Coarse Sand
45	0.35	1.5	Medium Sand
60	0.250	2.0	Medium Sand
80	0.177	2.5	Fine Sand
120	0.125	3.0	Fine Sand
170	0.088	3.5	Very Fine Sand
230	0.062	4.0	Very Fine Sand

<u>Silt-Clay Analysis Based on Settling Velocities</u>. The silt-clay fraction retained on the filter paper from the separation process was weighed and the weight was added to the weight of material that had been caught in the pan during the sieve analysis. This weight represented the total weight of the silt-clay fraction.

It was decided that unless the total weight of the silt-clay fraction equaled or exceeded 10 percent of the total weight of the sample a silt-clay analysis would not be required. Three samples, 1-7, 5-4, and 6-1, contained over 10 percent by weight of silt-clay size particles. The ten percent limit was chosen because 10 and 90 percent of the sample by weight are the minimum and maximum percent values needed to determine the sedimentary parameters used in this study.

The silt-clay analysis was based on the settling velocities of different sized particles in a fluid medium. The numerous theories and methods pertaining to this type of analysis are thoroughly discussed by Krumbein and Pettijohn (1938, p. 147-176). In this study the silt-clay fraction was put in a 1000 ml. graduated cylinder and completely dispersed. A 0.1 gram sample of [illegible]ium lignosulfonate, known industrially as Marasperse N, was added to prevent flocculation. At calculated time intervals based on Wadell's sedimentation formula (Krumbein and Pettijohn, 1938, p. 104-108) a hydrometer calculated to read grams per liter of material in suspension was inserted in the cylinder and a reading was taken. The procedure enabled the writer to determine the distribution of silt-clay sizes by weight.

Mineralogical Analysis

Selection of Samples. Three or more samples from each section were chosen to be analyzed. The first sample above the Lion Mountain-Welge contact, the first sample below the Welge-Morgan Creek contact, and an arbitrarily selected sample from the middle part of the Welge section were chosen for analysis. The writer believes that this plan of sample selection provides a better opportunity to detect vertical variation within the section than does mixing of several samples together and making one analysis of a composite sample. Any significant variation in mineralogical composition could be located within narrow vertical limits simply by analyzing additional samples between any two samples that show the variation. Intermediate samples were analyzed at sections 2, 4, 5, and 6.

Sample Preparation. The normal procedure involved in making a petrographic study consists of first thoroughly cleaning the sample and removing all coatings, especially iron oxides, from the grains. This may apply either to the entire sample or to certain size fractions only, depending on the nature of the study. The secondary disaggregation process used in this study, and already described, served a dual purpose in that it not only completely disaggregated the grains but it also sufficiently cleaned the grains that they could be studied petrographically without further preparation.

Each sample selected for petrographic study was separated into two fractions based on the specific gravity of the grains constituting that particular sample. This separation is commonly known as a "heavy mineral" separation. Most of the grains in every sample were quartz grains which have a specific gravity of 2.66. By placing the sample in a funnel filled with bromoform ($CHBr_3$, specific gravity 2.87) the quartz grains and grains of any other mineral with a specific gravity less than that of bromoform were separated from those grains that had a specific gravity greater than that of bromoform. The grains that sink to the bottom are referred to as the heavy mineral fraction and those that float belong to the light mineral fraction.

The entire sand-size portion of the sample was separated so that the weight of heavy minerals could be determined. The 0.088 to 0.177 millimeter size fractions are better suited for petrographic study than others so the sample was separated into three parts as follows: the 0.088 to 0.125 millimeter fraction; the 0.125 to 0.177 millimeter fraction; and all remaining material of the sand-sized portion of the sample. The heavy and light fractions from each separation were saved for petrographic study.

The weight of the heavy mineral fraction from each of the three separations was determined and then added to get the total weight of heavy minerals in a particular sample. The percent of heavy minerals was obtained by dividing the weight of the sample into the total weight of heavy minerals in that sample and multiplying the quotient by 100.

A magnet was passed over the heavy fraction from every sample to separate any magnetite that might be present from the other heavy minerals. No magnetite was found in any of the samples.

Mounting. Permanent slides of the heavy minerals in the 0.088 to 0.125 mm. and 0.125 to 0.177 mm. fractions were made from each sample for which a heavy mineral separation was made at sections 1, 2, 4, 6, 8, and 10. These sections were selected because of their distribution within the area of study. The heavy mineral fractions were split using the alternate quarter method until only the number of grains desirable for making a slide remained. The alternate quarter method involves placing the heavy minerals on a piece of paper and quartering the pile; then rejecting two alternate quarters and combining the remaining alternate quarters and repeating the process on the combined quarters until the desired number of grains remain.

The grains were sprinkled on a slide containing melted aroclor 4465 (n=1.66) and evenly distributed by stirring the mixture gently with a pin point. The slide was allowed to remain on the hot plate after it had been stirred until all air bubbles had been expelled. It was then removed from the heat and a cover glass placed over the grains and pressed into position.

A portion of the light mineral fraction of the samples from the highest and lowest stratigraphic position at every section was used to make a temporary light mineral slide. A mixture of clove oil and bromobenzene ($n=1.53$) was used as the mounting medium.

Mineral Identification. The minerals on each heavy and light mineral slide were identified with a petrographic microscope. A count of 300 or more grains per slide was made to determine the frequency of occurrence for each mineral species. Systematic traverses were made across the slide with the aid of a mechanical stage so that the grains identified and counted were not selected at random.

A distinction was made between the opaque grains on the basis of color in reflected light. The opaque grains were designated either as brown opaque or black opaque when counting the frequency of occurrence.

A thin section was prepared from each of five samples, selected because they were characteristic of the five lithologic changes noted in the Welge sandstone. These were studied with a petrographic microscope in an attempt to obtain more information about the nature of the cementing material and the overgrowths on the quartz grains than could be obtained by examination of hand specimens.

Roundness

Roundness is a measure of the extent to which the perimeter of a fragment has been rounded. It is therefore independent of the shape of the fragment and is an index of the textural maturity of a sediment

(Pettijohn, 1957; Folk, 1951). Roundness values were determined for a sample from the middle portion of each section of Welge sandstone. A roundness determination was not made for each sample because the presence of secondary quartz overgrowths on a great many of the grains prevented obtaining accurate values within significant reproducible limits.

The method of roundness determination described by Powers (1953) could not be used as a distinction between the original grain and the secondary overgrowth cannot be made by viewing the grains in reflected light with a binocular microscope. The grains appear to be more angular in reflected light than they really are because of the quartz overgrowths. An experimental error would be introduced if only those grains that do not show overgrowths were chosen for roundness determination by the Powers method. By mounting the grains in a high index liquid, alphamonobromonapthalene plus methylene iodide ($n=1.66$ @ $32^{\circ}C$), and observing them in plane polarized transmitted light, it was possible to make some distinction between the primary grain and the secondary overgrowth.

The 0.250 to 0.35 millimeter size fraction (2.0 to 1.5 phi) was chosen for the roundness analysis because it was the most abundant grain size of Welge sandstone samples collected for this study. The outlines of the original grains were compared with standard grain silhouettes (Krumbein, 1941) having roundness values in arithmetic progression from 0.1 to 0.9. Krumbein did not divide the roundness values into descriptive classes as Powers did so it was necessary to employ the roundness grades designated by Powers and shown in Table 2.

Table 2: Roundness Grades (after Powers, 1953).

Roundness Designation	Class Interval
Very Angular	0.12 - 0.17
Angular	0.17 - 0.25
Subangular	0.25 - 0.35
Subrounded	0.35 - 0.49
Rounded	0.49 - 0.70
Well Rounded	0.70 - 1.00

Determinations were made on 50 grains from each sample. The average roundness for each sample and for all samples was calculated by the formula:

$$Ra = \frac{\sum R_{1 \text{ to } n}}{N}$$

where:

Ra	is average roundness.
$R_{1 \text{ to } n}$	is the roundness value of each of the grains on which a determination is made.
N	is the total number of grains for which roundness is determined.

Beal and Sheppard (1956) found the results of roundness determinations by the Powers and Krumbein methods to be comparable.

X-ray Diffraction of Glauconite

A part of field sample 9-7 was placed in very dilute 1.5 N (1:8) hydrochloric acid and all calcareous material was slowly digested. After this treatment, the sample was thoroughly washed with distilled water and dried at a temperature less than 100 degrees Centigrade. The glauconite was separated from quartz and other non-magnetic parts of the sample with a Franz Isodynamic Separator. Glauconite, being moderately magnetic, was retained on the separator while quartz and other material passed through the magnetic field into a container. Diminishing the current into the separator caused the electromagnet to release the glauconite and it was caught in a separate container. The glauconite was separated several times after the initial separation in an attempt to remove all non-glauconitic material.

An examination of the glauconite with a binocular microscope showed that a majority of the larger grains contained limonite in crevices of the grains. The smaller grains appeared to be less contaminated. For this reason the glauconite was sieved and the fraction smaller than 0.125 millimeter was taken for x-ray diffraction.

Approximately two grams of glauconite were ground into a very fine powder in a Diamonite mortar. Part of the powder was packed into a bakelite well-slide and a random-powder diffractogram was made using a General Electric XRD-5 x-ray machine.

The remaining powder was placed in distilled water and centrifuged until only clay-size particles remained in suspension. An oriented slide of glauconite was prepared by placing some of the suspended clay-size glauconite on a glass slide and allowing it to settle. A diffractogram of the oriented slide was also made.

SEDIMENTARY PARAMETERS

The data obtained in the sieve analyses were used to obtain parameters with which the textural properties of the samples from the Welge sandstone could be compared.

The weight of material retained on each screen was converted to percent by weight of the total sample weighed. This was accomplished by dividing the weight of a screen's contents by the total weight of the sample sieved and multiplying the quotient by 100.

Median Diameter

The percent by weight of all fractions in a sample was added beginning with the coarsest fraction. These results were plotted on arithmetic graph paper as cumulative frequency curves with cumulative percent as the dependent variable plotted along the ordinate axis and grain diameters in phi values as the independent variable plotted along the abscissa. The median diameter, Md ϕ, was defined by Krumbein and Pettijohn (1938, p. 229) as "that diameter which is larger than 50 percent of the diameters in the distribution and smaller than the other 50 percent." The median diameter is determined by reading the phi value corresponding to the point where the cumulative curve intersects the 50 percent line.

Quartile Deviation

Quartile deviation is a measure that expresses the spread of diameters on either side of the median diameter. It is therefore an expression of the sorting of a sample.

Quartile deviation is calculated by the formula:

$$QD\phi = \frac{Q3\phi - Q1\phi}{2}$$

where:

$Q1\phi$ is the diameter in phi (ϕ) units that is larger than 75 percent of the diameters in the sample and smaller than 25 percent of the diameters.

$Q3\phi$ is the diameter in phi (ϕ) units that is larger than 25 percent of the diameters in the sample and smaller than 75 percent of the diameters.

The sorting coefficient (So) of Trask may be calculated from quartile deviation by the equation:

$$\log_{10} So = \log_{10} 2 \times QD\phi = 0.301 \times QD\phi.$$

Trask (1930), who first introduced the use of quartile measures in sedimentary data, stated that a value of sorting (So) less than 2.5 indicated a well-sorted sediment.

Quartile Skewness

The parameter that expresses the deviation of the mean of the first and third quartiles ($Q1\phi$, $Q3\phi$) from the median ($Md\phi$) is called quartile skewness ($Skq\phi$) and is calculated by the equation:

$$Skq\phi = \frac{Q1\phi + Q3\phi}{2} - Md\phi$$

where $Q1\phi$, $Q3\phi$, and $Md\phi$ have the values already defined.

A value of 0 for Skqϕ indicates that the grain size distribution in phi units is symmetrical about the median as far away as the first and third quartiles. A negative value for Skqϕ indicates that the grain size distribution in phi units is asymmetrical, with the mean of the quartiles being coarser than the median value. Conversely a positive value for Skqϕ indicates asymmetry toward the finer side of the curve.

Quartile Kurtosis

According to Krumbein and Pettijohn (1938, p. 238), kurtosis is a measure of the degree of peakedness of a curve. Peakedness as used by Krumbein and Pettijohn is a comparison of the spread of the central portion of a distribution to the entire spread of the distribution. In this study the ratio of the quartile deviation to the spread of the cumulative curve between the tenth and ninetieth percentiles is used as quartile kurtosis (Kqϕ).

Kurtosis is determined by the formula:

$$Kq\phi = \frac{\frac{Q3\phi - Q1\phi}{2}}{P_{90} - P_{10}}$$

where:

P_{90} is the diameter in phi units that is finer than 90 percent of the diameters in a sample and coarser than the other 10 percent.

P_{10} is the diameter in phi units that is finer than 10 percent of the diameters in a sample and coarser than the other 90 percent.

As defined above, kurtosis values will decrease with increasing peakedness. However, it is possible mathematically to decrease the value of kurtosis without the peakedness increasing.

PRESENTATION AND DISCUSSION OF TEXTURAL DATA

General Statement

The textural and mineralogical data obtained by the analyses of the seventy-six samples of Welge sandstone are presented on the following pages in several figures and tables. For the reader who is not familiar with the popular phi notation adhered to by most sedimentologists today, the sedimentary parameter values appearing on the charts and graphs may be misleading. A phi (Ø) value is defined as the negative logarithm, to the base 2, of any grain diameter. The phi notation was devised so that, and is popular because, grain diameters in Wentworth grades may be graphically illustrated more conveniently on an arithmetic scale. The phi value for each Wentworth grade used in this study is shown in Table 1. In the following discussion it should be remembered that as the phi value increases the actual grain diameter decreases and conversely.

Several methods of presenting data are used to illustrate and compare textural differences in the Welge sandstone. Cumulative curves and histograms are used to show the percent distribution of a parameter. Parameter-variation graphs (Krumbein, 1939, p. 588) are useful for showing the linear variation of related data. Another method is to combine all the values of a particular parameter for each section and determine the average value such as would have been obtained if a composite sample had been collected. Average data are useful for making areal comparisons of data by means of isopleth maps. Still another method of data presentation is the scatter diagram, which is a graphic comparison of the same two parameters of a large set of samples plotted on rectangular coordinates.

A plot on triangular coordinates is used to show the percentage range of three variables, the total of which must equal 100 percent.

Grain Size Distribution

The results of the sieve analyses are presented in Appendix A. The stratigraphic position and the percent by weight of material in each of the half phi grades is shown for each sample. It can readily be seen from an inspection of Appendix A that most of the detrital grains of Welge sandstone are in the medium sand-size (1.0 to 2.0 ø) fraction. Only samples from sections 10, 6, and 4 had a median diameter in the fine sand fraction (2.0 to 3.0 ø).

Cumulative curves were drawn for each sample as a graphic means of showing grain size distribution. The individual curves of all samples at each section were placed on one set of coordinates and the maximum and minimum limits traced and shaded to show the amount of variability. The results are shown in Figure 3. Figure 3 shows, in addition to the range of cumulative curves, an unshaded area on each set of coordinates that is the average cumulative curve for each section from the tenth to the ninetieth percentile. Section 7 exhibits the least grain size variability, as shown in Figure 3, with a range of median diameters (Mdø) from 1.40 to 1.65 phi. Section 10 exhibits the largest grain size variation with a range of median diameters from 0.75 to 2.81 phi. This large variation is caused by the presence of a bed containing granule-size material at the base of section 10. In general the cumulative curves are characterized by a steepness of the central part of the curve which reflects the high percent by weight of material in a small range of phi values. It can be

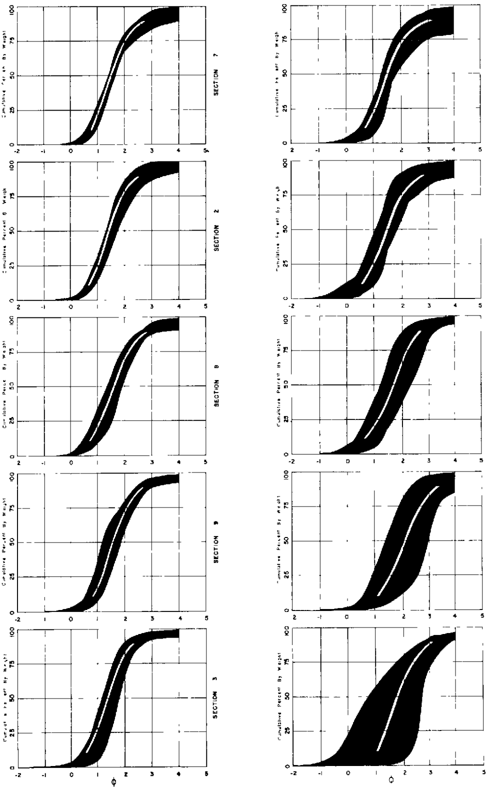


FIGURE 3. MAXIMUM, MINIMUM, AND AVERAGE CUMULATIVE CURVES OF WELGE SANDSTONE

seen, especially in the average curves, that the size distributions are all nearly the same and that the range in grain size is small. This is interpreted as an indication that similar energy conditions existed over a wide area during the time of Welge deposition.

The total insoluble portion of each sample of Welge sandstone was divided into three component fractions as follows: coarse fraction, less than 1.0 phi; medium fraction, 1.0 to 2.0 phi; and fine fraction, greater than 2.0 phi. The sum of the percent by weight of these three fractions is 100 percent by weight of the insoluble part of a sample. These data were plotted on triangular coordinates and are presented as Figure 4. The area outlined shows the total range of grain size distribution as percent by weight of each of the three above described groups. This figure is presented to show the homogeneity of the Welge sandstone both areally and vertically. Sixty-three (83 percent) of the seventy-six samples are plotted within the main body of the outline and are characterized by 40 to 65 percent of medium sand. Within this part of the outline there is no relationship between percent of coarse, medium, and fine material and section locality or stratigraphic position. The plots of eleven samples fall in the tail portion of the outline. These samples are predominantly from sections 6 and 10 and are characterized by more than 40 percent of material in the fine (greater than 2.0 ∅) fraction and less than 40 percent in the medium-sand fraction. Two samples, 10-1 and 10-2, contain greater than 55 percent coarse material, an anomalously large percentage, and are therefore represented in Figure 4 by the small isolated outline toward the coarse corner of the triangle.

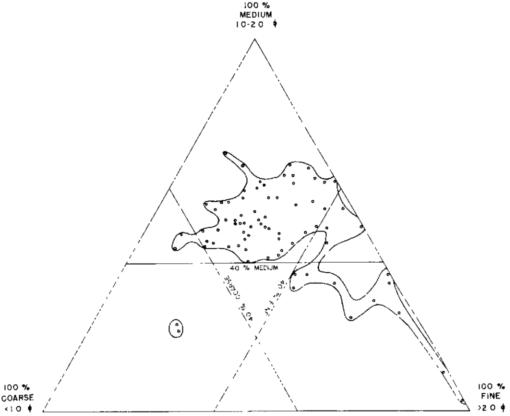


FIGURE 4 GRAIN SIZE DISTRIBUTION OF WELGE SANDSTONE

In order to show the vertical variation of grain size a plot of median diameter (Mdϕ) and stratigraphic position was made for each section. These parameter-variation graphs are presented as Figure 5. The graphs exhibit a fluctuation of grain size from the base to the top of the sections, indicating either that the Welge sea was characterized by oscillations of sea level or that there were repeated uplifts in the source area. In every section, except 10, 6, and 4, the fluctuation of median diameter is within the grade range of medium sand (1.0 to 2.0 ϕ), thereby signifying that the oscillations or uplifts were relatively minor. If the Welge sandstone is a multicycle deposit, as it seems to be, the vertical grain-size fluctuations were most likely caused by oscillations of sea level and the changes of wave and current energy produced by such oscillations. However, if it is a first-cycle deposit, the grain-size fluctuations would probably be a reflection of tectonic instability in the source area during the time of Welge deposition. The writer believes the grain-size fluctuations to have been caused by oscillation of sea level.

A correlative characteristic is noted at each section where the disconformity between the Lion Mountain and Welge sandstones is observable (1 to 6, 10, and possibly 7). Above the basal 2 to 3 feet of Welge sandstone the grain size begins to decrease and in most cases decreases in a short stratigraphic interval to the minimum grain size for the entire section. The vertical decrease in grain size is typical of a transgressive sea. Daugherty (1959, p. 19) noted that the grain size of the underlying Lion Mountain sandstone is coarsest at the top of the unit. The presence of 2 to 3 feet of coarser material before the Welge begins to decrease in grains size suggests that the Welge sea reworked the upper Lion Mountain

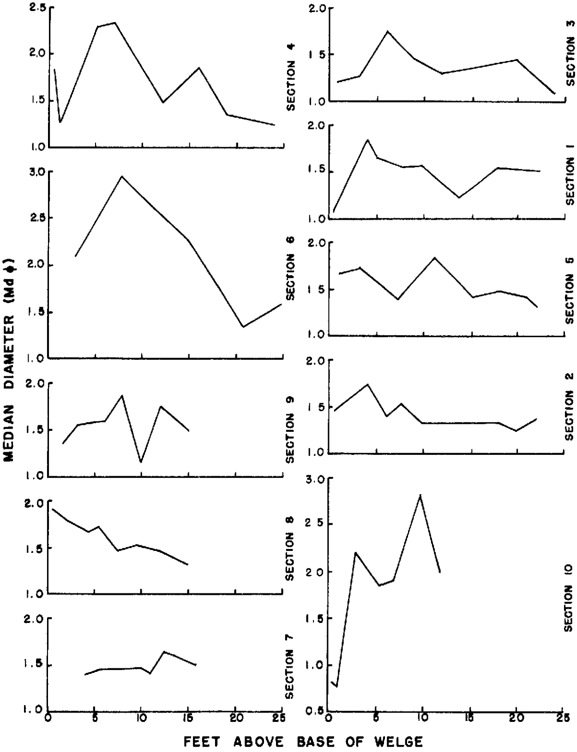


FIGURE 5: SIZE VARIATION OF THE WELGE SANDSTONE.

sediments as it transgressed the exposed surface and incorporated some Lion Mountain grains in the basal beds of the Welge. The fact that the grain size of the Welge does not continue to decrease to the top of the section indicates, as has been noted, the probable oscillatory nature of sea level of the Welge sea.

The graph of section 6 in Figure 5 does not show the vertical grain-size fluctuations that exist at other sections. After the initial decrease in median diameter, the grain size increases uniformly to near the top of the section. This, along with the unusually small median diameters recorded for section 6, is interpreted as indicating that the Welge sea was deeper and farther from a source area in the present Cherokee area than in areas to the west and southwest. After the Welge sea had transgressed the area leaving the initially coarse deposit, fine sand-size material was the predominant sediment size deposited. The increased water depth was sufficient to permit the continued deposition of fine sand-size material even during the oscillations of sea level recorded in other sections.

The average median diameter in phi units (Mdaϕ) for each section was determined to simulate the median diameter (Mdϕ) that would have been obtained if a composite sample had been collected. The results are presented in Figures 6 and 7 in the form of isopleth maps of average median diameter for the Welge sandstone in the Central Mineral region. The values shown in Figure 6 were determined by averaging the median diameters (Mdϕ) of all samples at each section. The values shown in Figure 7 are different from those shown in Figure 6 because only those samples that were collected

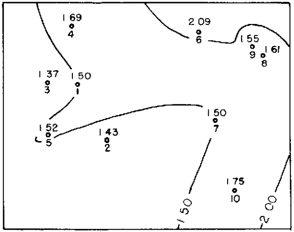


FIGURE 6: AVERAGE Mdϕ OF WELGE *

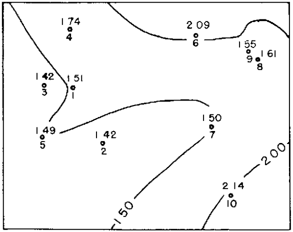


FIGURE 7· ADJUSTED AV. Mdϕ OF WELGE.*

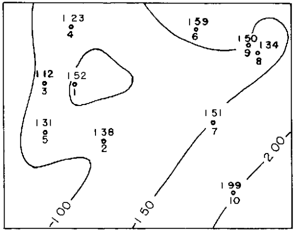


FIGURE 8: Mdϕ OF UPPER WELGE. *

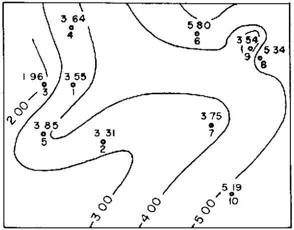


FIGURE 9: AV. % SILT-CLAY OF WELGE *

* SEE FIGURE I FOR LIMIT OF AREA COVERED BY MAPS AND POSITION OF NUMBERED LOCALITIES RELATIVE TO GEOGRAPHIC FEATURES.

above the basal beds containing coarse, reworked Lion Mountain grains were used to determine the average median diameters (Mda0) plotted on Figure 7. The two methods are both used and presented because one (Figure 6) has the advantage of being unbiased and represents the actual average median diameter of the Welge sandstone, and the other (Figure 7) is interpretive, but desirable, because it presumably does not include in the average any grains that were derived from the immediately underlying upper Lion Mountain sandstone.

Figure 8 shows the median diameters of the grains in the top two feet of the Welge sandstone at each section and is presented to point out the similarity between the average median diameter and the median diameter of the upper Welge. Each control point on the maps represents the location of one of the sections sampled.

The writer is aware that only 10 control points for an area of approximately 4000 square miles do not provide the degree of resolution that is desirable for this type of graphic presentation. Before discussing the possible causes for the Welge grain-size distribution the writer wishes to emphasize that there is not sufficient variation of the small amount of available data to make dogmatic statements concerning the direction of the source area and the position of the strand line. However, as one of the objectives of this study is an interpretation of the direction of the source area during the time of Welge deposition, and because the only analytical data pertinent to the subject are contained in this report, Figures 6, 7, and 8 are presented as plausible interpretations. It is hoped that the implication of the interpretations may stimulate interest for further study of the sedimentological problems of the Upper Cambrian rocks of the Central Mineral region.

Pettijohn (1957, p. 607) stated that, in general, grain size tends to coarsen toward the source area. The most general direction of increasing grain size, as shown in Figures 6, 7, and 8, is from east to west, thus indicating a source area west of the present Llano region. This inference is based largely on the occurrence of the two sections with the smallest median diameter (6 and 10) on the eastern side of the area.

The writer believes that the lack of control and the relatively small variation in grain size between most sections does not justify a more specific direction of source area, however, several possibilities are suggested and will be discussed.

Barnes (1956, p. 8-9) concluded that the source area of the Welge sandstone was northwest of the Central Mineral region. This conclusion was based on the fact that the sandstone unit thins toward the southeast. In another statement he (Barnes, 1956, p. 8) was less specific when he said, "much of the sand, especially in the upper part of the Hickory and higher, is thought to have been derived from the north, northwest, or west." The values shown for section 10, the most southeasterly section sampled for this study, are in every instance (Figures 6, 7, and 8) indicative of a finer grain size than those shown for section 2 and 3 to the northwest, thus supporting Barnes' statement that terrigenous material was derived from a source area to the northwest.

Section 6 is also typically a fine-grain section and its location in the northern part of the area makes it difficult to postulate a northern source area. Instead the isopleth lines honoring this point trend northwest-southeast, suggesting a west or southwest source. Within the area of study it seems likely that the sea floor sloped upward to the west or slightly south of west as indicated by the isopleth lines in Figures 6, 7, and 8. It was pointed out that in Figure 5 the graph of median diameter (Mdϕ) at section 6 does not show the fluctuating changes in grain size that are characteristic of the other sections. Instead, it shows a gradual increase in grain size from just above the base of the section to near the top. It was postulated that this might be due to increased water depth in the vicinity, in which case the surface of deposition was below the base of strongly agitated water even during the frequent oscillations recorded elsewhere.

Referring again to Figures 6, 7, and 8, a northeast trending nose involving sections 5, 2, and 7 can be seen in each of the interpretations. This, although interpretive, further suggests sediment influx from the southwest. The only other evidence supporting this suggestion lies outside the area of study. The Forest Oil Corporation, No. 1 Stapp well drilled in southeastern Kimball County encountered a section composed entirely of coarse-grained Welge sandstone (Barnes et al, 1959, Plate 3).

By comparing Figures 6 and 7 with Figure 8, it may be noted that the uppermost part of the Welge at section 4 is coarser than the average size at that locality. This suggests either that the area was nearer to the strand line when the upper beds were deposited than it had been during most of the time of Welge deposition or that there was an influx of coarse material from the northwest.

Sections 8 and 9 appear to be coarser grained than would be expected from their location in the eastern part of the area. No definite explanation for this fact can be accepted even by combining mineralogical and roundness data with grain size data. Three possible explanations are suggested.

Hills of Precambrian rock that extended above the Upper Cambrian depositional surface and were in some instances islands in the Upper Cambrian seas are known to have existed in the Llano uplift area. Barnes (1956) described a buried granite hill located less than 0.5 mile northeast of section 9. There is good evidence that the hill was not covered by sediments until after the end of Welge sandstone deposition because "locally derived microcline cleavage fragments occur in the basal few feet of Morgan Creek limestone on the eastern side of the dome" (Barnes, 1956, p. 16). Barnes further stated that, "the decomposing granite supplied coarse microcline and quartz grains to the sediments immediately adjacent to the dome, but these fragments did not move far. For example, along the eastern edge of the granite outcrop near the highest point on the dome, the Welge sandstone is very feldspathic; and where the Lion Mountain rests on the granite it is scarcely identifiable because of the coarse feldspar and quartz which it contains. On the opposite side of the dome and only 300 yards away, Cap Mountain limestone, highly feldspathic in its basal few feet, is overlain by Lion Mountain sandstone followed by Welge sandstone, both of which are entirely normal in appearance and free from locally derived detritus" (Barnes, 1956, p. 16).

Roundness and mineralogical data which will be presented in forthcoming chapters tend to support Barnes' belief that clastics derived from the granite hill were not transported far from the hill. It is possible, however, because of its proximity, that the granite hill is responsible for the coarsening at sections 8 and 9 as a result of some locally derived clastics being mixed with those from a more distant source.

Another possible and certainly plausible explanation is that the hill obstructed normal currents and caused secondary currents which had a tendency to scour in some places and deposit in others. These local currents would have prevented the deposition of much of the fine sizes that would normally have been deposited and thus imparted to the section an overall grain size that was coarser than normal.

Not to be denied is the possibility of a source area northeast of the Central Mineral region. The interpretations shown in Figures 6, 7, and 8, were not made to show a northeastern source area mainly because there is no other evidence suggesting such a source area. The fact that the Welge sandstone is calcareous in sections 8 and 9 suggests that this area was at a lower elevation and was covered by deeper, less agitated waters farther from shoreline, than those sections to the west which are non-calcareous.

Figure 9 is an isopleth map showing the average percent by weight of the silt-clay fraction at each of the sections. It is noted that there is a general increase toward the east in the average silt-clay content of the Welge sandstone. This further suggests a western source area. One would expect to find the least amount of silt-clay size material near the shore of an open platform sea. The winnowing effect of wave action presumably separated the fine material from sandy material. As a result the silt-clay material was transported away from the source area and the shoreline. The extent to which it would be removed, of course, depends on the energy imparted to the waves and the effectiveness of currents.

In the preceeding discussion of textural data a possible source direction or source area was mentioned in several places, yet no mention was made of the nature of the source area. This discussion will be reserved for the chapter in which the mineralogical data are discussed. The writer would like to state here that textural data such as have been presented are useful for determining either the direction of the source area or the position of the strand line regardless of the nature of the source. That is, if all of the terrigenous material of the Welge sandstone was derived from the land, carried to the sea, and distributed and deposited by the sea, then the source could be located by analyses of textural data. If, however, the Welge sediments were derived from a preexisting deposit that was transgressed and redistributed by the Welge seas, then the original scurce area cannot be located geographically. In the event that the latter of the two possibilities actually occurred, it may be possible to locate the strand line by means of textural data, and with this information it is possible to predict a general source direction of any first-cycle terrigenous material that is found in the deposit.

The homogeneity of grain size in the Welge seems to suggest that the sea in which it was deposited transgressed rapidly and then oscillated slightly, but maintained almost constant energy conditions for the remainder of the time of deposition of the Welge member. As the sea transgressed, most material finer than the maximum size that could be transported at a specified time was carried away from the shore in the same way as described for the silt-clay fraction. Thus, in a stable area where energy conditions are relatively constant, a well-sorted deposit such as the Welge would be expected. The relative direction of the shoreline can be ascertained by noting that the coarsest deposits would tend to be nearer shore where water was presumably more strongly agitated. The widespread homogeneity of the Welge indicates stability in that there were presumably nearly constant water depths over the platform on which the Welge was deposited.

Parameter Variation

The statistical parameters calculated for the grain size distribution of each sample of Welge sandstone are presented in Appendix B. An examination of Appendix B indicates that the range of sorting coefficients (So) is between 1.19 and 1.98. A value of So less than 2.5 indicates a well-sorted sediment according to Trask (1930), who first introduced the measure. The Welge sandstone is everywhere typically a well-sorted sedimentary rock unit. Further inspection of Appendix B shows that there is no uniform increase or decrease in sorting either areally or vertically. The minor variation of the sorting coefficients (So) occurring in a non-uniform nature through the Welge sections suggests a possible oscillatory nature of the Welge sea under uniform energy conditions.

The scatter diagram in Figure 10 shows the distribution of plots of median diameter (Md0) and quartile deviation (QD0) on rectangular coordinates. No trend is observable from the plots so it seems that there is no linear arithmetic relationship between grain size and sorting in the Welge sandstone. The relationship between quartile deviation (QD0) and sorting coefficient (So) has been described on page 30. Both parameters express the spread of the distribution and are therefore indices of sorting. The lack of an observable relationship between grain size and sorting may be in part explained by the fact that the Welge is typically a well-sorted, medium-grained sandstone. A relationship might exist if there were a larger variation of both sorting and grain size.

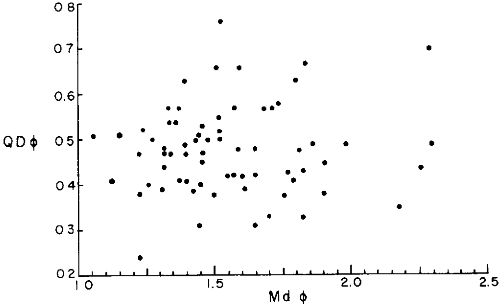


FIGURE 10: RELATION BETWEEN QUARTILE DEVIATION AND GRAIN SIZE.

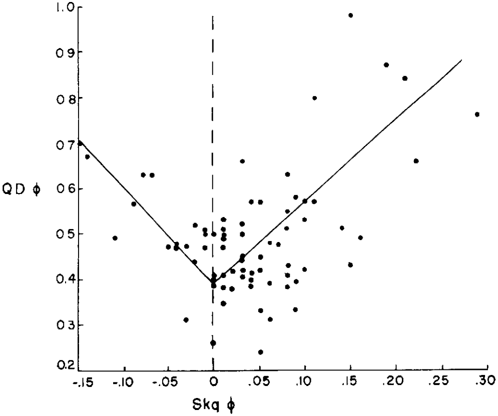


FIGURE 11: RELATION BETWEEN QUARTILE DEVIATION AND SKEWNESS.

Skewness and quartile deviation values of the Welge sandstone are plotted in the scatter diagram shown in Figure 11. A relationship between these two parameters is suggested by the fact that quartile deviation increases as skewness increases in either a positive or negative direction. This relationship is without geologic significance because it is due to the attributes being measured.

Skewness is a measure of the asymmetry of the grain-size distribution and quartile deviation is a measure of the spread of the grain-size distribution. If samples from a single well-sorted unit are analyzed, any asymmetry may tend to increase the spread of the distribution. This relationship is suggested in Figure 11.

Positive skewness prevails for the Welge sandstone. It can be seen in Figure 11 that five percent (4 samples) of the grain-size distributions are symmetrical between the first and third quartile measures because the samples have a 0 skewness value. Of the remaining skewness values, 73 percent are positive and 22 percent are negative. Positive skewness indicates that the grains coarser than the median size are grouped more closely about the median than are the sizes finer than the median, or simply that Q1Ø is closer to MdØ than Q3Ø. Likewise a negative skewness also indicates that Q3Ø is closer to MdØ than is Q1Ø.

Roundness

Roundness data for the ten samples analyzed are recorded in Table 3. The range in average roundness is from 0.54 for sample 9-6 to 0.64 for sample 1-6. A roundness determination was made on one of the original ten samples (2-5) one week after the results listed in Table 3

Table 3: Roundness Values of the Welge Sandstone.

Section	Sample	Strat. Position (feet above base)	Average Roundness	Grade	Secondary Overgrowths*
1	6	14	0.64	Rounded	Rare
2	5	10	0.58	Rounded	Common
3	6	20	0.60	Rounded	Common
4	5	12	0.61	Rounded	Rare
5	3	7	0.58	Rounded	Rare
6	5	18	0.63	Rounded	Rare
7	5	12½	0.60	Rounded	Rare
8	6	9½	0.56	Rounded	Common
9	6	10	0.54	Rounded	Common
10	5	7	0.56	Rounded	Common

* Common >15% (est.)

Rare < 15% (est.)

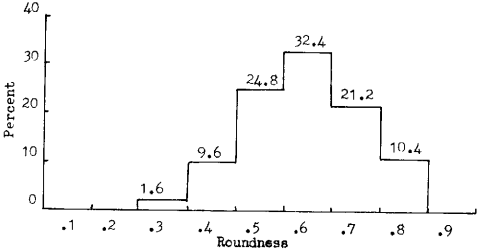


FIGURE 12: Histogram of Roundness of 500 Grains From Ten Samples of Welge Sandstone.

were determined to test their reproducibility. The redetermined average roundness value for sample 2-5 was 0.52 and the initial value was 0.58. Therefore, the 0.54 to 0.64 difference between the ten samples is probably not significant because variations within a sample due to experimental errors or to overgrowths may be this great. A column showing the relative abundance of overgrowths in the samples for which roundness was determined is included as part of Table 3 to further show the effect of the overgrowths on roundness determinations. The lowest roundness values were in general recorded for those samples in which overgrowths were common, thereby suggesting a possible personal bias on the part of the investigator. In Figure 12 the percent frequency by number of grains in each of Krumbein's (1941) standard roundness grades is shown in histogram form. The average roundness of all grains was 0.60.

The most significant statement that can be made concerning the roundness of the grains in the Welge sandstone is that they are typically rounded; only small percentages of broken grains are present. According to Pettijohn (1957, p. 554-5), "roundness is an index of maturity and as such should be closely correlated with the other indices of maturity." The three indices of textural maturity as defined by Folk (1951) include: (1) removal of clay, (2) good sorting of the non-clay fraction, and (3) rounding of the grains. It has already been shown in Figure 9 that the Welge sandstone contains very little silt-clay size material and all samples that were analyzed are well-sorted, therefore roundness is correlative with the other indices of textural maturity. The Welge sandstone is classified as a supermature sandstone according to Folk's (1951) classification of the stages of textural maturity.

PRESENTATION AND DISCUSSION OF MINERALOGICAL DATA

Variation in Mineralogical Content

Heavy mineral separations were performed on thirty-five samples. At each section the samples from the lowest and highest stratigraphic position plus one or more intermediate samples were analyzed. The heavy mineral content as determined from the separations is given as percent by weight in Table 4. The average percent by weight of heavy minerals for each section is also given in the table. It can be seen that the heavy mineral content was less than one percent of the total weight of the insoluble portion of the sample larger than 0.062 millimeter in every instance except sample 10-1. This sample appeared to contain a concentration of heavy grains. As already pointed out, sample 10-1 had an anomalously coarse median diameter. It may be that the concentration of heavy minerals was related to the coarse grain-size of the sample. The content of heavy minerals, excluding sample 10-1, varied from 0.03 percent to 0.90 percent of the weight of the sample. The high degree of mineralogical maturity that is indicated by the low content of heavy minerals in the Welge sandstone may have been caused by derivation of the terrigenous sediments from a mature sedimentary source or by tectonic stability in a source area of low relief or by both of these factors. Certainly the Welge sediments have been exposed to climatic conditions that favored the removal of all unstable and metastable minerals.

There is no observable relationship in the Welge sandstone between percent of heavy mineral content and geographic position. This might be expected if the Welge is a multicycle deposit. The highest

Table 4: Percent by Weight of Heavy Minerals.

Section	Sample	% Heavy Minerals
1	8	0.20
1	5	0.49
1	1	0.53
1	Average	0.41
2	8	0.17
2	7	0.09
2	4	0.61
2	1	0.18
2	Average	0.26
3	7	0.26
3	5	0.48
3	1	0.48
3	Average	0.41
4	8	0.27
4	6	0.26
4	2	0.19
4	1	0.14
4	Average	0.21
5	8	0.73
5	7	0.03
5	5	0.04
5	2	0.04
5	1	0.07
5	Average	0.18
6	7	0.18
6	6	0.23
6	2	0.32
6	1	0.24
6	Average	0.24
7	7	0.19
7	4	0.68
7	1	0.49
7	Average	0.45
8	8	0.51
8	4	0.74
8	1	0.90
8	Average	0.72
9	8	0.14
9	5	0.61
9	1	0.41
9	Average	0.39
10	7	0.52
10	4	0.18
10	1	1.87
10	Average	0.86

percentage of heavy minerals should occur in those sections nearest to the source area in a first cycle deposit. As the sediments are redistributed and deposited in succeeding cycles it becomes impossible to determine the original source direction solely from the percent by weight of heavy mineral content of the rock unit.

It was observed from a scatter diagram of median diameter and percent of heavy minerals plotted on arithmetic graph paper that no clear relationship existed between these two parameters. The plots of some samples suggested that the percent of heavy minerals increases with increasing grain size and plots of other samples showed an alignment that suggested that the percent of heavy minerals increases as grain size decreases. There was no correlation between areal or vertical position of any samples and the heavy mineral-grain size relationships of those samples. Therefore, these relationships are probably only significant in that they suggest that local concentrations of heavy minerals in the Welge sandstone are not uncommon.

Mineralogy

The terrigenous heavy mineral suite of the Welge sandstone is composed of minerals that are noted for their mechanical and chemical stability. Opaques (probably ilmenite), zircon, leucoxene, and tourmaline were present in all twenty-one slides for which a frequency-of-occurrence determination was made. The opaque minerals normally accounted for more than 80 percent of the heavy mineral grains. Tourmaline never occurred in abundance but was always present. Rutile and garnet were present as traces (less than one percent) in several slides. Authigenic anatase and leucoxene are also constituents of the Welge sandstone heavy mineral suite. The limited variety of stable terrigenous heavy minerals indicates that the immediate source area was a sedimentary terrane (Tyler, 1936, p. 82). The frequency of occurrence of the heavy minerals is tabulated in Table 5.

Quartz is the predominant light mineral in the Welge sandstone. Glauconite and chalcedony are other minerals having a specific gravity less than 2.86 that are present in varying amounts. Glauconite in any quantity other than an occasional scattered grain was restricted to samples collected at sections 7, 8, 9, and 10. It is estimated that glauconite constituted less than five percent of the light fraction in most samples at sections 7, 8, 9, and 10. Two beds at sections 8 and 9 contain an abundance of glauconite (estimated 25%) in the compact irregular form and may properly be termed glauconitic sandstones. Glauconite was destroyed when the sample was heated in hydrochloric acid to remove the iron stains from the grains.

Description of Heavy Minerals

For purpose of frequency determination the opaque heavy minerals were divided into two types, black opaques and brown opaques, on the basis of their color in reflected light. It was difficult to make this division because all gradations from completely black to completely brown opaques were present. If a grain possessed any brown at all it was counted with the brown opaques. Most of the black opaques were believed to be ilmenite. They exhibited a shiny bluish-black color in reflected light and were not attracted by a magnet that was passed over the grains at a distance of one centimeter. Ilmenite was present as well-rounded grains

Table 5: Percent Frequency of Occurrence of Heavy Minerals.

Sample	Black Opaque	Brown Opaque	Zircon	Leucoxene	Anatase	Tourmaline	Rutile	Garnet
1-8	3	89	6	1	Trace	1	-	Trace*
1-5	8	88	4	Trace	Trace	Trace	Trace	-
1-1	89	4	5	1	-	1	-	-
2-8	1	75	12	2	10	Trace	Trace	-
2-7	1	85	9	2	3	Trace	-	-
2-4	4	89	3	2	2	Trace	-	-
2-1	90	4	4	2	-	Trace	Trace	-
4-8	12	77	9	2	Trace	Trace	-	-
4-6	5	86	7	2	Trace	Trace	-	-
4-2	3	86	9	1	1	Trace	Trace	-
4-1	2	81	11	4	1	1	-	-
6-7	3	79	16	Trace	2	Trace	Trace	Trace
6-6	5	87	5	2	1	Trace	-	-
6-2	2	79	6	9	4	Trace	Trace	-
6-1	2	78	8	5	6	1	Trace	-
8-8	73	21	5	1	-	Trace	Trace	-
8-4	92	3	5	Trace	-	Trace	Trace	Trace
8-1	90	2	6	2	-	Trace	-	-
10-7	25	71	4	Trace	-	Trace	Trace	-
10-4	74	24	1	1	-	Trace	-	-
10-1	93	1	3	3	-	Trace	-	-

* Trace = present, but less than 1%.

as shown in Plate 1 (C), and as broken fragments of once well-rounded grains. The surfaces of the grains were generally smooth but a few grains had irregular surfaces. The irregular surfaces were most commonly noted on the brown opaques.

The brown opaques are thought to be oxidized ilmenite. This statement is based on the suggested relationship between percentage of authigenic anatase and percentage of brown and black opaques. It is shown in Table 5 that authigenic anatase was absent from the samples of Welge sandstone in those sections where black opaques predominated. Where brown opaques were predominant there was always some anatase present in the heavy mineral suite. This suggests to the writer that the opaques are all one and the same mineral because both anatase and ilmenite are titanium minerals. Gradation from all black to all brown grains is also suggestive that the opaques are some form of ilmenite. Leucoxene, which is an alteration product of ilmenite, was found in all samples regardless of the nature of the opaques. This further suggests that the brown opaques are oxidized ilmenite. It is believed that the irregular surfaces noted above were due to solution or weathering effects because they were seen almost entirely on the brown opaques. It is not impossible that the brown opaques are oxidized glauconite pellets; however, if this is true then the variation in the content of ilmenite in some samples would have to be explained. It is recognized that other opaque minerals, excluding magnetite, may have been included with the ilmenite in some samples.

Zircon occurs as both spherical and prolate, well-rounded to slightly rounded grains as shown in Plates 1 (D) and 3 (C). The less well-rounded grains commonly are in the form of euhedral prismatic grains.

The well-rounded grains are more noticeably frosted and pitted than the less well-rounded ones. Gradations in color from colorless to faint pink and faint brown are present among the zircon grains. Colorless and opaque inclusions are common in many of the grains.

Tourmaline grains in the Welge sandstone are characteristically well rounded as shown in Plate 3 (D). Angular fragments of broken rounded grains were recognized by a well worn outline on part of an otherwise angular grain. In general the grains were too well worn to show a distinct elongation, but the prominent absorption exhibited by tourmaline provided a means of easy orientation. The predominant color of the tourmaline grains is brown, however, several grains of the green and blue varieties were seen. Inclusions, while not common, are present in some grains as needle-like (acicular) crystals and as irregular colorless and opaque masses.

Because of its dull white and opaque character, the presence of leucoxene could be easily detected by viewing the grain in reflected light. The outline of some grains could be seen between crossed nicols as very thin edges appear to be translucent and show a high birefringence. The irregular nature of the surface of some of the leucoxene is interpreted as evidence that the grain has not been transported. Also, it was not uncommon to see plates of anatase protruding from the authigenic leucoxene grains. This type of leucoxene was probably derived from the alteration of ilmenite since the time of Welge deposition. Some leucoxene also occurs as smooth, rounded grains which suggests that it may have formed before being deposited with the Welge sediments.

Only a few grains of rutile were identified in several slides. Two grains are present in the view shown in Plate 1 (B). A deep brownish-red color was characteristic of all grains of rutile identified in the Welge sandstone. The surfaces were rounded but not so much that the original euhedral outline could not be recognized in several grains. Some grains appeared to have been rounded and then broken, producing an irregularly shaped grain.

Garnet occurs as pale pink grains that were readily identified by their isotropic nature and high index of refraction. Garnet, although rare in the Welge sandstone, suggests that some of the material was initially derived from a metamorphic terrane.

Anatase was common in several slides and was present in all those in which brown opaques were predominant. It was not found in those slides in which black opaques predominated in the heavy mineral suite. Anatase is characterized by tabular euhedral grains as shown in Plate 3 (A, B). Some grains appeared to have been either partially destroyed by solution or imperfectly formed. However, none of the grains showed any degree of rounding. This establishes the fact that anatase is an authigenic mineral. All grains are a straw yellow color. In some grains zoning could be seen. Small, dust-like inclusions were also common. A uniaxial negative interference figure was obtainable from practically every grain because they tended to lie on a 001 face due to their tabular nature.

Description of Light Minerals

Quartz grains are the predominant constituent of the Welge sandstone. The grains of quartz vary from granule to silt size, but most are in the medium-sand grade. The larger grains tend to be better rounded than the smaller grains. Frosting, such as would have been produced by aeolian action, is common on most of the grains in the medium sand and coarser sizes. It was also observed on the smaller grains but was not nearly so common. The grains in the fine and very-fine sand grades are more glassy and more angular than the coarser grains. Inclusions are common and range from numerous dust-like ones up to individual grains large enough to be identified with the petrographic microscope. Tourmaline was identified as an inclusion in several quartz grains. The variations in the types of inclusions may indicate that the original source or sources of the Welge sandstone consisted of both acid igneous and metamorphic terranes.

Secondarily enlarged quartz grains, several of which are shown in Plate 2 (A, B, C, D) are common in the Welge sandstone. The overgrowths appeared to be more common on frosted grains that were rounded and contained inclusions than on angular glassy grains, however, it was not uncommon to find overgrowths on all kinds of quartz grains. Both singly and doubly terminated overgrowths give a grain a prismatic appearance; those grains having only a singly terminated overgrowth still retain their rounded appearance on one side as shown in Plate 3 (D). The fact that none of the overgrowths seemed to be broken or worn indicates that they were formed after the Welge was deposited and that they do not effectively serve to cement the grains.

Only several grains of chalcedony were identified in the Welge sandstone. These grains showed evidence of transport in that they had been rounded. It was very easy to recognize the chalcedony grains because of their microcrystalline nature. Between crossed nicols the grains sparkled as the stage was rotated but they never showed complete extinction.

Glauconite is present in the Welge sandstone both as rounded pellets in a calcareous sandstone and as irregularly shaped compact masses that serve as a cementing agent for quartz grains. The green color of pellets that were studied with a petrographic microscope served to mask some of their optical properties. Glauconite appears to be microcrystalline when viewed between crossed nicols.

The Welge glauconite has X-ray properties like those designated by Burst (1958) as representative of well-ordered group one glauconite. The symmetrical basal reflections corresponding to a "d" spacing within the crystal lattice of 10 and 3.3 angstrom units are a characteristic of group one glauconite that can be seen in the diffractogram of a sedimented sample of Welge glauconite in Figure 13. The random-powder diffractogram has several peak reflections besides those at 10 and 3.3 angstrom units. By using a sedimented sample the particles are oriented so that only the basal reflections appear on the diffractogram as shown in Figure 13. The peaks shown on the lower diffractogram are symmetrical, thus indicating a high degree of crystal-stacking regularity. It is postulated, although in no way proven, that a high degree of crystal-stacking regularity is indicative of stable conditions where there is sufficient time for glauconite formation to be carried on to its final stages.

Thin Section Description

A thin section was prepared from each of five selected samples. These five samples, 5-2, 7-7, 10-4, 8-2, and 9-5, were selected because

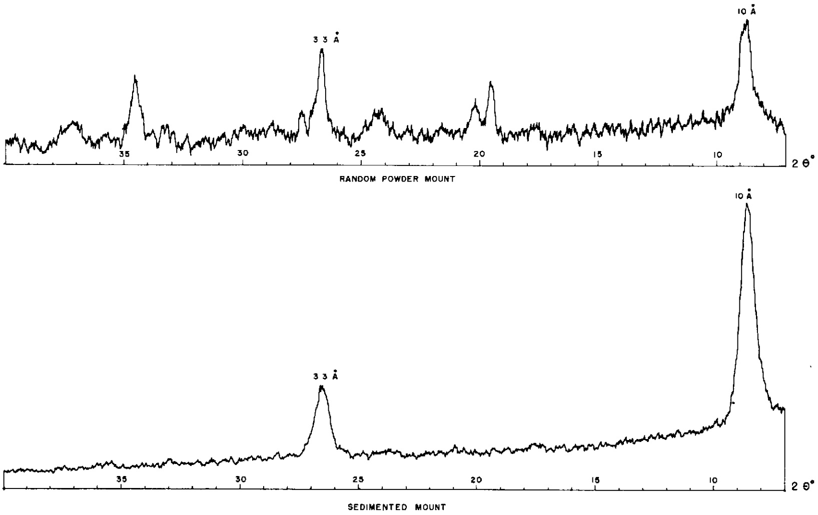


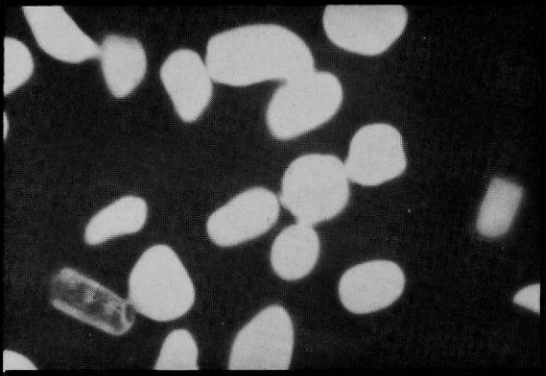
FIGURE 13. X-RAY DIFFRACTOGRAMS OF WELGE GLAUCONITE

A

Exposure of Welge sandstone at Section 2. This is near the type locality. Squaw Creek flows over Lion Mountain sandstone; bluff, above lower few feet, is Welge; and Morgan Creek limestone caps bluff. Travertine can be seen covering parts of bluff.

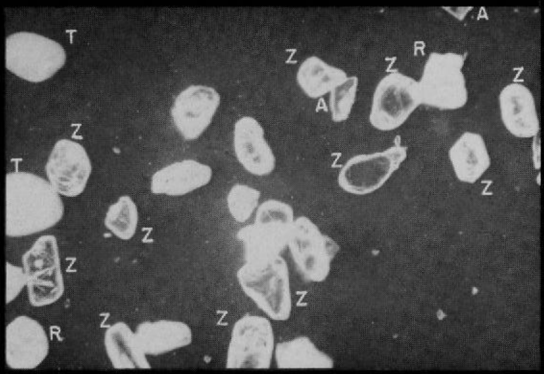
B

Exposure of Welge sandstone at Cedar Point, Section 6. Lion Mountain-Welge contact is marked by abrupt change in slope. Morgan Creek limestone caps ridge.



C

Opaque heavy minerals from sample 2-1 showing roundness. Transmitted light, X50.



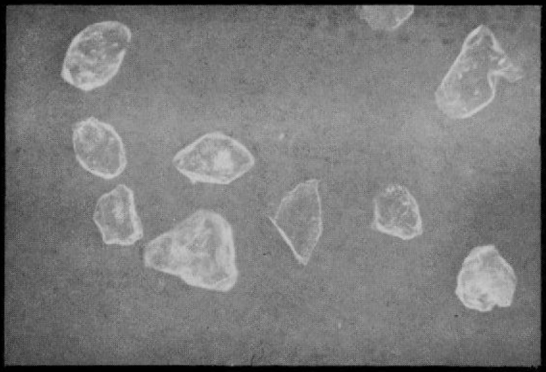
D

Typical specimens of some non-opaque heavy minerals from sample 6-8. Z, zircon; T, tourmaline; A, anatase; R, rutile. Transmitted light, n=1.66, X48.

PLATE 1

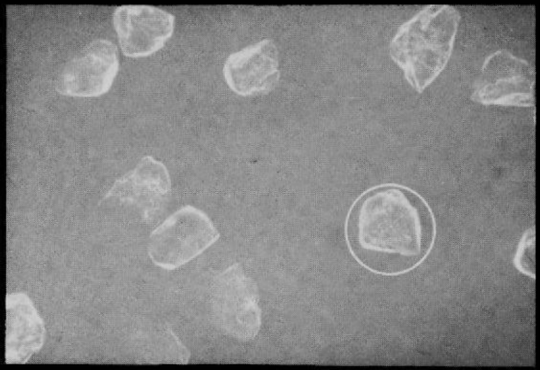
A

Quartz grain from sample 2-1 showing doubly terminated secondary overgrowth. Transmitted light, n=1.47, X48.



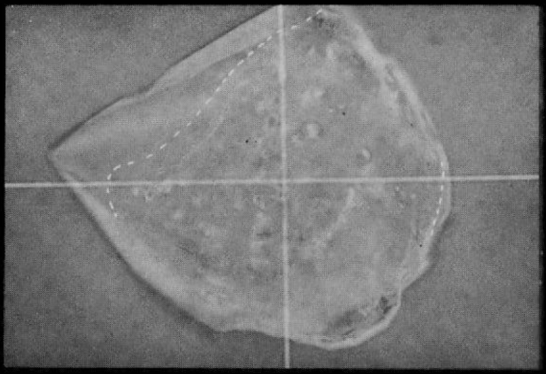
B

Quartz grains from sample 2-1 showing singly and doubly terminated secondary overgrowths. Transmitted light, n=1.47, X48.



C

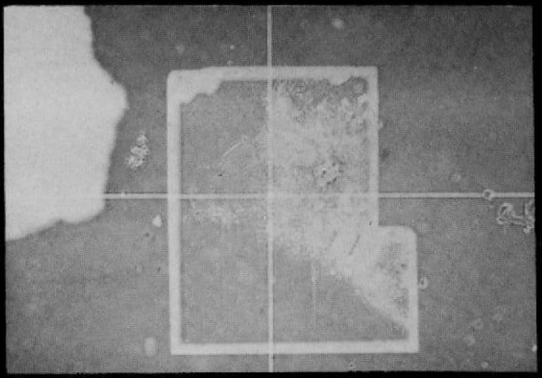
Quartz grains from sample 2-1 showing singly terminated secondary overgrowths. Transmitted light, n=1.47, X48.



D

Enlarged view of circled grain shown in C. The dotted line shows the outline of the original grain. Transmitted light, n=1.47, X225.

PLATE 2



A

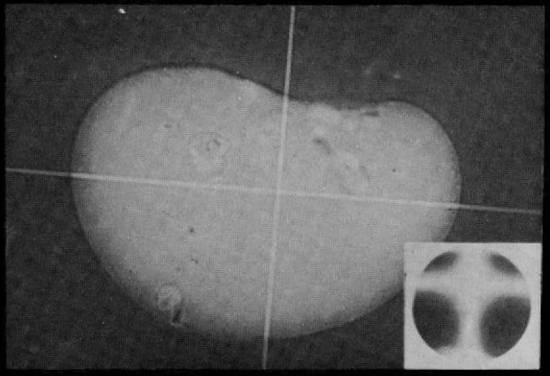
Euhedral grain of authigenic anatase from sample 6-7 lying on 001 face. Transmitted light, n=1.66, X225.

B

Euhedral grain of authigenic anatase from sample 2-8 lying on 001 face. Transmitted light, n=1.66, X225.

C

Three rounded grains of zircon from sample 2-7. Prolate grain is result of original prismatic crystal shape of zircon. Transmitted light, n=1.66, X150.



D

Well rounded grain of tourmaline from sample 2-8. Insert shows uniaxial interference figure obtained from this grain. Transmitted light, n=1.66, X225.

PLATE 3

they were characteristic of the minor variations in lithology exhibited by the Welge sandstone throughout the entire area of its exposure. It was necessary to impregnate all samples except 10-4 in order to make a thin section. It should be pointed out that these samples did not, in every instance, represent the lithology of the entire section from which they were taken, nor were they all from the same stratigraphic position.

Sample 5-2, in hand specimen, appeared to be characteristic of all samples of Welge that have been described earlier as being composed of typical Welge sandstone except that it was better indurated than some of the friable samples. In thin section this sample was found to be a rounded, well-sorted, medium-grained, quartz sandstone. As a result of the almost total absence of interstitial material and loosely packed grains the sample appeared to have a high porosity. The one to two percent of interstitial material was limonite, part of which was presumably deposited after the deposition of the Welge sandstone. This is evidenced by the fact that limonite occurred both as interstitial material and as coatings of some grains. There was a minor amount of silicious cement. Overgrowths were much less conspicuous in thin section than in mounts of loose grains; however, a thin section and loose grain mount of the same sample were not compared. Dust-like inclusions were common in the quartz grains, however, some grains were completely void of inclusions. In a few grains the inclusions showed a tendency toward parallel alignment.

Sample 7-7 was similar to sample 5-2 except that it had a higher percentage of interstitial limonite (estimated 3 to 4 percent), and a few small irregular patches of calcite (estimated 2 percent). The limonite and calcite served as the cementing material. Quartz constituted about 95 percent of the sample. There was a noticeable irregularity of the surface of some quartz grains. This was probably the frosted and pitted edges of the grains but it may have represented replacement of the quartz by calcite. When comparing thin sections of samples 5-2 and 7-7 it was seen that 7-7 was less well sorted than 5-2. This observation can be checked by the results shown in Appendix B.

The slide of sample 10-4 was characterized by tightly packed quartz grains with an almost negligible amount of limonite. Calcite was more common (estimated 7 percent) than in either of samples 5-2 or 7-7 and occurred as coarse irregular patches of crystalline calcite. The Welge sandstone at section 10 is less friable than at any of the other sections studied except at those where the cement is entirely calcareous. The decreased friability of the sandstone at section 10 is due to the presence of some silicious cement, a tighter packing of the quartz grains, and more calcareous cement than is present in the sections to the northwest.

Sample 9-5 was a calcareous, quartz sandstone in which the calcite cement (estimated 20 percent) occurred as an irregular crystalline mosaic between the widely spaced quartz grains. This was the sparry calcite cement described by Folk (1959). The quartz grains were noticeably less closely packed than in samples which have little or no calcareous cement. This sample appeared to be completely cemented so that it had a lower porosity than the non-calcareous sandstones. In some places the pores between quartz grains were filled with more than one grain of calcite, but in some parts of the slide a calcite grain was large enough to completely enclose several grains of quartz.

The sparry calcite cement was probably formed during diagenesis by recrystallization of a microcrystalline calcareous mud. It is possible that the cement was deposited directly as a sparry calcite and has not been recrystallized (Folk, 1959, p. 10). However, according to Williams, Turner, and Gilbert (1954, p. 317), calcareous material is readily recrystallized during diagenesis. The main evidence that recrystallization of a microcrystalline matrix has occurred was the loose packing of the quartz grains. They appeared to float in the sparry calcite cement, and Folk (1959, p. 34) stated that, "rock could not have been deposited that way."

Fossil fragments, although not present in the thin section of sample 9-5, are present in the Welge sandstone at sections 8 and 9 where it is composed of calcareous, quartz sandstone. Several rounded outlines were seen in the thin section of sample 9-5 in which calcite appeared to have replaced limonite that represented oxidized glauconite pellets but no trace of original detrital carbonate fragments was visible.

Sample 8-2 was a glauconitic, quartz sandstone that contained an estimated 75 to 80 percent quartz and 25 to 20 percent glauconite. All of the glauconite existed as compact masses without regular outlines and, aided by some secondary quartz overgrowths, served as the cementing material in this sample. There are only two 1- to 2-foot beds at sections 8 and 9 that have this lithology. Volumetrically they represent only a small portion of the Welge studied, however, the environmental implications of these two beds is of great significance. In each instance they are overlain by beds of calcareous, quartz sandstone containing scattered rounded pellets of glauconite. The writer believes that the glauconite that occurs as irregularly shaped compact masses has not been transported and that the rounded glauconite pellets probably have been transported. The association of terrigenous sand grains, glauconite that presumably has not been transported, and very little of anything else suggests an environment in which turbulence was sufficient to prevent the deposition of silts, clays, and carbonate muds, but was not as great as in those areas where pure quartz sand was deposited. It is likely that after the glauconite formed, quartz particles and some newly formed glauconite were further reworked enough by wave and current action to round the glauconite. These were redeposited with microcrystalline carbonate mud which recrystallized during diagenesis.

There remains to be explained the differences between deposition in Paleozoic shelf seas and more recent shelf areas. It is not uncommon in Paleozoic quartz sandstones, such as the Welge, to find a gradation from pure quartz sandstone to calcareous, quartz sandstone to arenaceous limestone and dolomite with an absence or scarcity of shale (Pettijohn, 1957, p. 299). In Cenozoic and younger deposits there is usually a gradation from sandstone to shale to limestone. The reason for these differences in facies is related to the greater tectonic stability of Paleozoic shelf areas than of Cenozoic shelf areas. During the deposition of Paleozoic sediments there was more time for a thorough winnowing and reworking of the sediments so that silt-clay size material was largely removed. It is believed that there were periods of quiescence in the offshore parts of the platform, in which the water was not sufficiently agitated to prevent the deposition of a microcrystalline calcareous mud.

CONCLUSIONS

The Welge sandstone was deposited by a transgressing sea on a stable Paleozoic platform that sloped upward almost imperceptibly toward the west. There was very little relief except for local hills of Precambrian rock, which by the time of Welge deposition, protruded only slightly above the general level of the platform. Because of the low relief and gentle slope of the platform the Welge sea was able to transgress rapidly.

The sea that deposited the Lion Mountain sandstone regressed beyond the location of all of the sections of Welge sandstone sampled for this investigation except sections 8 and 9. There was no break in sedimentation between the Lion Mountain and Welge sandstones at sections 8 and 9. The shoreline regressed only a short distance to the east of section 10. A slightly irregular contact between the Welge and Lion Mountain members and a color change from green to yellow-brown, caused by the presence of glauconite in the Lion Mountain and its absence in the Welge, are evidences of the disconformity that exists between these two sandstone members. The basal Welge beds just above the disconformity usually have a coarser median diameter than the remainder of the Welge section, however, the difference in grain size is not always great enough to be recognized in the field.

After the rapid transgression of the Welge sea from east to west there were frequent minor oscillations of sea level. Throughout the time of Welge deposition, even during the minor oscillations, there was nearly uniform wave and current action so that only particles within a small size distribution were deposited. The selective sorting was accomplished by a thorough winnowing and reworking of the deposits. All material finer than the minimum size that was being deposited was swept away to some yet undetermined site of deposition in the Welge sea. The supply of terrigenous material was never great and the waves and currents were able to winnow, rework, and redistribute the sand so that by the time of final deposition the total environmental characteristics of a shallow-water stable platform were impressed on the deposit.

The terrigenous material was originally derived from an acid igneous and metamorphic terrane, however, it is likely that the direct source of the Welge sandstone was a sedimentary terrane. Sometime after the original derivation and before the final deposition the material was probably exposed to aeolian action.

The Welge grades laterally from pure quartz sandstone in the western exposures to glauconitic, calcareous, quartz sandstone in the eastern and southeastern parts of the area which were farther from the strand line of the Welge sea.

BIBLIOGRAPHY

Barnes, V. E., 1944, "Gypsum in the Edwards Limestone of Central Texas," Univ. Texas Pub. 4301, p. 35-46.

____________, 1956, "Lead Deposits in the Upper Cambrian of Central Texas," Univ. Texas, Bur. Econ. Geol., Rept. Investigation No. 26, 68p.

____________, 1960, personal communication.

Barnes, V. E., and Bell, W. C., 1954, "Cambrian Rocks of Central Texas," San Angelo Geol. Soc. Guidebook, March 19-20, p. 35-67.

Barnes, V. E., Cloud, P. E., Jr., Dixon, L. P., Folk, R. L., Jonas, E. C., Palmer, A. R., and Tynan, E. J., 1959, "Stratigraphy of the Pre-Simpson Paleozoic Subsurface Rocks of Texas and Southeast New Mexico," Univ. Texas Pub. 5924, p. 1-198.

Beal, A. M., and Sheppard, F. P., 1956, "A Use of Roundness to Determine Depositional Environments," Jour. Sed. Petrology, vol. 26, p. 49-60.

Bokman, John, 1953, "Lithology and Petrology of the Stanley and Jackfork Formations," Jour. Geology, vol. 61, p. 152-170.

Bridge, Josiah, 1937, "The Correlation of the Upper Cambrian Sections of Missouri and Texas with the Section in the Upper Mississippi Valley," U.S. Geol. Survey Prof. Paper 186-L, p. 233-237.

____________, 1940, "Correlation of Early Paleozoic Sections in Central Texas," (abst.), Geol. Soc. America Bull., vol. 51, p. 1921-22.

Bridge, Josiah, and Barnes, V. E., 1941, "Stratigraphy of the Upper Cambrian, Llano Uplift, Texas," (abst.), Geol. Soc. America Bull., vol. 52, p. 1996.

____________, 1942, "Report of Facies Changes in the Cambrian of Central Texas," Nat. Res. Council, Rept. of Committee on Marine Ecology as Related to Paleontology, 1941-42, p. 11-12.

Bridge, Josiah, Barnes, V. E., and Cloud, P. E., Jr., 1947, "Stratigraphy of the Upper Cambrian, Llano Uplift, Texas," Geol. Soc. America Bull., vol. 58, p. 109-124.

Burst, J. F., 1958a, "Mineral Heterogeneity in 'Glauconite' Pellets," Am. Mineralogist, vol. 43, p. 481-497.

____________, 1958b, "Glauconite Pellets: Their Mineral Nature and Applications to Stratigraphic Interpretations," Am. Assoc. Petroleum Geologists Bull., vol. 42, p. 310-327.

Cloud, P. E., Jr., Barnes, V. E., and Bridge, Josiah, 1945, "Stratigraphy of the Ellenburger Group in Central Texas - A Progress Report," Univ. Texas Pub. 4301, p. 133-161.

Cloud, P. E., Jr., and Barnes, V. E., 1948, "The Ellenburger Group of Central Texas," Univ. Texas Pub. 4621, 473p.

Cloud, P. E., Jr., 1955, "Physical Limits of Glauconite Formation," Am. Assoc. Petroleum Geologists Bull., vol. 39, p. 484-492.

Cogen, W. M., 1935, "Some Suggestions for Heavy Mineral Investigations of Sediments," Jour. Sed. Petrology, vol. 5, p. 3-8.

Comstock, T. B., 1890, "A Preliminary Report on the Geology of the Central Mineral Region of Texas," Texas Geol. Survey Ann. Rept. no. 1, 1889, p. 237-391.

Dapples, E. C., 1947, "Sandstones and Their Associated Environments," Jour. Sed. Petrology, vol. 17, p. 91-100.

Daugherty, T. D., 1959, "A Petrologic and Mineralogical Analysis of the Lion Mountain and Welge Sandstones of Southern Mason County, Texas," Unpub. M.S. Thesis, A. & M. College of Texas, 88 p.

Dryden, A. L., 1931, "Accuracy in Percentage Representation of Heavy Mineral Frequencies," Proc. Nat. Acad. Sci., vol. 17, p. 233-38.

Folk, R. L., 1951, "Stages of Textural Maturity in Sedimentary Rocks," Jour. Sed. Petrology, vol. 20, p. 85-97.

__________, 1956, "The Role of Texture and Composition in Sandstone Classification," Jour. Sed. Petrology, vol. 26, p. 166-171.

__________, 1959, "Practical Petrographic Classification of Limestones," Am. Assoc. Petroleum Geologists Bull., vol. 43, p. 1-38.

Goldstein, August, Jr., and Hendricks, T. A., 1953, "Siliceous Sediments of Ouachita Facies in Oklahoma," Geol. Soc. America Bull. vol. 64, p. 421-442.

Griffith, J. C., 1951, "Size Versus Sorting in Some Caribbean Sediments," Jour. Geology, vol. 59, p. 211-243.

Hutton, C. O., 1950, "Studies of Heavy Detrital Minerals," Geol. Soc. America Bull., vol. 61, p. 636-716.

Jacobsen, Lynn, 1959, "Petrology of Pennsylvanian Sandstones and Conglomerates of the Ardmore Basin," Okla. Geol. Survey Bull. 79, 144 p.

Keller, W. D., 1945, "Size Distribution of Sands in Some Dunes, Beaches, and Sandstones," Amer. Assoc. Petroleum Geologists Bull., vol. 29, p. 215-221.

Krumbein, W. C., 1934a, "Size Frequency Distribution of Sediments," Jour. Sed. Petrology, vol. 4, p. 65-77.

____________, 1934b, "The Probable Error of Sampling Sediments for Mechanical Analysis," Am. Jour. Sci., vol. 227, p. 204-214.

____________, 1936, "The Use of Quartile Measures in Describing and Comparing Sediments," Am. Jour. Sci., vol. 232, p. 98-111.

____________, 1938, "Size Frequency Distribution and the Normal Phi Curve," Jour. Sed. Petrology, vol. 8, p. 84-90.

____________, 1941, "Measurement and Geologic Significance of Shape and Roundness of Sedimentary Particles," Jour. Sed. Petrology, vol. 11, p. 64-72.

Krumbein, W. C., and Pettijohn, F. J., 1938, "Manual of Sedimentary Petrography," Appleton-Century-Crofts, Inc., New York, 549 p.

Krynine, P. D., 1940, "Petrology and Genesis of the Third Bradford Sand," Penn. State Coll. Min. Ind. Exp. Sta. Bull. 29, 134 p.

Kuenen, P. H., 1950, "Marine Geology," John Wiley and Sons, Inc., New York, p. 266-67.

Moorhouse, W. W., 1959, "The Study of Rocks in Thin Section," Harper and Bros., New York, p. 342-356.

Paige, Sidney, 1911, "Mineral Resources of the Llano-Burnet Region, Texas, with an Account of the Pre-Cambrian Geology," U.S. Geol. Survey Bull. 450, p. 23.

____________, 1912, "Description of the Llano-Burnet Region, Texas," U.S. Geol. Survey Geol. Atlas 183, p. 41-48.

Pettijohn, F. J., 1933, "Mineral Analysis of Sediments," Recent Marine Sediments, Amer. Assoc. Petroleum Geologists, Tulsa, p. 592-615.

____________, 1957, "Sedimentary Rocks," Harper and Bros., New York, 718 p.

Plummer, F. B., 1942, "A New Quartz Sand Horizon in the Cambrian of Mason Co., Texas," Univ. Texas Bur. Econ. Geol., Min. Res. Circ. 22, 2 p.

Pollack, J. M., 1961, "Significance of Compositional and Textural Properties of South Canadian River Channel Sands, New Mexico, Texas, and Oklahoma," Jour. Sed. Petrology, vol. 31, p. 15-37.

Powers, M. C., 1953, "A New Roundness Scale for Sedimentary Particles," Jour. Sed. Petrology, vol. 23, p. 117-119.

Rittenhouse, Gordon, 1943, "The Transportation and Deposition of Heavy Minerals," Geol. Soc. America Bull., vol. 54, p. 1725-1780.

Ross, C. S., 1926,"Methods of Preparation of Sedimentary Materials for Study," Econ. Geology, vol. 21, p. 454-68.

Sellards, E. H., Adkins, W. S., and Plummer, F. P., 1933, "The Geology of Texas, Volume I - Stratigraphy," Univ. Texas Pub. 3232, p. 56.

Sherzer, W. H., 1910, "Criteria for the Recognition of the Various Types of Sand Grains," Geol. Soc. America Bull. vol. 21, p. 625-662.

Trask, P. D., 1930, "Mechanical Analysis of Sediments by Centrifuge," Econ. Geology, vol. 25, p. 581-599.

____________, 1932, "Origin and Environment of Source Sediments of Petroleum," Gulf Publishing Co., Houston, 323 p.

Twenhofel, W. H., 1945, "The Rounding of Sand Grains," Jour. Sed. Petrology, vol. 15, p. 59-71.

____________, 1950, "Principles of Sedimentation," McGraw-Hill Book Co., Inc., New York, 2nd ed., p. 282-373.

Tyler, S. A., 1936, "Heavy Minerals of the St. Peter Sandstone in Wisconsin," Jour. Sed. Petrology, vol. 6, p. 55-84.

Wentworth, C. K., 1922, "A Scale of Grade and Class Terms for Clastic Sediments," Jour. Geology, vol. 30, p. 377-392.

____________, 1929, "Method of Computing Mechanical Composition Types in Sediments," Geol. Soc. America Bull., vol. 40, p. 771-790.

Williams, Howell, Turner, F. J., and Gilbert, C. M., 1945, "Petrography: An Introduction to the Study of Rocks in Thin Sections," W. H. Freeman and Co., San Francisco, p. 289-325.

Wilson, J. L., 1950, "Upper Cambrian Trilobites From the Welge Sandstone, Eastern Llano Uplift, Texas," (abst.), Geol. Soc. America Bull., vol. 61, p. 1515.

Winnet, E. R., 1961, "Composition, Grain Size, Roundness, and Sphericity of Potsdam Sandstone (Cambrian) in Northeastern New York," Jour. Sed. Petrology, vol. 31, p. 5-14.

Wollman, C. E., 1952, "Fauna of the Basal Welge Sandstone, Llano Uplift, Texas," Unpub. M.A. Thesis, The Univ. of Texas.

Ziegler, Victor, 1911, Factors Influencing the Rounding of Sand Grains," Jour. Geology, vol. 19, p. 645-654.

APPENDIX A

SIZE ANALYSIS DATA - WELGE SANDSTONE

Legend: S = Section number

N = Sample number

SP = Stratigraphic position of sample in feet above base of Welge sandstone.

The numbers above each column indicate the minimum size in phi (Ø) units of material retained in respective $\sqrt{2}$ Wentworth grades (Ø increases as grain size decreases).

Percent by weight

S	N	SP	-1.5	-1.0	-0.5	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	>4.0
							Section 1								
1	8	22½	——	0.03	0.08	1.26	5.90	16.15	25.75	25.24	13.35	6.93	0.88	0.33	4.00
1	7	18	——	——	——	0.33	5.49	16.91	25.34	18.23	7.43	8.56	4.06	1.43	12.49
1	6	14	——	——	——	0.03	1.13	21.53	51.45	18.01	3.01	2.08	1.37	0.50	0.70
1	5	10	——	0.01	0.05	0.37	4.06	16.10	25.65	22.21	11.83	12.40	2.08	0.33	4.95
1	4	8	——	——	0.02	0.30	3.64	14.16	28.03	29.25	12.07	6.79	1.32	0.32	4.06
1	3	5	——	0.05	0.09	0.44	2.05	5.74	23.89	42.40	17.02	7.39	0.64	0.09	0.22
1	2	4	0.15	0.39	3.20	6.94	6.11	6.78	10.63	22.89	23.27	16.34	1.91	0.29	0.67
1	1	½	0.14	0.41	0.86	4.82	16.09	24.59	24.09	19.86	5.85	1.52	0.39	0.10	1.29

Percent by weight

S	N	SP	-1.5	-1.0	-0.5	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	>4.0
Section 2															
2	8	22	——	——	0.02	0.22	3.45	21.09	32.82	24.48	11.69	4.98	0.43	0.11	0.74
2	7	20	——	——	-0.01	0.32	5.46	24.27	33.10	23.13	9.06	3.48	0.25	0.06	0.73
2	6	18	——	——	——	0.17	6.29	22.87	30.30	20.93	9.93	8.12	1.18	0.14	0.14
2	5	10	——	——	0.01	0.36	6.06	26.31	29.16	25.24	6.77	1.93	0.41	0.15	3.50
2	4	7½	——	——	0.01	0.51	5.33	16.95	24.74	24.34	13.62	5.42	1.97	0.75	6.17
2	3	6	——	——	0.01	0.46	8.09	23.81	21.92	18.08	11.81	5.52	2.35	0.55	7.37
2	2	4	——	——	——	0.07	2.07	12.17	23.36	24.89	15.57	9.26	3.40	1.82	7.48
2	1	½	——	——	——	0.01	1.82	17.46	36.47	29.65	10.94	2.88	0.26	0.05	0.35
Section 3															
3	7	24	0.03	0.21	0.57	2.97	11.08	28.61	30.43	17.57	4.87	1.94	0.35	0.12	1.17
3	6	20	——	0.13	0.20	2.12	8.29	18.18	24.62	23.41	11.68	8.18	1.39	0.25	1.53
3	5	12	——	0.01	0.21	1.90	10.26	21.86	28.40	20.65	8.36	5.96	0.71	0.06	1.51
3	4	9	——	——	0.05	0.94	8.32	18.82	24.05	23.12	11.52	6.10	0.82	0.21	6.12
3	3	6	——	——	0.01	0.02	0.41	4.72	25.37	36.61	21.10	9.19	1.02	0.13	1.44
3	2	3	——	0.03	0.09	0.62	8.97	27.53	24.11	21.31	12.58	3.77	0.46	0.07	0.41
3	1	1	——	0.02	0.18	3.95	12.67	21.05	28.94	19.91	8.27	2.98	0.35	0.08	1.56

Percent by weight

S	N	SP	-1.5	-1.0	-0.5	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	>4.0
Section 4															
4	8	24	——	0.01	0.09	1.17	5.70	26.62	35.51	20.50	6.94	2.27	0.22	0.05	0.82
4	7	19	——	0.10	0.48	2.60	7.91	19.75	27.05	16.60	9.78	8.56	1.03	0.21	5.87
4	6	16	——	——	0.01	0.04	0.43	2.63	17.25	43.87	24.64	7.87	0.64	0.07	2.45
4	5	12	——	0.02	0.09	0.89	5.73	16.61	28.18	22.68	12.10	8.92	1.03	0.13	4.00
4	4	7	——	——	0.07	0.34	2.19	5.04	10.65	19.22	24.94	28.16	4.57	0.57	4.68
4	3	5	——	0.08	0.24	1.44	5.35	8.62	10.88	13.94	16.39	26.66	9.26	2.03	5.42
4	2	1	——	0.04	0.34	2.83	13.84	22.79	23.49	20.66	7.39	4.51	0.76	0.19	3.11
4	1	½	——	0.24	1.07	4.02	7.91	8.82	13.09	24.70	19.13	13.16	3.62	1.14	2.74
Section 5															
5	8	22	——	0.41	0.56	1.61	4.82	20.95	34.14	22.23	7.36	3.34	0.47	0.15	3.39
5	7	21	——	——	0.03	0.38	2.77	20.16	33.84	25.28	8.38	4.01	0.75	0.31	4.36
5	6	18	——	0.12	0.47	2.59	7.62	16.41	24.75	27.77	10.35	4.85	1.12	0.31	3.88
5	5	15	——	0.01	0.18	1.89	7.52	18.76	27.61	23.06	10.37	5.24	0.70	0.14	4.72
5	4	11	——	——	0.02	0.59	5.44	13.28	17.77	19.09	12.42	8.20	2.00	0.83	21.21
5	3	7	——	0.08	0.18	0.95	8.80	21.90	24.44	19.80	10.00	6.01	1.28	0.39	6.12
5	2	3	——	——	——	0.02	0.39	4.50	23.42	41.86	18.68	8.37	0.95	0.17	1.54
5	1	1	——	——	0.02	0.04	0.66	9.56	27.97	33.10	15.58	8.56	1.25	0.39	2.57

Percent by weight

S	N	SP	-1.5	-1.0	-0.5	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	>4.0
							Section 6								
6	7	25	——	——	0.04	0.86	5.42	15.70	23.21	28.68	16.97	6.96	0.96	0.16	0.76
6	6	21	——	——	0.14	1.39	6.48	23.18	27.85	23.94	11.63	4.01	0.57	0.15	0.47
6	5	18	——	——	——	0.01	0.41	6.24	20.90	33.22	23.18	10.40	1.02	0.29	4.11
6	4	15	——	——	——	——	0.13	1.37	8.19	26.07	29.37	27.41	4.58	0.88	2.18
6	3	11½	——	——	——	——	0.33	2.68	9.27	17.21	15.73	25.43	15.16	4.82	8.80
6	2	8	——	——	——	——	0.18	1.00	2.94	7.20	11.62	30.65	26.84	9.46	9.63
6	1	3	——	——	——	0.12	2.89	11.38	18.13	16.07	8.29	12.59	11.38	4.38	14.67
							Section 7								
7	7	16	——	——	——	0.02	2.08	18.96	28.75	18.01	8.76	7.70	3.68	2.31	9.39
7	6	13½	——	——	——	0.05	1.64	10.12	30.53	32.75	15.78	7.22	1.13	0.37	3.21
7	5	12½	——	——	——	0.01	0.97	11.84	27.98	27.25	14.63	12.04	3.25	1.22	3.67
7	4	11	——	——	——	0.06	1.37	18.53	35.64	24.32	10.94	6.04	1.11	0.33	1.48
7	3	10	——	——	——	0.07	1.22	16.49	35.68	25.13	10.91	6.75	1.36	0.46	2.00
7	2	5½	——	——	——	0.36	7.34	19.84	26.02	24.32	10.62	5.11	1.82	0.94	3.39
7	1	4	——	——	0.03	0.42	7.89	20.95	26.12	24.83	10.50	4.07	1.38	0.70	3.10

Percent by weight

S	N	SP	-1.5	-1.0	-0.5	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	>4.0
Section 8															
8	8	15	——	——	0.21	1.98	10.78	21.39	23.57	20.58	10.55	5.21	1.80	0.81	3.94
8	7	12	——	——	0.14	1.29	6.90	18.12	25.40	24.35	12.77	5.77	1.47	0.76	4.38
8	6	9½	——	——	0.03	0.41	5.34	17.19	26.27	22.88	9.76	6.66	2.12	1.25	8.42
8	5	7½	——	——	0.03	0.42	5.52	17.59	29.25	24.33	9.92	4.96	1.57	1.00	5.88
8	4	5½	——	——	0.05	0.82	7.27	15.40	16.40	25.66	20.86	10.85	0.89	0.17	0.94
8	4	4½	——	——	0.03	0.37	4.10	14.30	22.46	23.99	15.35	11.03	1.27	0.41	6.17
8	2	2	——	——	——	0.04	1.57	9.37	20.27	29.58	19.88	10.86	2.21	0.96	4.98
8	1	½	——	——	0.08	0.57	3.04	6.52	14.43	30.63	20.91	12.83	1.40	0.31	7.99
Section 9															
9	8	15	——	——	——	0.27	2.50	15.37	32.26	28.95	11.84	5.80	1.30	0.57	2.14
9	7	12	——	——	——	0.08	0.96	7.07	23.79	32.99	17.61	12.38	2.10	0.85	2.63
9	6	10	——	——	0.03	0.74	10.15	28.00	28.29	17.57	6.74	3.74	1.19	0.64	3.04
9	5	8	——	——	——	0.16	1.21	7.37	19.70	29.81	20.73	11.95	2.68	1.03	4.95
9	4	6	——	——	——	0.10	2.08	13.88	28.22	29.01	13.22	6.47	1.19	0.59	5.21
9	3	4½	——	0.01	0.12	2.51	7.32	16.24	19.92	21.31	14.40	12.44	2.59	0.79	2.37
9	2	3	——	——	0.01	0.07	0.81	8.93	32.48	30.65	11.23	6.30	1.98	1.14	6.51
9	1	1½	——	——	0.01	0.28	4.74	24.63	27.70	18.58	11.25	956	1.24	0.40	1.46

Percent by weight

Section 10

S	N	SP	-1.5	-1.0	-0.5	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	>4.0
10	7	12	—	—	—	—	0.01	0.69	11.44	38.23	20.44	13.00	4.84	2.56	8.03
10	6	10	—	—	—	—	—	0.02	0.34	2.49	19.55	49.57	12.40	8.30	6.68
10	5	7	—	—	—	—	0.04	2.22	16.28	38.29	24.18	12.62	1.92	0.64	3.27
10	4	5½	—	—	—	—	—	0.41	21.56	39.87	16.20	14.08	2.64	0.92	2.84
10	3	3	—	—	—	0.02	0.02	0.55	3.15	33.32	36.73	14.67	2.60	1.22	7.16
10	2	1½	—	0.26	3.41	16.09	23.03	14.49	11.74	10.14	7.78	6.04	1.90	0.79	4.41
10	1	½	0.20	2.14	4.47	14.37	19.17	16.44	12.81	11.11	6.10	5.69	2.21	1.14	3.92

APPENDIX B

SEDIMENTARY PARAMETERS OF WELGE SANDSTONE

Legend:	S	Section number
	N	Sample number
	SP	Stratigraphic position of sample in feet above base of Welge sandstone
	$Q_{1\phi}$	First quartile diameter
	Md_{ϕ}	Median diameter
	$Q_{3\phi}$	Third quartile diameter
	QD_{ϕ}	Quartile deviation
	Skq_{ϕ}	Skewness
	Kq_{ϕ}	Kurtosis
	So	Sorting coefficient

S	N	SP	$Q_{1\phi}$	Md_{ϕ}	$Q_{3\phi}$	QD_{ϕ}	Skq_{ϕ}	Kq_{ϕ}	So
Section 1									
1	8	22½	1.03	1.52	2.02	0.50	0.01	0.25	1.42
1	7	16	1.07	1.54	2.59	0.76	0.29	0.16	1.70
1	6	14	1.04	1.23	1.51	0.24	0.05	0.24	1.19
1	5	10	1.10	1.57	2.24	0.57	0.10	0.26	1.48
1	4	8	1.16	1.55	2.00	0.42	0.03	0.22	1.34
1	3	5	1.40	1.65	2.01	0.31	0.06	0.22	1.25
1	2	4	1.03	1.84	2.37	0.67	-0.14	0.24	1.59
1	1	½	0.56	1.06	1.57	0.51	0.01	0.28	1.43
Section 2									
2	8	22	1.01	1.38	1.82	0.41	0.04	0.25	1.33
2	7	20	0.90	1.26	1.70	0.40	0.04	0.27	1.32

S	N	SP	$Q_{1\phi}$	Md_{ϕ}	$Q_{3\phi}$	QD_{ϕ}	Skq_{ϕ}	Kq_{ϕ}	So
2	6	18	0.92	1.32	1.80	0.44	0.03	0.24	1.37
2	5	10	0.80	1.32	1.75	0.48	-0.04	0.32	1.40
2	4	7½	1.05	1.54	2.08	0.52	0.03	0.24	1.43
2	3	6	0.85	1.40	2.10	0.63	0.08	0.24	1.54
2	2	4	1.25	1.74	2.40	0.58	0.09	0.23	1.50
2	1	½	1.11	1.45	1.72	0.31	-0.03	0.23	1.24

Section 3

S	N	SP	$Q_{1\phi}$	Md_{ϕ}	$Q_{3\phi}$	QD_{ϕ}	Skq_{ϕ}	Kq_{ϕ}	So
3	7	24	0.62	1.12	1.53	0.41	0.01	0.26	1.33
3	6	20	0.93	1.45	1.95	0.51	-0.01	0.24	1.42
3	5	12	0.82	1.33	1.75	0.47	-0.04	0.24	1.39
3	4	9	0.94	1.46	1.99	0.53	0.01	0.24	1.45
3	3	6	1.40	1.76	2.15	0.38	0.02	0.27	1.31
3	2	3	0.80	1.27	1.80	0.50	0.03	0.29	1.42
3	1	1	0.72	1.22	1.66	0.47	-0.03	0.25	1.39

Section 4

S	N	SP	$Q_{1\phi}$	Md_{ϕ}	$Q_{3\phi}$	QD_{ϕ}	Skq_{ϕ}	Kq_{ϕ}	So
4	8	24	0.86	1.23	1.61	0.38	0.01	0.27	1.31
4	7	19	0.88	1.34	2.02	0.57	0.11	0.25	1.48
4	6	16	1.55	1.83	2.20	0.33	0.05	0.26	1.27
4	5	12	1.03	1.46	2.04	0.51	0.08	0.25	1.42
4	4	7	1.70	2.30	2.67	0.49	-0.11	0.26	1.41
4	3	5	1.43	2.29	2.82	0.70	-0.16	0.27	1.63
4	2	1	0.70	1.24	1.74	0.52	-0.02	0.25	1.43
4	1	½	1.10	1.80	2.35	0.63	-0.07	0.24	1.56

S	N	SP	$Q_{1\phi}$	Md_{ϕ}	$Q_{3\phi}$	QD_{ϕ}	Skq_{ϕ}	Kq_{ϕ}	So
Section 5									
5	8	22	0.96	1.31	1.73	0.39	0.04	0.23	1.32
5	7	21	1.02	1.40	1.83	0.41	0.03	0.21	1.33
5	6	18	0.94	1.46	1.88	0.47	-0.05	0.23	1.39
5	5	15	0.92	1.40	1.90	0.49	0.01	0.24	1.41
5	4	11	1.16	1.83	2.89	0.87	0.19	0.13	1.83
5	3	7	0.85	1.37	1.98	0.57	0.05	0.25	1.48
5	2	3	1.46	1.70	2.12	0.33	0.09	0.24	1.27
5	1	1	1.28	1.65	2.12	0.42	0.05	0.24	1.34
Section 6									
6	7	25	1.07	1.59	2.02	0.48	-0.04	0.26	1.40
6	6	21	0.88	1.34	1.82	0.47	0.01	0.28	1.39
6	5	18	1.46	1.79	2.28	0.41	0.08	0.26	1.33
6	4	15	1.80	2.26	2.67	0.44	-0.02	0.31	1.37
6	3	11½	1.88	2.59	3.14	0.63	-0.08	0.25	1.56
6	2	8	2.55	2.95	3.35	0.40	0	0.19	1.32
6	1	3	1.27	2.10	3.23	0.98	0.15	0.23	1.98
Section 7									
7	7	16	1.07	1.51	2.38	0.66	0.22	0.21	1.59
7	6	13½	1.22	1.61	1.99	0.39	0	0.25	1.32
7	5	12½	1.24	1.65	2.20	0.48	0.07	0.26	1.40
7	4	11	1.09	1.42	1.86	0.39	0.06	0.23	1.32
7	3	10	1.14	1.45	1.93	0.40	0.09	0.24	1.32
7	2	5½	0.94	1.44	1.93	0.50	0	0.24	1.42
7	1	4	0.92	1.40	1.85	0.47	-0.01	0.24	1.39

S	N	SP	$Q_{1\phi}$	Md_{ϕ}	$Q_{3\phi}$	QD_{ϕ}	Skq_{ϕ}	Kq_{ϕ}	So
Section 8									
8	8	15	0.81	1.34	1.89	0.54	0.01	0.25	1.46
8	7	12	0.97	1.48	1.96	0.50	-0.01	0.25	1.42
8	6	9½	1.05	1.52	2.14	0.55	0.08	0.21	1.47
8	5	7½	1.04	1.46	1.94	0.45	0.03	0.21	1.38
8	4	5½	1.05	1.71	2.18	0.57	-0.09	0.28	1.48
8	3	4½	1.15	1.68	2.29	0.57	0.04	0.27	1.48
8	2	2	1.39	1.81	2.34	0.48	0.06	0.25	1.40
8	1	½	1.51	1.91	2.41	0.45	0.05	0.20	1.38
Section 9									
9	8	15	1.14	1.50	1.90	0.38	0.02	0.23	1.31
9	7	12	1.42	1.77	2.27	0.43	0.08	0.26	1.36
9	6	10	0.78	1.15	1.80	0.51	0.14	0.26	1.42
9	5	8	1.43	1.86	2.40	0.49	0.06	0.25	1.41
9	4	6	1.20	1.60	2.04	0.42	0.02	0.22	1.34
9	3	4½	0.96	1.59	2.27	0.66	0.02	0.28	1.59
9	2	3	1.25	1.57	2.08	0.42	0.10	0.22	1.34
9	1	1½	0.93	1.36	1.99	0.53	0.10	0.26	1.45
Section 10									
10	7	12	1.66	1.99	2.63	0.49	0.16	0.21	1.41
10	6	10	2.55	2.81	3.06	0.25	0	0.17	1.21
10	5	7	1.60	1.90	2.35	0.38	0.08	0.25	1.31
10	4	5½	1.55	1.83	2.40	0.43	0.15	0.27	1.36
10	3	3	1.85	2.19	2.54	0.35	0.01	0.23	1.78
10	2	1½	0.12	0.75	1.79	0.84	0.21	0.28	1.80
10	1	½	0.10	0.80	1.72	0.81	0.11	0.26	1.75

APPENDIX C

MEASURED SECTIONS

The following stratigraphic sections of Welge sandstone were measured and described at the ten localities in the Central Mineral region of Texas that are discussed in this paper. The location of each section is shown in Figure 1. The names for each section were determined with the assistance of V. E. Barnes (1960, personal communication).

SECTION 1 - MASON SECTION

Section 1 is located within the city limits of Mason, Mason County, Texas. The section starts on Garfield Street 0.1 mile north of the intersection of Garfield and El Paso streets, in the southwestern part of Mason.

	Thickness in feet
Wilberns formation:	
Welge sandstone member:	
<u>Sandstone</u>; brown-yellow, weathering to yellow-brown, massive, medium-grained, rounded, friable quartz sandstone	1
<u>Sandstone</u>; yellow-brown, weathering to brown-red, massive, medium-grained, rounded, friable, quartz sandstone.	6.5
<u>Sandstone</u>; brown-yellow, weathering to yellow-brown, massive, medium-grained, rounded, friable, quartz sandstone.	10
<u>Sandstone</u>; yellow-brown, weathering to red-brown, massive, fine- to medium-grained,	

	Thickness in feet
rounded, slightly friable, quartz sandstone. Secondary quartz faces present on some grains	1
Sandstone; buff, weathering to brown-yellow, massive, medium- to coarse-grained, rounded, friable, quartz sandstone. Secondary quartz faces present on some grains	4
Total thickness of Welge measured	22.5

SECTION 2 - SQUAW CREEK SECTION

Section 2 is located along Squaw Creek where it flows from east to west 0.25 mile north of the Mason-Gillespie County line, in Mason County, Texas. The section of Welge sandstone described and sampled is a part of the bluff along the north side of Squaw Creek.

Wilberns formation:

Welge sandstone member:

Sandstone; yellow-brown, weathering to red-brown, massive, medium-grained, rounded, friable, quartz sandstone	8
Sandstone; olive-yellow, weathering to yellow-brown, massive, medium-grained, rounded, slightly friable, very slightly calcareous, quartz sandstone. Secondary quartz faces present on some grains	14

	Thickness in feet
Total thickness of Welge measured	22

SECTION 3 - STREETER SECTION

Section 3 is located 2.75 miles west of the Post Office at Streeter, Mason County, Texas along U.S. Highway 377. The section starts in the bed of an intermittent stream 0.25 mile south of U.S. Highway 377.

Wilberns formation:

Welge sandstone member:

<u>Sandstone</u>; yellow-brown, weathering to red-brown, massive, medium-grained, rounded, friable, quartz sandstone.	9
<u>Sandstone</u>; brown-yellow, weathering to yellow-brown, massive, medium-grained, rounded, friable, quartz sandstone. Secondary quartz faces are present on some grains	15
Total thickness of Welge measured	24

SECTION 4 - BROOK-KATEMCY RANCH SECTION

Section 4 is a composite section. The basal 16 feet of the section is located on the bank of an intermittent stream south of the cemetery at Camp San Saba, McCulloch County, Texas. The upper eight feet of the section is located 2.7 miles south of Camp San Saba, 0.3 mile east of U.S. Highway 377 on the Katemcy ranch road.

Wilberns formation:

Welge sandstone member:

	Thickness in feet
Sandstone; buff, weathering to yellow-brown, massive, medium-grained, rounded, friable, quartz sandstone. Secondary quartz faces are present on sone grains	8
Sandstone; brown-red, weathering to red-brown, massive, medium-grained, rounded, friable, quartz sandstone.	9
Sandstone; brown-yellow, weathering to yellow-brown, massive, fine-grained, rounded, friable, quartz sandstone.	5
Sandstone; brown-yellow, weathering to yellow-brown, faintly cross-bedded, medium-grained, rounded, slightly friable, sparingly glauconitic, quartz sandstone	2
Total thickness of Welge measured	24

SECTION 5 - UPSTREAM JAMES RIVER SECTION

Section 5 is located along the James River 2.8 miles east of a private airfield in southwestern Mason County, Texas, 15.8 airline miles southwest of Mason, Mason County, Texas. The section begins on the east side of the river about half-way up a nearly vertical bluff formed by the Welge and underlying and overlying rocks.

Wilberns formation:

Welge sandstone member:

	Thickness in feet
Sandstone; green-yellow, weathering to green-brown, massive, medium-grained, rounded, sparingly glauconitic, slightly calcareous, friable, quartz sandstone.	2
Sandstone; brown-yellow, weathering to red-brown, massive, medium-grained, rounded, slightly calcareous, quartz sandstone.	2.5
Sandstone; yellow-brown, weathering to brown-red, massive, medium-grained, rounded, resistant, quartz sandstone.	17.5
Total thickness of Welge measured	22.0

SECTION 6 - LITTLE LLANO RIVER SECTION

Section 6 is located at Cedar Point, 4.25 miles southeast of Cherokee, San Saba County, Texas. The section begins at the base of a bluff composed of Welge sandstone and capped by basal Morgan Creek limestone.

Wilberns formation:

Welge sandstone member:

Sandstone; yellow-brown, weathering to red-brown, massive, medium-grained, rounded, friable, quartz sandstone.	4
Sandstone; brown-yellow, weathering to yellow-brown, massive, medium-grained, rounded, friable, quartz sandstone	3

	Thickness in feet
Sandstone; buff, weathering to brown-yellow, massive, fine-grained, rounded, friable, quartz sandstone.	16
Sandstone; green-yellow, weathering to green-brown, massive, coarse-grained, rounded, sparingly glauconitic, friable, quartz sandstone	2
Total thickness of Welge measured	25

SECTION 7 - EAST CANYON SECTION

Section 7 is located in the Riley Mountains on the west side of the ranch road to Click, 4.2 miles southwest of the intersection of the Click road and State Highway 77, Llano County, Texas. The section starts near the top of an unnamed ridge immediately south of Moore Hollow.

Wilberns formation:

Welge sandstone member:

Sandstone; yellow-brown, weathering to brown, massive, medium-grained, slightly calcareous, slightly friable, quartz sandstone	2.5
Sandstone; green-white, weathering to green-brown, massive, medium-grained, rounded, sparingly glauconitic, calcareous, quartz sandstone.	1.5
Sandstone; olive-brown, weathering to light brown, massive, medium-grained, rounded,	

	Thickness in feet
sparingly glauconitic, slightly friable, quartz sandstone.	6.5
Sandstone; olive-white, weathering to yellow-brown, massive, medium-grained, rounded, slightly calcareous, slightly friable, quartz sandstone	1.5
Total thickness of Welge measured	12.0

The Lion Mountain-Welge contact is covered at this section. The contact was picked at an abrupt change in slope. The first exposure of Welge is four feet stratigraphically above the estimated contact. Therefore, the thickness of this section includes 12 feet of measured section and an estimated four feet of covered section.

SECTION 8 - MORGAN CREEK SECTION

Section 8 is located near the mouth of the South Fork of Morgan Creek, on the eastern side of Lake Buchanan, Burnet County, Texas. The section starts in a bluff along the north side of the road 0.5 mile from the ford across the South Fork of Morgan Creek.

Wilberns formation:

Welge sandstone member:

Sandstone; green-white, weathering to light brown, massive, fossiliferous, medium-grained, rounded, sparingly glauconitic, calcareous, quartz sandstone	5
Sandstone; purple-green, weathering to green-brown, massive, medium-grained, rounded, glauconitic, quartz sandstone.	3

	Thickness in feet
Sandstone; green-white, weathering to light brown, massive, fossiliferous, medium-grained, rounded, sparingly glauconitic, calcareous, quartz sandstone	4
Sandstone; purple-green, weathering to green-brown, massive, medium-grained, rounded, glauconitic, quartz sandstone	1.5
Sandstone; green-white, weathering to light olive-brown, massive, fossiliferous, medium-grained, rounded, sparingly glauconitic, calcareous, quartz sandstone. Trilobite casts are common in the lower bed. Barnes (1956) identified these as belonging to the *Elvinia* fauna.	1.5
Total thickness of Welge measured	15.0

SECTION 9 - SILVER-BEAVER CREEK SECTION

Section 9 is located near the junction between Silver Creek and Beaver Creek on the eastern side of Lake Buchanan, Burnet County, Texas. The section starts in a road-cut on the east side of the road, 0.2 mile east and 0.1 mile south of the junction between Silver Creek and Beaver Creek.

Wilberns formation:

Welge sandstone member:

Sandstone; olive-white, weathering to olive-brown, massive, fossiliferous, medium-grained

	Thickness in feet
rounded, sparingly glauconitic, calcareous, quartz sandstone	6.5
Sandstone; olive-yellow, weathering to yellow-brown, massive, medium-grained, rounded, slightly calcareous, friable, quartz sandstone	1.5
Sandstone; olive-white, weathering to olive-brown, massive, slightly fossiliferous, medium-grained, rounded, sparingly glauconitic, calcareous, quartz sandstone.	1.5
Sandstone; green, weathering to yellow-brown, massive, medium-grained, rounded, glauconitic, quartz sandstone.	2.0
Sandstone; olive-white, weathering to olive-brown, massive, fossiliferous, medium-grained, rounded, sparingly glauconitic, calcareous, quartz sandstone	2
Sandstone; green, weathering to yellow-brown, massive, medium-grained, rounded, glauconitic, quartz sandstone	1.5
Sandstone; olive-white, weathering to olive-brown, massive, fossiliferous, medium-grained, rounded, sparingly glauconitic, calcareous, quartz sandstone	2
Total thickness of Welge measured	17.0

SECTION 10 - KLETT-WALKER SECTION

Section 10 is located about five airline miles west-northwest of Johnson City, Blanco County, Texas, on the Pedernales River. The section starts at the base of a small bluff on the east side of the river.

	Thickness in feet
Wilberns formation:	
Welge sandstone member:	
<u>Sandstone</u>; pale yellow-brown, weathering to dark yellow-brown, massive, medium- to fine-grained, rounded, slightly calcareous, well-cemented, quartz sandstone.	1
<u>Sandstone</u>; yellow-brown, weathering to dark yellow-brown, cross-bedded, fine- grained, rounded, well-cemented, quartz sandstone. Some of the grains have secondary faces.	3
<u>Sandstone</u>; yellow-brown, weathering to brown, cross-bedded, medium- to fine-grained, rounded, slightly calcareous, quartz sandstone.	3
<u>Sandstone</u>; brown-green, weathering to brown, cross-bedded, fine-grained, rounded, glauconitic, slightly calcareous, quartz sandstone . . .	3
<u>Sandstone</u>; green-brown, weathering to brown, massive, coarse-grained, rounded, glauconitic, slightly calcareous, well-cemented, quartz sandstone.	2
Total thickness of Welge measured	12