AIR VIEW OF TODILTO PARK

MEMOIR 14

Sedimentology of the Upper Cretaceous Rocks of Todilto Park, New Mexico

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Abstract

This study involves the fundamental sedimentology of the complex transgressive-regressive Upper Cretaceous sediments exposed at Todilto Park, west of Tohatchi, New Mexico.

The three measured and sampled sections represent approximately 300o feet of strata ranging from the Jurassic Morrison Formation through the Cretaceous sandstones, siltstones, and shales of the Dakota(?), Mancos, and Mesaverde. These sections have been differentiated and correlated on the basis of physical and mineralogical charcteristics.

Five principal petrographic zones have been recognized and each zone has been further subdivided on the basis of its clay mineralogy. Each principal zone is named for the distinctive accessory heavy mineral or minerals it contains. The recognized zones in their order of occurrence, starting at the base of the sections, are (1) staurolite, (2) tourmaline-garnet-zircon, (3) biotite-chlorite, (4) sphene-zoisite, and (5) epidote. At Todilto Park, the mineral zones and the formations do not coincide. It appears that any attempt regionally to characterize a formation on the basis of its mineralogy will fail.

Interpretations of the statistical parameters obtained from the size analyses of the Todilto Park samples result in conclusions that are consistent with currently accepted ideas concerning the history of Cretaceous sedimentation in the San Juan Basin. There are no large-scale abrupt changes in the mechanical composition of the sediments, and hence it appears that during their deposition there were no rapid changes in the tectonic framework of this area. As sedimentation proceeded from deposition of the Dakota(?) through the Point Lookout, there was a gradual decrease in the energy level, a decrease in the rate of deposition, and an increase in the amount of reworking. The characteristics of the sediments above the Point Lookout are typical of backshore and transitional sediments. As the basin filled, these deposits encroached on the earlier beach and neritic deposits. Comparisons with recent deposits support these conclusions.

Detailed interpretations of the mechanical analyses suggest that many of the Cretaceous formations include both marine and nonmarine sedimentary units. This is especially true for the Dakota(?) and Gallup sandstones. It appears that formations deposited during a stillstand of the sea are made up of sedimentary units that are mechanically similar and characteristically very well sorted. The sedimentary units that make up a formation deposited during an interval of fluctuating sea level differ greatly and have a wide range of sorting.

Clay and heavy mineral data suggest that the effects of intrastratal solution have not appreciably altered the character of the original mineral assemblages. Most of the diagenetic alterations were produced by acid solutions. The observed products of alkaline reactions are associated with montmorillonite that probably was derived from the alteration of volcanic ash.

The Cretaceous provenance was first sedimentary and then crystalline rock. Below the Gallup Sandstone, the section contains mainly multicycle sediments. Mineralogically, they are similar to the immediately underlying Jurassic sandstones and probably were derived from them. The ultimate source was largely igneous. The source of the Gallup and overlying deposits was in part sedimentary and in part crystalline, both igneous and metamorphic.

The distribution of feldspar and the nature of its alteration suggest that in the distributive province both temperature and rainfall were high. The abundance of kaolinite in the marine sediments below the Menefee suggests that the climate of their source area was moderate. The montmorillonite and bentonite beds in these marine parts of the section are products of the environment of deposition. They originated from the marine alteration of volcanic ash. The predominance of montmorillonite in the nonmarine Menefee Formation suggests that during its deposition there was a change to a desert climate in the distributive provenance. Probably this change was associated with an increase in volcanic activity.

Introduction

The occurrence of large, economic concentrations of coal, oil, gas, and uranium in the Cretaceous rocks of northwestern New Mexico has stimulated interest in these rocks to such an extent that this System is probably one of the most extensively studied and written about in the western United States. Several reports dealing with special aspects of the sedimentology of specific formations have been published, but no comprehensive laboratory studies of the mineralogy and petrography of these exceedingly variable sedimentary rocks have been reported. Hence, the value of mineralogic and petrographic methods in unraveling the complex stratigraphy of the Upper Cretaceous has been largely unknown. It is felt that any approach offering the possibility of resolving some of the complexities of this geology is worthy of investigation. The present study was undertaken for these reasons.

The Fort Defiance and Tohatchi quadrangles mapped by John Eliot Allen and Robert Balk (1954) provide representative exposures of Upper Cretaceous sandstone, siltstone, and shale. Stratigraphic sections were measured in connection with the geologic mapping of these quadrangles. Samples systematically collected from the sedimentary units making up three of the measured sections have been studied in the laboratory.

The objectives of the investigation were to describe quantitatively the petrographic aspects of the Upper Cretaceous sediments of this part of the San Juan Basin, to interpret the collected data, if possible, in terms of provenance, environment of deposition, agent of transport, maturity, and paleoclimate; and to determine whether these sediments could be divided into petrographic units that were recognizable from place to place. A further objective was to determine the relation of the petrographic units to the named formations of the study area. It was hoped that the mineralogy, especially the clay mineralogy, would make possible the recognition of thin time zones within the sediments, and hence supply a time basis for the correlation of stratigraphic units on a scale not possible by paleontologic means.

This study principally involves the fundamental sedimentology of a complex of transgressive and regressive sediments. The results, however, should furnish a basis for the practical investigation of this and similar areas of deposition. The study should be of help to the oil and gas industry and should facilitate subsurface explorations related to mining and other engineering projects. The description of the clay mineral assemblages and their distribution, particularly of the swelling clays, should be of value to the construction engineer, especially the highway engineer.

To simplify the use of the report by readers of differing interests, the descriptive parts have been kept separate from the parts concerning geologic interpretation.

ACKNOWLEDGMENTS

The study of the sedimentology of Upper Cretaceous rocks was initiated as part of the Tohatchi and Fort Defiance mineral resources survey of John Allen and Robert Balk (1954). Allen and Balk, through discussion of the problems, contributed much to the results of this study, both in the field and in the laboratory. The general field geology upon which this study is based was derived for the most part from mapping done by Allen.

The sampled sections were measured by John Allen, Willow Burand, and John Schilling. Most of the samples were collected by Wayne Bundy. The help of these associates is greatly appreciated.

The writer is also indebted to Eugene Callaghan for his enthusiastic support of the project in its early stages and to Frank Kottlowski for many helpful discussions and for his critical review of the manuscript. Acknowledgment is made of the help of Miss Teri Ray and William Arnold in the preparation and publication of the report.

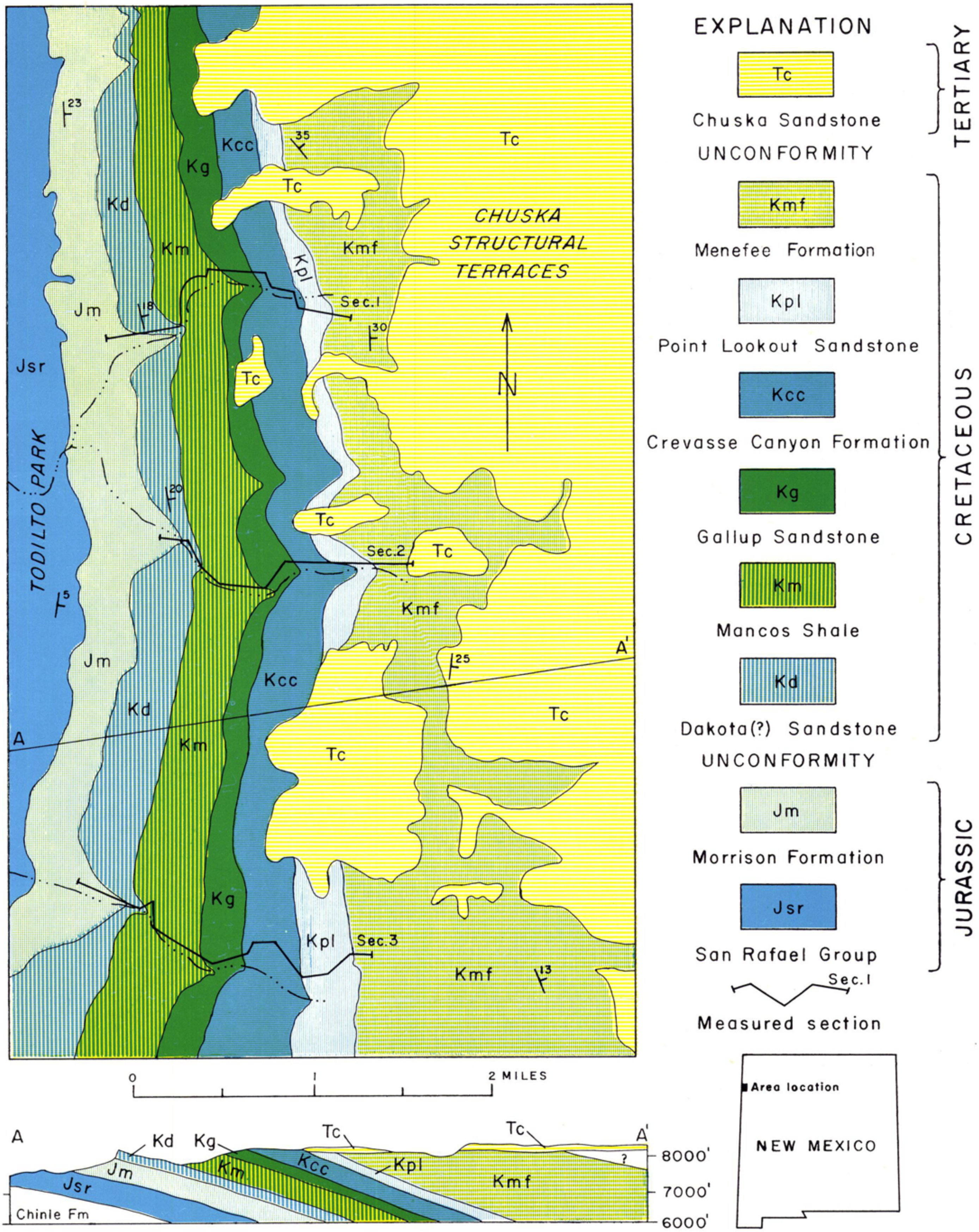

Figure 1

Generalized Geologic Map, east side Todilto Park

General Geology and Stratigraphy

The study area lies near the Arizona—New Mexico boundary, a short distance south of latitude 36 degrees north. It includes parts of Todilto Park and the Chuska structural terraces. It is an area of spectacular cuestas produced by the erosion of the crest of the Todilto Park anticline (pl. i). Erosion of this anticline has exposed rocks ranging from the San Rafael Group and Morrison Formation of Jurassic age through Upper Cretaceous sandstones, siltstones, and shales of the Dakota(?), Mancos, and Mesaverde. These in turn are uncomformably overlain by the Tertiary Chuska Sandstone.

The details of the areal geology and the location of the measured and sampled sections are shown in Figure i. This is an interpretive and somewhat generalized map based on a published outcrop map by John Allen (1954). The three sampled sections include rocks ranging from the Westwater Canyon Sandstone into the Menefee Formation. A part of the Recapture Shale Member of the Morrison Formation is included in section three; the Chuska Sandstone is present only in section two.

The distance between measured sections one and three is roughly three miles, and in that distance there is little apparent change in the lithology of the several formations present, even though a change in lithology might be expected inasmuch as a line connecting the sections is at an angle to the supposed general northwest and southwest trend of the Upper Cretaceous shoreline (Pike, 1947).

Diagrammatic columnar sections representing the sedimentary units in the measured sections are presented in Figure 2. The difference in total thickness of section three as shown here and as shown by Allen (1954, plate 11) is due to an error in plotting during preparation of his plate 11.

Between zoo and 30o feet of Morrison Formation are present in these measured sections. They include parts of the Recapture Shale Member and all of the Westwater Canyon Sandstone Member. In the sections, the Recapture Shale consists of white to light gray, massive, poorly cemented siltstone with interbedded sandstone and variously colored, discontinuous shale layers. The Westwater Canyon Sandstone includes a group of thick, cross-bedded, coarse- to fine-grained, light gray to white, feldspathic sandstones.

In each of the sections, from 1800 to 2300 feet of intertonguing Upper Cretaceous sandstone, siltstone, shale, and coal overlie the Morrison. These Cretaceous sediments were deposited in several environments. They are products of coastal plain, lagoonal, littoral, and offshore-marine deposition.

The choice of formation names and correlations shown on the diagrammatic sections were made by Allen (1954). To those familiar with Cretaceous stratigraphic nomenclature, the assignment of a formation name to one of these sedimentary units implies that that unit originated in a particular environment or combination of environments. In the Todilto Park area, as elsewhere, the assignment of the various Cretaceous sedimentary units to a particular formation, and hence by implication to a particular environment or environments, has been done in accordance with the classic ideas concerning marine transgression and regression (Sears, Hunt, and Hendricks, 1941) and with regional stratigraphic trends as outlined by Pike (1947) and others.

Within limited areas, the correlation of formations has been based on the matching of similar lithologic sequences. The datum for the matching of sequences in the San Juan Basin has commonly been the Dakota(?) Sandstone. In lieu of other evidence, the Dakota(?) Sandstone has been identified as the sandstone, shale, and coal sequence resting on Jurassic or older strata.

DAKOTA(?) SANDSTONE

No fossils except unidentifiable plant fragments were found in the Dakota(?) Sandstone of the Tohatchi quadrangle. The thin sandstones and carbonaceous shales of the Dakota(?), as mapped, rest disconformably upon the Westwater Canyon Sandstone Member of the Morrison Formation. In the three measured sections, the Dakota(?) Sandstone ranges in thickness from 218 to 253 feet. Typically, it represents deposition in both marine and nonmarine environments. The shales and coals are probably of lagoonal origin; the sandstones are beach deposits.

MANCOS SHALE

Along the east side of Todilto Park, the Mancos Shale is from 600 to 800 feet thick. The main body of the Mancos is predominantly a homogeneous, buff-weathering, gray to black, thinly laminated siltstone and silty shale, with subordinate sandstone beds up to ten feet thick. The Mancos typically is an offshore marine deposit, as attested by its lithology and contained fossils. In the study area, its silty character and the presence of intertonguing thin sandstones suggest deposition in relatively shallow water close to the shore of the Cretaceous sea.

The Mulatto tongue of the Mancos Shale was not recognized in the Tohatchi area; if present, it is included as part of the Dilco Member of the Crevasse Canyon Formation. The Satan tongue of the Mancos is also poorly represented in the measured sections, but the fossiliferous (shark teeth, pelecypods), thinly bedded standstone, siltstone, and shale between the upper and lower cliff-forming sandstones of the Point Lookout have been assigned to it. The Satan tongue in the measured sections ranges in thickness from 8o feet in section one to no more than a few feet in section three. It consists of buff- to yellowish orange alternating beds of fissile to massive sandstones separated by siltstone and shale. The lithology of the Satan tongue in the measured section suggests that it was deposited even nearer shore than the main body of the Mancos.

GALLUP SANDSTONE

The Gallup Sandstone in section three consists of two massive, cliff-forming, yellow-gray sandstone beds separated by a 14-foot bed of gray carbonaceous shale and a thin bed of coal. Northward in sections one and two, these sandstones split and thin and are interlayered with thin, red, gray, and chocolate-brown sandstone and black siltstone, shale, and coal. The Gallup Sandstone at this locality is a product of

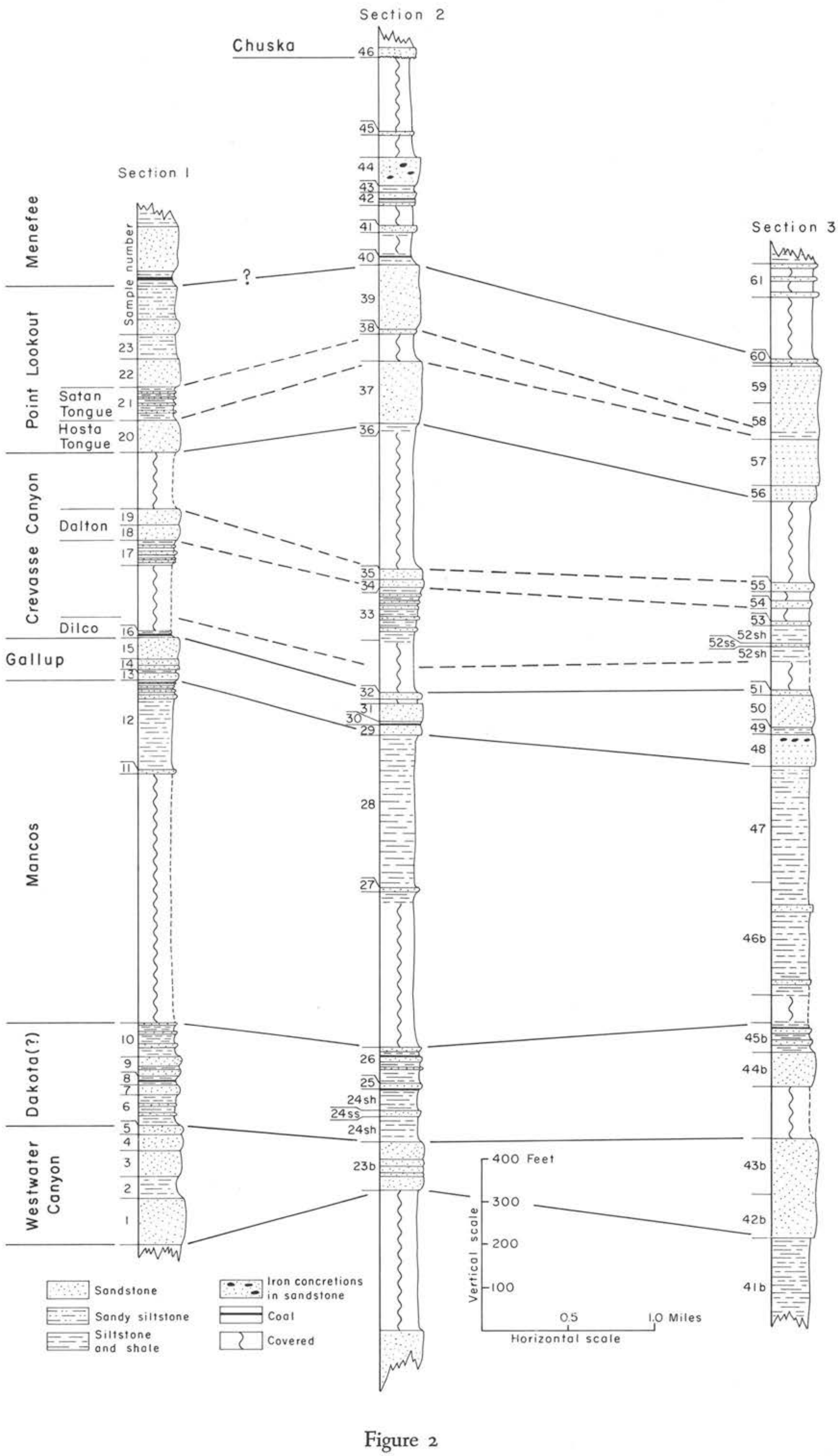

Figure 2

Stratigraphic sections and suggested correlations alternate littoral and lagoonal deposition. The alternations probably resulted from minor fluctuations of sea level.

CREVASSE CANYON FORMATION

The name *Crevasse Canyon* (Allen, 1954) is applied to the sedimentary units between the top of the Gallup Sandstone and the base of the Point Lookout Sandstone. In the three measured sections, the formation is from 42o to 62o feet thick. It includes the Dilco, Dalton Sandstone, and lower Gibson members in ascending order.

The Dilco Member consists of 190 to 240 feet of silty shale, laminated siltstone, thin coal, and thin- to medium-bedded, fine-grained sandstone. Colors are uniform in individual beds, but beds range from white through buff to pale olive-brown and from gray to black. The Dilco Member is not completely exposed in the measured sections, and, as already pointed out, may include sediments equivalent to the Mulatto tongue of the Mancos.

In the measured sections, the Dalton Sandstone Member of the Crevasse Canyon Formation is composed of two sandstone units; the lower contains massive orange-pink beds, the upper is characteristically pale gray to white and contains somewhat thinner massive and cross-laminated beds. These upper and lower sandstone units thin southward, and in section three they are separated by roughly 20 feet of slumped siltstone and shale that has been included as part of this member. The Dalton Member in the measured sections is from 4o to 70 feet thick. These sandstones are believed to be beach and offshore bar deposits.

The lower Gibson Member ranges from 135 to 335 feet in thickness. In the measured sections, it is largely covered so that its exact lithology is not known. Elsewhere in the Tohatchi area, it consists of gray shale, carbonaceous shale and coal, shaly siltstone, thin-bedded sandy siltstone, and silty sandstone, with a few coarser, massive, cross-laminated, pale grayish yellow, friable sandstone beds. These lithologies suggest that the lower Gibson Member was deposited in nonmarine and transitional environments. Allen (1954) believed that the sandstone beds represent stream-channel sandbars.

POINT LOOKOUT SANDSTONE

The Point Lookout Sandstone at Todilto Park includes several sandstone beds that have a combined maximum thickness of roughly 30o feet. It is divided into two parts by the Satan tongue of the Mancos Shale (already described). The lower cliff-forming unit has been called the Hosta tongue. It is made up of uniform pale orange or yellowish gray, massive, and slightly cross-bedded feldspathic quartzose sandstone beds. The lower beds are poorly cemented. The upper unit of the Point Lookout Sandstone is somewhat darker and contains abundant iron-oxide concretions, but it is otherwise similar to the Hosta tongue. The top and bottom of the Point Lookout Sandstone in sections two and three are easily located in the field, on the basis of abrupt changes in gross lithology. In section one, the upper limit has not been so easily defined and the upper contact as shown in Figure z is questionable. Both units of the Point Lookout are considered to be littoral deposits.

MENEFEE FORMATION

Approximately 36o feet of Menefee Formation, out of a total known thickness of more than 2000 feet, are exposed along the measured sections. These exposed parts consist of interlayered red, green, purple, and pinkish white shale and mudstone; carbonaceous shale and coal; white to yellowish gray sandy siltstone; and pale yellowish brown to reddish brown, well- to poorly cemented, fine-grained, feldspathic sandstone. Iron-oxide and carbonate concretions are common. In section two, the ratio of sandstone to siltstone-and-shale is approximately 1:5. Individual sandstone beds are extremely variable in thickness and discontinuous in extent.

The measured part of the Menefee Formation is environmentally equivalent to the upper Gibson Coal Member of Sears (1934) and it is assumed to have been deposited in nonmarine and transitional environments. The sandstones have been interpreted as stream-channel deposits.

CHUSKA SANDSTONE

The Tohatchi Formation is missing in the measured sections, and the Tertiary Chuska Sandstone, which is present only in section two, rests unconformably on the Menefee Formation. Approximately 100 feet of medium-bedded, white and gray, medium-grained feldspathic sandstone and white shale and siltstone are exposed at the top of section two and have been assigned by Allen to the Chuska Sandstone. Their stratigraphic position suggests a correlation with fluvial Deza Formation of Wright (1954), but lithologically they are different. The red, pink, brown, and green sandstones and shales of the Deza Formation are not present. The "Chuska Sandstone" as described by Wright overlies the Deza Formation and is a massive, thick-bedded, cross-laminated, buff to yellowish gray eolian sandstone that contains no shale. Inasmuch as the loo feet at the top of section two is approximately half siltstone and shale, it cannot be correlated with the "Chuska Sandstone" on the basis of general lithology. The thin basal conglomerate, reported by Allen (1954, p. 98) to mark the base of the Chuska Sandstone in most places, is missing in the measured section. It is evident from the above that the exact stratigraphic position within the Chuska Sandstone of the top 1 oo feet in section two is not established. However, John Schilling, who prepared the field descriptions of section two, is of the opinion that these units are equivalent to the Deza Formation (oral communication).

Methods of Investigation

There is no uniformity in the methods employed by different investigators in the field of sedimentary petrology, and hence it is difficult to compare results. Inasmuch as it is hoped that the results of this investigation may serve as a foundation on which more comprehensive studies can be based, it is essential that a careful accounting be made of the field and laboratory procedures employed.

Each of the three stratigraphic sections was measured by plane table and alidade and all samples described were taken from outcrops along the lines of these measurements. Insofar as possible, samples were taken from sedimentary units without regard for formation boundaries. Each sample consisted of a series of chips taken regularly across these sedimentary units. Several of the larger units were represented by more than one sample *(see* sample limits, fig. 2). Each sample weighed several pounds and was believed to be representative of the unit from which it was taken.

The principal laboratory operations are outlined in Figure 3. Each sample was crushed to approximately quarter-inch fragments and split in a Jones ore sample splitter, a Loo- to 200-gram fraction being retained for study. This fraction was further crushed, the amount being adjusted to avoid breaking of individual mineral grains. The weighed sample was then disaggregated in warm, dilute hydrochloric acid; if necessary, the disaggregation was hastened by working with a rubber pestle. The sample was then washed, dried, and weighed, and the loss determined by difference. The difference is reported as percent soluble.

After disaggregation, a two-vessel rising water current elutriator was used to separate the size fraction below 0.01 mm and the fractions from 0.015 mm to 0.05 mm. The losses during these operations were largely in the size range between 15 and 1 o microns.

A sieve analysis was made of the portion containing grains larger than 0.05 mm using U.S. Standard sieves ranging in opening from 2 mm through 0.062 mm and spaced in accord with the grades of Wentworth's size classification. Each sample was placed in a nest of sieves and shaken in a Ro-Tap machine for ten minutes. The percent in the size grades was determined from the weight retained on each sieve and in the pan.

Ruby (1933), Cogen (1935), and others have recognized that the heavy mineral suites in the various grade sizes of the same sediment differ. Hence, quantitative comparison studies of many samples, to be useful, require that the assemblages compared be from material of the same size. For this reason, the light and heavy mineral analyses reported here were made on the size fraction between 0.250 mm and 0.125 mm, insofar as possible. In several of the samples, the percent of heavy minerals within this range was inadequate, and in these the size fraction between 0.125 mm and o.062 mm was used. When this was necessary, it is indicated in the presentation of the data.

A Standard laboratory funnel with a short length of rubber hose attached to its lower end and sealed by a pinch cork was partly filled with tetrabromoethane (sp. gr. = 2.95o at 20° C) and the weighed sample fraction poured in. The sample was periodically stirred until there was no more apparent settling. The heavy fraction was then removed, washed, dried, and weighed. For most samples, the whole heavy fraction was mounted in piperine (n = i.68); in some, however, the percent of limonite and/or hematite was large and was magnetically removed, together with other highly magnetic minerals, from a part of the heavy concentrate, and two microslides were prepared, one of the nonmagnetic fraction, the other of the complete assemblage as collected. The light fraction was also washed and dried and a portion mounted in Canada balsam (n = 1.537).

The minerals of both the light and heavy assemblages were identified by optical, X-ray, and spectrographic means and the frequencies of each determined by grain counts. Between zoo and 30o grains of each sample were counted. Counting was done along randomly chosen traverses across the micro-slides.

During optical identification of the minerals, various physical features, such as color, grain shape, surface textures, nature of inclusions, presence of secondary growths, and degree of alterations, were recorded. Angularity of individual mineral grains was determined by Fisher's method of computation, as described by Krumbein and Pettijohn (1938, p. 289). The computations were applied to between 20 and 3o grains of a mounted sample of the light minerals. Fluorescence of the zircon in samples from section one was also observed in both long and short wave length ultraviolet.

X-ray analyses, using a Geiger counter diffractometer, were made of the less-than- o-micron size fractions collected during elutriation. A part of each fraction was mounted in a standard sample holder and reflections between 2° and 50° 2Ø were measured. The specimen was then removed, mixed with glycerol, and allowed to stand. The mixture was then mounted on a glass slide and measurements between 2° and 20° 2Ø were made. In both the dry and the glycerol mounts, there was a tendency to develop oriented aggregates, which enhanced the observed basal reflections. However, the objective was identification of the clay minerals and inasmuch as the first-order basal reflections are the most diagnostic, no effort was made to overcome this tendency toward orientation.

The relative abundance of the various clay minerals in a sample is based on the amplitudes of the principal basal reflections compared with the amplitudes obtained from American Petroleum Institute clay mineral standards. No systematic quantitative comparison was made between samples.

An Eberbach portable apparatus was used to obtain differential thermal curves. The heating curve of this apparatus flattens abruptly between 75o° and 800° C; hence, only the strongest thermal reactions above those temperatures are recorded. Many of the clay-silt-size samples were analyzed several times; the results demonstrate that curves obtained with this apparatus are reproducible but not closely comparable to curves obtained with more elaborate equipment.

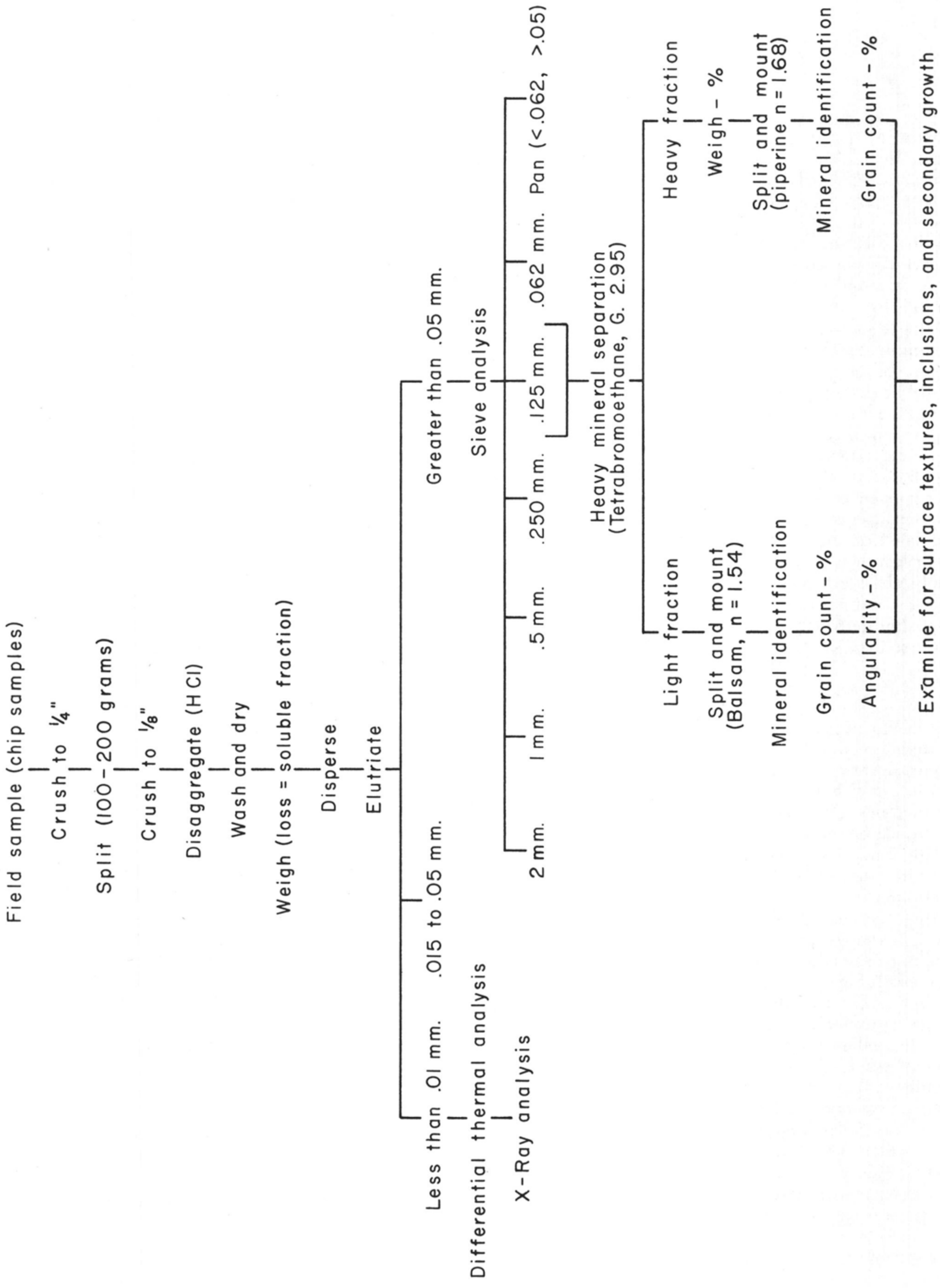

Figure 3
FLOW SHEET OF LABORATORY OPERATIONS

Petrography and Sedimentology

This part of the report deals with the detailed petrographic aspects of the sedimentary units making up the three measured sections. The field descriptions of the named formations have been presented, and it is apparent that superficially many of the formations appear very similar. The formations are products of marine transgressions and regressions; under these conditions nonmarine, littoral, and marine sedimentary facies are deposited simultaneously within relatively short distances. There are comparatively few fossil-bearing beds in the measured sections, and these indicate only large zones of time equivalence. Hence, where only a portion of the stratigraphic sequence is exposed, the assignment of a particular sandstone or shale to a formation and the recognition of its time-equivalent elsewhere presents a problem. For these reasons, as was pointed out by McKee (1949), it is well to bear in mind that many minor and not readily observable differences are doubtless present in superficially similar rocks. It seems extremely improbable that all the physical factors that affected sediments deposited during one interval of time should have been repeated precisely during another interval. The problem then is, first to detect the differences and, second, to establish criteria based on these differences by which sedimentary units of the same age may be recognized. These are the ultimate objectives of the detailed descriptions and statistical studies that follow.

PERCENT SOLUBLE

The amount of material soluble in dilute hydrochloric acid was determined during disaggregation of the samples. The reported percentages in Figure 4 were determined from the difference in weight before and after disaggregation. That the soluble portions of the samples were largely calcium carbonate is verified by the vigorous effervescence observed during treatment of many of the samples.

In each of the stratigraphic sections, high solubility and vigorous effervescence are characteristic of the sedimentary units from the Dilco Member up. Maximum solubility was observed in samples 44 and 45 from the Menefee Formation in sections two and three, and in sample 23A at the top of the Point Lookout Sandstone in section one. These samples were from 3o to 45 percent soluble. Slightly less than 3o percent of sample 33 from the Dilco Member was soluble. Solubility of the other sedimentary units above the Dilco Member was somewhat less. High solubility is not limited to sediments of a particular grain size; it was observed in medium-, fine-, and very fine-grained sandstones and in siltstone.

Below the Dilco Member, solubility is low and effervescence was not observed except for samples 46 and 47 from the Mancos Shale of section three. These samples contained small carbonate concretions and fragments of brachiopod shells; the carbonate is not present as cement.

SIEVE ANALYSES AND ELUTRIATION

Data from the sieve analyses and elutriation have been combined in cumulative frequency curves. These curves are based on the weight percentages retained on each sieve and are of the "more than" or "larger than" type. The sieves, as already noted, correspond to the divisions of Wentworth's size classification (table 1). Curves for the sandstones,

TABLE 1. GRAIN SIZE SCALE

Opening (mm)	*Phi (Ø)*	*Wentworth grades*
4.0	−3.0	Pebbles
3.0	−2.0	Granules
2.0	−1.0	Very coarse sand
1.0	0.0	Coarse sand
0.50	1.0	Medium sand
0.250	2.0	Fine sand
0.125	3.0	Very fine sand
0.062	4.0	

grouped in accordance with the formation boundaries, are included in Figures 5 through II. The statistical values used in describing the samples were read directly from these curves; they are the median and percentile values. The median (MdØ)) is the middle diameter of the frequency distribution; 5o percent of the diameters are larger and 5o percent are smaller. The quartiles lie on either side of the median and are the diameters which correspond to frequencies of 25 and 75 percent. The smaller value is taken as the first quartile (4)75), the larger as the third quartile (Ø25). The values of Ø5, Ø95, Ø16, and Ø84 are similarly determined.

Three measures of the curves' deviation were determined for each sample; they are sorting, skewness, and kurtosis. The sorting is expressed as the graphic standard deviation which is the spread in diameter between the 16 and 84 percentiles. The equation is

$$\sigma_G = \frac{\phi 84 - \phi 16}{2}$$

Sediments having a graphic standard deviation less than 1.5Ø are considered well sorted. Skewness is a measure of the symmetry of a curve. In a perfectly symmetrical curve, the median diameter is exactly midway between the percentile diameters. If the median diameter deviates from the midpoint, the curve is skewed. Skewness (SKqØ)) measures were obtained from the equation

$$SKq\phi = \frac{\phi 25 + \phi 75 - 2(Md\phi)}{2}$$

If SKqØ is negative, the sample is rich in coarse-grained material; if it is positive, the sample is rich in fines.

Kurtosis is expressed as the ratio between the sorting in the central part of the curve and in the tails. The measure used here is the graphic kurtosis (K_G) that is expressed by the formula

$$K_G = \frac{\phi 95 - \phi 5}{2.44(\phi 75 - \phi 25)}$$

The more peaked the frequency curve is, the larger the ratio will be.

TABLE 2. STATISTICAL PARAMETERS OF GRAIN SIZE DISTRIBUTION

	Section 1					Section 2					Section 3				
	Sample No.	MdØ	σG	SKqφ	K_G	Sample No.	MdØ	σG	SKqφ	K_G	Sample No.	MdØ	σG	SKqφ	K_G
Chuska						46	2.80	1.16	.21	1.24					
						45	2.85	2.08	.51	1.54					
						44	2.80	1.82	.26	1.19					
Menefee						43	5.70	1.72	.05	1.21					
						42	4.43	2.02	.17	1.00					
	23	3.76	1.64	.17	1.64	41	3.51	1.78	.14	1.17	61	3.38	1.65	.07	1.51
	22	3.30	.81	−.02	2.30	39	2.92	.87	.13	1.76	60	2.50	.99	.01	3.09
Point	21	3.66	.63	−.005	3.48	38	3.53	.69	.005	2.44	59	2.61	.95	.10	1.90
Lookout	20	3.55	.65	−.04	3.93	37	3.40	2.30	.10	4.56	58	3.35	.65	.00	3.05
											57	2.50	.79	.01	2.36
											56	2.67	.88	.13	1.07
	19	2.56	1.24	−.03	2.20	36	3.60	1.80	.22	1.10	55	2.47	1.14	−.01	2.51
Crevasse	18	2.95	1.07	.22	1.30	35	2.36	.73	−.05	2.41	54	3.60	.52	.01	2.43
Canyon	17	3.84	1.29	−.09	2.40	34	2.87	1.13	.19	1.53	53	3.80	.76	.00	1.71
	16	3.90	1.38	.35	1.10	33	3.70	1.30	.28	1.40					
	15	2.10	1.30	.16	1.31	32	1.82	.69	.14	1.16	51	3.80	1.15	.05	2.00
Gallup	14	1.40	.73	.05	1.78	31	2.10	1.20	.005	1.61	50	1.20	.98	.01	1.43
	13	1.93	1.64	.21	1.29	29	2.67	1.13	.19	2.06	48	2.18	1.45	−.01	1.67
Mancos	12	3.58	1.50	−.11	1.31	27	2.40	.90	−.34	1.86	47	4.85	1.71	.34	.79
	11	2.95	.85	.13	1.10										
	10	2.55	.55	−.01	1.50	26(ss)	2.82	.89	.15	1.50	456	3.31	1.24	.03	1.42
	9	3.13	.92	.19	.71	26(sh)	4.27	1.85	.31	1.02	446	2.58	.87	.06	2.20
Dakota(?)	8	3.40	.90	−.07	1.70	25	3.20	.92	.02	1.32					
	7	3.00	.94	.15	1.70	24	2.10	1.94	.005	1.84					
	6(ss)	2.80	1.42	.25	1.65										
	6(sh)	4.70	2.48	.17	.71										
	5	2.21	1.08	.01	1.87	236		1.14	.00	2.04	436	2.41	1.94	.14	1.63
	4	2.37	2.08	1.26	.96						426	2.25	1.25	.06	1.43
Westwater	3	1.44	1.30	.07	1.20						416	2.70	.96	.10	1.37
Canyon	2	2.90	2.67	1.40	.65										
	1	2.05	1.07	−.10	.98										

No clay-shales or coarse-grained sediments are present in the sampled sections, although coarse-grained sediments appear elsewhere in the Westwater Canyon Sandstone and Gallup Sandstone of the Tohatchi area. The median diameters in the sections shown in Table z range from 1.5Ø (medium sand) to 5Ø (silt). The Westwater Canyon Sandstone and the Gallup Sandstone have the largest median diameters; they range from fine- to medium-grained sand. The remaining parts of the sections have median diameters between silt and fine sand. This range is similar in part to that reported by McMasters (1954) for present-day beach sands and near-shore bottom sediments along the New Jersey coast. The median diameters are slightly coarser than the medians of recent sediments deposited at depths between 50 and 100 fathoms on Pigeon Point Shelf, California (Moore and Shumway, 1959). The median diameters are also coarser than the medians of recent sediments deposited in the coastal lagoons of Baja California (Phleger and Ewing, 1962).

There are no systematic differences between the median diameters of the supposed marine and nonmarine sediments of the sampled section. Neither is there any marked change in the over-all grain size of the sediments between sections one and three, and the median grain size of individual formations does not change systematically. The nature of the sedimentation makes these results expectable.

Table 2 shows that the graphic standard deviations *(ðG)* ranged between 0.52Ø and 2.48Ø; the majority are slightly above or below 1.00. Hence, most of the samples from the measured sections would be classified as well sorted. Many of the minor irregularities of sorting, recorded in Table 2, may be due to the sampling and analyzing methods.

In Figure 12, the graphic standard deviation is plotted against the median diameter. From this, it is evident that the degree of sorting does not change appreciably with grain size. Normally, sorting is poorest in coarse- and fine-grained sediments. As already reported by Willard (Allen and Balk, 1954), the lack of conspicuous change in degree of sorting is continuous through the Westwater Canyon, Summerville, Entrada, and Wingate. At the top of the Chinle, there is a marked decrease in degree of sorting.

The degree of symmetry of the cumulative curves as expressed by the coefficient of skewness (SKqØ) is shown in Table z. For most of the samples, the skewness values are zero or positive, which means that the percentages by weight on opposite sides of the median diameters either are equal or the samples are rich in fines. Several samples in each section have negative values. From section to section, these negative values of skewness are not limited to the same formation or formations.

In Figure 13, the variations in degree of skewness are compared with changes in median diameter. No systematic variation with change in grain size is evident. There is, however, a decrease in the number of negative values between sections one and three; that is, an increase in the relative amounts of fines.

Kurtosis values shown in Table z range from 4.56 to 0.79.

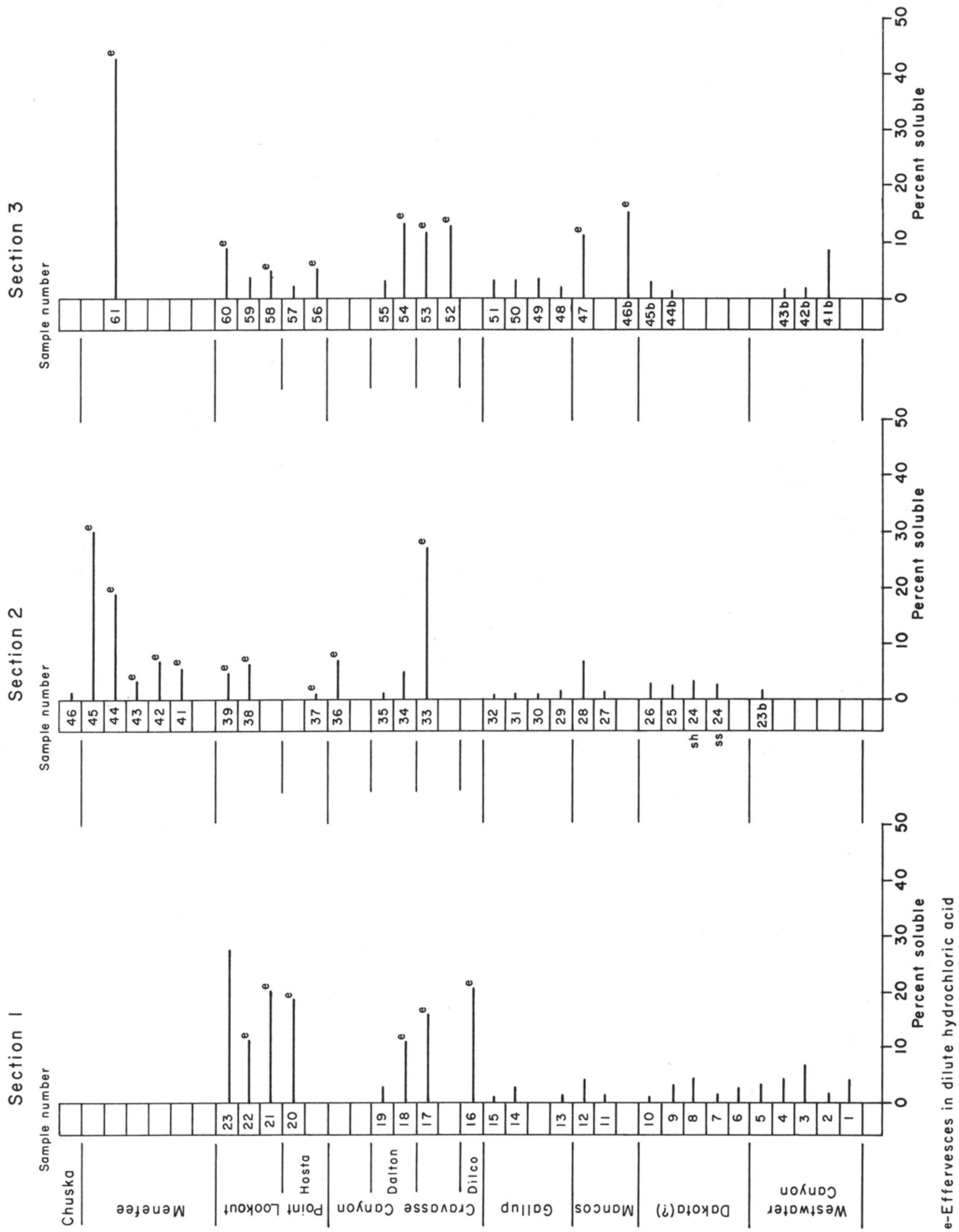

Figure 4
PERCENT SOLUBLE

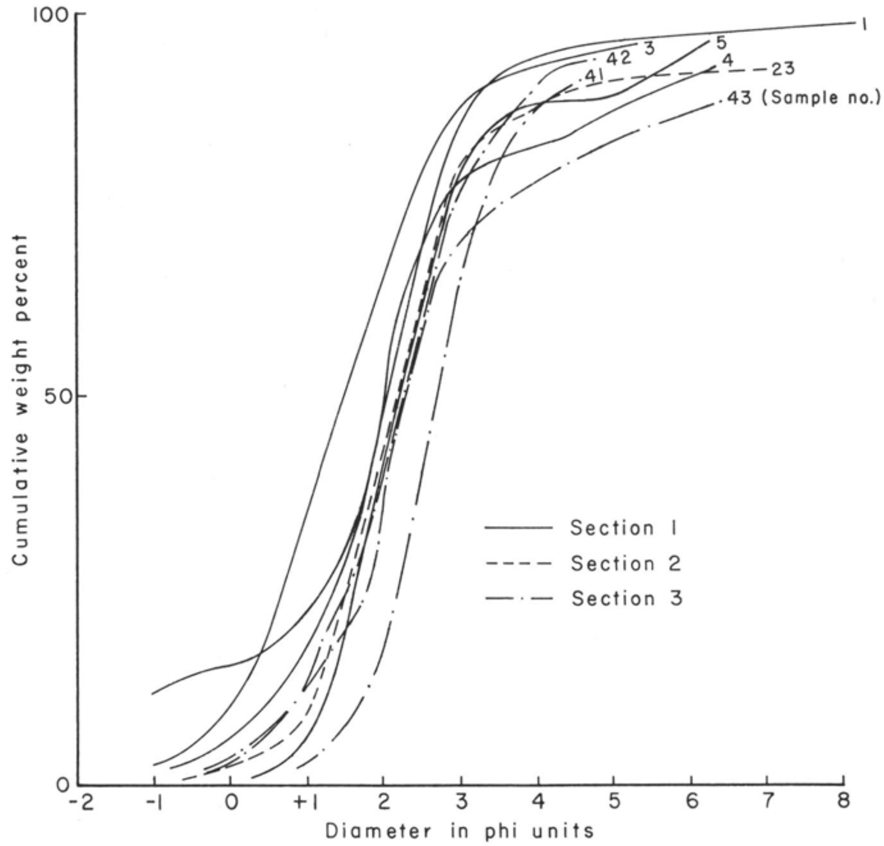

Figure 5
Cumulative curves of Westwater Canyon sandstones

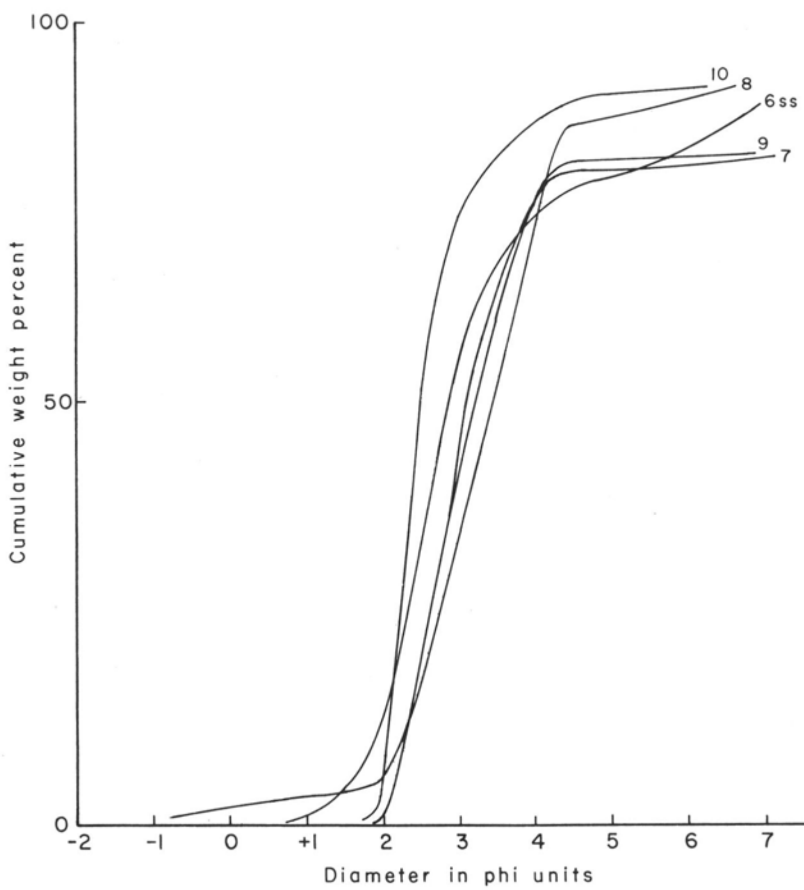

Figure 6
Cumulative curves of Dakota(?) sandstones, section 1

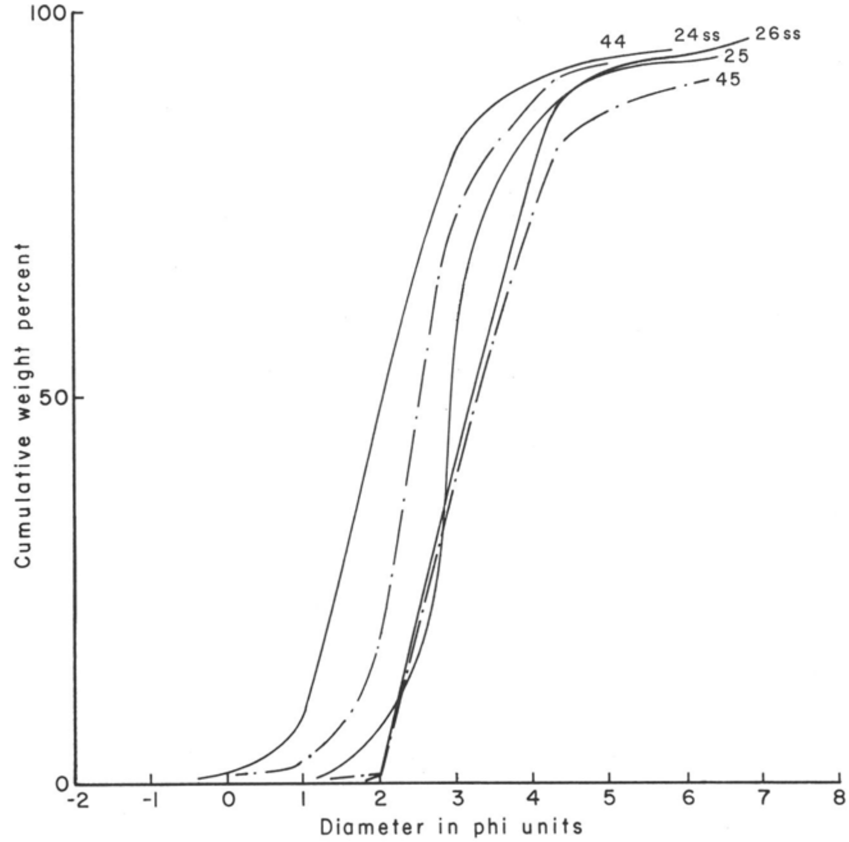

Figure 7
CUMULATIVE CURVES OF DAKOTA(?) SANDSTONES, SECTIONS 2 AND 3

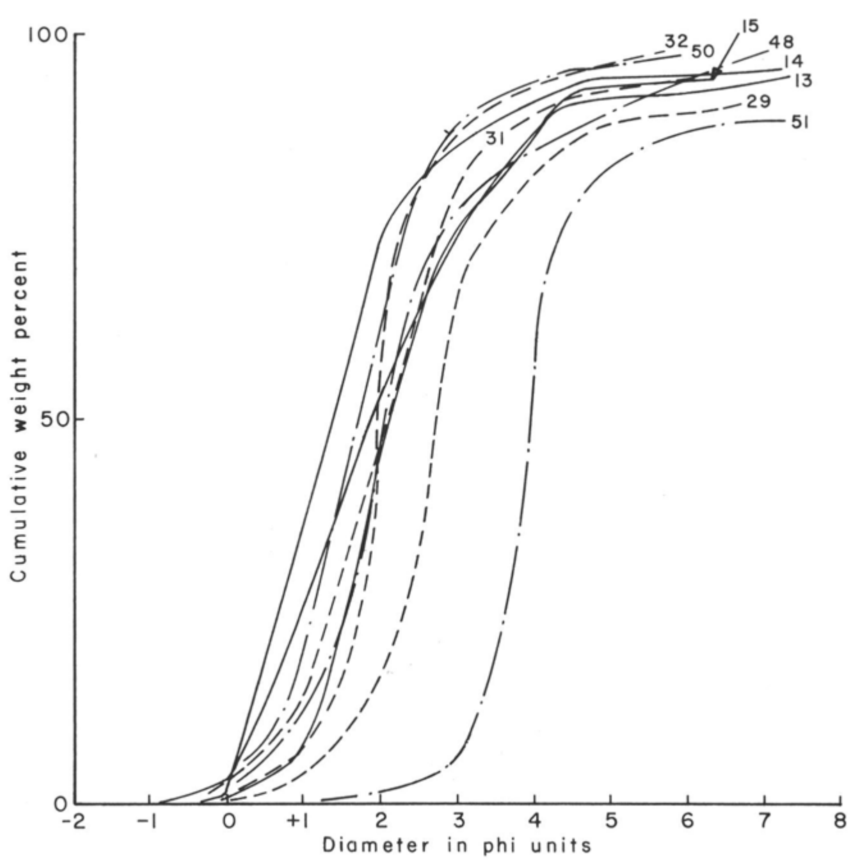

Figure 8
CUMULATIVE CURVES OF GALLUP SANDSTONES

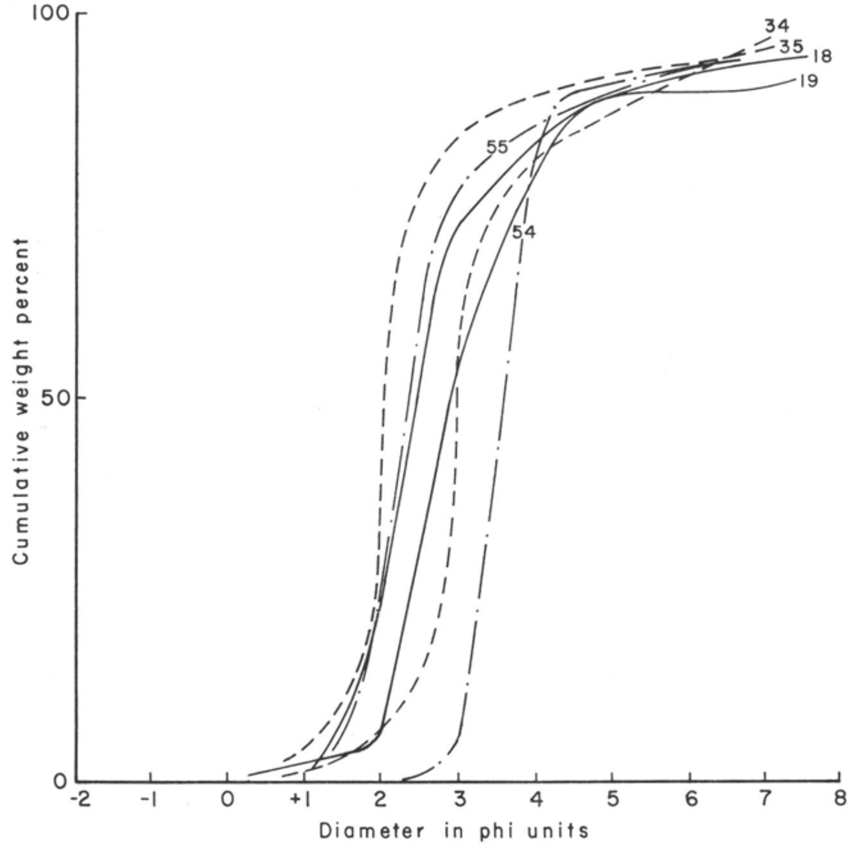

Figure 9
Cumulative curves of Dalton sandstones

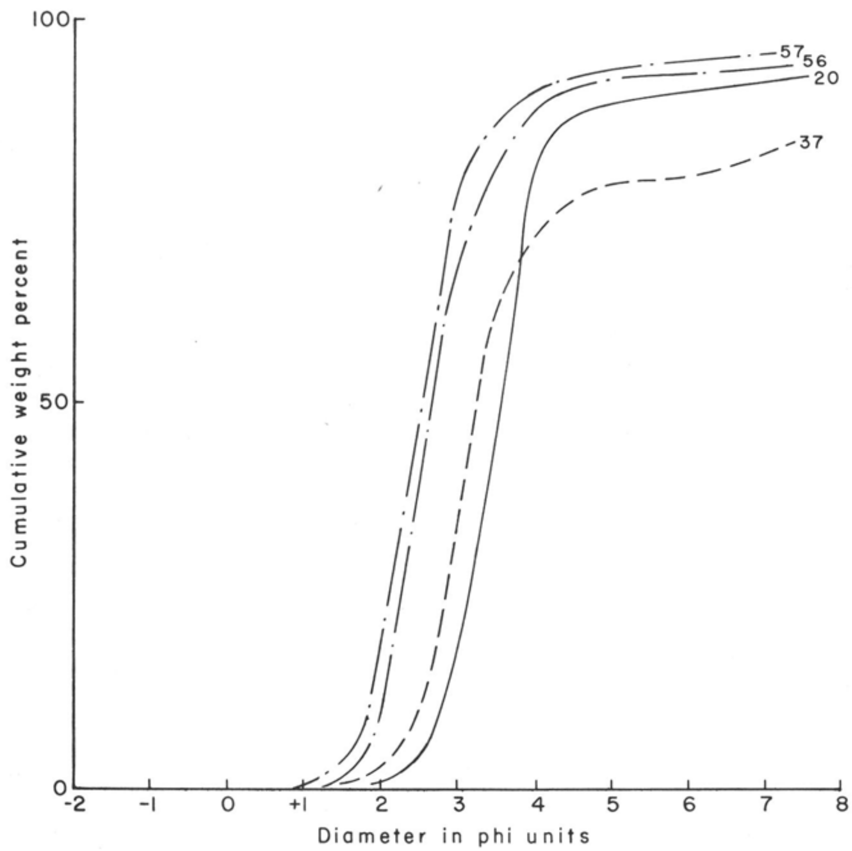

Figure 10
Cumulative curves of Hosta sandstones

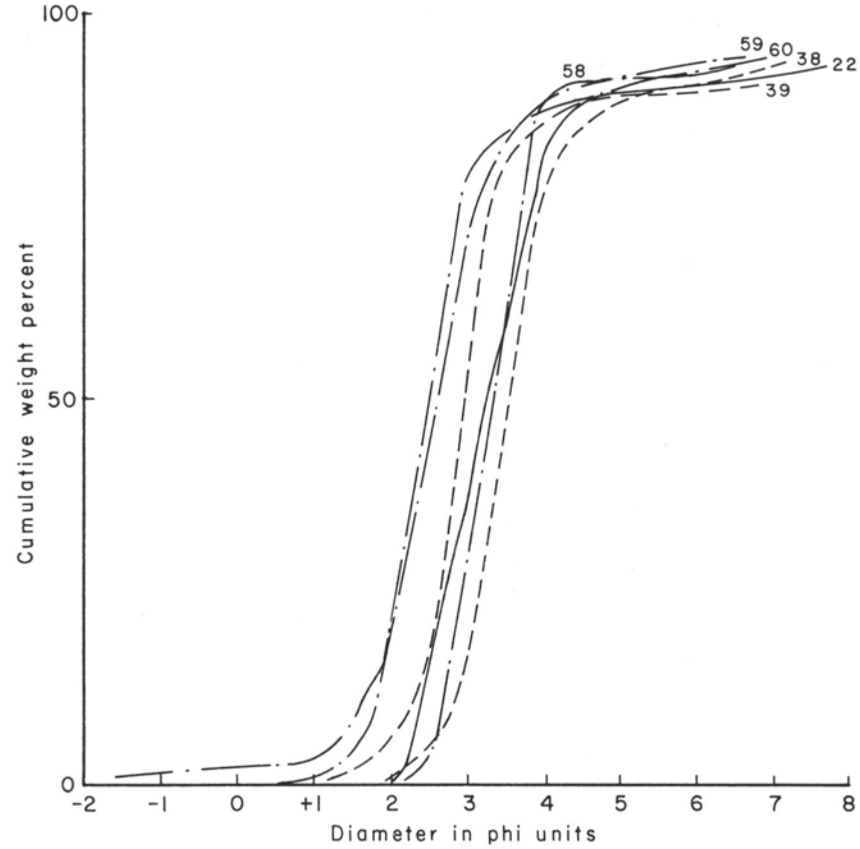

Figure 11
CUMULATIVE CURVES OF POINT LOOKOUT SANDSTONES

However, most of the curves are leptokurtic, those from the Point Lookout Sandstone extremely so.

ANGULARITY

Unless otherwise indicated, the angularity measurements recorded in Figure 14 are based on measurements made on the 0.125 mm size-fraction of the light-mineral suites. The average angularity range is roughly between 25 and 80 percent. In each section, angularity increases markedly above the top of the Dakota(?) Sandstone. Above the upper unit of the Dakota(?), most of the samples have an angularity greater than 50 percent. From the top of the Dakota(?) through the Westwater Canyon Sandstone, angularity averages 36 percent. In the upper parts of each section, angularity within a single sample ranges from 0 to 100 percent.

Thus, on the basis of angularity measurements, each section is divided into two distinct parts, and, in each, the division occurs near the top of the Dakota(?).

MINERALOGY

HEAVY MINERALS

As has been pointed out, the percentages by weight of heavy minerals in the 0.125 mm size-fraction were determined for each sample. The total percentages determined are probably of limited value inasmuch as they include, in differing amounts, the authigenic minerals; limonite, hematite, and barite. In general, however, the percent of heavy minerals in each of the three sections is markedly less in the Westwater Canyon Sandstone, Dakota(?) Sandstone, and Mancos Shale than in the remaining parts of the sections. In the lower parts of the sections, the 0.125 mm size-fraction generally contains less than 0.05 percent of heavy minerals. Above the Mancos Shale, the heavy minerals make up roughly 0.05 to 1 percent of the 0.125 mm size-fraction. A part of the observed increase above the Mancos is due to an increase in the amount of iron ores, but a part is also due to an increase in amount of nonopaque heavy minerals.

Qualitative relations between the total mineral suite and named formations of the measured sections are presented in Figures 15 through 17. The frequency variations of the most abundant nonopaque heavy minerals are shown in Figures 18 through 20. The frequency variations shown in the figures were determined from the total grain counts minus magnetite and/or ilmenite and the authigenic minerals (leucoxene, hematite, limonite, and barite). The frequency numbers in Figures 18 through 20 approximate the logarithms of the frequency percentages.

Tourmaline

Tourmaline makes up a large part of most of the heavy-mineral suites. It is, however, absent in sample 18 of the Dalton Sandstone in section one and in samples 40, 41, and 42 of the Menefee Formation. Samples above 42 in section two contain relatively less tourmaline than the remaining parts of the sections. Other than these differences, the variations in amount of tourmaline are so small they cannot be considered significant.

All the typical grain shapes of detrital tourmaline are represented; prismatic, irregular, and rounded. These types are not, however, uniformly distributed throughout the sections. Below sample 10 to the base of section one and from the designated top of the Dakota(?) Sandstone to the exposed lower limits of the Westwater Canyon Sandstone in sections two and three, the tourmaline grains are largely rounded. These rounded grains have a high degree of sphericity and their surfaces are highly polished; they appear beadlike.

Above the zone of rounded tourmaline to the base of the Gallup Sandstone, the relative number of rounded tourmaline grains decreases and irregular, angular fragments become abundant.

Through the Gallup Sandstone and overlying parts of the sections, elongated prismatic grains and basal plates are numerous, and in some samples they are the dominant form. Typically, the elongated prismatic grains are highly striated and terminated at basal partings.

Black-brown tourmaline and blue-green tourmaline are in all the samples from the Westwater Canyon Sandstone and

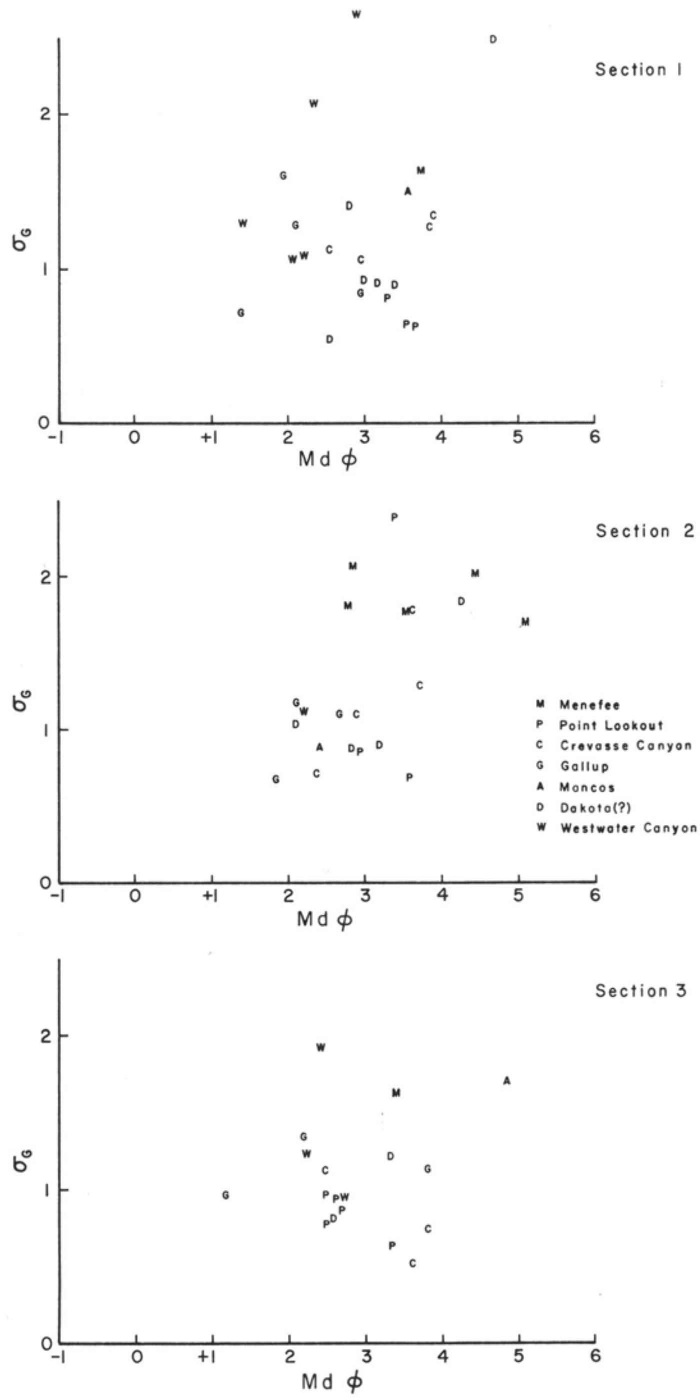

Figure 12
RELATIONSHIP OF SORTING TO MEDIAN DIAMETER

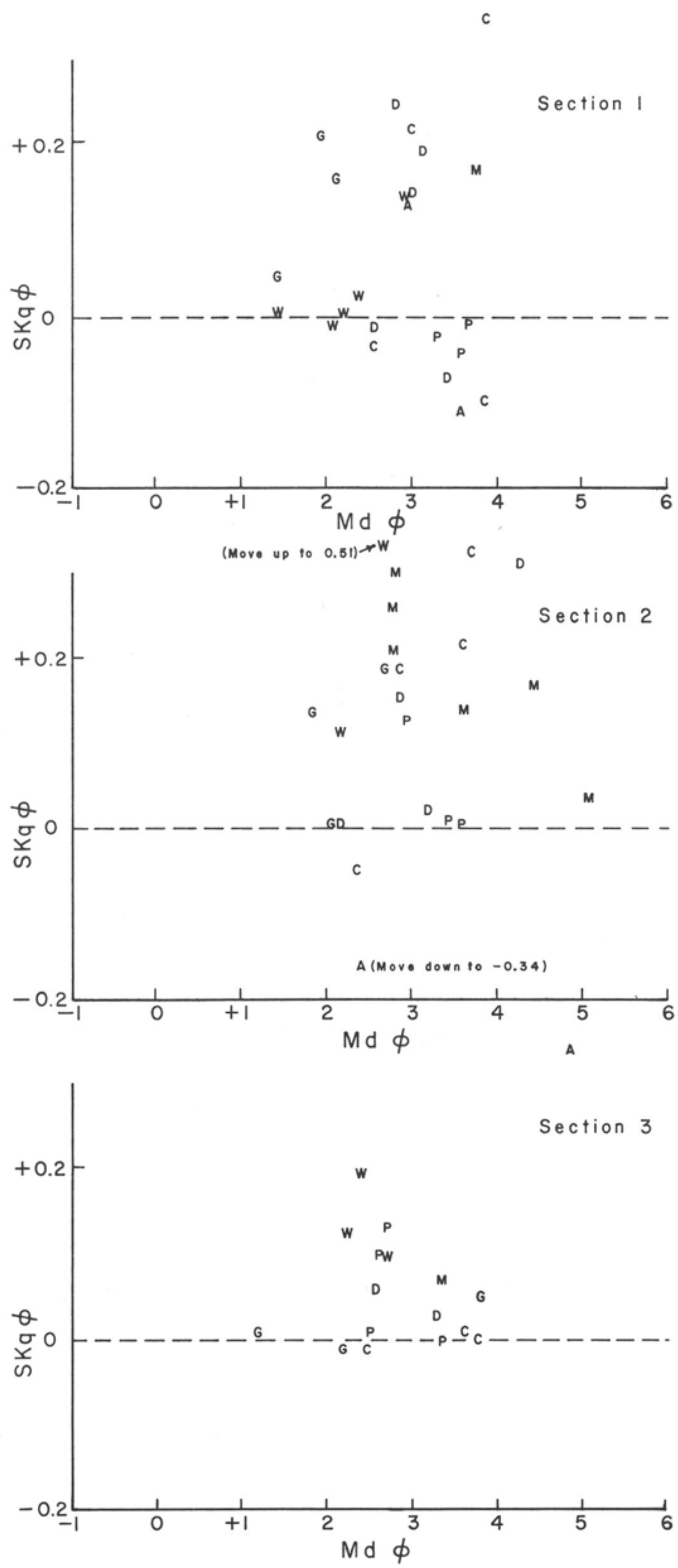

Figure 13
RELATIONSHIP OF SKEWNESS TO MEDIAN DIAMETER

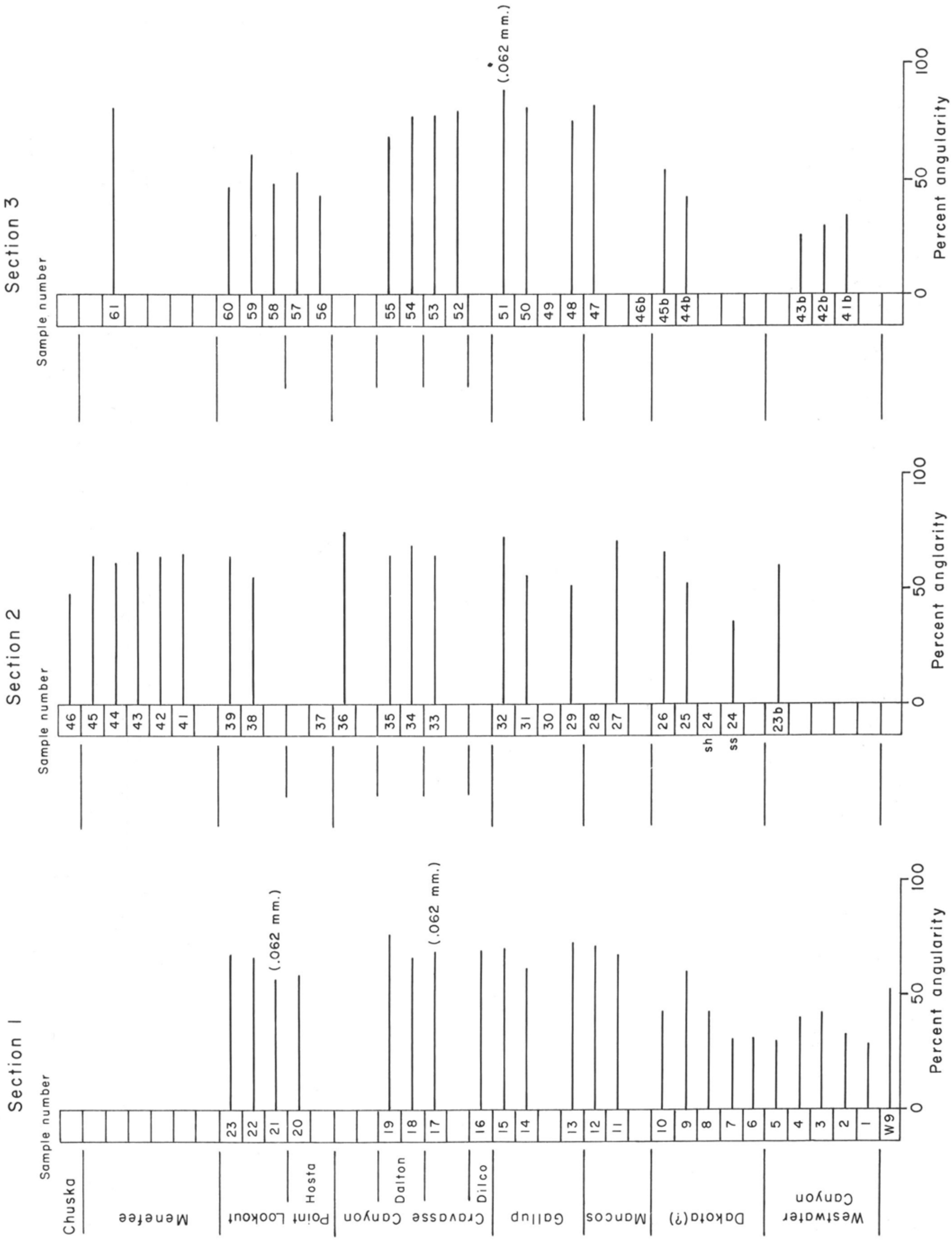

Figure 14
PERCENT ANGULARITY

Formation name		Westwater Canyon					Dakota (?)					Mancos		Gallup			Crevasse Canyon (Dilco)	Crevasse Canyon	Crevasse Canyon (Dalton)	Crevasse Canyon	Point Lookout (Hosta)	Point Lookout	Point Lookout	Point Lookout	Menefee	Chuska
Sample number		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23		
Quartz	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×		
Secondary quartz		×		×	×		×	×	×	×	×	×		×	×	×	×		×	×	×	×				
Inclusions in Quartz: none				×	×	×																				
Inclusions in Quartz: regular		×	×																							
Inclusions in Quartz: irregular	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×		
Inclusions in Quartz: acicular	×		×	×			×		×		×		×			×							×			
K-feldspar	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×		
Plagioclase		×		×									×						×					×		
Muscovite	×									×		×		×	×	×	×	×	×	×	×		×	×		
Tourmaline: prismatic						×			×			×	×		×	×	×				×	×				
Tourmaline: angular										×	×	×	×		×			×		×	×	×		×		
Tourmaline: rounded	×	×	×	×	×	×	×	×	×	×	×	×		×		×	×	×		×	×	×	×	×		
Tourmaline: polished	×	×	×	×	×	×	×	×	×	×	×	×		×		×	×	×			×	×	×	×		
Tourmaline: black-brown	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×		×		×	×	×	×	×		
Tourmaline: green-blue	×	×	×	×	×	×	×	×	×	×	×			×		×	×	×		×		×		×		
Garnet: euhedral																										
Garnet: angular	×	×	×	×				×	×	×	×	×	×	×	×	×	×	×	×	×	×	×		×		
Garnet: rounded	×	×																								
Garnet: colorless-pink	×	×	×	×				×			×	×	×	×	×	×	×	×	×		×			×		
Garnet: red-brown	×	×	×						×	×			×	×					×	×	×	×				
Garnet: etched	×							×			×					×			×							
Zircon: euhedral		×	×	×	×	×	×	×					×	×	×	×	×	×	×	×	×		×	×		
Zircon: angular				×				×								×						×				
Zircon: rounded		×			×																×	×	×			
Zircon: colorless-pink		×	×	×	×	×	×	×					×	×	×	×	×	×	×		×	×	×	×		
Zircon: yellow-brown			×		×	×	×	×					×	×		×	×									
Zircon: zoned			×			×	×						×			×										
Hematite	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×		
Ilmenite-magnetite	×		×		×							×	×			×		×				×				
Leucoxene	×	×	×	×	×	×	×	×	×	×	×	×	×	×		×	×	×	×	×	×	×	×	×		
Staurolite			×	×	×	×	×						×													
Biotite		×																×	×		×		×	×		
Chlorite																		×	×					×		
Sphene																								×		
Epidote													×													
Zoisite																								×		
Apatite			?				×																			
Augite																?										
Anatase										×						×							×			
Rutile							×					×		×	×	×					×					
Actinolite-hornblende																										
Talc																										
Spinel (green)		×			×					?		?						×								
Barite				×						×										×	×					
Dolomite																		×		×						
Pyrite									×				×													
Opaline (cement)		×		×									×													
Calcite (cement)																			×		×	×	×	×		
Quartzite fragments																				×						
Chert fragments		×		×	×						×															

Figure 15

Mineralogy and relation to stratigraphy, section 1

Formation name	Westwater Canyon (b)	Dakota(?)			Mancos		Gallup				Crevasse Canyon	Crevasse Canyon (Dalton)	Crevasse Canyon	Crevasse Canyon	Point Lookout (Hosta)	Point Lookout		Menefee						Chuska
Sample number	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
Quartz	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Secondary quartz	X	X	X	X	X		X		X		X	X	X										X	X
Inclusions in Quartz: none			X								X	X	X							X	X	X		X
Inclusions in Quartz: regular									X	X	X					X			X	X			X	X
Inclusions in Quartz: irregular	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Inclusions in Quartz: acicular	X	X	X	X	X				X	X	X	X	X		X		X			X		X	X	
K-feldspar	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Plagioclase	X																				X			X
Muscovite					X		X		X		X	X	X	X	X	X	X			X	X	X		
Tourmaline: prismatic				X	X		X		X	X		X			X						?		X	X
Tourmaline: angular					X		X		X	X					X		X						X	X
Tourmaline: rounded	X	X	X	X					X	X	X	X	X	X	X	X	X						X	
Tourmaline: polished	X	X	X	X					X	X			X	X	X	X	X						X	
Tourmaline: black-brown	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X				?		X	X
Tourmaline: green-blue	X	X	X	X					X	X			X				X							X
Garnet: euhedral							X																	
Garnet: angular	X		X	X	X		X		X	X	X	X	X	X	X	X	X			X	X	X	X	X
Garnet: rounded																								
Garnet: colorless-pink	X		X	X	X		X		X	X	X	X	X	X	X	X	X			X	X	X	X	X
Garnet: red-brown			X																			X	X	X
Garnet: etched	X		X						X	X			X							X	X	X		X
Zircon: euhedral	X	X	X		X		X		X	X	X	X	X			X	X			X	X	X	X	
Zircon: angular					X				X	X		X		X						X	X	X		
Zircon: rounded	X	X		X					X		X	X			X									
Zircon: colorless-pink	X	X		X	X		X		X	X	X	X	X	X	X	X	X			X	X	X	X	
Zircon: yellow-brown	X	X	X		X															X				
Zircon: zoned	X	X			X				X	X		X	X							X		X		
Hematite	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Ilmenite-magnetite										X			X	X	X	X				X	X	X	X	X
Leucoxene	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Staurolite	X	X							X								X						X	
Biotite			X	X			X				X	X	X	X	X	X	X		X	X	X	X	X	
Chlorite											X	X	X	X					X	X	X	X		
Sphene																					X	X	X	X
Epidote																	X			X	X	X	X	X
Zoisite					X							X	X		?		X				X	X	X	X
Apatite																X								
Augite																								
Anatase	X	X	X	X	X		X				X			X					X	X			X	
Rutile			X	X	X							X	X	X	X	X								
Actinolite-hornblende																								X
Talc																								
Spinel (green)										X														
Barite	X	X					X		X	X	X	X	X	X		X	X			X			X	
Dolomite																X				X				
Pyrite					X																X			
Opaline (cement)											?	?	?	?		?	?		X	X	X	X	X	X
Calcite (cement)											X			X	X	X	X			X	X	X	X	
Quartzite fragments	X	X																						
Chert fragments																								

Figure 16

Mineralogy and relation to stratigraphy, section 2

Formation name	Westwater Canyon			Dakota(?)		Mancos		Gallup				Crevasse Canyon				Point Lookout					Menefee	Chuska
												Dilco		Dalton		Hosta						
	b	b	b	b	b	b																
Sample number	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	
Quartz	×	×	×	×	×		×	×		×	×	×	×	×	×	×	×	×	×	×	×	
Secondary quartz		×	×	×	×					×			×	×	×		×		×	×		
Inclusions in Quartz: none	×							×													×	
Inclusions in Quartz: regular	×												×									
Inclusions in Quartz: irregular	×	×	×	×	×		×	×		×	×	×	×	×	×	×	×	×	×	×	×	
Inclusions in Quartz: acicular	×	×	×	×	×		×	×		×	×	×	×	×			×	×	×		×	
K-feldspar	×	×	×	×	×		×	×		×	×	×	×	×	×	×	×	×	×	×	×	
Plagioclase		×																				
Muscovite		×		×	×		×	×			×	×	×	×	×				×		×	
Tourmaline: prismatic				×				×		×	×	×	×	×	×	×	×		×		×	
Tourmaline: angular				×	×		×	×		×	×	×	×		×	×	×					
Tourmaline: rounded	×	×	×	×	×			×		×	×	×	×	×	×	×	×	×	×	×	×	
Tourmaline: polished	×	×	×	×	×			×				×	×	×	×	×	×	×	×	×	×	
Tourmaline: black-brown	×	×	×	×	×		×	×		×	×	×	×	×	×	×	×	×	×	×	×	
Tourmaline: green-blue	×	×	×	×	×			×		×	×	×		×	×	×	×		×		×	
Garnet: euhedral			×	×						×												
Garnet: angular	×	×	×	×	×		×	×		×	×	×	×	×	×		×	×	×		×	
Garnet: rounded		×	×											×								
Garnet: colorless-pink	×	×	×	×	×		×	×		×	×	×	×	×			×	×	×		×	
Garnet: red-brown		×	×					×		×					×							
Garnet: etched	×			×	×								×					×			×	
Zircon: euhedral	×	×	×	×	×		×	×		×	×	×	×	×	×	×		×				
Zircon: angular	×	×								×	×					×			×	×	×	
Zircon: rounded	×	×		×	×							×			×							
Zircon: colorless-pink	×	×	×	×	×		×	×		×	×	×	×	×	×	×		×	×	×	×	
Zircon: yellow-brown								×														
Zircon: zoned	×	×			×		×	×		×	×					×						
Hematite	×	×	×	×	×		×	×		×	×	×	×	×	×	×	×	×	×	×	×	
Ilmenite-magnetite	×	×	×	×	×		×	×		×			×	×				×	×		×	
Leucoxene	×	×	×	×	×		×	×		×	×	×	×	×	×	×	×	×	×	×	×	
Staurolite	×	×	×					?									×					
Biotite							×	×				×	×	×				×			×	
Chlorite												×	×	×							×	
Sphene																					×	
Epidote																		×	×			
Zoisite																×	×			×	×	
Apatite													×	×								
Augite																						
Anatase	×		×					×		×	×	×	×	×	×	×	×	×		×		
Rutile				×	×						×	×		×		×				×		
Actinolite-hornblende															×							
Talc	×		×	×			×															
Spinel (green)										×												
Barite			×											×		×		×		×		
Dolomite								?		×	×		×		×							
Pyrite													×									
Opaline (cement)			×										?		?				×	×	×	
Calcite (cement)	×						×						×	×		×		×			×	
Quartzite fragments		×	×					×								×	×		×			
Chert fragments			×																			

Figure 17

Mineralogy and relation to stratigraphy, section 3

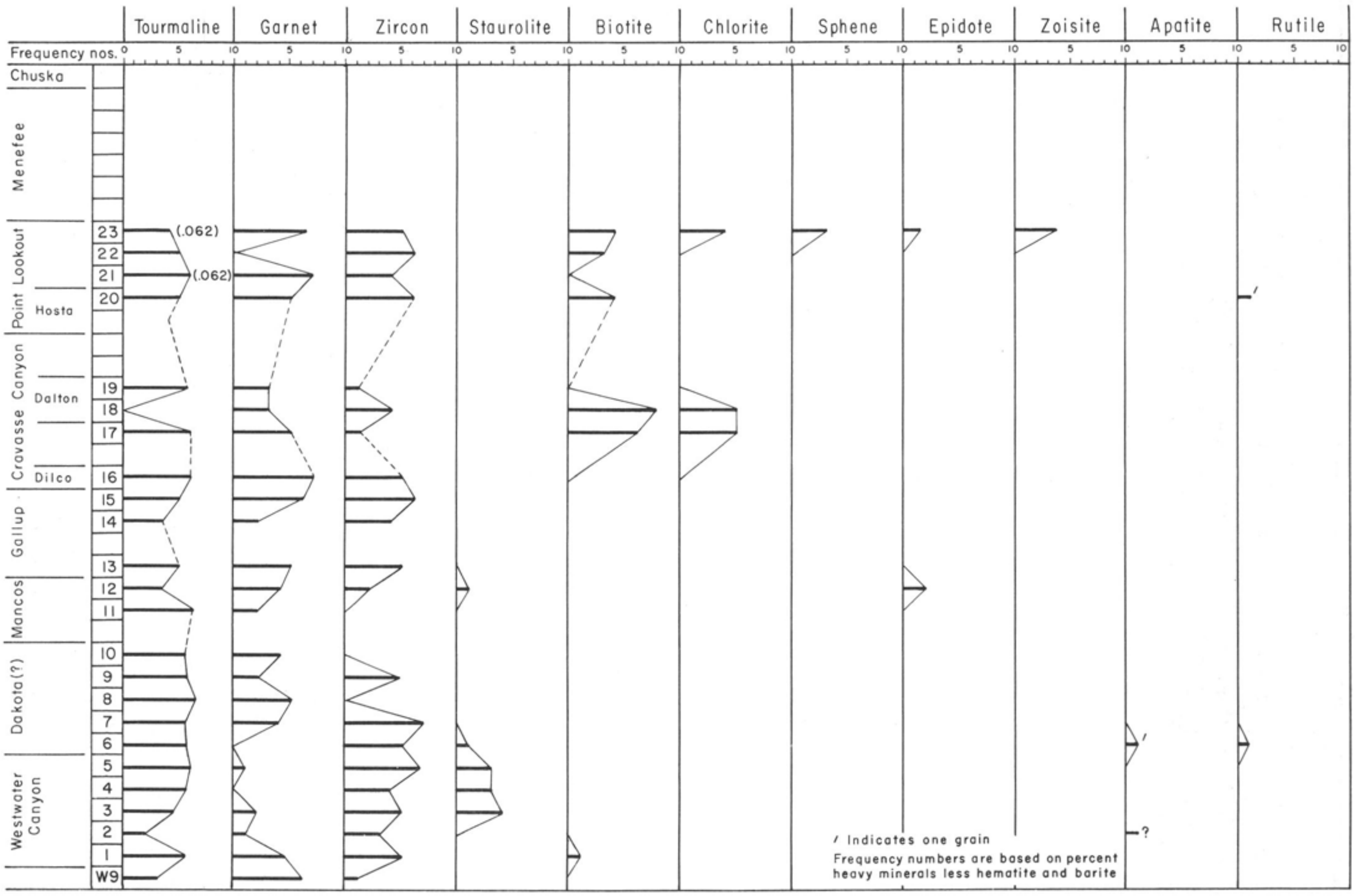

Figure 18

RELATION OF HEAVY MINERAL FREQUENCIES TO STRATIGRAPHY, SECTION 1

the Dakota(?) Sandstone. Above the Dakota(?), these tourmaline color types are not uniformly present. A few grains of colorless and pink tourmaline were observed in samples 5 and 44b from the Dakota(?) Sandstone; pink grains are present in sample 3 from the Westwater Canyon Sandstone.

There is no correlation between grain shape and color; prismatic, irregular, and rounded grains of all the colors were observed. Quantitative data were not collected, but rounded grains appear to be most commonly of the black-brown varieties. Tourmaline grains with inclusions are not numerous, but cavity, opaque (carbonaceous?), and acicular inclusions are present in a few grains of most suites. Cavities or bubbles are the most common and generally occur in light brown or brown grains. The available information on color and inclusions suggests that more complete quantitative data on these characteristics might contribute to the solution of some of the problems of differentiating and zoning these Cretaceous rocks.

Garnet

As is generally true for detrital sediments, garnet is one of the most persistent and abundant heavy minerals in the Todilto Park sections. It was absent in only eight of the samples, and these absences did not occur at the same horizon in each section. In the other samples, the variations in frequency percent did not appear to be systematically related to the stratigraphic units. The available information suggests that neither the presence or absence nor the relative amount of garnet will be of appreciable value in the differentiation of these rocks.

Samples from the upper sandstones of the Menefee Formation and from the Chuska Sandstone in section two contain from 12 to 30 percent garnet in the 0.125 mm size fractions. Samples of these formations were not available from sections one and three, and in view of the known variations in frequency elsewhere in the stratigraphic column, it is not advisable to conclude that these amounts of garnet are characteristic of these sandstones.

The varietal characteristics of the observed garnet are numerous, but their correlation value appears to be limited. They do, however, have significance in matters of provenance and intrastratal alteration.

In all samples in which garnet is present it occurs mainly as angular fragments. Typically, these fragments are so irregular and so sharply angular that they have the appearance of broken glass. Small quantities of rounded and euhedral garnet were observed in a number of samples (fig. 15 through 17). Both forms appear most commonly in the Morrison Formation. Above this formation, rounded garnet occurs only in sample 54 of the Dalton Sandstone. Euhedral grains are present in the Gallup Sandstone of sections two and three but are not present in section one. The Dakota(?) Sandstone of section three also contains euhedral garnet, but it is absent in the Dakota(?) of the other two sections.

Many of the angular garnet grains are highly etched; their surfaces are covered by regularly spaced rectangular and triangular pits. The distribution of these etched grains relative to the various formations is not the same in each section. Etched garnet is present in most of the sandstones and is especially abundant in the Menefee Formation and Chuska Sandstone of section two. Inasmuch as these formations are not represented in the other two sections, it is not certain that this abundance of etched garnet will prove diagnostic.

The garnet in the sections is for the most part of colorless and pink varieties; colorless and light pink types are most common, and these are the types most etched. Deep red and amber-brown garnets are present in a number of samples, but their places of occurrence are not the same in each section. The amount of red garnet is greater in the Chuska Sandstone than in other parts of the sections.

Zircon

Zircon, like tourmaline and garnet, is one of the most persistent minerals in the sampled sections. Similarly, the variations in quantity of zircon from one formation to another are not the same for each section. There is, however, a suggestion that the quantity of zircon in the Dalton Sandstone is less than in adjacent stratigraphic units, but the differences are slight and may not be significant.

Zircon is one of the most nearly ubiquitous minerals in detrital sediments and its presence is of little use in the differentiation of stratigraphic units. Due to the great range of varietal characters, however, it is often a most useful species, particularly in studies of provenance. Hence, a careful investigation was made of each variety in the sampled sections.

Colorless, pink, and light lavender zircon crystals are present throughout the sampled sections. Amber, brown, and reddish brown zircon crystals, although not limited to the lower parts of the sections, are most abundant below the Crevasse Canyon Formation.

Zircon from sandstones are often well rounded, but in the Todilto Park sections, angular and euhedral forms predominate. The angular grains are, for the most part, colorless. Euhedral forms (prisms with pyramid terminations) are commonly colored; pink and lavender varieties predominate. The amber and brown zircon below the Crevasse Canyon Formation is typically euhedral.

Rounded zircon grains are especially numerous in the Westwater Canyon Sandstone of all three sections, and rounded to subrounded euhedral grains are present in the Recapture Shale of section one. Lesser amounts of rounded

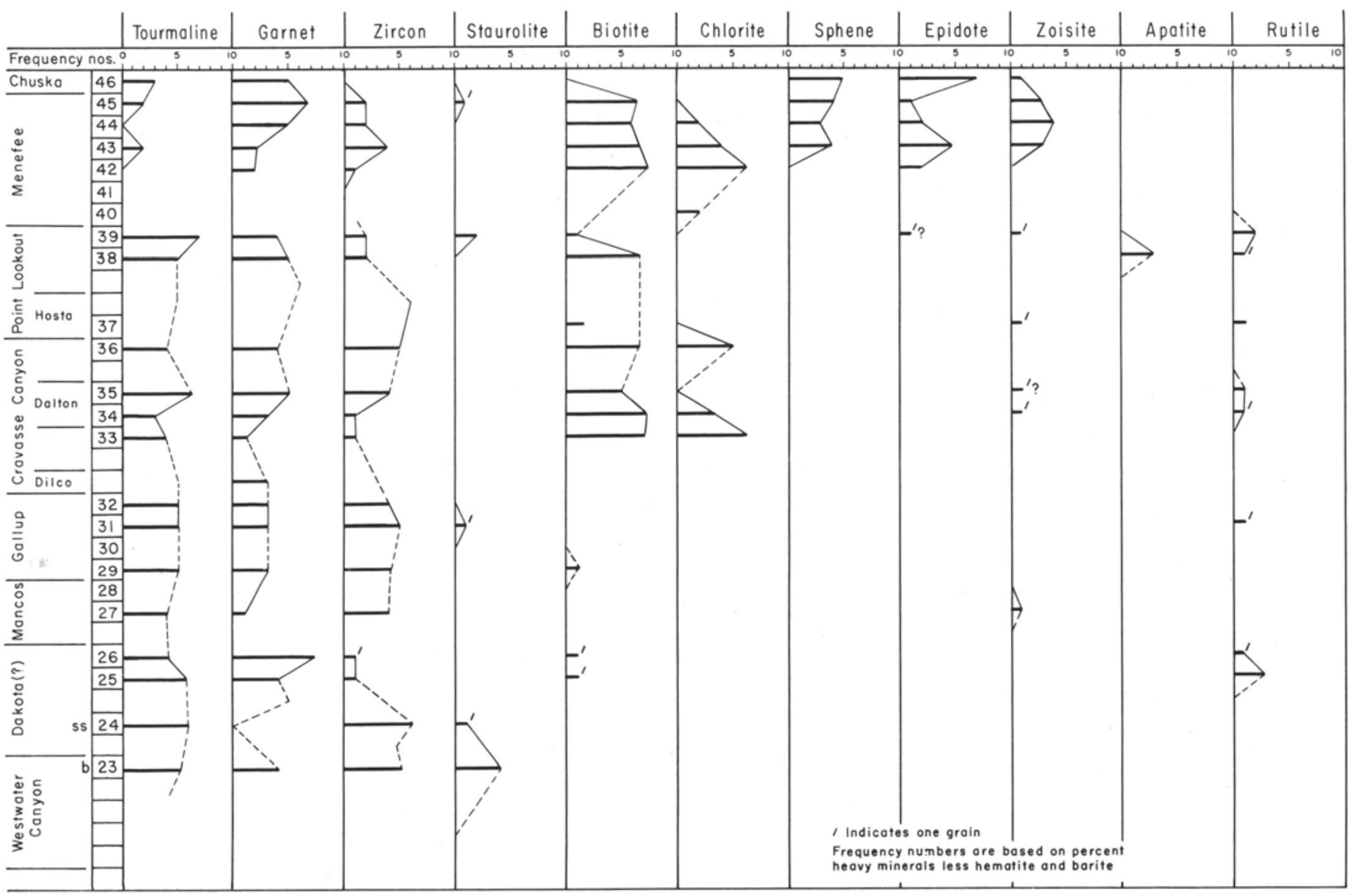

Figure 19

Relation of heavy mineral frequencies to stratigraphy, section 2

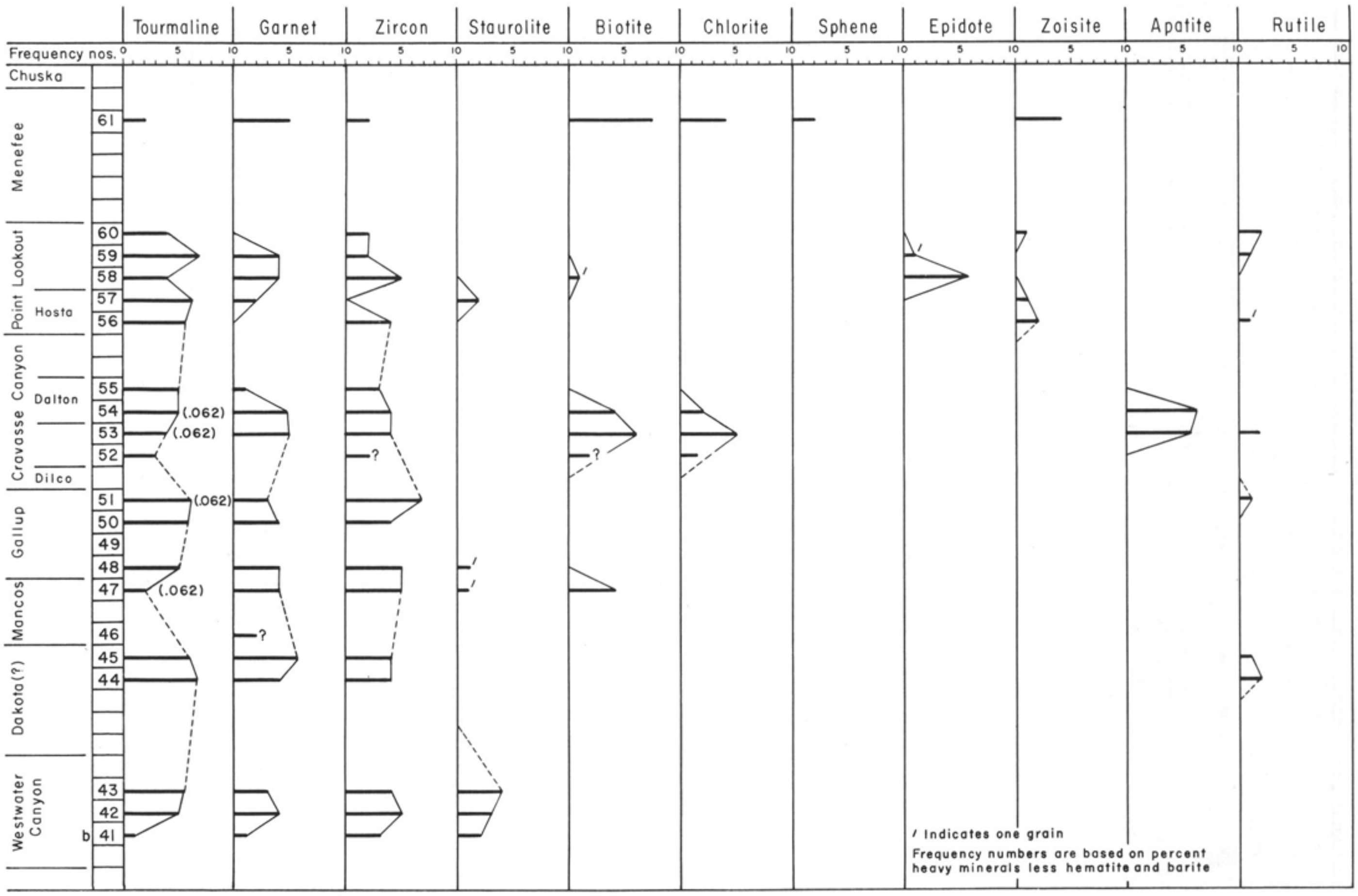

Figure 20

RELATION OF HEAVY MINERAL FREQUENCIES TO STRATIGRAPHY, SECTION 3

zircon grains were observed in the Point Lookout Sandstone of section one, the Crevasse Canyon Formation and Dakota(?) Sandstone of sections two and three, and in the Gallup Sandstone of section two.

Zoned and unzoned crystals of zircon occur together in most samples (fig. 15, 16, and 17). The zoned zircons are not limited to particular formations but are randomly distributed in the three sections. The frequency of their occurrence is slightly greater in the lower parts of the sections.

Zoning was observed only in colored varieties and was most common in lavender and brown euhedra. It was not recognized in angular or rounded grains. Typically, the zones are numerous, thin, and closely spaced and are parallel to the surfaces of the zoned crystal. In most, the zoning shells are alternately clear and turbid. Usually the turbid parts are due to concentrations of dustlike inclusions. Concentrations of this dustlike material frequently occur, like cores, in the center of the crystal and extend in rays toward its corners. Zoning due to differences in color intensity was also observed. In a few crystals, the zones are alternately clear and opaque; the opaque parts are generally white or brown. The opaque shells, and the few completely opaque crystals that are present, are probably metamict.

Grains made up of small, colorless zircon crystals and attached quartz were noted in samples from several of the sedimentary units between the top of the Dakota(?) Sandstone and the Dalton Sandstone. Fluid, acicular, and regular crystalline inclusions are common in the zircons throughout the sections.

Fluorescence of zircon as a petrographic aid has been suggested by W. R. Foster (1948) and by A. F. Wilson (195o). Zircon may be nonreactive or it may fluoresce yellow-orange, green, or red, and the fluorescence may range from faint to intense. Zircon examined by Wilson did not fluoresce under long-wave (365oA) radiation; others report fluorescence from both short- (2537A) and long-wave sources.

The fluorescence of the zircon in section two was investigated under both short- and long-wave radiations. Both reactive and nonreactive grains are present in most samples. Only intense yellow-orange fluorescence occurred, and this reaction persisted regardless of the wave length of the radiation used. Above the Westwater Canyon Sandstone, only colorless or very light lavender euhedral and angular grains fluoresced; most rounded, colorless grains and all deeply colored varieties failed to fluoresce. Fluorescent, colorless, and rounded grains are present in sample 23b from the West-water Canyon Sandstone.

It appears from the study of the fluorescence of the zircon in section two that this feature will be of very limited value in the differentiation and correlation of these Cretaceous sedimentary units; therefore, similar studies of sections one and three were not made.

Staurolite

Small amounts of staurolite occur in samples from the Menefee Formation in section two. Several grains were also found in samples from the Point Lookout and Gallup sandstones of sections two and three and from samples of the upper part of the Mancos Shale of sections one and three (fig. 18, 19, and 20). In all three sections, staurolite is present in the lower half of the Dakota(?) Sandstone and is abundant in the Westwater Canyon Sandstone. It is also abundant in the Summerville Formation below section one but was not observed in older rocks (Allen and Balk, 1954).

Within the limits of this study, abundant staurolite appears to be characteristic of the lower part of the Dakota(?), Westwater Canyon, and Summerville. Its limited stratigraphic range in the studied sections suggests that the species may be similarly limited elsewhere in the San Juan Basin and may be a means of identifying time-equivalent rocks over a wide area.

Much of the staurolite in the measured sections occurs as unaltered, translucent, yellow or golden brown, irregular cleavage fragments. Well-formed crystals are not present.

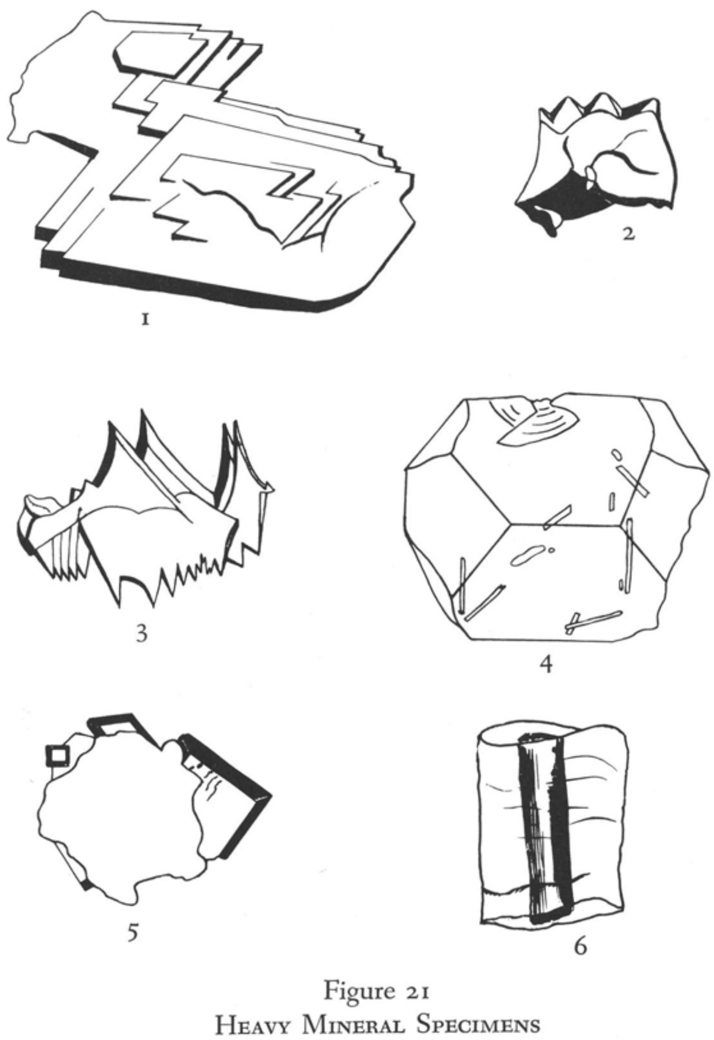

Figure 21
Heavy Mineral Specimens

1-3 Etched ("concertina") staurolite—Westwater Canyon and Dakota(?) sandstones.
4 Euhedral sphene from the top of the Point Lookout Sandstone.
5 Authigenic anatase crystals on leucoxene—Gallup sandstone.
6 Apatite containing gray to grayish-purple pleochroic core—Crevasse Canyon Formation.

Many of the staurolite fragments have sharply angular "concertina" or "sawtooth" boundaries (fig. 21). Similar boundaries on staurolite from Red Rocks of the West of England were reported by H. H. Thomas (1909) to have resulted from the intersection of cleavage faces. It seems likely that the boundary faces on the staurolite in the Todilto Park rocks are similarly oriented. Many of the "concertina" grains are extremely delicate, so it is unlikely that they were transported and deposited in their present form. It seems probable that the "concertina" phenomenon displayed by these grains is the result of deep etching by intrastratal solutions.

Inclusions are not common in staurolite from the Todilto Park rocks. Fine black dust is present in some grains; larger inclusions that impart a porous appearance to the grains are rare.

Biotite and Chlorite

These minerals, for the most part, are confined to formations above the Gallup Sandstone. Minor occurrences were observed in the Mancos Shale in section three, in the Dakota Sandstone in section two, and near the base of the Westwater Canyon Sandstone in section one.

Above the Gallup Sandstone, biotite and chlorite, although generally present, are not everywhere in the same proportions. In each section, biotite and chlorite occur in the lower parts of the Crevasse Canyon Formation. In the upper parts of the Crevasse Canyon (upper beds of the Dalton and the lower Gibson member), the Point Lookout Sandstone, and the Satan tongue of the Mancos, biotite is the dominant species. Both biotite and chlorite are abundant in the Menefee Formation.

No systematic variations in the physical characteristics of either biotite or chlorite were observed. The chlorite is various shades of green, much of it very pale. Most samples include both reddish brown and black varieties of biotite. Warped flakes of biotite and chlorite are common and nearly all show undulatory extinction. Much of the biotite appears to have been bleached. The outlines of most biotite and chlorite grains are irregular, but a few have characteristic pseudohexagonal boundaries. A few flakes of both micas contain irregular and acicular inclusions; inclusions with halos are rare.

Sphene

Sphene appears to be characteristic of the upper parts of each of the sampled sections. It is in sample 23 from the top of the Point Lookout Sandstone in section one, in sample 61, and in the only sample of the Menefee Formation in section three. The Menefee is well exposed along section two, and sphene is present in most samples from these exposures. Sample 46 from section two, the only sample of the Chuska Sandstone, also contains abundant sphene. Sphene does not occur in the measured sections below the top of the Point Lookout Sandstone and, except for a questionable grain in the lower part of the De Chelly Sandstone, it is not present in the formations between the bottom of the sections and the top of the Precambrian.

Most of the grains of sphene are colorless to light yellow-brown. Rounded and angular grains are common, but euhedral grains (fig. 21) were observed in sample 23 of section one. Many of the grains, especially in samples from section two, appear to have been partly altered to leucoxene. Pitted surfaces are common on rounded and irregular grains from each section. The cause of the pitting is not evident, but its association with apparent alteration to leucoxene suggests that it may be the result of solution and alteration. Few sphene grains contain inclusions; however, unidentified acicular inclusions are numerous in the euhedral grains from sample 23 (fig. 21(4)).

Epidote

Epidote was identified in samples from the Chuska Sandstone, Menefee Formation, the top of the Point Lookout Sandstone, and in one sample from the Mancos Shale. Epidote, as was reported in New Mexico Bureau of Mines Bulletin 36, has also been identified in samples from the Carmel and the top of the Chinle. It was not present in the other formations above the Precambrian in this area.

The heavy-mineral suite from the Chuska Sandstone is 44 percent epidote. Epidote ranges from z to II percent in the heavy-mineral suites from the Menefee Formation. It ranges from o to 16 percent in suites from the Point Lookout Sandstone. Very small amounts of epidote were in one sample from the Mancos Shale. Like sphene, epidote is concentrated in the upper parts of the measured sections.

Most of the epidote occurs in rounded or irregular grains that are yellow-green or colorless. Many of the grains are clouded and cut by seams of alteration material. Large, irregular, black, opaque inclusions are common. Some grains consist of a mosaic of variously oriented intergrown crystals. A few grains, particularly in sample 58 from the Point Lookout Sandstone, are remarkably transparent and sharply angular.

Zoisite

Zoisite is not abundant in any of the collected heavy-mineral suites. When present, it seldom makes up more than 5 percent of the nonopaque assemblages. Very small amounts of zoisite occur in the Chuska and Dalton sandstones. A thin sandstone near the middle of the Mancos Shale also contains a small amount. Zoisite is present in the largest amounts and is most persistent in samples from the Menefee Formation in sections two and three. Sample 23, section one, from strata tentatively assigned by Allen to the top of the Point Lookout Sandstone, contains several percent of zoisite. These strata may actually be part of the Menefee Formation.

Irregular, rounded, pitted, and colorless grains showing typical blue interference colors are most usual. Many grains are clouded by alteration material and inclusions; a few are highly transparent and sharply angular.

Apatite

One grain of apatite was identified in sample 6 from the base of the Dakota(?) Sandstone and two questionable grains were found in sample 2 from the Westwater Canyon Sandstone in section one. Approximately 4 percent of the heavy-mineral suite in sample 38 from the top of the Point Lookout Sandstone of section two was apatite. In section three the heavy minerals from samples 53 and 54 of the Crevasse Canyon Formation were 14 and 25 percent apatite. The relatively large amounts of apatite in the Crevasse Canyon of section three may be due to the fact that the 0.125 mm size fraction normally used was inadequate, and the heavy minerals were collected from the 0.062 mm fraction. Milner (1952, p. 502) reports that apatite tends to be concentrated in fine-grained sediments, silt, clay, and shale.

From the foregoing, it is evident that apatite is not systematically distributed in the measured sections, and therefore, within the limits of this study, has little correlation value.

Slightly worn to angular elongate prismatic grains with pleochroic gray to gray-purple cores are most common (fig. 21). Grains that are oval to nearly circular in plan, containing irregular inclusions and vacuoles, were also observed.

Rutile

In each of the three sections, the heavy mineral assemblages from the Dakota(?) Sandstone contained between 1 and 2.5 percent of optically identifiable rutile. The upper parts of the Point Lookout Sandstone in each section also contained assemblages that included from one grain to 1.5 percent of rutile. Rutile is irregularly distributed in the remaining parts of the sections, and in these occurrences the heavy minerals seldom include more than one or two grains.

Rutile in the studied samples is translucent reddish brown to dark brown. Irregular angular grains are most common; a few are bounded in part by crystal faces. Generally, the grains of rutile are slightly larger than other mineral grains in the suite. The optically identified rutile in these sections is allogenic; none was derived from the decomposition in *situ* of other titaniferous minerals.

X-ray studies of authigenic leucoxene grains indicate that some are made up largely of cryptocrystalline rutile. This occurrence of rutile is discussed in the section on opaque heavy minerals.

Opaque Heavy Minerals

Heavy-mineral suites from each of the sections contained one or more of the following opaque minerals: pyrite, hematite, limonite, magnetite, ilmenite, and leucoxene.

Pyrite is a minor constituent occurring in only a few samples, and usually these are from argillaceous units. Most grains are euhedral; several pseudomorphs of hematite after pyrite were observed. The pyrite in these sections is chiefly authigenic.

Hematite and limonite were identified in all the heavy-mineral suites, and in many they were the dominant minerals. They are especially abundant in the upper parts of the sections. These minerals are largely products of the in *situ* alteration of other iron-bearing minerals, especially magnetite and ilmenite.

Ilmenite and magnetite are present in many of the samples, but under the microscope it is difficult to separate them, and For this reason only their combined amounts were determined. The observed abundance of secondary iron and titanium minerals in most samples indicates that extensive alteration has occurred. Inasmuch as magnetite is more easily altered than ilmenite, it is likely that ilmenite comprises a large part of the reported ilmenite-magnetite.

Ilmenite and magnetite were not present in some samples, and in others they make up as much as 75 percent of the heavy-mineral suites. They are most abundant in samples from the Jurassic Summerville Formation and Westwater Canyon Sandstone and in samples from the Cretaceous Menefee Formation and the Tertiary Chuska Sandstone. Formations between the upper Menefee and the Westwater Canyon Sandstone contain little or no ilmenite or magnetite (fig. 22).

Leucoxene is ubiquitous in the studied samples and is one of the most abundant heavy minerals. Ordinarily the heavy-mineral suites are from 10 to 60 percent leucoxene. In each section the largest amounts are in sedimentary units above the Westwater Canyon Sandstone.

White, brown, and cream-colored leucoxene grains are present. Many of the brownish grains are magnetic. White and cream-colored grains commonly include black skeleton crystals or irregular cores. Recent X-ray studies have indicated that the ilmenite lattice is destroyed very early in the process of alteration to leucoxene (Karkhanavala, Momin, and Rege, 1959). Hence, inasmuch as none of the black grains was examined by X ray, the observed black cores are identified only tentatively as ilmenite. Much of the leucoxene occurs as white to cream-colored, hollow, globular masses lined with tiny yellow-brown transparent plates of "geometrically patterned" anatase. These geodelike grains are extremely fragile and many were broken in the preparation of the sample. Grains of sphene with alteration rims of leucoxene are present at several places in the sections.

A few of the smooth, rounded, porcelainlike grains of leucoxene may be detrital. However, the observed mineral relations and morphologies indicate that most of the leucoxene is authigenic and derived largely from ilmenite. Only a small amount is due to the alteration of sphene. Hence, it seems likely that the amount of leucoxene plus ilmenite will equal approximately the amount of ilmenite originally present in these sediments.

In Figure 26, the cumulative percentages of ilmenite-magnetite and leucoxene are plotted in stratigraphic order. In each section, the combined percentages are relatively low opposite the Dilco and Dalton members of the Crevasse Canyon Formation. Opposite the remaining parts of the sections, the percentages are uniformly high. In each sample, a reciprocal relation exists between the amount of ilmenite-magnetite and the amount of leucoxene. In sealed environments such as shale, the percent of ilmenite-magnetite is highest; in porous sandstone, it is low. The reverse is true for leucoxene.

These relations suggest that the ratio of ilmenite-magnetite to leucoxene is largely dependent on the effectiveness of postdepositional alteration processes.

Ana tase

As already noted, anatase was optically identified in several of the heavy mineral assemblages. Its stratigraphic occurrences are indicated in Figure 22.

Much of this optically identified anatase occurs as tiny tabular crystals attached to shells of leucoxene (fig. 21). The close association between recognizable anatase and leucoxene suggests a genetic relationship and the possibility that at least part of the leucoxene may be cryptocrystalline anatase. X-ray diffractometer patterns from the total heavy-mineral suite of sample 27 (section two) showed primarily the presence of rutile (not recognized microscopically) with lesser amounts of anatase, pseudobrookite, and possibly brookite. It appears that most of the leucoxene grains in this sample are made up of rutile. However, samples containing different proportions of these several titania polymorphs probably are present. Several varieties of leucoxene were recognized under the microscope, and these can be grouped, as was done by Karkhanavala (1959), into brown, intermediate, and white varieties. X-ray studies of individual grains of each variety have not been made, but inasmuch as the diffractometer pattern from the composite sample shows the presence of the same titanium-bearing minerals as were identified by Karkhanavala in the Quilon, India, leucoxene deposits, it seems likely that the varieties recognized in this sample and in the Quilon samples have much the same mineral composition. As established by Karkhanavala, "brown leucoxene is a mixture of rutile and pseudobrookite with small amounts of hematite"; intermediate leucoxene contains rutile, anatase, pseudobrookite, and hematite; and white leucoxene contains only rutile, anatase, and a very small amount of hematite.

The X-ray diffractometer charts of the heavy minerals from sample 27 have been compared with a chart obtained from a sample of the Gallup titaniferous sandstone deposit described by Sun and Allen (1957). These charts showed the presence of the same titania polymorphs, but a somewhat larger amount of anatase was indicated in the Gallup Sandstone. Brookite may be present in the Gallup deposit, as reported by Sun (1957), but it is in only very small amounts in the sample X-rayed. Pseudobrookite and possibly brookite are minor constituents in the heavy minerals from sample 27. The d-values for pseudobrookite and brookite are similar and may be confused. Pseudobrookite, however, is distinguished by a 4.9oA peak which was clearly present on the chart from sample 27; it was very weakly developed or absent in the chart of the Gallup titaniferous sandstone.

Barite

Barite is randomly distributed in the collected heavy-mineral suites. Its stratigraphic occurrences vary from section to section (fig. 15, 16, and 17). It is most widely distributed and abundant in section two. "Floods" of barite also were observed in a number of samples from section three.

Much/of the barite occurs as irregular, pitted, and cloudy white grains. Many of these grains are fragile and others include small clastic grains of quartz. Small angular cleavage fragments were also observed. None of the barite appears to be detrital, and most of it is clearly authigenic, occurring as a constituent of the cement. Because of the nature of its occurrence, barite was not included in the quantitative heavy-mineral analyses.

Dolomite

Cleavage fragments of dolomite were observed in several of the formations above the Mancos Shale. It probably is more abundant than indicated in the figures, for a part was certainly lost during the process of disaggregation. Like barite, the dolomite is an authigenic constituent in the cement. It is not included in the quantitative study.

Talc

Talc is present in samples from section three and is abundant in sample 47 from the Mancos Shale. It is present in megascopically identifiable fragments in the coarser fractions

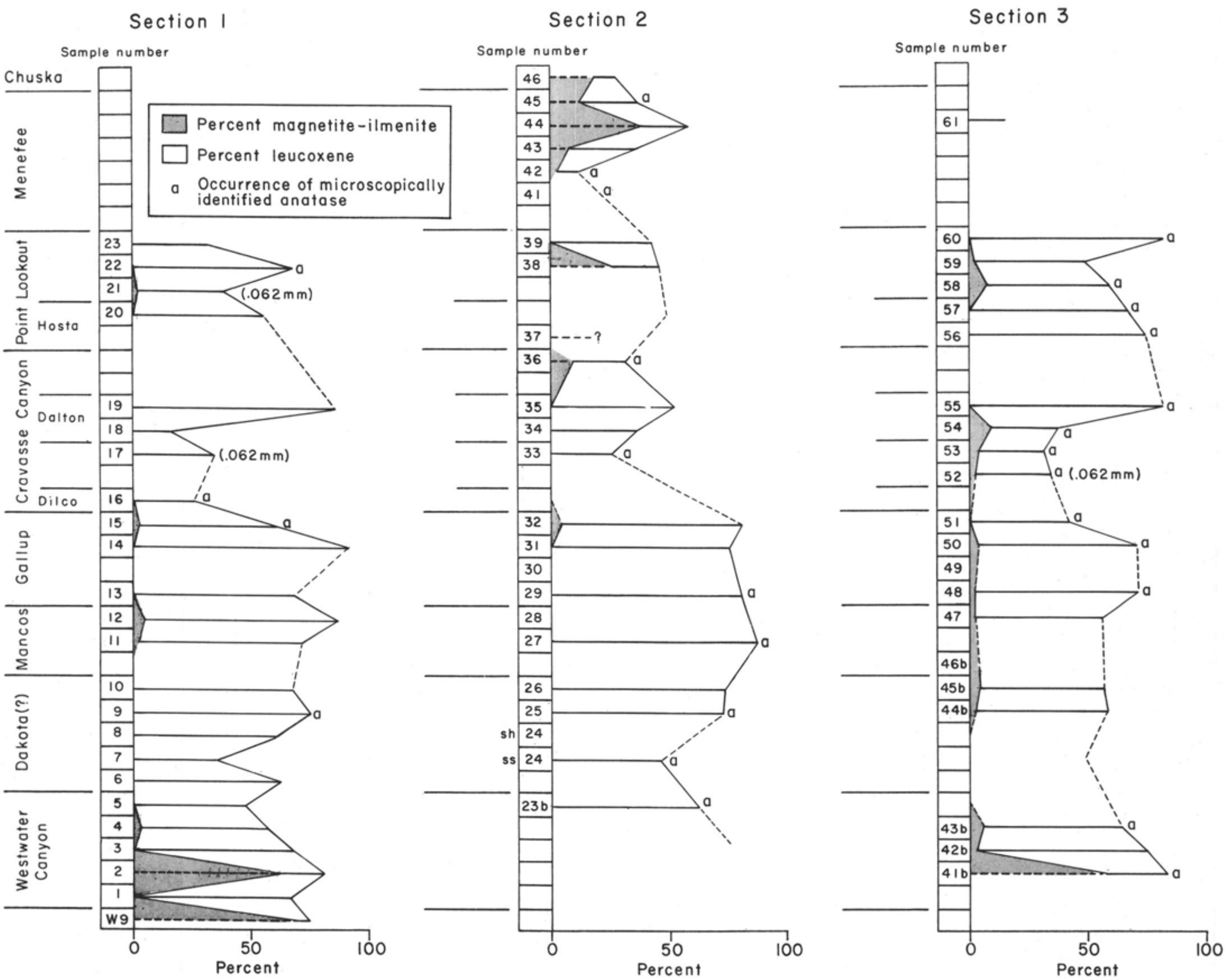

Figure 22

Cumulative variation diagram for magnetite-ilmenite and leucoxene

of samples 41b and 42b from the Westwater Canyon Sandstone and sample 44 from the Dakota(?) Sandstone.

Spinel(?)

Angular, transparent, emerald green, isotropic grains are present in the Westwater Canyon Sandstone of section one, in the Mancos Shale of sections one and two, and in the Gallup Sandstone of sections two and three. These grains have the general characteristics of both spinel and garnet. However, they appear to have a poorly developed cleavage, and for this reason, they are tentatively identified as spinel. None of the samples contained more than one or two grains of this mineral.

Muscovite

Muscovite is in one or more samples of each of the formations from the Summerville through the Menefee. In each of the sections, it is abundant in the Gallup Sandstone and overlying strata. Below the Gallup, its occurrences are fewer and the relative amounts are less.

The increase in the amount of muscovite in the Gallup Sandstone and overlying formations coincides with a similar increase in the amount of feldspar and with the appearance of such unstable minerals as biotite and chlorite. These relations persist in each of the studied sections.

Most of the muscovite is in very thin, flat colorless, cleavage flakes that are rounded. Numerous corrugated grains were observed, and these grains together with a few less obviously deformed grains have undulose extinction, suggesting derivation from metamorphic rocks.

The reported specific gravity of muscovite ranges between 2.76 and 3. The specific gravity of the heavy media used in the separation of heavy minerals was 2.95. As a result, muscovite occurs in both the heavy and light mineral fractions of many samples, and for this reason the amounts of muscovite in the heavy mineral fractions are of limited significance. It is possible (Milner, 1952, p. 319) that two distinct varieties of muscovite are present and that the heavier flakes may be in part bleached biotite; the majority, however, are not.

Minor Heavy Minerals

Several mineral species occur in minor amounts irregularly distributed through the sampled sections. The identifications of a few of these are doubtful and a few of the identifications are less specific than may be desired.

Amphibole, probably common hornblende, was identified in sample 55 from the upper part of the Dalton Sandstone and in sample 48 from the lower part of the Gallup Sandstone. Both of these occurrences are in section three. Green-yellow and blue-green amphiboles were present in sample 46 from the Tertiary Chuska Sandstone. In this sample, these amphiboles are relatively abundant and may be characteristic of the Chuska. This is further suggested by the occurrence of similar varieties in samples collected by Edward Bingler from the Chuska Sandstone near Sanostee, northeast of Chuska Mountain.

Several mineral grains tentatively identified as kyanite occur in the Dakota(?) Sandstone (sample 3) and the Mancos Shale (sample 47) of sections one and two. These are the only occurrences in the Todilto Park sections. Colorless angular grains of corundum occur in the Dakota(?) Sandstone (sample 9) of section one, and two grains tentatively identified as corundum were observed in the Mancos Shale (sample i i) of section one.

Small amounts of authigenic pyrite and malachite were identified in a number of samples. The composition of the malachite was checked by qualitative spectrographic analysis. X-ray analyses by John Carmen verified the presence of smithsonite in the Gallup Sandstone (sample 48).

LIGHT MINERALS

The light-mineral suites from the sampled sections consist largely of quartz, potassium feldspar, and muscovite. Minor amounts of plagioclase, chalcedony, chert, opal, and gray quartzite were also observed.

Muscovite

Muscovite, as already noted, occurs in both the light- and heavy-mineral suites, and the total percentages could not be determined by grain counts. In general, however, muscovite is most abundant above the Mancos Shale.

Feldspar

Plagioclase is not present in excess of a few percent in any sample and usually is represented by only one or two grains. Grains of sodic andesine are present in the Westwater Canyon Sandstone in each of the three sections, and 2.4 percent of the light fraction of the Chuska Sandstone is sodic andesine. A very small amount of plagioclase feldspar is present in the Crevasse Canyon Formation in section one and in the Menefee Formation in section three. The occurrences of andesine are accompanied by an increase in the amount of potassium feldspar.

Variations in the percentage of potassium feldspar in the light mineral fractions of the three sections are shown in Figure 23. Potassium feldspar, both orthoclase and microcline, are most abundant in the upper parts of the Mancos Shale and overlying formations. Sample 13 from the Gallup Sandstone in section one contained 21 percent. In all three sections, the Dakota(?) Sandstone contains only a small amount, never exceeding 5 percent. In the underlying Westwater Canyon Sandstone, the amount was as much as 17 percent of the light-mineral suite. The variations in the amount of feldspar divided the Todilto Park sections into three distinct zones. A small amount of feldspar is characteristic of the Dakota(?) Sandstone and the lower parts of the Mancos Shale and may be characteristic of equivalent parts of the column elsewhere.

The feldspars in all the samples are characteristically more angular than the quartz. All the feldspar grains in the lower half of each of the sections is kaolinized. Mixed fresh and altered feldspar grains are present in the upper halves of the sections. Fresh angular grains are especially abundant in the Crevasse Canyon Formation and Chuska Sandstone.

Quartz

Silica in various forms makes up the bulk of most of the samples. Its principal occurrence is in detrital grains of quartz. Lesser amounts are present in grains of chert and quartzite. At places, outgrowths of quartz on allogenic grains are common; also, locally, the sandstones have been cemented by opal.

Quartz is ubiquitous and one of the most interesting of the detrital minerals studied. Much of the quartz contains inclusions, and differences in the nature of these inclusions are noted in Figures 15, 16, and 17. The characteristics used in the classification of these inclusions are the ones suggested by Mackie (1896). This classification of inclusions contains three main groups plus the one in which inclusions are absent. "Regular inclusions consist of such minerals as micas, zircon, apatite, and black iron ores. "Irregular" inclusions consist of fluid segregations or cavities often arranged in lines. Acicular inclusions consist of dark lines and colorless needles probably of rutile or sillimanite. Mackie demonstrated that the inclusions in quartz are different in different types of rocks. Metamorphic rocks characteristically contain quartz with regular or no inclusions, and igneous rocks characteristically contain quartz with irregular or acicular inclusions. Basically, this is a genetic classification and its application should supply information concerning the ultimate source of the quartz and, when combined with other data, a clue to the nature of the provenance. Empirically, the distribution of inclusion types may also furnish a means of differentiating and correlating the Cretaceous sediments.

Most of the quartz in the Todilto Park sections contains inclusions of igneous rock types (irregular and acicular); vacuoles and fluid segregations most common. Grains containing regular inclusions or none are present at various places in each section. In the Cretaceous formations, these metamorphic types are most abundant in the Gallup Sandstones and overlying strata. Quartz without inclusions is especially abundant in the Tertiary Chuska Sandstone. It can be concluded from this that igneous rock was the ultimate source of most of the quartz in these sections. The immediate source, however, as will be shown, was probably sedimentary rock. A part of the quartz, especially in the upper half of the Cretaceous section and in the Chuska Sandstone, was derived from the metamorphic rock.

Secondary outgrowths on elastic quartz grains are scattered throughout the Todilto Park sections. They are common in

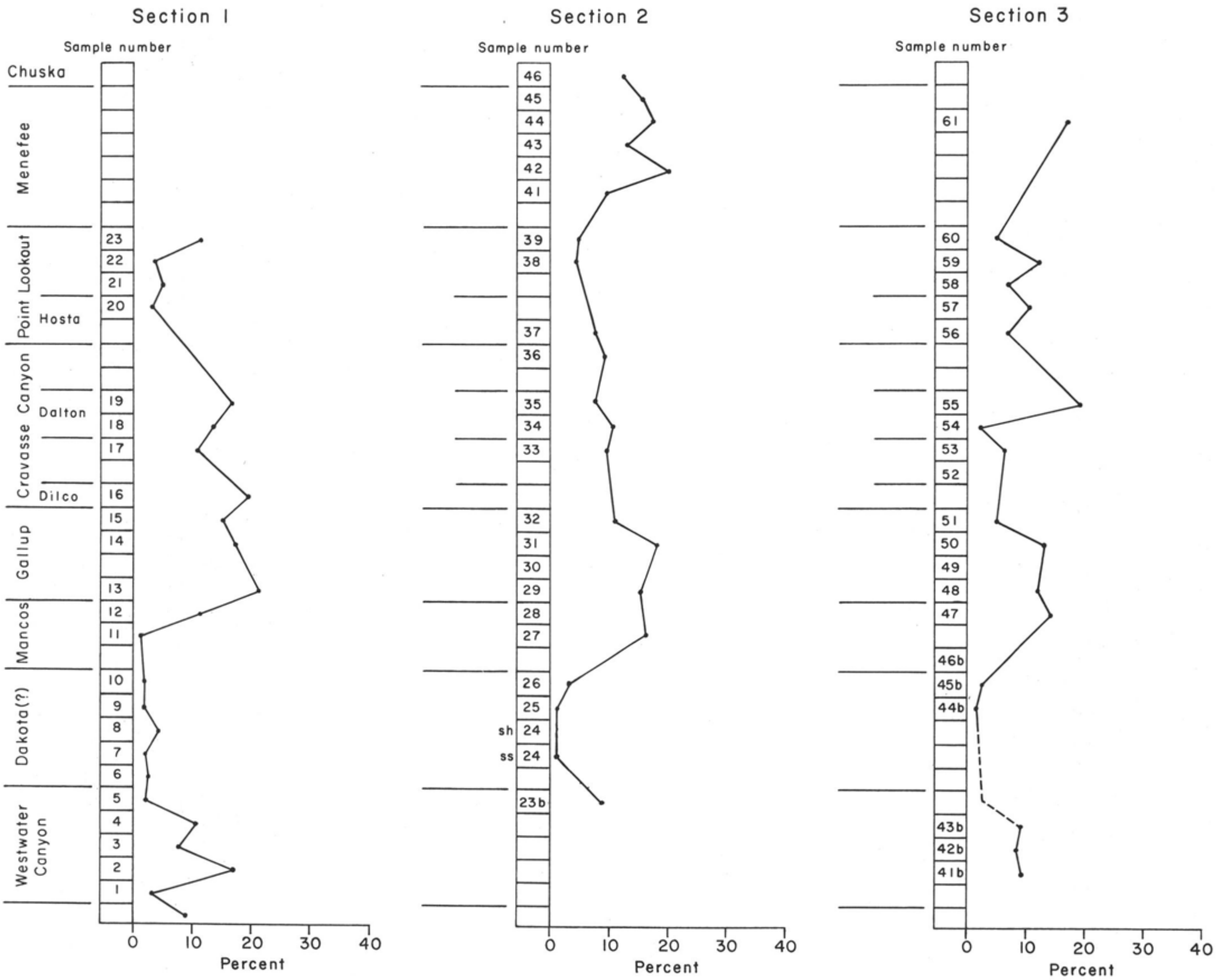

Figure 23
FELDSPAR STRATIGRAPHIC VARIATION DIAGRAMS

the Jurassic and Tertiary as well as Cretaceous strata and, as was reported by Willard (Allen and Balk, 1954), outgrowths on quartz also occur in the Triassic Chinle Formation.

Secondary outgrowths on quartz are not uniformly distributed in any of the Cretaceous formation and are not characteristic of a particular part of the section. These observations suggest that the presence or absence of outgrowths will be of little value in differentiating these sediments.

Many outgrowths have produced doubly terminated euhedra. In most, the allogenic nuclei and the outgrowths are in optical continuity. Because of staining on the surfaces of the allogenic grains, they are easily distinguished from the outgrowth. Ordinarily, the elastic cores are filled with vacuoles or inclusions, whereas the outgrowths contain none. Outgrowths on top of one another on a single grain were not observed. Hence, it is concluded that there is only one stage of overgrowth. There has been no rounding of the outgrowths, as most grains show sharp prism edges or delicate serrations and clearly developed after the last depositional processes.

Opaline cement was observed in sample 46 of the Chuska Sandstone. This cement tends to break loose from the sand grains, giving rise to cellular fragments that are conspicuous in the light fractions of the disaggregated sample.

As has already been pointed out, it is not possible to demonstrate that the Chuska Sandstone of section two is a dune deposit, but H. E. Wright (1951), on the basis of extensive work at Chuska Mountain, concluded that the Chuska Sandstone was largely of that origin. Because of this, he also concluded that the silica cement could not have been derived from marine water or siliceous fossils—the commonly assumed source of this type of cement. He postulated that the opaline cement was localized in the Chuska Sandstone by a periodically rising water table in dunes in a desert basin and that the source of the silica was "the weathering of volcanic rocks (long since completely eroded) on the margins of the basin."

It does not seem necessary to postulate that the silica was derived from a now nonexistent group of volcanic rocks at some distance from the present outcrops. Recognizable layers of volcanic ash occur at several places in the Chuska Sandstone and Deza Formation (Wright, 1956, p. 416); between 5 and 6 percent of sample 46 is in the less-than- 10-micron size range. X-ray analysis shows the montmorillonite is the only clay in this size fraction. Montmorillonite is essentially a product of the alteration of volcanic rock, especially of natural glass (Grim, 1953, p. 363).

It has been suggested (Deffeyes, 1959) that the principal source of sedimentary zeolites is the diagenetic alteration of volcanic glass. In a few places zeolites have been found intimately mixed with montmorillonite. H. E. Wright (1956) identified heulandite in the cement of the Chuska Sandstone; this mineral has been tentatively identified in sample 46 from Todilto Park.

From the above, it is clear that volcanic ash made up an important part of the original Chuska and Deza sediments. Bentonite and montmorillonitic beds, also derived from volcanic ash, occur in a number of places in the underlying Cretaceous, Jurassic, and Triassic strata.

In most instances, the ash from which montmorillonite and sedimentary zeolites are derived contains an excess of silica; hence, the volcanic ash that was in the Chuska Sandstone and adjacent formations appears to be an adequate source of silica. The migration and localization of the silica as opaline cement may have depended on variations in porosity of the rocks or the pH of the solutions and, therefore, as suggested by Wright, may be related to variations in the position of the water table during diagenesis.

A similar source of silica is also postulated for the secondary quartz outgrowths in the Cretaceous and earlier strata. Those parts of the sections that contained the most montmorillinite would be expected to contain the most secondary quartz, and this is true in a very general way. However, silica has migrated through most of the stratigraphic column, as evidenced by its wide distribution in quartz outgrowths (fig. 15, 16, and 17).

CLAY MINERALS

The X-ray identification of the clay minerals depends largely on basal spacing determined from diffractometer records. Diffractometer charts of typical clay mineral assemblages are reproduced in Figure 25. Kaolinite, illite, montmorillonite, and mixed-layer illite-montmorillonite were identified; minor amounts of halloysite, chlorite, and pyrophyllite may be present in several of the samples.

Each sample was X-rayed dry and again after treatment with glycerol. A few samples, in which the presence of chlorite was suspected, were heated to 600°C and again X-rayed. The dry samples were packed in the usual sample holders and the surface smoothed with a glass slide. This procedure oriented the grains and thus enhanced the basal reflections. Glycerol-treated samples were placed as a thin smear on microslides; this process also resulted in a preferred orientation and an enhancement of basal reflections. Diffractometer charts of untreated samples were made between 2 and 5o degrees 29; charts of treated samples were made between 2 and 20 degrees 20.

The (oo r) and (002) reflections of kaolinite and the (002) and (004) reflections of chlorite roughly coincide. The characteristic (001) 14A peak for chlorite occurs at the same place as several possible montmorillonite peaks and is characteristically weak for iron-rich varieties of chlorite (Grim, 1953, p. 87). The (003) reflection of kaolinite at 37.8 degrees 20 is strong and, if developed, verifies the presence of kaolinite; the (oo6) chlorite reflection, which should occur at the same place, is never present. The chlorite (003) reflection at 18.9 degrees 20 may be strong and, if developed, verifies the presence of chlorite. When the above reflections were not clearly diagnostic, the samples were heated to 600°C; at this temperature, the structure of kaolinite is destroyed and only chlorite peaks are obtained (Grim, 1953, p. 87).

X-ray identification of montmorillonite in the collected samples depended largely on the position of the (001 1) basal reflection before and after treatment with glycerol. Kaolinite, illite, and chlorite are unaffected by this treatment. Under normal conditions, montmorillonite has a first-order basal reflection between 12.5A and 15.5A, depending on whether the exchange ion is sodium or calcium. As pointed out above, these reflections may be confused with the first-order basal reflection of chlorite. However, treatment with glycerol expands the structure and produces a sharp peak 17.7A.

The recognition of the mixed-layer clays and the identification of the two pure minerals, plus the determination of their relative proportions, was based principally on the positions of the 001/002 peak after treatment with glycerol. The positions of the 001/002 peak was measured and compared with the curve prepared by Brown and MacEwan (Brindley 1951, p. 277). Only illite-montmorillonite mixed-layer clay is present in the sections and all specimens are randomly interstratified; systematic series of submultiple high-order reflections were not observed.

X-ray identification of illite is based on the (ool) spacings with the first order occurring at 10A. No attempt was made to differentiate polymorphs or degraded forms.

The relative amounts of the various clay minerals in each of the sample assemblages were estimated by visual comparison of the amplitudes of their basal X-ray peaks and the amplitudes of the X-ray peaks obtained under similar conditions from A.P.I. reference clays. Results obtained in this way are only approximate and, except for the order of relative abundance, are not comparable from sample to sample. For example, the total amount of kaolinite in a sample in which kaolinite is the dominant clay may be less than the total amount in another sample in which it is not the dominant clay.

The collecting and treatment methods employed are such that more elaborate methods of analysis are not justified, as they would give only the appearance of greater accuracy.

Differential thermal curves from the samples of section one were obtained using a portable apparatus. The heating curve for this apparatus flattens abruptly between 75o° and 800°C; hence, only the strongest reactions above this temperature were recorded. The curves obtained are not directly comparable with curves obtained using more elaborate equipment. Hence, differentiation of the sedimentary units in section one based on these curves is largely empirical and may not be reproducible by other investigators.

It is possible, however, to divide the curves obtained into distinct groups, each group containing similar curves (fig. 24). The relationships of these groups to the stratigraphy of section one have been discussed by Willard (in Allen and Balk, 1954). After completion of the differential thermal analysis of the samples from section one, it was decided that more

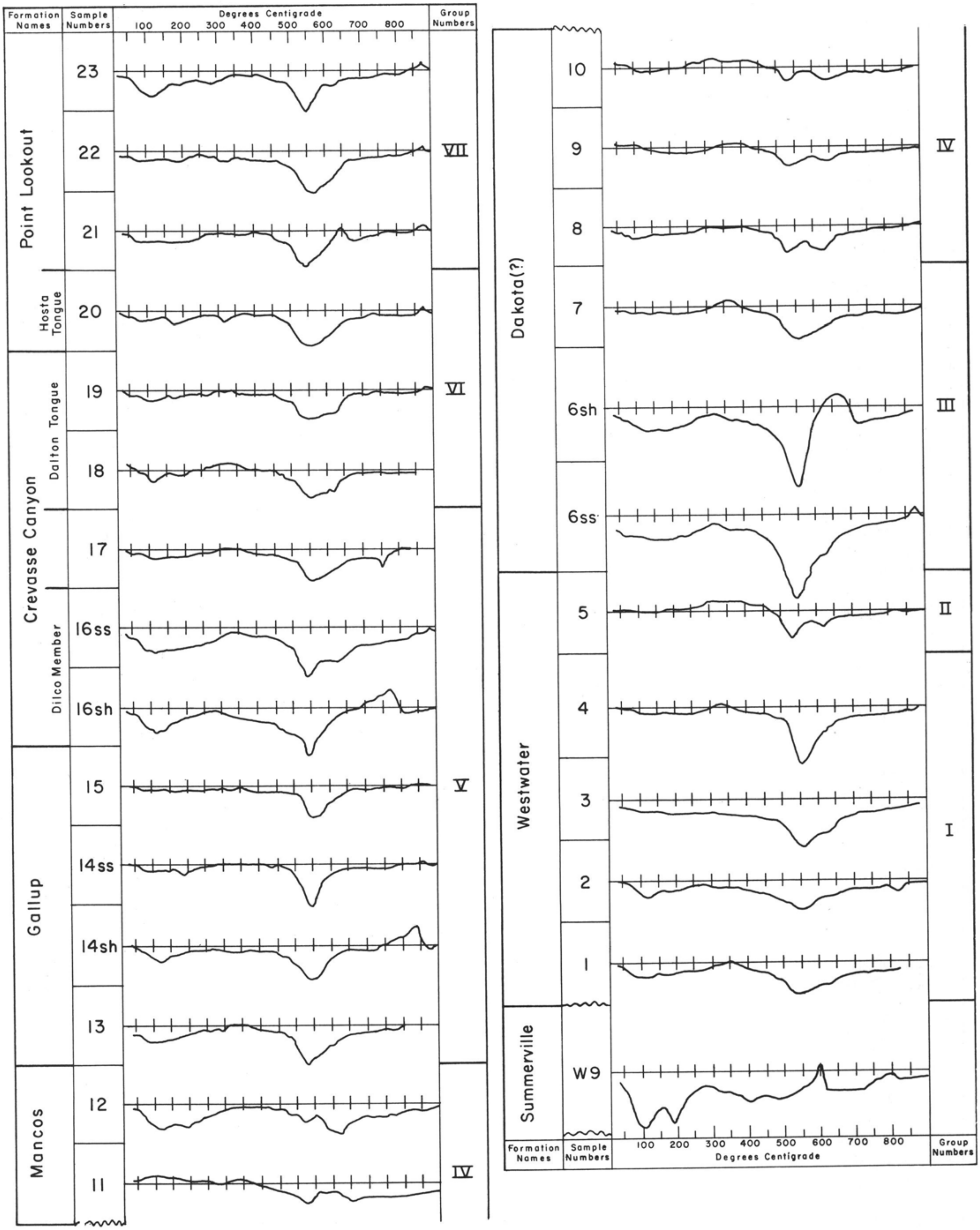

Figure 24

DIFFERENTIAL THERMAL CURVES AND THEIR RELATION TO STRATIGRAPHY OF SECTION I detail and accuracy could be obtained by other means, and this part of the investigation was discontinued.

The distribution of the various clay minerals in the Todilto Park sections is diagrammatically presented in Figure 25.

Kaolinite is the major clay mineral in most of the sediments whether they are of marine or nonmarine origin and regardless of their lithologies. In all three sections, kaolinite is especially abundant in the Dakota(?) Sandstone. Four of the Dakota(?) samples contain only kaolinite.

X-ray charts of samples 14, 3o, and 49 from the Gallup Sandstone in sections one, two, and three indicate basal spacing similar to kaolinite, but the peaks are broad and some are not well defined. These charts suggest the presence of either halloysite or poorly crystallized kaolinite. The uncertainty of the identification is probably due to the fact that the samples had been oven-dried at a low temperature which would have partially dehydrated halloysite. Attempts, using the electron microscope available, to determine which of these minerals was present were unsuccessful. The X-ray charts are unique, however, and were obtained only from samples of the Gallup Sandstone.

Illite is the second most abundant clay mineral in the Todilto Park sections. It is limited in its occurrence to formations below the Menefee, and is present in only two samples from the Jurassic rocks. In none of the samples is illite the major constituent of the clay mineral assemblage. In all samples in which illite occurs, it is associated with kaolinite and in most samples kaolinite is the major constituent. Assemblages made up of only illite, montmorillonite, and/or mixed-layer clay are not present.

In each of the sections, montmorillonite is the major clay mineral in assemblages from the Jurassic Westwater Canyon Sandstone and underlying shale. It is the principal clay in shale layers in the Cretaceous Dakota(?) Sandstone, lower parts of the Mancos, Menefee Formation, and the Tertiary Chuska Sandstone. In the Cretaceous parts of the sections, it is especially abundant in the sandstones and shales of the Menefee Formation. Montmorillonite is the second most abundant clay mineral in the Dalton Sandstone of section one and in those parts of the Mulatto tongue of the Mancos Shale that underlie the Dalton Sandstone in sections two and three. Trace amounts of montmorillonite are present in shale sample 36 from the top of the Crevasse Canyon Formation of section two and in sample 44 from a sandstone bed near the top of the Dakota(?) Sandstone of section three.

CLASSIFICATION OF SANDSTONES

The sandstones in the Todilto Park sections have been classified according to the mineral composition of the detrital fraction (fig. 26). Inasmuch as these rocks are largely clay, feldspar, and quartz, a standard classification based on the ratio of these components was used. The ratio is based upon the percent of clay and very fine silt, as determined during the mechanical analysis, and the percent of quartz and feldspar, as determined by grain counts of the o.125 mm size fraction. These data were recalculated to 100 percent. A ratio thus obtained can be only an approximation of the CQF ratio in the total sample. However, the results are probably no less reliable than the results of thinsection analyses.

Two samples from the Menefee Formation and one from the Westwater Canyon Sandstone are classified as subgraywacke or graywacke; all the rest were either quartzose or feldspathic sandstone. In general, the sandstones in the lower Mancos and the underlying Dakota(?) Sandstone are quartzose; above the Mancos they are feldspathic.

Well samples from the Dakota(?) Sandstone were classified by Burton (1955, p. 84-85), based on thinsection analyses, as principally subgraywackes and quartzose sandstone. From his study, it also appears that the Dakota(?) is generally poor in feldspar, but his samples contained much more clay than the samples from Todilto Park.

Normal sandstones are present above the Mancos Shale; their composition closely approximates the composition of the average sandstone as given by Pettijohn and Clarke (Pettijohn, 1957, p. 293). Sandstones below the Mancos contain several percent less feldspar than the average. As would be expected, these feldspar-poor sandstones are also poor in both variety and quantity of heavy minerals, and the suites include mainly stable minerals.

Calcarenites are not present, but many of the sandstones, particularly from the Crevasse Canyon and overlying formations, contain between Io and 5o percent calcium carbonate cement (fig. 4), and therefore may be further classified as calcareous feldspathic or quartzose sandstone.

DIFFERENTIATION AND CORRELATION OF PETROGRAPHIC UNITS

The Cretaceous sedimentary rocks, on the basis of megascopic field descriptions, have been differentiated into a succession of formations. Further differentiation into mineralogic zones has been accomplished by recognizing essential differences in the detrital accessory and clay minerals and less obvious physical characteristics of the various parts of this sequence of sedimentary units. At places, the limits of the mineralogic and petrographic zones coincide with formation boundaries; elsewhere they do not. This lack of coincidence is due to the fact that formations and mineralogic zones are the result of very different elements of the sedimentations.

A formation is only a convenient mappable unit; lithologically, it is different from the rocks above and below it. Therefore, it need not, and seldom does, have a fixed or recognized relation to time planes. The lithologies that characterize a formation are the product of a special environment or combination of environments. Inasmuch as similar environments do exist at different times at different places during one cycle of sedimentation, the age of a formation may change from place to place. On the other hand, the types and combinations of detrital accessory and clay minerals in a sediment will change, in general, as the composition of the source of supply changes, regardless of the environment in which they are deposited. Hence, mineralogic zones are expected to coincide in time with changes in the composition of the source. They will parallel time planes and, like time planes, will cut across formation boundaries. Theoretically, then, it should be possible to recognize and correlate time-equivalent rock units even though their lithologies change. Practically, this is difficult because of recycling of sediments, intrastratal solution, diagenetic changes, hydraulic effects, and the mixing of sediments from contemporaneous but different distributive provinces. Nevertheless, similar petro-

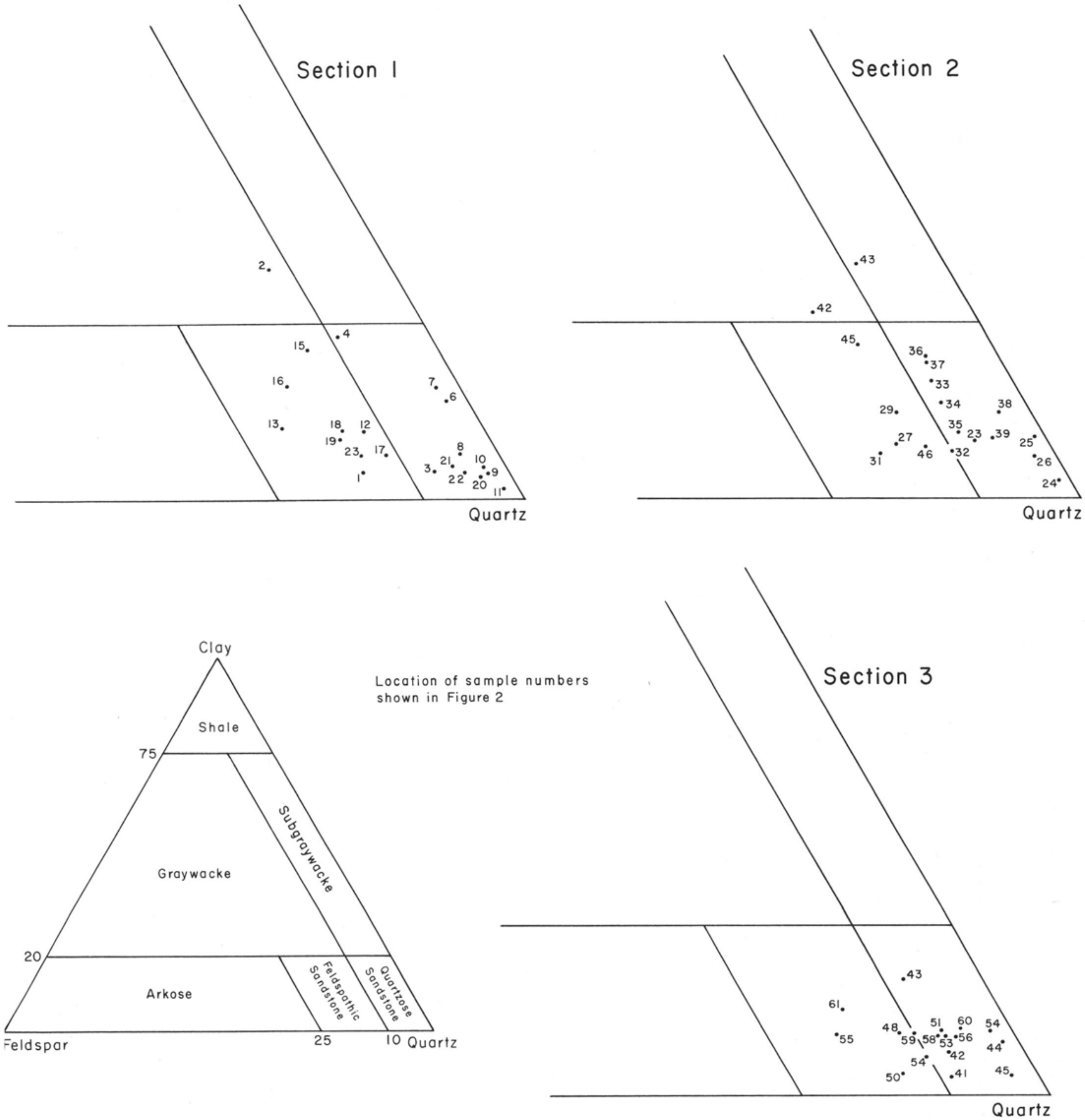

Figure 26
CLASSIFICATION OF SANDSTONES IN THE TODILTO PARK SECTIONS

graphic zones similarly arranged are recognizable in each of the Todilto Park sections.

The degree to which petrographic zoning is carried depends on the number and type of known petrographic features. For example, on the basis of only the "percent soluble," each section can be divided into two parts. The solubility below the top of the Gallup Sandstone is low; above, it is markedly higher (fig. 4). More elaborate description results in more detailed zoning. The zones thus far recognized in the Todilto Park sections are based on changes in heavy mineral assemblages, light mineral assemblages, clay mineralogy, mechanical composition, solubility, inclusions in quartz, and grain morphology. A summary of the results obtained is shown diagrammatically in Figures 25 and 27. Each of the five principal petrographic zones in the Todilto Park sections is recognized by the presence of one or more charac-

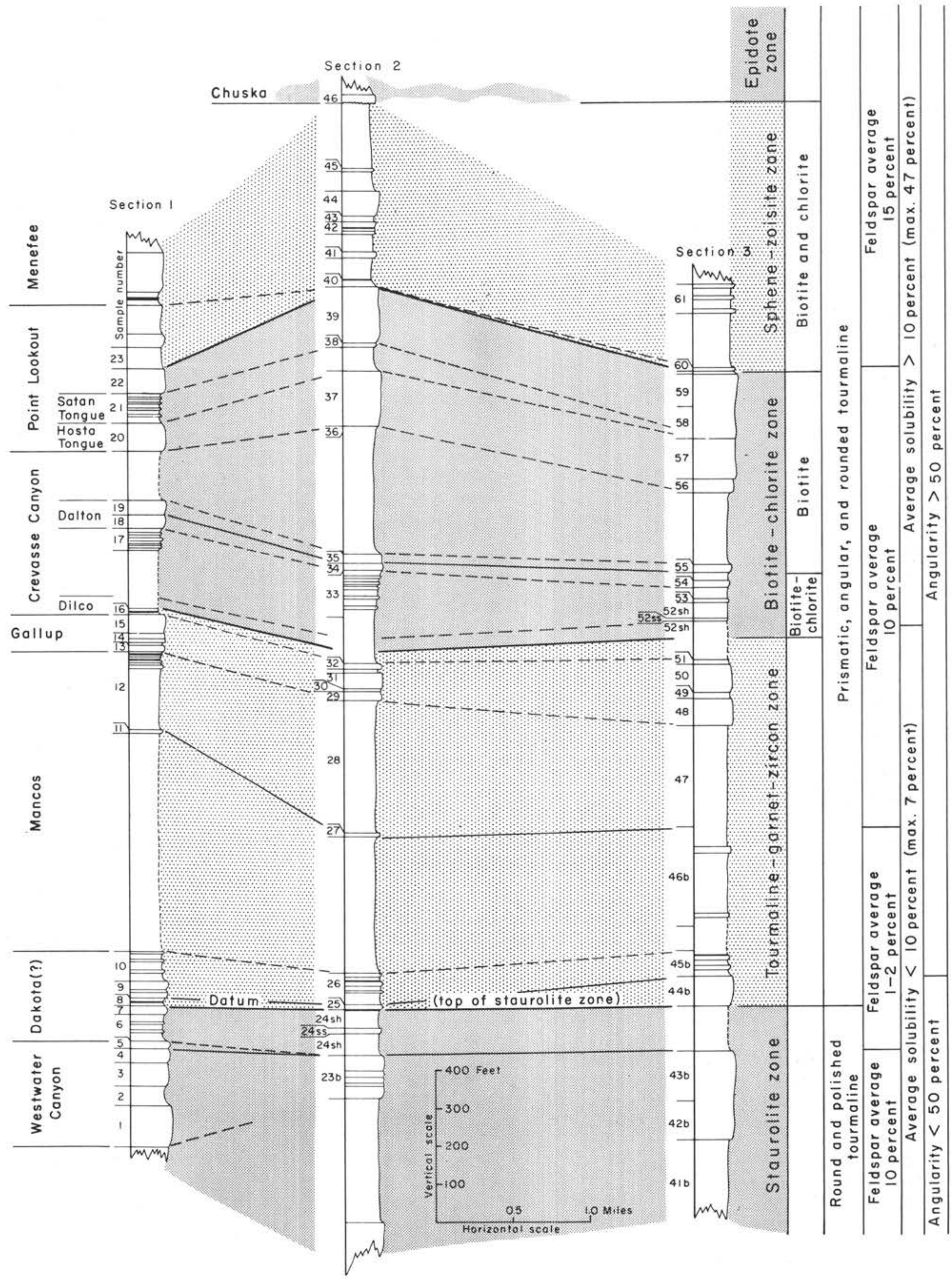

Figure 27

MINERALOGIC AND PETROGRAPHIC ZONATION AND CORRELATION OF TODILTO PARK SECTIONS teristic mineral species, and the zones are named for these minerals. The five petrographic zones shown in Figure 27 are further subdivided on the basis of their clay mineralogy (fig. 25).

STAUROLITE ZONE

In the sections, the Westwater Canyon Sandstone and the lower half of the Dakota(?) Sandstone contain etched staurolite grains. In this staurolite zone, as in all others, tourmaline, zircon, and garnet are present. Most of the tourmaline grains are spherical, well rounded, and highly polished. Prismatic and irregularly angular grains are rare. Zircon grains are sub-rounded, angular, and euhedral. Associated garnets are typically angular, but subrounded grains are present. In this zone, feldspar, principally microcline and orthoclase, ranges from x o percent of the light mineral assemblage in the West-water Canyon to less than 2 percent in the Dakota(?) Sandstone. In the Dakota(?) above the staurolite zone, the percent of feldspar is also low. Solubility within this zone is low, angularity is generally less than 5o percent, and except for staurolite, only highly stable heavy minerals are present. Igneous-type inclusions (irregular and acicular) predominate in the quartz.

The Dakota(?) Sandstone at the top of the staurolite zone is characterized by a high percent of kaolinite. The shale beds in the central parts of the Dakota(?) in sections two and three contain mainly montmorillonite. The clay mineral assemblages from the sandstones below the Dakota(?) were a mixture of kaolinite, illite, and mixed-layer (illite-montmorillonite) clay. Montmorillonite is the principal clay mineral in the shales.

In the construction of Figures 25 and 27, the limits of any of the petrographic zones could have been used as the datum. The top of the staurolite zone was chosen because it is easily recognized, probably is closely parallel to the time planes, and is in the same part of the stratigraphic column as the Dakota(?) Sandstone (the top of which is conventionally used as the reference plane).

At Todilto Park, the top of the Dakota(?) Sandstone and the top of the staurolite zone are roughly parallel and separated vertically by only a few feet. Over greater areas, they may become widely separated and at an angle to each other. The possible amount and direction of this divergence is unknown; to determine the original attitude will require detailed study of a much larger area. Goldstein (195o) reported staurolite as a common constituent of the Dakota(?) Sandstone in the Front Range of Colorado. Its occurrence in the uppermost Triassic and Jurrasic rocks of the Navajo Country was reported by Harshbarger, Repenning, and Irwin (1957). These and other reported occurrences suggest that the staurolite zone may be regionally persistent.

TOURMALINE—GARNET—ZIRCON ZONE

Overlying the staurolite zone is a tourmaline-garnet-zircon zone that in Todilto Park includes the upper half of the Dakota(?) Sandstone, the Mancos Shale, the Gallup Sandstone, and a part of the Dilco Member of the Crevasse Canyon Formation.

Tourmaline, garnet, and zircon are present throughout the Todilto Park sections. Differentiation of this zone is based largely on the fact that these are the only heavy minerals present in abundance. It can be distinguished from the underlying zone by the absence of staurolite and from the overlying zone by the absence of unstable minerals, particularly biotite and chlorite.

In the tourmaline-garnet-zircon zone, black and brown tourmaline predominate, as elsewhere in the sections. Blue-green tourmaline was identified in several of the assemblages but is not uniformly present. Angular, prismatic, and highly rounded tourmaline grains are generally present in this zone. Angular fragments are especially abundant below the Gallup Sandstone. In and above the Gallup Sandstone, prismatic grains are common. This abundance of angular and prismatic tourmaline grains in the tourmaline-garnet-zircon zone is in marked contrast to the predominance of rounded, polished, and spherical tourmaline grains in the underlying staurolite zone.

Colorless to pink, highly angular garnet grains are abundant in this zone. Red and brown varieties are also present but are not uniformly distributed. The surfaces of many of the garnet grains are etched.

Colorless euhedral to subrounded and zoned zircon grains are most common. Angular zircon grains are present in small amount but are not uniformly distributed. Zoned zircon grains, although not confined to this zone, are most abundant in it. They are especially abundant in the Gallup Sandstone and are relatively rare above.

The few sandstones in the lower half of this zone contain one to two percent feldspar, whereas the sandstones in the upper part of the zone are roughly ten percent feldspar. The feldspars are principally orthoclase and microcline; only a few plagioclase grains were observed.

In this zone, the solublity is low (7 percent) and angularity is markedly higher (5o to 7o percent) than in the underlying staurolite zone. Irregular and acicular (igneous type) inclusions are by far the most abundant types in the quartz. Metamorphic quartz, with no inclusions, is rare but was observed in a sample from the upper part of the Mancos Shale.

In the tourmaline-garnet-zircon zone and the underlying zone, leucoxene is the dominant opaque heavy mineral, often making up more than 5o percent of the heavy mineral suite. A small amount of magnetite-ilmenite is present in a few samples but is generally absent. There is a marked decrease in the combined amount of leucoxene and magnetite-ilmenite above this zone (fig. 23).

The clay mineralogy of the less-than-10-micron size fraction divides the tourmaline-garnet-zircon zone into three parts. The lower part, which at Todilto Park includes the upper half of the Dakota(?) Sandstone, contains kaolinite and illite. Above this, in the Mancos Shale, the assemblage is dominantly montmorillonite with lesser amounts of kaolinite. The upper half of the zone through the Gallup and part of the Dilco contains, in order of abundance, kaolinite, illite, and montmorillonite-illite mixed-layer clay. The montmorillonite in the lower part of the Mancos Shale may occur in distinct bentonite beds, as observed elsewhere by Dane (196o), or may be disseminated through the shale. Because of the sampling methods, its mode of occurrence at Todilto Park is unknown.

BIOTITE—CHLORITE ZONE

Biotite and chlorite are the dominant heavy minerals in a zone that at Todilto Park includes much of the Crevasse Canyon and Point Lookout formations. In stratigraphic sections two and three, the upper limit of the biotite-chlorite zone coincides with the Point Lookout—Menefee contact. In section one, the Menefee contact as tentatively located by Allen (1954, pl. 1) is approximately 8o feet above the top of the biotite-chlorite zone (fig. 27) and a change in clay mineralogy that coincides with the top of the zone (fig. 25).

Biotite is generally the most abundant of the heavy minerals in this zone. This is especially true above the Dalton Sandstone, where it may make up as much as 25 to 5o percent of the heavy mineral suites. Chlorite is not so abundant and is not uniformly present; it is most common in the Dalton Sandstone and the immediately underlying sediments. Muscovite is most abundant in the biotite-chlorite zone.

Tourmaline, garnet, and zircon are present. Prismatic tourmaline is more common than in underlying zones. Pink to colorless angular garnet is common, and angular and euhedral zircon grains are abundant. Small, euhedral zircon crystals attached to quartz are present in a few samples. The ratio of tourmaline to zircon is essentially the same as in the underlying zone, but there is a slight increase in the amount of angular garnet.

At the base of the biotite-chlorite zone, there is a marked decrease in the combined percent of leucoxene and magnetite-ilmenite, but upward, the amount increases until it is approximately equal to the amount in the underlying mineral zones.

The light mineral fraction averages 10 percent feldspar and angularity is high. Inclusions in the quartz are of igneous types, but regular inclusions and grains with none (characteristic of metamorphic rocks) are present in a number of samples. The bulk samples from this zone are usually more than 10 percent soluble.

Kaolinite and illite are the principal clay minerals in this part of the Cretaceous section. However, there is a thin kaolinite-montmorillonite zone that includes the Dalton Sandstone in section one and a part of the Dalton and underlying siltstones and sandstones in sections two and three (fig. 25). The upper limit of the biotite-chlorite zone coincides with a change to a clay mineral assemblage consisting largely of montmorillonite.

SPHENE—ZOISITE ZONE

The sphene-zoisite zone includes all the Menefee Formation in sections two and three and the Menefee and the upper parts of the Point Lookout Sandstone in section one. These upper parts of the Point Lookout were tentatively assigned to that formation by Allen (1954) on the basis of the thicknesses of the formation in the other two sections. It appears now, on the basis of the petrographic data, that the upper contact of the Point Lookout in section one should be relocated as shown in Figure 27. The thickness is then less than in the other two sections, but the lithologic sequences are similar.

One or two grains of zoisite occur at places below the sphene-zoisite zone. Within this zone, zoisite makes up from 2.5 to 12 percent of the heavy mineral assemblages. Sphene is absent below this zone, but within it, the heavy mineral suites are between 2.5 and 6 percent sphene. Epidote is present in the sphene-zoisite zone and below but in relatively small amounts. It is the principal heavy mineral in the overlying Chuska Sandstone.

Biotite, chlorite, tourmaline, garnet, and zircon are all present, and their characteristics are similar to those in the underlying zone.

Leucoxene, magnetite, and ilmenite are present in about the same amounts as in the underlying zone, but the relative amount of magnetite-ilmenite increases. Leucoxene alteration crusts are present on both ilmenite and sphene.

All samples from this zone effervesce and are between Io and 40 percent soluble.

Highly rounded to completely angular grains are present in all samples; the average angularity is generally greater than 5o percent. In the heavy-mineral suites, angular, euhedral, and rounded sphene grains are present. Irregularly and regularly outlined flakes of biotite are common and both types show undulating extinction. Most tourmaline and zircon grains are prismatic or angular.

Inclusions in the quartz of this zone are predominantly igneous types. Grains containing metamorphic-type inclusions are present, however, and in amounts greater than in any of the underlying rocks. Pitted fragments of opaline cement are common in disaggregated samples from the sphene-zoisite zone. Pitted fragments were not observed below this zone, but are abundant in the overlying Chuska Sandstone.

Feldspar is more abundant in this zone than in any of the underlying zones, averaging 15 percent of the o.125 mm size fractions. Fresh to moderately altered potassium feldspars are most common; a few grains of plagioclase are present.

There is a marked change in the clay mineralogy above the base of the sphene-zoisite zone. All samples in this zone contain montmorillonite and kaolinite. Montmorillonite is the most abundant and is present in sufficient amount in the clay mineral fractions to produce positive benzidine dihydrochloride tests.

EPIDOTE ZONE

The Chuska Sandstone is present only in section two and its heavy mineral assemblage is distinctly different from the assemblages from underlying parts of the section. It is characterized by an abundance of epidote, dark brown and green hornblende, and deep red garnet. Small amounts of sphene and zoisite are present. A few basal plates and angular grains of brown, black, and blue-green tourmaline are also present. Biotite is absent. Magnetite-ilmenite and leucoxene are abundant.

In the epidote-rich zone, grains range from completely rounded to sharply angular. The average angularity is 49 percent. In the heavy mineral suite, epidote is the most highly rounded mineral, tourmaline the least rounded. In this zone there are a large number of quartz grains with none or regular inclusions. The remaining grains contain igneous-type vacuoles that are aligned in planes. There is a small amount of secondary growth on some of the quartz. The light fraction contains many pitted fragments of opaline cement. Approximately 15 percent of the 0.125 mm fraction is feldspar, most of which is potassium feldspar; a few grains of plagioclase are present. Montmorillonite is the only clay mineral in this zone.

The characteristics of the epidote zone, as given above, are based entirely on a single sample collected from section two at Todilto Park. Bingler (1961) has recently described a stratigraphic section at Sanostee, New Mexico, 35 miles north-northwest of Todilto Park. Petrographically and mineralogically, the Chuska Sandstone in the Sanostee section and in section two at Todilto Park are the same. The existence of this similarity at these two widely separated occurrences of the Chuska justifies at least tentative acceptance of the epidote zone.

At Todilto Park, epidote as an essential heavy mineral is limited to the Chuska Sandstone. Inasmuch as formations below the Chuska and above the Menefee are not represented in the Todilto Park sections, the lower limit of the epidote zone could not be established. Epidote, however, occurs as an essential mineral in the Fox Hills Sandstone and Laramie Formation in the Colorado Front Range (Goldstein, 195o) and may be expected in equivalent formations below the Chuska in New Mexico.

ENVIRONMENT OF DEPOSITION

In general, the sandstones of the Todilto Park sections are fine-grained and well sorted, and their frequency curves are leptokurtic and slightly skewed, principally on the positive side. These data suggest that in general the Todilto Park sandstones are products of a large amount of reworking in a medium- to low-energy level environment.

In the Todilto Park sections there are no abrupt large-scale changes in the mechanical composition of the sediments (table 2). Hence, it can be concluded that there were no rapid changes in the tectonic framework during their deposition.

Minor and gradual changes do occur. Grain size decreases slightly in the upper parts of the sections. The graphic standard deviations decrease gradually from the base through the Point Lookout, then increase in the Menefee. Skewness is approximately the same from the Dakota(?) through the Point Lookout; it is greatest in the Westwater Canyon and Menefee. Slight negative skewness is common in the Point Lookout; the majority of samples from the rest of the formations contain an excess of fines. These changes suggest that as sedimentation proceeded from deposition of the Dakota(?) through the deposition of the Point Lookout, there was a gradual decrease in the energy level, a decrease in the rate of deposition, and an increase in the amount of reworking. This gradual decrease in the energy level suggests an interval of tectonic quiescence during which erosion and deposition were able gradually to lower the slope of the profile of equilibrium.

Above the Point Lookout, the sediments are not so well sorted, the average grain size distribution is less peaked and less symmetrical, and the average grain size decreases slightly. Similar changes in sediments elsewhere have been interpreted as indicating an increase in the rate of subsidence and a proportional increase in the rate of sedimentation (Cadigan, 1961, p. 137). Simple continuous basin filling without subsidence or uplift, however, could also produce the observed differences. As filling of the basin progressed, backshore, non-marine, and transitional deposits would encroach on the earlier beach and neritic sediments. Typically, backshore deposits are subjected to less reworking than contemporaneously deposited beach sediments and so would differ mechanically from adjacent beach sediments in very much the same manner as the Menefee differs from the Point Lookout. Under these conditions, no major change in the tectonic framework of the region is required. In the Todilto Park area, the Menefee represents only the culmination of a process of basin filling.

Phleger and Ewing's (1962) study of the recent sediment in coastal lagoons off Baja California, Mexico, demonstrated a difference in the mechanical composition of deposits in the various environments. Most of the dune, beach, and intertidal flat sediments show no skewness and are fine-grained, well-sorted sands. Lagoon channel samples, believed to have been subjected to river processes, are coarser and more poorly sorted; most have positive skewness.

Friedman (1961) suggests that the third moment (skewness) is sensitive to environment differences and that degree of sorting is of help in distinguishing beach from river sand. His plot of the third moment against the standard deviation gives a separation into two fields, one representing beach sand and the other river sand. Friedman's samples were collected from rivers, ocean beaches, and Great Lake beaches. They were taken parallel to the bedding, where possible, to avoid mixing of populations. The Todilto Park samples were taken from the sedimentary units that make up the measured sections. The samples from these units are composites. They represent material deposited below a number of depositional interfaces each of which undoubtedly had been exposed to slightly different energy levels. Hence, the Todilto Park samples probably represent mixtures of several populations. This difference in the nature of the samples creates a problem that will always arise when Friedman's conclusions are applied to sedimentary rocks. Comparison with Friedman's results is further complicated when, as in the Todilto Park study, different methods of mechanical analyses and calculation are used. Nevertheless, the results of such a comparison are useful.

In Figure 28, the skewness of the Todilto Park samples is plotted against the graphic standard deviation. The separation between the nonmarine Menefee and the marine Point Lookout Sandstone, although not coinciding numerically with that reported by Friedman, is marked. On the basis of this separation, the diagram is tentatively divided into non-marine and marine fields. The variation in skewness of the samples is slight and the separation of points is largely dependent on the degree of sorting. However, samples in the nonmarine field tend to have slightly greater positive skewness which, as pointed out, was suggested as a characteristic of sediments subjected to river processes.

Few of the Todilto Park formations, because of the nature of Cretaccous sedimentation, can be considered as products of a single environment. In general, each formation is dominantly marine or nonmarine, but each contains sedimentary units of both origins. This conclusion is supported by the distribution of points shown in Figure 28.

The sedimentary units of the predominantly nonmarine Crevasse Canyon Formation fall largely in the nonmarine field. The Gallup Sandstone points are principally in the nonmarine field, which suggests that at Todilto Park the Gallup sediments were largely deposited in the shoreward part of a transitional environment. The Gallup is generally considered to be a beach deposit. The Mancos sandstones fall in both fields. The Dakota(?) points, as would be expected, are widely distributed but largely on the marine side.

The range in sorting of the various sedimentary units making up any of the Cretaceous sandstone formations at a particular place may be an indication of whether it was deposited during a stillstand of sea level or during an interval of rising sea level. Sedimentation during a stillstand will

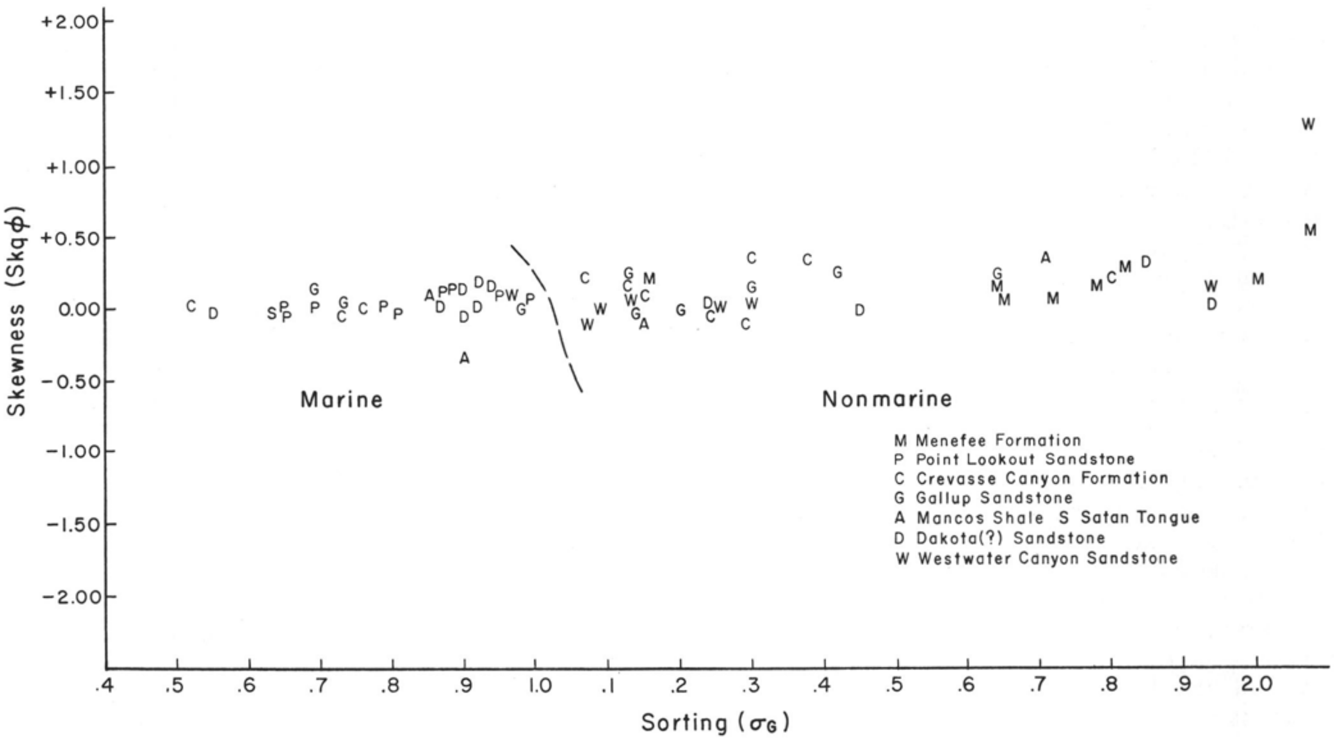

Figure 28

PLOT OF GRAPHIC STANDARD DEVIATION AND SKEWNESS FOR TODILTO PARK SAMPLES, USING PHI (φ) SCALE

result in regression of the shoreline. Rising sea level, depending on rate of rise and sedimentation, may cause either transgression or regression. A formation deposited during a stillstand regression will be in large part the product of a single environment. Hence, physically, the sedimentary units making up such a formation will be similar and the range of sorting small. During rising sea level, a less stable environment will exist and the resulting transgressive and regressive sediments will be less well defined, and the physical parameters of the sedimentary units will have a much greater range. These relations are suggested by the data from the Todilto Park sections.

The Point Lookout Sandstone has been interpreted as a product of one of the major Cretaceous stillstand regressions. The sedimentary units that make up this formation at Todilto Park are similar and have a limited range in sorting. The Gallup Sandstone is made up of numerous discontinuous sedimentary units that differ widely in gross lithology and sorting. Both marine and nonmarine units are present. From this, it appears that although in general regressive, the Gallup Sandstone in detail is a product of alternating intervals of relatively small-scale transgression and regression and was deposited during a period of rising sea level. The Dakota(?) Sandstone, which is transgressive and certainly was deposited during an interval of rising sea level, includes sedimentary units of various lithologies that have a wide range of sorting.

DIAGENETIC AND EPIGENETIC ALTERATIONS

The lack of precision in the term *diagenesis* has been recognized by many. It has even been suggested that its use be discontinued and elaborate terminology has been proposed to modify or take its place (Teodorovich, 1961, p. 8-16). Diagenesis as defined by Twenhofel (1932, p. 108) embraces all modifications of sediments which occur between deposition and lithification. All changes in lithified rock, except metamorphism, are products of epigenesis. Packham and Crook (1960, p. 392) subdivide diagenesis into halmyrolysis, early diagenesis, and epigenesis. They include, in epigenesis, alterations *under* "deep-seated conditions." Diagenesis, as they have defined it, includes all changes that occur in sediments and sedimentary rocks prior to actual metamorphism.

Twenhofel's definitions seem to be the most useful for the discussion of the many alterations that have occurred in the mineralogy of the Todilto Park Cretaceous sediments. The abundance of hematite and of authigenic TiO_2 poly-morphs, the development of etched surfaces on garnet and staurolite, glassy polish on tourmaline, the devitrification of volcanic ash with the formation of montmorillonite, the presence of outgrowths on quartz, the presence of barite, and the calcite and opaline cements are evidences that diagenetic and epigenetic alteration, have taken place in these rocks.

Montmorillonite, especially in those marine strata where it predominates, probably formed during or shortly after deposition. Mixed-layer clay may have resulted from the degrading of detrital illite during transportation and deposition. Illite, which characteristically forms in alkaline nonleaching conditions, may have developed in part in the marine sediments during their deposition. The authigenic minerals, anatase, rutile, brookite, and pseudobrookite, probably formed after consolidation of the sediment. They are most abundant in the unsealed parts of the sections. Barite and calcite are probably epigenetic. Calcite is most abundant in the nonmarine parts of the sections where there is no evidence of a fossil source. The calcite must have been introduced from without or have been formed by direct precipitation during sedimentation. If calcite is mixed with sand, and sand dominates, the calcite is generally thought of as secondary and introduced. Opaline cement is present only in the nonmarine sediments; if derived from the alteration of volcanic ash, as postulated, it must have formed after deposition of the sediments. Quartz outgrowths, especially where not associated with montmorillonite, must have been introduced and, like opal, may be either diagenetic or epigenetic. The etched garnet and staurolite grains are so fragile that they could not have been transported in their present form. They must have been etched in the deposit, probably after its consolidation.

The material present and the nature of the chemical environment have determined the character of the observed epigenetic and diagenetic alterations. These alterations may be related to the environment of deposition, or they may be related to later and very different chemical conditions. The works of Stevens and Canon (1948) and of Packham and Crook (196o) are especially useful in the interpretation of the observed alterations.

Stevens and Canon ground minerals in water and determined the pH of the resulting suspension; this they called *the abrasion* pH. In table 3, the principal authigenic and detrital minerals in the Todilto Park sections have been arranged according to their abrasion pH's.

TABLE 3. DETRITAL AND AUTHIGENIC MINERALS ARRANGED ACCORDING TO ABRASION pH

	Authigenic	
< pH 7	pH 7	> pH 7
opal		calcite
pyrite		
barite		
anatase		
brookite		
leucoxene		
hematite		
quartz		
kaolinite		
rutile		
	Detrital	
rutile	spinel	talc
*staurolite	*garnet	actinolite
zircon		augite
quartz		apatite
montmorillonite		*zoisite
kaolinite		*epidote
		*sphene
		*chlorite
		*biotite
		*tourmaline
		plagioclase
		*K-feldspar
		muscovite

pH values from Stevens and Carron (1948).
*Show evidence of solution and alteration.

Packham and Crook (1960) have concluded that reaction, solution, or alteration may be expected when a mineral of alkaline abrasion pH is placed in an acid environment. A similar result may be expected when the mineral is acid and the environment alkaline. They also concluded that, in general, minerals with alkaline abrasion pH's will not form under markedly acid conditions and vice versa.

The authigenic titanium minerals in the Cretaceous heavy mineral suites are the same minerals that have been identified in altered "black sands" and bauxite deposits throughout the world. From the chemistry of the constituents in bauxite, Hartman (1959) surmised that the pH of the solutions responsible for the alteration of the parent material must lie between 4 and 10. Most of the authigenic titanium minerals in the Cretaceous sandstones, and probably in many bauxite deposits, were derived from ilmenite, with small amounts being produced from the alteration of sphene. Alteration of ilmenite with the solution of iron can occur only in acid; it is also likely that sphene, with an abrasion pH of 9, would only be altered in an acid solution.

Authigenic outgrowths on quartz, present at many places in the Cretaceous sandstones, and the opaline cement in the Chuska Sandstone very probably were deposited in an acid environment. The transporting solutions probably were alkaline. This can be inferred from the abrasion pH and is established by the fact that silica is only slightly soluble in acid and that its solubility increases rapidly with rising pH. Devitrification and alteration of volcanic ash is suggested as the source of the opaline cement and of the montmorillonite in the Chuska and some of the secondary quartz elsewhere. If, as in most instances, the ash contained an excess of alkalies as well as silica, then probably this was the source of the silica and the transporting solutions. Dilution could be the cause of precipitation. A part of the secondary outgrowths on quartz may also represent the precipitated silica that is normally dissolved in marine connate water.

Alkaline detrital heavy minerals are common above the Gallup Sandstone, and most of them show effects of partial solution and alteration. Chlorite (pH 7-8-9) and biotite (pH 8-9) grains are bleached. Sphene (pH 9), characteristic of the Menefee, is pitted and altered to leucoxene. Tourmaline (pH 7-8) is present throughout the sections and is unaltered, except possibly for the glassy polish on many of the grains in the Dakota and Westwater Canyon sandstones. This possibility is suggested because abrasion tends to produce a mat surface, but if subjected to solution for a sufficient time, the mat surface is lost and the grains will become shiny. Highly etched garnet (pH 7) is present in most of the Cretaceous sandstones and is especially abundant in the Menefee sandstones. Zircon (pH 6), present in all parts of the sections, is principally angular or euhedral and shows no evidence of either solution or alteration. Magnetite and ilmenite are present in relatively small amounts above the Westwater Canyon Sandstone and below the Menefee (fig. 22). They are most abundant in sealed shale-siltstone environments.

The above data suggest that most of the observed alteration was produced by acid solutions. However, the solutions that produced the delicate etched staurolite (pH 5-6-7) grains in the Dakota(?) and Westwater Canyon sandstones probably were alkaline. These alkaline solutions may be related to the alteration of volcanic ash. Their effects were localized in the part of the Cretaceous section that contained the most montmorillonite.

Acid and alkaline intrastratal solutions are capable of modifying the heavy-mineral suites. The actual assemblage is a function of both source rock composition and the ability of the mineral to persist through the diagenetic and epigenetic environments. The extent to which the original assemblage has been modified must be evaluated before a discussion of provenance is justified.

The persistence of the heavy minerals in the Todilto Park sections is summarized in Figure 29. In this figure, the minerals are arranged in accordance with the "order of per sistence" reported by Pettijohn (1941).

In all the sections, the least stable heavy minerals are most abundant and confined to strata above the Mancos Shale. Feldspar also is most abundant in the upper parts of the sections (fig. 23). There is no apparent relation between the amount of feldspar and its degree of alteration. Hence, it seems that the differences in amounts are largely initial differences and not related to intrastratal solution. The appearance of biotite and chlorite coincides with the increase in amount of feldspar. The less stable minerals, with the exception of staurolite, are also associated with this increase. Staurolite, one of the least stable minerals, is most abundant in Dakota sandstones which contain less feldspar than any of the other Cretaceous sands. In the Jurassic Westwater Canyon Sandstone, staurolite is associated with a marked increase in the amount of feldspar.

In the Cretaceous sandstones, the appearance of less stable heavy minerals and the increase in amount of feldspar are accompanied by a marked change in grain morphology. The percent of angularity based on measurement of the light minerals increases (fig. 14). There is a decrease in amount of highly rounded tourmaline; prismatic and angular grains become abundant. In general, there is a decrease in the amount of rounded zircon.

All the changes in mineralogy and grain morphology occur rather abruptly and at the same place in the sections. This suggests that although intrastratal solutions produced some alterations, they did not greatly modify the original assemblages.

PROVENANCE

The detrital grains in the Cretaceous sandstones at Todilto Park were derived from igneous, metamorphic, and sedimentary sources. The amounts contributed by each of these sources varied. Below the Gallup Sandstone, sedimentary rocks were the principal immediate source; the ultimate source was largely igneous. In the Gallup Sandstone and overlying parts of the sections, the immediate source was partly sedimentary and partly crystalline rocks. The crystalline source rocks were largely metamorphic; intermediate igneous rocks contributed small amounts.

Pettijohn (1957, p. 66) has concluded that only well washed, many-times-reworked sediments are well rounded or even moderately rounded. Below the Gallup Sandstone, rounding of both the light and heavy minerals is high. In the Gallup and overlying sandstones, the grains are more angular, generally more than 5o percent (fig. 14). In the upper parts of the sections, angularity of quartz in the 0.125 mm size fraction of a single sample ranges from o to 10o percent. Typically, the quartz is more highly rounded than the associated feldspar. This abnormal relation between hardness and rounding and the occurrence of rounded and angular quartz grains in one grain size indicate a multiple source for the Cretaceous and Chuska sandstones.

Rounded and nonrounded heavy mineral grains are distributed in the Todilto Park sections in the same way as the light minerals. Most of the tourmaline grains in the Dakota(?) and Westwater Canyon sandstones are highly polished, well rounded, and highly spherical. In the Gallup and above, prismatic and angular grains are abundant. Euhedral and angular zircon grains are in all the samples. The Dakota(?) and Westwater Canyon sandstones contain many well-rounded zircon grains. Sphene and zoisite that occur above the Gallup are euhedral or angular. Biotite, which is characteristic of the upper parts of the sections, oc-

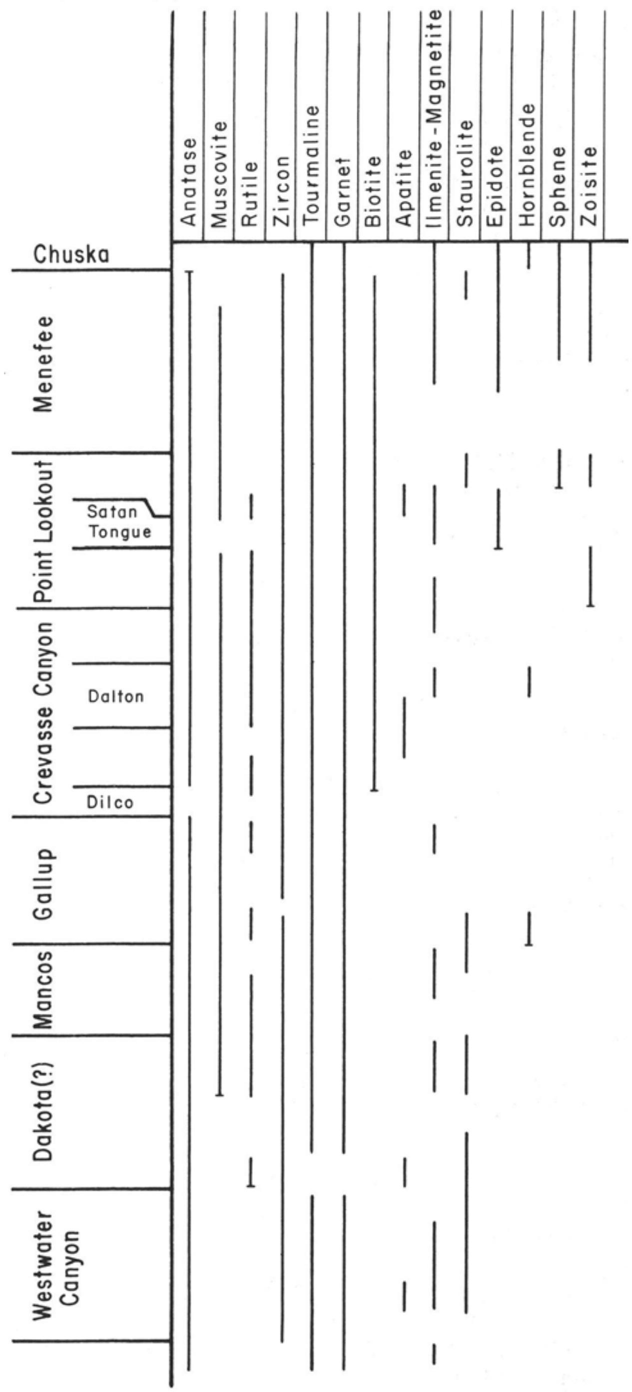

Figure 29
PERSISTENCE DIAGRAM

curs in euhedral or irregular flakes. Garnet, present throughout the sections, is for the most part sharply angular. Epidote in the Chuska and adjacent Cretaceous sediments is well rounded.

From the foregoing, it appears that below the Gallup the immediate source of most of the deposits was pre-existing sedimentary rocks and that in the Gallup and overlying sediments the immediate source of a significant part of the sediments was crystalline rocks. The rounded epidote in the Point Lookout, Menefee, and Chuska probably has been through more than one cycle of sedimentation.

The nature of the crystalline sources of the first cycle and multicycle sediments in the Todilto Park sections can be inferred from their mineralogy. Detrital mineral suites characteristic of various source rock types are listed in Table 4 (Pettijohn, 1957, p. 513).

TABLE 4. SOURCE ROCKS OF DETRITAL MINERALS
(Italicized species are present in the Todilto Park samples)

Reworked Sediments	
Barite	*Rutile*
Glauconite	*Tourmaline, rounded*
Quartz	*Zircon, rounded*
Quartzite fragments	
Leucoxene	
Low-rank Metamorphic	
Slate and phyllite fragments	*Quartz and metaquartzite*
Biotite and muscovite	*Tourmaline* (brown euhedra carbonaceous inclusions)
Chlorite	
Feldspars generally absent	*Leucoxene*
High-rank Metamorphic	
Garnet	*Staurolite*
Hornblende (blue-green)	*Quartz*
Kyanite	*Muscovite and biotite*
Sillimanite	*Feldspar*
Andalusite	*Epidote*
Magnetite	*Zoisite*
Acid Igneous	
Apatite	*Sphene*
Biotite	*Zircon, euhedra*
Hornblende	*Quartz*
Monazite	*Microcline*
Muscovite	*Magnetite*
	Tourmaline (pink euhedra)
Basic Igneous	
Anatase	*Leucoxene*
Augite	Olivine
Brookite	*Rutile*
Hypersthene	*Plagioclase, intermediate*
Ilmenite and magnetite	Serpentine
Chromite	
Pegmatites	
Fluorite	*Muscovite*
Tourmaline, blue	Topaz
Garnet	Albite
Monazite	*Microcline*

Staurolite, present in the lower half of the Dakota(?), is characteristic of high-rank metamorphic rocks. Staurolite is commonly associated with garnet, kyanite, and sillimanite in schists. In the heavy-mineral suites from the Dakota(?), it is associated with garnet and probably kyanite.

Zircon characteristic of acid igneous rock is present throughout the sections. The occurrence of mixtures of zoned, unzoned, rounded, and euhedral zircon in many of the samples suggests a mixed crystalline and sedimentary provenance. The observation that the colorless and light lavender zircon grains fluoresce and that the colorless and deeply colored, rounded grains do not implies that they are from different ultimate sources. Callender and Folk (1958) suggested that abundant euhedral zircon may be a key to volcanism. These authors reported a marked increase in the amount of zircon in the volcanic-rich Tertiary sands of central Texas. In the Todilto Park sediments, no such relation exists. The amount of zircon does not increase systematically with the appearance of bentonite beds or with an increase in the amount of montmorillonite.

Tourmaline, one of the most uniformly distributed minerals in the Cretaceous sandstones, may be derived from metamorphic, pegmatitic, or acid igneous rocks. Brown-black and blue-green varieties predominate; very minor amounts of colorless and pink tourmaline are present. These relations suggest that the ultimate source of most of the tourmaline was pegmatites and low-rank metamorphic rocks. The diversity of types suggests that the immediate source was a provenance of sedimentary rocks (Krynine, 1946).

Garnet, which occurs throughout the Cretaceous at Todilto Park, is characteristic of igneous and metamorphic rocks, especially gneisses and schists. Red, pink, and colorless varieties predominate and all are sharply angular.

Biotite, common above the Gallup Sandstone is characteristic of igneous and low-rank metamorphic rocks. Its close association with detrital chlorite, which is derived principally from metamorphic rocks, suggests that most of the biotite is also metamorphic. Muscovite, present throughout the sections, may also be derived from either igneous or metamorphic sources. Many of the mica flakes have the undulose extinction that is common in metamorphic rocks.

Sphene, abundant in the Menefee and Chuska, is characteristic of granite, intermediate igneous rocks, and metamorphic rocks such as gneisses, schists, and altered limestones. It is not a common detrital mineral, and because it has low abrasion resistance probably will not persist through more than one cycle of transport.

At Todilto Park, zoisite is associated with the sphene. Zoisite is usually derived from schists, amphibolite, and altered basic igneous rocks. Like sphene, it has low abrasion resistance and is seldom derived from the reworking of earlier sediments. Epidote, which is also common in the Menefee and Chuska sandstones, is also derived principally from amphibolites, altered basic igneous rocks, and altered limestones.

Magnetite and ilmenite, although now much altered, were originally abundant. They are characteristically derived from basic igneous rocks. The ultimate source of much detrital rutile is also basic igneous rocks, but because of its persistent character, its immediate source is commonly sedimentary rock. Rutile in small amounts is scattered through most of the Todilto Park samples.

Hornblende, present in the Gallup and Dalton sandstones and especially abundant in the Chuska Sandstone, may have been derived from metamorphic source rocks, for it is largely of the blue-green variety.

Apatite occurs in several samples and is most common above the Gallup. It is commonly derived from igneous rocks, especially granites, syenites, and pegmatites. It may also be derived from metamorphosed limestones.

Below the Gallup, rounded and angular detrital chert grains are present in each of the sections. This is one of the best indications that those sediments were in part derived from earlier sedimentary rocks.

The potassium feldspars in all the Todilto Park samples may have been derived from either an igneous or metamorphic source. The plagioclase in the Crevasse Canyon, Menefee, and Chuska sandstones may have been derived from intermediate igneous rocks, but its association with sphene, epidote, and zoisite suggests a metamorphic source. Inasmuch as feldspars are very susceptible to chemical decay and have a relatively low abrasion resistance, it seems unlikely that they were derived from earlier sediments. The angularity and freshness of the feldspar in the Crevasse Canyon especially supports this conclusion.

As already noted, the Todilto Park samples contain both igneous and metamorphic types of quartz, and in general igneous types predominate. Metamorphic types are most abundant in the Gallup and overlying strata. The metamorphic type (without inclusion) is especially abundant in the Chuska. From this, it is concluded that the ultimate source of most of the quartz is igneous, but that from the Gallup up, a significant part was derived from metamorphic sources.

The provenance characteristics suggested are summarized in Figure 3o, which is based on the following assumptions:

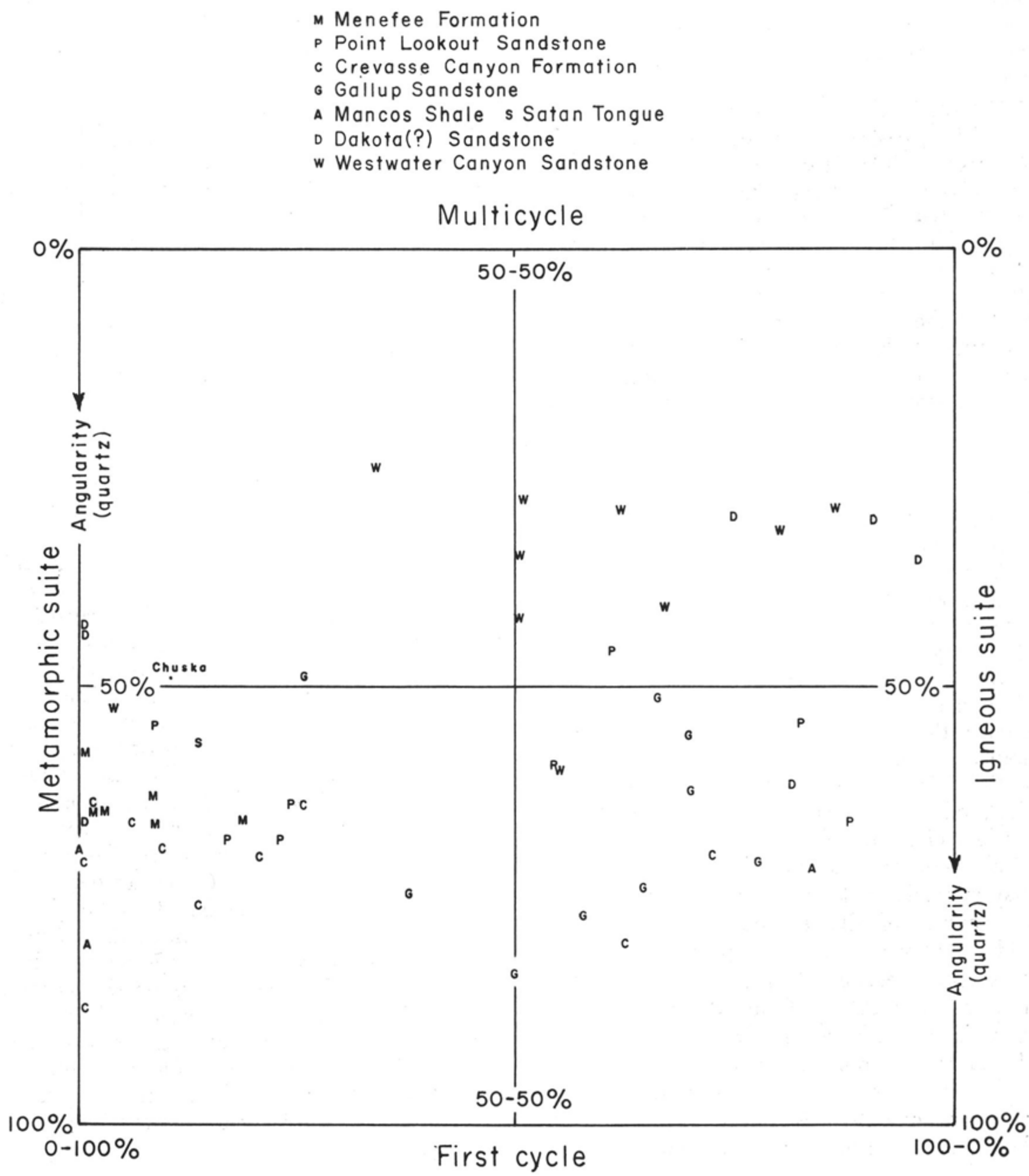

Figure 30
SUMMARY OF PROVENANCE CHARACTERISTICS

(I) that a 100-percent angular sediment would be a first cycle sediment, (2) that a 100-percent rounded sediment would be a multicycle sediment, and (3) that the heavy-mineral suite (zircon, sphene, apatite) is characteristic of igneous rocks and the suite (chlorite, biotite, staurolite, garnet, zoisite, epidote) is characteristic of metamorphic source rocks.

The diagram was constructed using the angularity measurements made on the 0.125 mm fraction of the light minerals. Not all mineral species of each suite were present in each sample. The percentages of those minerals of the metamorphic and igneous suites that were present were recalculated to 100 percent, and the relative percentages of igneous and metamorphic species determined.

The diagram does not include consideration of the quartz types or the angularity ranges in each sample; therefore, only the nature of the principal sources is indicated and the mixing of crystalline and sedimentary source material is not clearly revealed.

From the petrography of the Cretaceous sandstones, it may be inferred that the provenance was originally sedimentary and that progressive denudation exposed the crystalline basement rocks. The presumed orientation of the Cretaceous shoreline suggests that the source area was to the southwest (Pike, 1947). The crystalline provenance is not known. The similarities of the accessory minerals and grain morphologies between the Jurassic rocks and the Dakota sandstones suggest that they had the same source or, as seems more likely because of the presumed length of time that separates them, that the Dakota sandstones were largely derived from a Jurassic sedimentary provenance.

PALEOCLIMATE

Feldspars in sediments have been used as an indicator of the climatic conditions during deposition. Their significance has generally been discredited, but where both weathered and fresh feldspars occur together, the presumption is strong that both temperature and rainfall were high (Pettijohn, 1957, **p.** 127). A majority of the Todilto Park samples from below the Menefee Formation contain highly weathered and fresh feldspar; this is especially true of the Dakota(?) Sandstone. Hence, the general conclusion that the climate in the distributive province was warm and moist during deposition of the Upper Cretaceous sediments at Todilto Park seems justified. This conclusion is also supported by the clay mineralogy of these rocks.

The chemical conditions necessary for the formation of the various clay minerals are known from laboratory experiments. In the absence of alkalies and alkaline earths in neutral or acid conditions, kaolinite or pyrophyllite forms. In the presence of appreciable alkalies or alkaline earths, montmorillonite, mica, or chlorite forms, depending on the specific alkali or alkaline earth present (Grim, 1958).

Many of the natural environments in which clay minerals can form are also known. Kaolinite is a common product of acid nonmarine environments. It is formed by acid leaching during weathering in a cool to warm, moist climate. Illite is usually the principal clay mineral in marine deposits. **It** is presently forming in marine sediments (Grim, 1958). Montmorillonite typically results from the alteration of volcanic ash in a marine environment. It is also likely to develop from igneous rock in a desert, nonleaching, magnesium-rich environment. If the magnesium concentration is low and the potassium concentration is high, illite may Corm (Grim, 1953, p. 351). It has been demonstrated that allogenic clay minerals can persist in depositional environments that are fundamentally unfavorable to them. The clay minerals in a sediment may have formed in the environment of deposition or may have been inherited from the distributive province.

Kaolinite, as noted, is a product of acid leaching and, therefore, the abundant kaolinite in the marine parts of the Mesaverde Group must be allogenic and an indicator of conditions in the distributive province. Kaolinite is common in podsolic soils and is dominant in lateritic soils. These factors suggest that temperature and rainfall were moderate to high in the distributive province during deposition of the formations below the Menefee.

It is unlikely that both the montmorillonite and kaolinite in the marine parts of the Mesaverde Group were inherited from the same continental environment. This would require the simultaneous existence of leaching and nonleaching conditions. It is also unlikely that diagenetic processes have altered much of the kaolinite to montmorillonite, as the alteration processes are slow and probably would produce illite. Grim (1949, p. 1806) found that kaolinite in recent marine sediments is slowly being altered to illite and chloritic mica. This may be the origin of a part of the illite in the Todilto Park sediments. The montmorillonite in the marine sediments below the Menefee, therefore, must have originated from the alteration of direct volcanic ash falls in the marine environment. Hence, in these parts of the sections the montmorillonite is a product of the environment of deposition.

The predominance of montmorillonite in the Menefee Formation, which is generally believed to be of nonmarine origin, is more difficult to explain. Its occurrence may mean that, contrary to the consensus, these parts of the Menefee were deposited in marine or brackish waters and that the montmorillonite formed from direct ash falls. It also might be the result of a change in the distributive province from a moderate to a desert climate. Increased volcanic activity may have accompanied this change. The data available are not sufficient to establish which of these possible explanations is correct, but a climatic change seems necessary.

The Menefee and the underlying Crevasse Canyon, except the Dalton Member, are considered to be largely non-marine and products of similar depositional environments; hence, the change from a kaolinite-rich clay mineral assemblage in the Crevasse Canyon to a montmorillonite-rich assemblage in the Menefee (fig. 25) suggests a change in source material. This change in the nature of the source material is best explained as a result of a change in climate. If this change did occur, montmorillonite and illite would be expected to persist in most of the sediments above the Menefee, regardless of their environment of deposition. This possibility is being investigated.

Conclusions

From the petrographic data thus far collected from the Cretaceous sediments of northwestern New Mexico, several conclusions have been drawn:

(x) The Cretaceous stratigraphic section can be zoned petrographically. Within the limits of this study, these zones are persistent.

(2) At Todilto Park the formations and petrographic zones are only approximately parallel; regionally, they will diverge. The boundaries of the petrographic zones are approximately parallel to planes of synchronous deposition.

(3) The Cretaceous formations are not characterized by their mineralogy.

(4) The mechanical parameters of a sedimentary unit are helpful in establishing its environment of deposition. Most of the sandstones at Todilto Park are products of a large amount of reworking at a medium- to low-energy level. Most formations are mixtures of marine and nonmarine sedimentary units.

(5) There were no abrupt or large-scale changes in the tectonic framework of the region during deposition of the Todilto Park part of the Upper Cretaceous section.

(6) Diagenetic and epigenetic processes have not appreciably altered the detrital mineral assemblages. Hence, the assemblages are characteristic of the provenance.

(7) The lower parts of the Todilto Park Cretaceous section are multicycle sediments derived from a provenance made up largely of Jurassic sedimentary rocks. The upper parts were derived from a mixed sedimentary and crystalline provenance that supplied large amounts of first-cycle detrital material.

(8) The Cretaceous formations cannot be characterized by their clay mineral assemblages, but the stratigraphic section can be divided into a lower part that contains dominantly kaolinite and an upper part that contains dominantly montmorillonite.

(9) The clay mineralogy in the Todilto Park section is largely controlled by the composition of the rocks and the weathering processes in the source areas.

(o) During deposition of most of the sediments, both temperature and rainfall were high in the distributive province. It is likely that there was a change from a moderate to desert-like climate after deposition of the Point Lookout. This was associated with an increase in volcanic activity.

Work planned and in progress will test these conclusions and will determine whether the petrographic zones defined here are regionally persistent. If they are persistent, it will be of considerable basic significance and practical value.

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