Circular 68

Niobium-Bearing Sanostee Heavy Mineral Deposit, San Juan Basin, Northwestern New Mexico

by Edward C. Bingler

STATE BUREAU OF MINES AND MINERAL RESOURCES
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Abstract

The sedimentary sequence exposed near Sanostee, New Mexico, includes undifferentiated Jurassic rocks; Upper Cretaceous Dakota (?) Sandstone, lower Mancos Shale, Gallup Sandstone, and upper Mancos Shale; and Tertiary Chuska Sandstone. Heavy mineral and clay mineral zones in the section are correlated with similar zones at Todilto Park, New Mexico.

Littoral marine, lagoonal, and nonmarine facies are represented in the Gallup Sandstone. Mineralogic composition, grain morphology, and inclusions in quartz indicate that during deposition of the Gallup Sandstone sediments, the immediate source area contained both crystalline and sedimentary rocks with the latter predominating.

Six en enchelon heavy mineral lenses occur within the littoral marine unit of the Gallup Sandstone. The principal mineral constituents are quartz, ilmenite, zircon, tourmaline, leucoxene, and brookite. Both the heavy mineral lenses and the normal Gallup Sandstone contain niobium-bearing heavy minerals and similar mineral suites. It is concluded that the heavy mineral lenses were formed by local concentrations of heavy mineral during deposition of the Gallup Sandstone sediments.

Niobium-bearing ilmenite, leucoxene, anatase, and brookite impart a high niobium content to the deposit. Twenty-seven quantitative X-ray fluorescent analyses of three heavy mineral lenses reveal a range of 0. 09 to 0.15 weight per cent niobium pentoxide. The deposit is also estimated to contain 9 weight per cent zircon and 10 weight per cent titanium dioxide. Probable (57, 400 tons), possible (266, 100 tons), and maximum possible (2, 064, 500 tons) tonnage estimates are made.

Introduction

It is the purpose of this study to examine in detail heavy mineral lenses which occur within the Gallup Sandstone near Sanostee, New Mexico. Similar deposits have been located in other parts of the San Juan basin, but none has been studied in detail. All known deposits of heavy minerals in the upper Cretaceous of northwestern New Mexico contain substantial amounts of radioactive zircon which has led to their discovery by uranium prospectors. These deposits have been found to contain substantial amounts of titanium, and hence the common reference to them as "titaniferous black sand deposits." The Sanostee deposit has been studied especially because it has an unusually high niobium content which may make it a commercial source of this metal.

Field work consisted of preparing a reconnaissance geologic map and a plane table geologic map of the deposit; an organized sampling program was carried out during the summer of 1960. Laboratory work was performed at the New Mexico Institute of Mining and Technology during the fall of 1960.

An investigation of the Sanostee deposit was made by Birman (1959) with special regard to its potentialities as a source of titanium. A similar deposit near Gallup, New Mexico, has received attention from Sun and Allen (1957). Chenoweth (1957) has published a compilation of the known heavy mineral deposits within the San Juan basin, but little detailed data are furnished.

In this report, data are presented substantiating the opinion that the lenses are beach placers formed from pre-existing sediment and were concentrated by the reworking of these sediments during Upper Cretaceous time. The mineralogy of the deposit is determined and conclusions are presented with respect to the source of the heavy minerals. The niobium content of the individual lenses is determined by X-ray fluorescent spectroscopy.

ACKNOWLEDGMENTS

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Acknowledgment is also made to Mr. C. V. Collins of the Navajo Tribal Mining Department who granted the writer permission, on behalf of the Navajo Tribe, to perform geological studies in the Sanostee area.

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LOCATION AND ACCESSIBILITY

The region mapped comprises an area of 40.3 square miles wholly within the Navajo reservation along the western margin of San Juan County, New Mexico (fig. 1). The Sanostee Trading Post, which is about one mile east of the area, may be reached from U. S. 666 over a light-duty, graded, gravel road. All roads leading west from the trading post to and through the mapped area are little more than cart trails. Since almost all these traverse lower Mancos Shale, any rainfall renders them extremely treacherous if not impassable to conventional motor vehicles.

CLIMATE, WATER SUPPLY, AND VEGETATION

The climate of the Sanostee area is characterized by extreme seasonal and diurnal temperature variations. Daytime summer temperatures commonly exceed 95°F, but the temperature may fall to as low as 40° to 45°F at night. Daytime winter temperatures are often 32°F and night time extremes may drop to below 0°F. The mean annual rainfall of about seven inches, coupled with the temperature extremes, produces an inhospitable panorama of arid desert land. Violent local thunderstorms are common midafternoon occurrences during the summer months.

Both Pajarito and Pena Blanca creeks, the two major drainage networks in the area, are intermittent. They flow only during and after severe thunderstorm activity and would not provide an adequate or dependable water supply. The principal source of drinking water for the Navajos living in this area is a water well at the Sanostee Day School.

Sagebrush and a few scattered pinons are the principal growths in the lower valley bottoms. Atop the mesas and many cuestas which constitute the areas of intermediate elevation are a variety of grasses and more abundant growths of pinon and juniper. Beautiful Mountain, parts of which are at an elevation in excess of 9000 feet, supports a luxuriant forest growth of yellow pine and live oak. Presently, this forest is being utilized by the Navajos as a source of firewood.

PHYSIOGRAPHY

The Sanostee area lies within the Chuska Valley subdivision of the Navajo section of the Basin and Range Province. It is dominated by the elongated summit of Beautiful Mountain to the west and by Black Peak (designated VABM Black on the geologic map) in the east-central portion. Both features are erosional remnants, the former composed largely of Tertiary Chuska Sandstone capped by volcanics and the latter chiefly of Upper Cretaceous shale with a thin veneer of Tertiary rocks.

Maximum relief is more than 3000 feet between the valley bottom near Sanostee Trading Post and the summit of Beautiful Mountain. The area is well drained by two intermittent streams, Pena Blanca and Pajarito creeks.

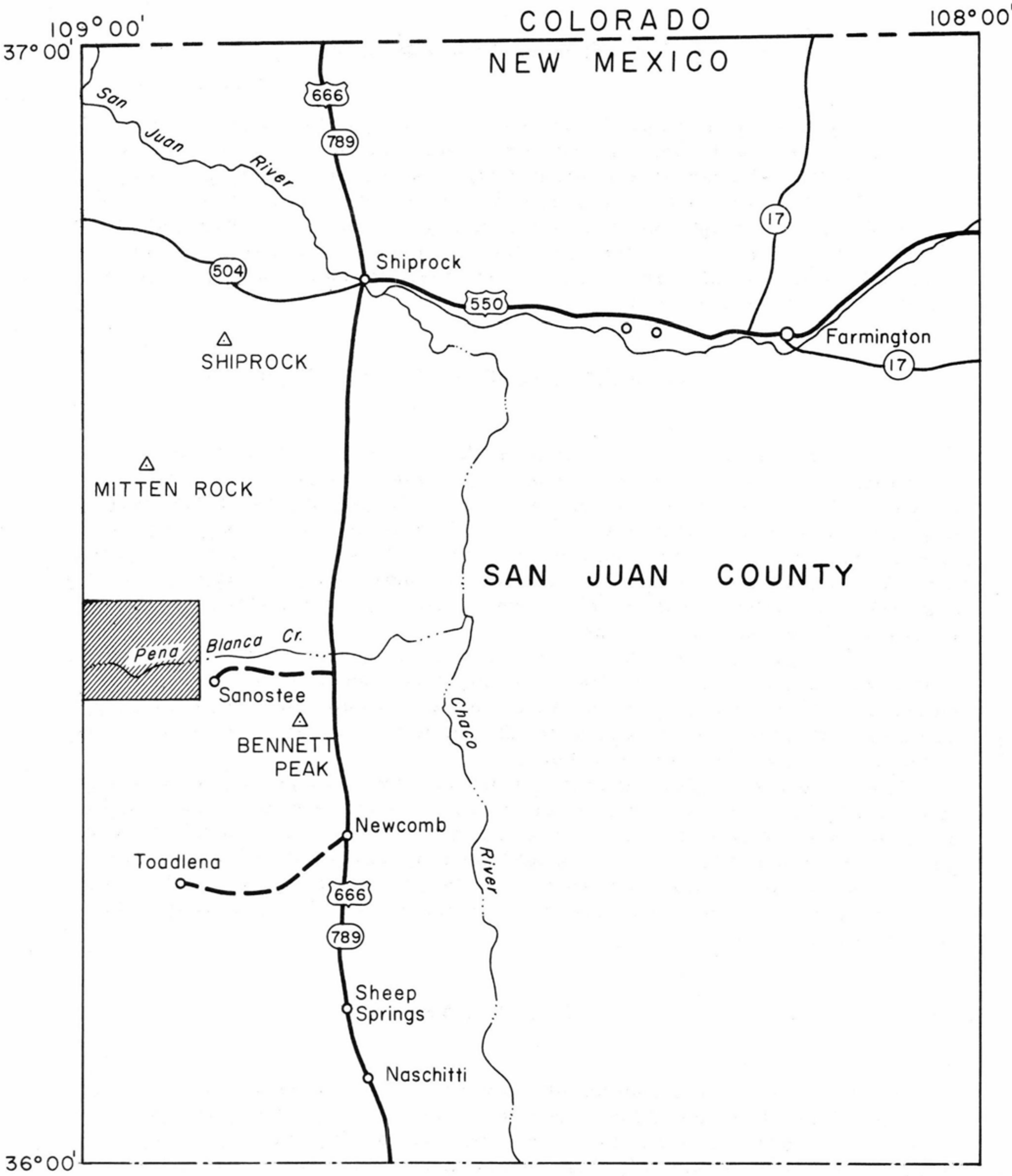


Figure 1 Index map showing location of mapped area

Erosion Surfaces

Four distinct, essentially horizontal erosion surfaces are developed in the Sanostee area. The oldest surface bevels the Upper Cretaceous and Jurassic strata and is overlain by the Chuska Sandstone. This surface is exposed on Black Peak at an elevation of about 7300 feet. On the east flank of Beautiful Mountain it occurs between 8000 and 8200 feet. A similar surface has been described by Cooley (1958) in the Black Mesa Basin area and is designated the Tsaile surface of middle Tertiary age.

The next younger erosion surface is developed upon the upper surface of the Chuska Sandstone. This surface is exposed from 50 to 200 feet above the underlying one. These two surfaces apparently slope to the east but at slightly different angles.

Pediment surfaces are developed on the upper and lower Mancos Shales as represented by the tops of erosional remnants at average elevations of 7100 feet and 6400 feet. The largest remnant of a pre-existing pediment surface is located at the mouth of the canyon in Gallup Sandstone by Pajarito Creek. The surface is about half a mile wide and about one and a half miles long. It is elongated in an east-west direction and has an eastward gradient of about 160 feet a mile. Erosion which produced the canyon in the eastward-facing cue sta of Gallup Sandstone has cut into this pediment and exposed north-south-trending channel fillings which probably represent meanders in a braided river system established on the pediment surface. These most recent pediment surfaces are probably related to temporary base levels established in the San Juan—Colorado River drainage systems.

Stratigraphy

The consolidated sedimentary rocks of the Sanostee area are chiefly of Jurassic and Upper Cretaceous ages. The general stratigraphic relations are summarized in Figure 2. The Jurassic rocks are a series of clastic sediments which crop out in the extreme southwestern part of the mapped area. Upper Cretaceous rocks are extensively and excellently exposed in cuestas and valley walls. Tertiary sediments and volcanics are exposed in the summits of Beautiful Mountain and Black Peak.

The dominant rock type in this area is shale and siltstone which form the valleys drained by Pena Blanca and Pajarito creeks. Fine-grained sandstone is the next most abundant lithologic unit and forms the margins of the valleys. The principal sandstone unit, the Gallup Sandstone, is continuous in outcrop for more than 25 miles in the Sanostee area. Limestone is absent and conglomeratic beds are scarce.

The stratigraphic nomenclature in this report follows that recommended by Beaumont, Dane, and Sears (1956). All pre-Upper Cretaceous rocks were mapped as Jurassic undifferentiated, and since no visible unconformity exists, the boundary between Upper Cretaceous and Jurassic strata was placed at the base of the first thick sandstone above the variegated shales and siltstones. Particle size designations employed in the lithologic descriptions are based on the Udden grade scale as modified by Wentworth (1922).

JURASSIC FORMATIONS (UNDIFFERENTIATED)

Pre-Upper Cretaceous sediments of Jurassic age occur in one small part of the extreme southwestern section of the Sanostee area. Pre-Upper Cretaceous rocks of similar color and lithology cropping out about 25 miles south of Sanostee at Toadlena, New Mexico, have been identified as the Brushy Basin member of the Morrison Formation by Harshbarger et al. (1957).

The Jurassic rocks exposed at Sanostee consist of variegated pale yellowish green (10GY7/2) to light brownish gray (5YR6/1) siltstone and medium to light gray (N6) platy carbonaceous shales. No conglomerates were observed nor were local conglomeratic facies of the thicker fine-grained sandstones in evidence. The entire sequence is in excess of 200 feet thick. Almost without exception the coarser-grained units are gradational into underlying finer-grained clastic rocks. The variegated and carbonaceous character of this sequence suggest that it is of continental, probably flood plain, origin.

Although the sediments immediately above the Jurassic sequence are of late Cretaceous (Beaumont, 1954) age, no angular unconformity exists. Consequently, the Jurassic—Upper Cretaceous contact is arbitrarily placed at the base of the first thick sandstone above the variegated shales and siltstones. The advantage of this choice is that it provides a readily recognizable key bed which has a distinct topographic expression. It should be stressed that the contact between Jurassic and post-Jurassic rocks may occur anywhere between the multicolored shales at the base of the section and the first appearance of what is unquestionably Mancos Shale.

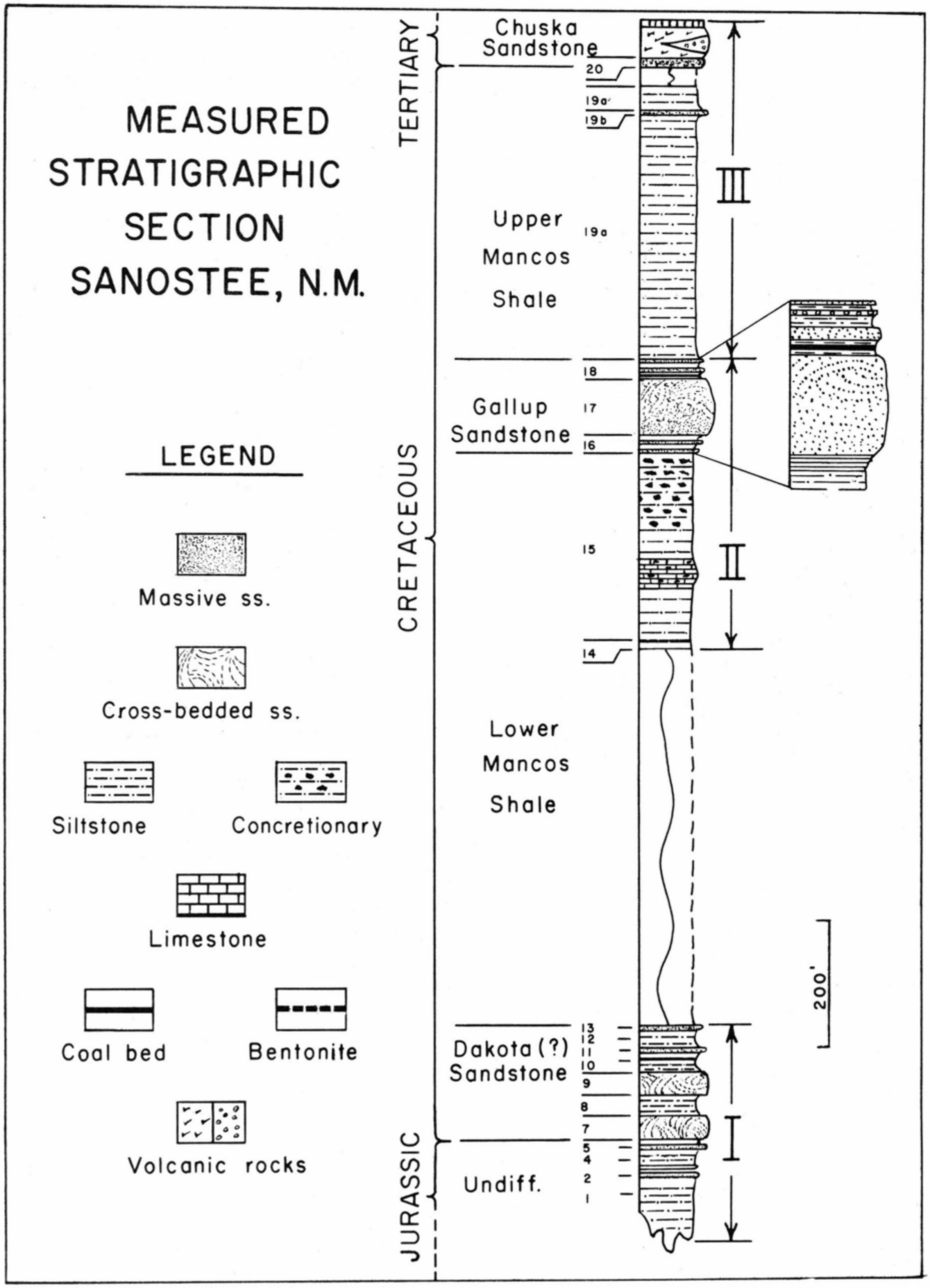


Figure 2 Measured stratigraphic section

Representative samples were taken of all the lithologic units present in the Jurassic sequence. The average median diameter for the siltstones and sandstones is 0.183 mm; the average coefficient of sorting is 1.32; and the average skewness is 0.950. Heavy minerals present are barite, garnet, zircon, tourmaline, ilmenite-magnetite, hematite, leucoxene, rutile, sphene, and staurolite. Most of the garnet, zircon, and leucoxene crystals are rounded, but the presence of some euhedra of zircon and angular garnet suggest a provenance of mixed sedimentary and crystalline rocks. Montmorillonite is the dominant clay mineral of the lowest unit (sample 1, table 2); the overlying units contain primarily kaolinite with subordinate illite-montmorillonite mixed-layer clay.

UPPER CRETACEOUS FORMATIONS

Dakota (?) Sandstone

The term Dakota (?) Sandstone is applied to all the sedimentary rocks from the upper contact of the Jurassic rocks to the top of the last persistent sandstone at the base of a thick shale sequence. This follows long-established practice of assigning the first Upper Cretaceous rocks to the Dakota (?) Sandstone. The outcrops of Dakota (?) Sandstone form the upper edge of the canyon cut by Pena Blanca Creek.

Rocks of Dakota (?) age form a composite sequence at Sanostee similar to described exposures elsewhere in northwestern New Mexico (Reeside, 1924; Gregory, 1917; Dane and Bachman, 1957). The basal unit of the Dakota (?) Sandstone consists of a grayish yellow, thick, cross-bedded, locally banded, quartz sandstone. Overlying this unit is a zone of pale greenish yellow (1 OY 8/2) interbedded shale and siltstone which becomes coarser-grained and thicker-bedded upward until it grades into a 35-foot-thick, fine-grained, cross-bedded sandstone. Above the thick sandstone there is a 36-foot sequence of interbedded light gray (N7) to medium bluish gray (5B5/1) carbonaceous shales, grayish yellow (5Y8/4) to yellowish gray (5Y7/2) massive, 2- to 3-foot-thick, fine-grained quartz sandstones, and moderate (10YR5/4) to dark yellowish orange (10YR6/6) thin, cross-bedded, iron-stained, fine-grained sandstones. The uppermost sandstone unit is about 2 feet thick and has a very distinctive appearance due to the separation of polygonal blocks of sandstone along joint surfaces. The upper surface of this unit also weathers to a characteristic nodular surface. A significant characteristic of the Dakota (?) Sandstone throughout New Mexico illustrated in the exposures at Sanostee on a minor scale is the lateral inconstancy of discrete units within the formation. Compositional, textural, and bedding plane features are extremely variable, and rapid changes are the rule rather than the exception. However, the two thick sandstones included in the Dakota (?) are uniform in thickness, texture, and composition wherever they crop out in the mapped area.

The Dakota (?) Sandstone is generally regarded as being the result of the accumulation of elastic lagoonal, littoral marine, and offshore marine facies during the inundation of the area by the early Late Cretaceous sea. This genetic representation is consistent with the mapped lithologies.

All the distinct varieties which make up the Dakota (?) Sandstone were sampled and the petrographic data determined. The average median diameter for the Dakota (?) Sandstone is 0.150 mm, the Trask sorting coefficient is 1.12, and the skewness is 0.952. From these data it is seen that the sandstone units within the Dakota (?) are in general very fine-grained, well sorted, and skewed very slightly on the fine-grained side. These facts are consistent with a marine origin for the Dakota (?) Sandstone.

The heavy mineral suite makes up less than one per cent by weight of the sediment. Heavy minerals present are garnet, zircon, barite, tourmaline, brookite, rutile, and a trace of staurolite and biotite. Angular, euhedral, and highly rounded grains are present. These data coupled with the presence of staurolite indicate that the source area for the lower Upper Cretaceous rocks was supplying clastic material from a mixed environment of sedimentary and crystalline rocks (in part metamorphic), but with the former predominating. Kaolinite is the dominant clay mineral with minor illite and illite-montmorillonite mixed-layer clay.

Lower Mancos Shale

The most extensively exposed formation in the Sanostee area is the lower Mancos Shale. The outcrop area of this unit is in excess of 55 square miles and is restricted to the valleys drained by Pena Blanca and Pajarito creeks (pl. 1). Its base is exposed only in the southwestern part of the area where the underlying Dakota (?) Sandstone crops out.

The lower Mancos Shale is composed of two easily recognizable horizons: a lower pale yellowish brown (10YR6/2) arenaceous shale to siltstone and an upper bluish gray (5B5/1) calcareous shale (pl. 2) with numerous septarian concretions. In section traverse No. 2 (pl. 3), a one-foot-thick bentonitic bed was found at the contact between these two units, but in most examined exposures no bentonite was found.

The lower unit is a dusky yellow (5Y6/4) to yellowish gray (5Y7/2) arenaceous shale to siltstone. Bedding planes are invariably warped and wrinkled rather than flat. This buff-colored zone of the lower Mancos is exposed throughout Sanostee valley; the maximum thickness is about 500 feet. The stratigraphic thickness of this unit, determined from the well record of the Navajo Company's Raymond No. 1 well at Sanostee and barometric measurements, is 600 feet, of which only about the top 20 feet were sampled. The buff unit of the lower Mancos thins westward from near the center of the Beautiful Mountain anticline to an indeterminate thickness where the Chuska Sandstone directly overlies the lower Mancos on the eastern flank of Beautiful Mountain.

The Mancos Shale is considered an Upper Cretaceous marine shale throughout the San Juan basin. The interpretation of a marine origin for this formation is based upon lithology and the presence of marine fossils of late Carlile age (Pike, 1947). The bluish gray and buff units within the lower Mancos Shale form very distinctive units in the Sanostee area. This difference in color may have important genetic implications and deserves further study.

Samples 14, 15, and 15a (pl. 4, table 2), representing the buff siltstones, bluish gray shale, and bentonitic bed of the lower Mancos, respectively, were examined in the laboratory. Since these samples were too fine-grained for mechanical analysis, the only information determined was the clay mineral composition. The lower buff siltstone contains primarily illite with minor kaolinite, and the upper bluish gray shale contains only kaolinite. The one-

Plate 1

Slopes of lower Mancos Shale capped by prominent cliffs of Gallup Sandstone

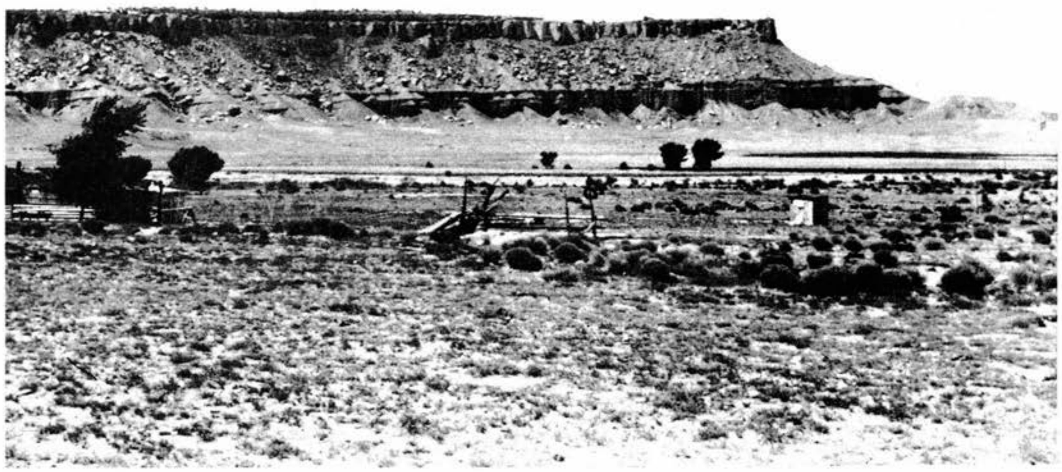


Plate 2

Southern margin of Sanostee cuesta

TABLE 1. Heavy Minerals in the Stratigraphic Section

	Jurassic und.			Dakota(?) ss.						Gallup ss.			U. Mancos shale		Chuska ss.
Sample Number	1	2	5	7	8	9	11	12	13	16	17	18	19a	19b	20
Tourmaline															
euhedral							—		—						
angular				—		—	—	—	—	—	—				
rounded	—	—	—	—	—	—	—	—	—			—			
polished	—	—	—	—	—	—	—	—	—						
black-brown	—	—	—	—	—		—	—	—	—	—	—			
green-blue		—	—	—	—	—	—	—	—			—			
Garnet															
euhedral		—													
angular	—		—	—	—	—	—	—	—	—	—				
rounded	—		—		—				—			—			
colorless-pink	—		—	—			—	—	—	—	—	—			
red-brown		—							—			—			
Zircon															
euhedral	—	—	—	—	—	—	—	—	—	—	—				
angular			—	—	—		—	—		—	—				
rounded	—	—	—	—	—	—	—	—	—	—	—	—			
colorless-pink	—	—	—	—	—	—	—	—	—	—	—	—			
yellow-brown							—								
zoned	—	—		—			—								
Illmenite-magnetite	—	—	—	—	—	—	—	—		—	—				
Leucoxene	—	—	—	—	—	—	—	—	—	—	—				
Hematite	—	—	—	—	—	—	—	—	—	—	—				
Staurolite	—														
Apatite						—			—	—	—	—			
Epidote			—						—	—	—	—			
Barite	—	—	—		—	—	—	—	—	—					
Biotite		—					—	—		—	—				
Chlorite											—				
Sphene	—			—			—		—			—			
Zoisite										—	—				
Rutile	—			—	—	—	—	—							
Augite															
Hornblende							—			—					
Enstatite							—								
Chloritoid															
Anatase-Brookite	—	—		—	—	—	—		—						
Quartz inclusions															
none	—	—	—	—		—						—			
regular		—	—			—	—	—	—			—			
irregular	—	—	—	—	—	—	—	—	—			—			
acicular	—		—	—								—			
Authigenic qtz.			—		—	—	—								
K-feldspar	—							—	—			—			
Muscovite		—	—				—	—	—	—					
Plagioclase												—			
Chert	—	—	—	—		—	—	—	—			—			
Dolomite											—	—			

Plate 4, Table I Heavy minerals in the stratigraphic column

TABLE 2. Clay Mineral Distribution

	Sample No.																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	15a	16	17	18	19a	19b	20
Kaolinite	t	X	X	X	X	X	X	X	X	X	X	X	X	x	X		X	X	X	t	x	t
Montmorillonite	X			t		t										X				t		X
Mixed layer		x		x				x		t	x						t	t		x	t	
Illite		t										x		X			x	x	x	X	X	

(X) Major constituent (x) Minor constituent (t) Trace amount

Plate 4, Table 2 Clay minerals in the stratigraphic column

				Lens A	Lens B	Lens C
Quartz (.125mm)			% authigenic overgrowths	18	18	46
			% angularity (quartz)	60.0	68.7	68.7
	Inclusions		% irregular	42	24	62
			% regular	26	74	14
			% acicular	12	2	8
			% absent	20	—	16
Opaques .125 mm			Rounded black (ilmenite)	27.3	36.2	63.8
			Angular block (ilmenite)	28.5	12.6	15.9
			Rounded white (leucoxene)	22.7	36.3	18.5
			Angular white (leucoxene)	21.5	14.9	1.8
Nonopaque Heavy Minerals (.062 mm)	Zircon	Colorless	Euhedral	12.7	15.1	1.9
			Subrounded	15.9	22.6	9.4
			Rounded	27.0	9.4	13.2
			Beadlike	25.4	24.5	43.4
			Fragments	19.0	32.4	33.1
		Pink	Euhedral	7.7	7.1	5.9
			Subrounded	27.0	35.7	29.4
			Rounded	—	0.2	11.8
			Beadlike	—	9.5	17.6
			Fragments	65.3	47.5	45.3
			Zoned	100	73.3	100
			Metamict	—	26.7	—
		Inclusions	Irregular	28.9	22.9	17.2
			Regular	40.0	52.0	71.4
			Acicular	6.7	10.4	1.4
			Absent	24.4	14.7	10.0

Frequency data between double lines are recalculated to 100 percent

Plate 4, Table 3 Mineral data, Sanostee deposit foot-thick bentonite bed of white to moderate orange-pink is essentially pure montmorillonite. The bentonite bed is arbitrarily included with the buff unit of the lower Mancos in the correlation between Sanostee and Todilto Park, New Mexico (fig. 3).

Gallup Sandstone

The Gallup Sandstone as it crops out in the Sanostee area is a tripartite unit composed of a lower, thick, fine-grained sandstone, a medial sequence of carbonaceous shales, siltstones, and coal beds, and an upper sequence of fine- to coarse-grained sandstones with interbedded shales and siltstones. The trace of the outcrop is sinuous, but it trends generally north-south through the central part of the mapped area and then northwest from the southern margin of the mapped area up to the flank of Beautiful Mountain. The hard, massive, lower unit of the Gallup Sandstone forms prominent cliffs along its entire outcrop length (pls. 1 and 2).

The lowermost unit of the Gallup Sandstone is a thick, massive, medium-to fine-grained quartz sandstone which is gradational into the underlying lower Mancos Shale. It varies in thickness from 60 to 80 feet and is grayish orange (10YR7/4) to dark yellowish orange (10YR6/6); locally, it becomes more pinkish. This is probably due to the amount of hematite disseminated as cement throughout the rock. The base of this unit is gradational into the underlying shale but the upper contact between the medial shale-siltstone sequence and the lower sandstone is sharp. It is in this lower thick sandstone unit that the heavy mineral lenses occur (pl. 5). In many places along the arroyo cut by Pajarito Creek where it intersects the northern edge of Sanostee cuesta, the lower sandstone becomes coarser-grained toward the top and develops "beehive" weathering.

The medial sequence of interbedded, light olive-gray (5Y5/2) to black carbonaceous shales and siltstones, and one thin coal bed, rests upon the thick sandstone described above (pl. 6). This succession varies in thickness from a maximum of about six feet to a minimum of about one foot. The coal bed is laterally discontinuous and commonly grades into carbonaceous shale.

The uppermost unit of the Gallup Sandstone consists of interbedded coarse-to fine-grained yellowish gray (5Y7/2) to white sandstones and grayish yellow to moderate yellowish brown siltstones which grade upward into the upper Mancos Shale. The coarser-grained parts of this upper unit contain interfingering conglomeratic lenses composed of clastic quartz, chert, and rock fragments in excess of 5 mm in diameter. Many of the sandstones contain plant fragments and one contained septarian concretions. Individual beds thicken and thin laterally, as does the aggregate thickness. Rapid changes in the aggregate thickness of this upper sequence are the principal cause for changes in thickness of the Gallup Sandstone. The upper part of the Gallup Sandstone has been variously interpreted as the "stray" sandstone of Sears (Pike), transgressive sediments derived in part by the reworking of a portion of the Gallup Sandstone (Beaumont, 1957), and as a regressive deltaic facies of the Gallup Sandstone (Budd, 1957).

The three major units of the Gallup Sandstone were sampled and a petrographic study made. The average sorting coefficient is 1.46; the average median diameter is 0.142 mm; and the average skewness is 0.90. The sorting

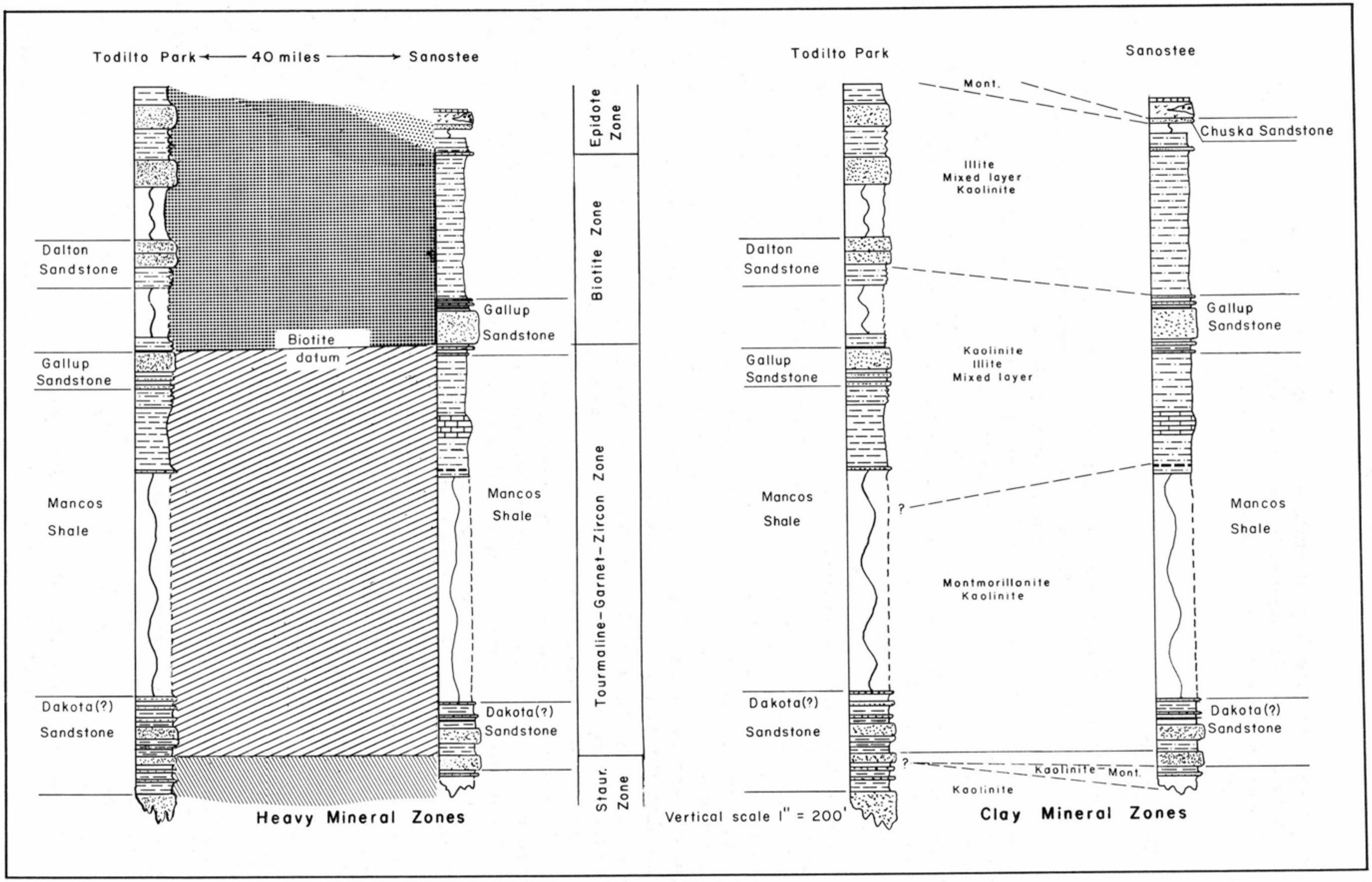


Figure 3 Correlation of Upper Cretaceous rocks based upon heavy mineral and clay mineral zones

Plate 5

East face of the Sanostee cuesta

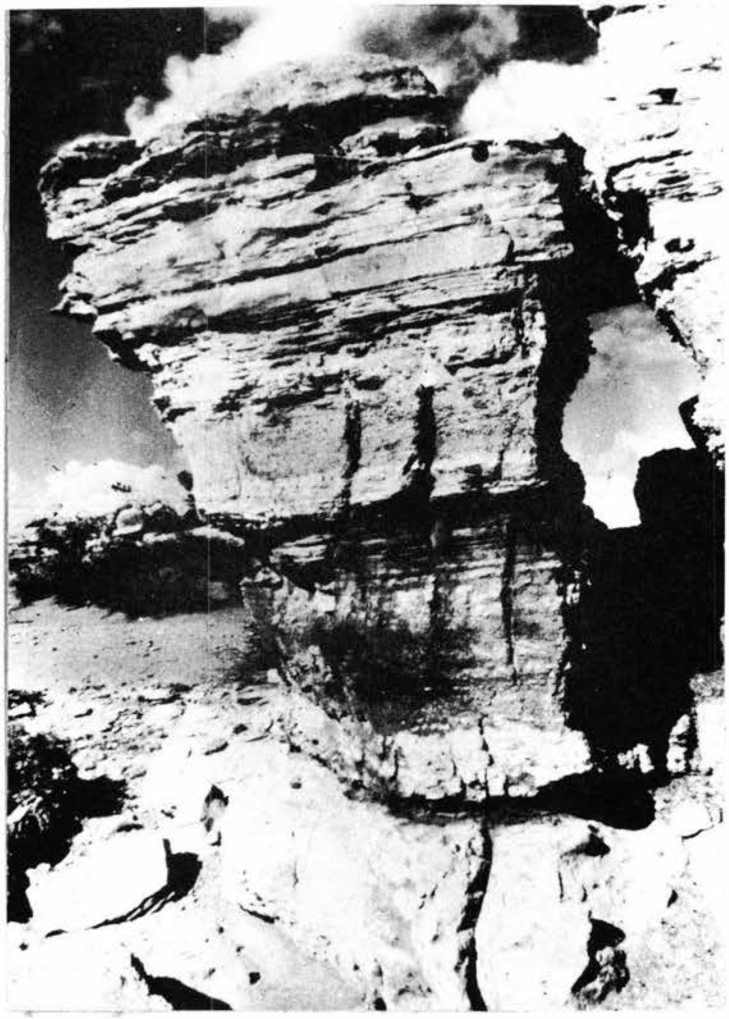


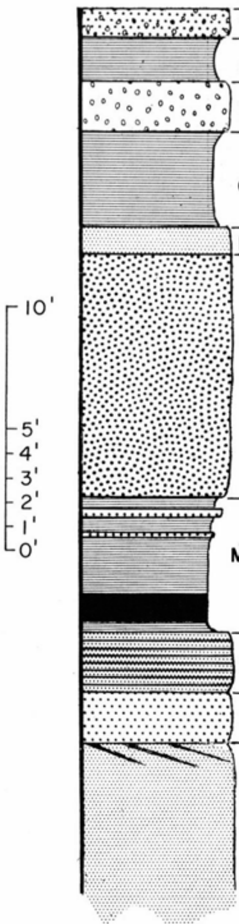
Plate 6

A portion of the upper part of the Gallup Sandstone exposed on Sanostee cuesta coefficient of the lower unit is 1.40 contrasted with 1. 56 of the upper unit. These data indicate that the lower thick sandstone is better sorted than the upper sand- and siltstones and lend support to the presumed marine origin of the former and the (in part) fluviatile origin of the latter. The heavy minerals present in the Gallup formation are angular garnet, angular euhedral, and rounded tourmaline, euhedral and rounded zircon, ilmenite-magnetite, leucoxene, and an occasional grain of hornblende and biotite. This suite of heavy minerals suggests a mixed sedimentary and crystalline source. The appearance of large quantities of garnet and a moderate amount of angular and euhedral tourmaline in the upper unit of the Gallup Sandstone suggests a change to a higher ratio of metamorphic to sedimentary rocks in the distributive province. Dominant kaolinite and minor illite are the clay minerals present.

The threefold nature and lithologic characteristics of the Gallup Sandstone are consistent with a concept of origin which assumes regression of the sea by virtue of a high ratio of available clastic material to available space in the basin of deposition as visualized by Spieker (1949). The thick, basal sandstone unit with sharp top and gradational base represents accumulation of sand in the littoral zone. The overlying coal and coaly shales are the products of the backshore lagoonal environment with the lateral discontinuity of the coal horizon being an expectable phenomenon. The uppermost sequence of coarser-grained material may represent an eolian and fluvial environment which produces a facies characterized by alternating poorly and well-sorted units and abrupt lateral variations in thickness.

A vertical section of the Gallup Sandstone, excluding the lower 80 feet, as exposed on Sanostee cuesta is shown in Figure 4. Compositional, mechanical, and mineralogical parameters for each lithology are also shown in Figure 4. The sequence is then divided into environments of deposition based upon the classification by Krumbein and Sloss (1951). All the rock units comprising the Gallup Sandstone were formed in the transitional zone; that is, between continental and marine environments. The thick lower unit is designated littoral because of its high degree of sorting, small median diameter, and gradational nature into underlying marine shale. Lithology X (fig. 4) intervenes between the littoral and lagoonal environments. It is characteristically less well sorted and coarser-grained than the littoral sandstone, and probably accumulated as a beach ridge. Lithologies Z to M probably were produced in a lagoonal environment. Thin coal beds and coalified plant fragments are common in this sequence. Thin-bedded gray and brown siltstones and shales which underlie and overlie the coal represent a gradual filling of the lagoonal area by fine clastics. Nonmarine deposits eventually encroach upon and completely bury the lagoonal deposits. Lithologies N to T represent nonmarine clastics deposited between the source area and the shoreline. Sorting and grain size variations are the rule in the sequence. Coalified plant fragments are common. The conglomeratic nature of lithologies T and R is interpreted as the direct result of proximity to the source rocks.

The interval between lithologies X and Z represents that part of the beach exposed to subaerial erosion and as such represents a diastem.



Lithology	Sorting	Skewness	Med. diam.	Plant frag.	Clay Minerals	Heavy Mineral Suite	Description	Environment of Deposition
T	1.35	.99	.32	X	Kaolinite-Illite	Garnet-Tourmaline-Biotite	Fine to med.-grnd., qtz. ss. Conglomeratic, grad. bedding.	Nonmarine
S					" "		Thinly laminated brown mudstone. Poorly exposed.	
R	1.58	1.03	.53	X	" "	Tour.-Zircon-Garnet-Biotite	Coarse-grnd. qtz. ss. Friable. Chert fragments common. Quartz predominantly subrounded. Feldspar rare.	
Q					" "		Brown siltstone. Poorly exposed.	
P				X	" "		Even-bedded, flaggy, brown mudstone.	
N	1.57	1.09	.21	X	" "	Muscovite Tourmaline Zircon Biotite	Medium-grained, gray quartz sandstone. Iron-stained; nodular surface; highly cross-bedded. Feldspar uncommon. Heavy minerals rare. Fills channels cut in the underlying shale.	
M				X	" "		Thinly laminated to flaggy, gray to brown siltstone and shale.	Lagoonal
Z	1.26	.96	.18		" "	Muscovite-Tourmaline-Garnet-Biotite-Epidote	Thin-bedded gray to brown ss. Large amounts of muscovite. Authigenic quartz very common.	
X	1.54	1.07	.46		" "	Muscovite-Tourmaline-Biotite	Med.-grnd. gray quartz ss. Feldspar up to 20%. Chert fragments common. Angular quartz grains.	Littoral Marine
Y	1.23	1.00	.18		" "	Tourmaline-Zircon	Fine-grained buff to dark brown quartz sandstone. Minor feldspar, secondary quartz overgrowths. Well sorted.	

Figure 4 Petrography of the Gallup Sandstone

Upper Mancos Shale

The thick, silty, very pale orange shale which overlies the Gallup Sandstone is designated the upper Mancos Shale (Beaumont, Dane, and Sears). Exposures of this unit are restricted to a north-south-trending oval area entirely within the outcrop trace of the Gallup Sandstone. The mapped surface of the upper Mancos extends northward to the northern margin of the map area and westward to the east flank of Beautiful Mountain. The upper Mancos Shale is very uniform texturally and compositionally except for one thin siltstone which crops out about 75 feet below the top of the formation (sample 19b, fig. 2). Slopes composed of upper Mancos Shale are invariably covered with a dense growth of grass and bushes; consequently, good exposures of fresh rock are rare. The thickness of this unit was measured as 450 feet, but it thickens westward toward Beautiful Mountain because of an eastward erosional beveling of the Mancos Shale. In the map area the upper limit of the upper Mancos Shale is determined by an erosion surface of mid-Tertiary age upon which the Tertiary Chuska Sandstone is deposited. The lower contact is gradational into the Gallup and is arbitrarily placed. It is set at the top of the last persistent sandstone in the upper unit of the Gallup Sandstone. Insufficient data are available for assigning a marine or nonmarine origin to this formation; however, it has been designated the Mulatto tongue of the Mancos formation by Pike, the marine equivalent of the "stray" sandstone.

Two samples were taken of the formation, 19a being representative of the entire thickness where measured and 19b being taken from a more resistant horizon near the upper contact, not included in sample 19a. The samples were too fine-grained for sieve analysis, so only the heavy and clay minerals were determined. Heavy minerals present in the upper Mancos are biotite, zoisite, epidote, apatite, zircon, garnet, ilmenite-magnetite, and leucoxene. Most of the opaque minerals are well rounded as contrasted with the nonopaque suite, which is characterized by angularity. The heavy mineral suite is composed of unstable minerals and was probably derived in large part from a metamorphic crystalline source. The highly rounded opaque minerals suggest that the distributive area may have been furnishing some clastic material derived from sedimentary rocks.

The clay mineral composition of this 400 feet of homogeneous shale is complex. In composite chip sample 19a, illite is the dominant species, and kaolinite and illite-montmorillonite mixed-layer clay are present in trace amounts. Because of the nature of the sample, the presence of montmorillonite may be accounted for by (1) the inclusion of a bentonite bed somewhere in the 400 feet of shale, (2) a very small amount of volcanic ash disseminated directly throughout the shale sequence by a fall of ash in the depositional area, or (3) inheritance from the provenance. The first two require a marine environment.

Point Lookout Sandstone

A limited exposure of sandstone occurs in the eastern face of Beautiful Mountain. This unit has been called the Point Lookout Sandstone by Beaumont (1954) but was not included in the stratigraphic section.

TERTIARY FORMATIONS

Chuska Sandstone

Unconformably overlying the Upper Cretaceous rocks in the Sanostee area is a thick Tertiary sedimentary unit named the Chuska Sandstone by Gregory. It crops out in subdued bluffs along the eastern flanks of Beautiful Mountain and, in fact, makes up the bulk of that topographic feature. It also crops out very near the summit of Black Peak where it is overlain by a volcanic sequence (pl. 5).

The Chuska Sandstone where it crops out in Black Peak is massive, medium- to fine-grained, friable, and grayish orange-pink. The measured section at Black Peak is only 12 feet thick, but in the Beautiful Mountain exposures less than three miles away it is approximately 300 to 400 feet thick. This great lateral change in thickness is due to the convergence of two bounding erosion surfaces. At Black Peak the unit is uniformly friable, but both Gregory and Wright (1956) report that differential cementation is common in this formation.

Wright concludes that the Chuska Sandstone is predominantly of eolian and, in part, fluviatile origin and was deposited in a desert basin.

One representative sample of the Chuska Sandstone was taken from the exposure at Black Peak. From a mechanical analysis, the sorting coefficient, median diameter, and skewness were determined to be 1.39, 0.235 mm, and 0.92, respectively. The heavy mineral suite contains an unusually large amount of epidote and sphene with subsidiary amounts of zircon, garnet, tourmaline, apatite, and dolomite. The amount of feldspar present is in excess of ten per cent of the light minerals present. Most grains are subrounded, but the rounding of epidote and sphene is pronounced. The appearance of large amounts of highly rounded epidote and sphene indicates that the immediate source of the Chuska Sandstone is largely of a sedimentary nature, whereas the late Upper Cretaceous provenance was largely crystalline metamorphic.

Montmorillonite is the only clay mineral present in the Chuska Sandstone. This is not surprising in view of the available volcanic ash during Tertiary time and because the Chuska Sandstone is believed to have been deposited in a nonmarine environment during a time when the climate was notably arid (Wright). Montmorillonite is a characteristic product of the weathering of volcanic ash in a nonleaching, alkaline environment.

Tertiary Volcanics

The summit of Black Peak is capped by a sequence of volcanic rocks and volcanic sedimentary rocks. Similar lithologic types occurring at the same stratigraphic position at the southern end of the Chuska Mountains have been assigned to the middle of late Pliocene (Wright). The pyroclastic and volcanic sedimentary rocks immediately above the Chuska formation are composed of two distinct lithologic units. Directly overlying the Chuska Sandstone is a 45-foot-thick mass of volcanic sediment consisting of deeply weathered fragments of crystalline volcanic rock in a fine-grained sandy, calcareous, very pale orange matrix. Included within this unit is a 20- to 30-foot-thick lens of pale red, fine- to medium-grained volcanic sandstone which exhibits pronounced current bedding.

The sandy calcareous matrix of the coarse-textured volcanic sandstones suggests that these rocks are the result of volcanic detritus deposited in an area where fluvial processes were active.

A two-foot-thick basalt flow caps the volcanic sediments. Numerous inclusions of quartzite from one half inch to two inches in diameter are a distinctive feature of this basalt. Opportunity was not afforded to examine the palisade-like lava flow which caps Beautiful Mountain, but it is probable that it is genetically related to the flow which caps Black Peak.

One volcanic neck with an associated dike was mapped in the area. It is located about one mile southeast of Beautiful Mountain and about two miles west of Black Peak. The composition of this igneous mass was not determined, but similar features nearby, Bennett Peak and Shiprock, were found by Shaler (1907) to consist chiefly of monchiquite.

Mineralogic data were collected from the measured section at Sanostee to determine whether the sedimentary sequence could be divided into petrographic zones and if these could be correlated with zones recognized in the Todilto Park section reported by Willard (Allen and Balk, 1954). Heavy mineral and clay mineral groupings have been made. Mineralogic zones have been recognized in the Sanostee section and an attempt has been made to match these zones between the two measured sections.

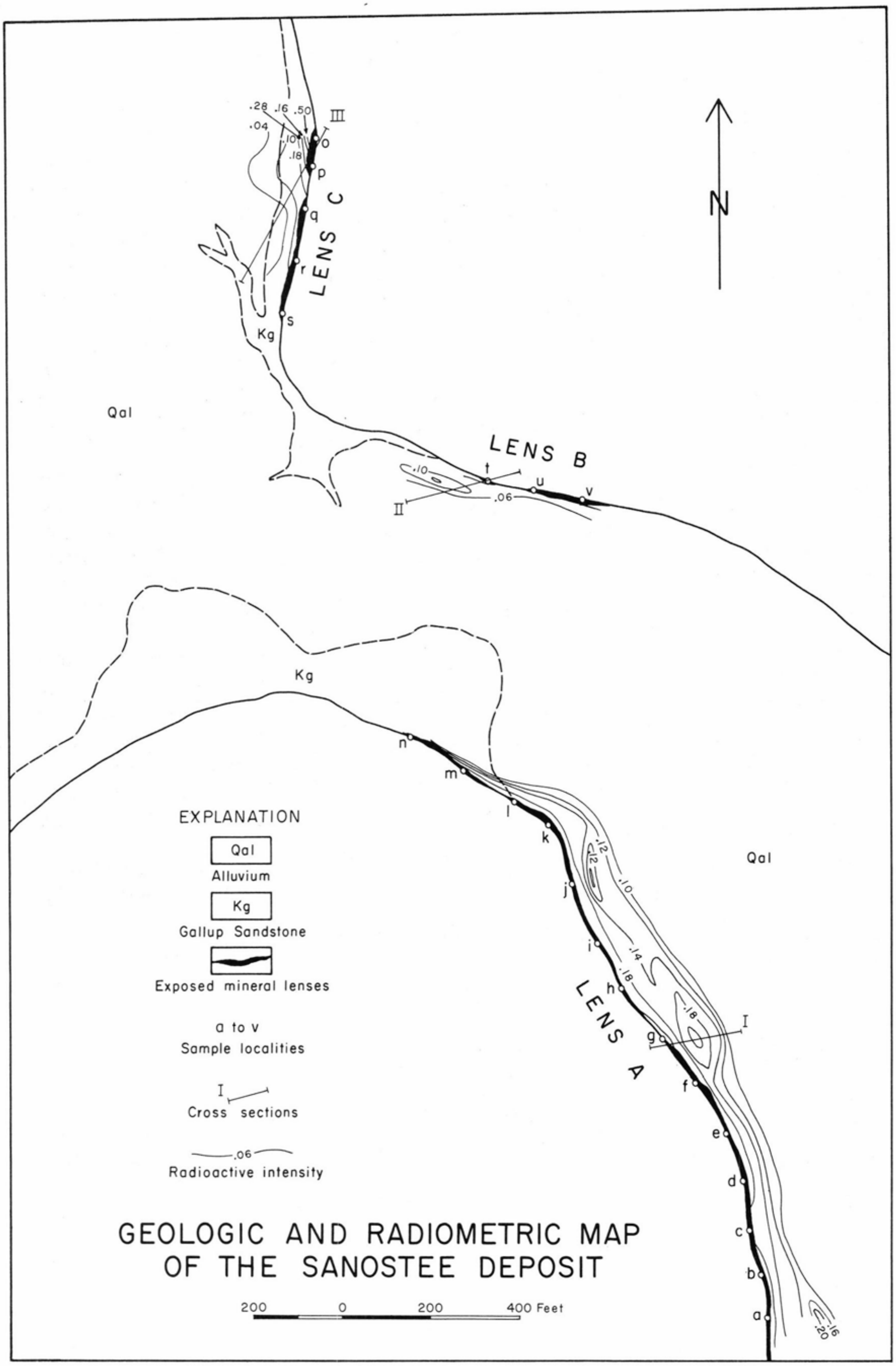
One of the problems involved in such a procedure is the selection of a datum plane which intersects both sections. In the past, the top of the Dakota (?) Sandstone has been the datum (Pike). The Dakota (?) Sandstone, if it represents the first encroachment of the Cretaceous seas in this area, must be a transgressive sequence, and hence it must cut the time planes at some angle. Mineralogic zones, however, are expected approximately to parallel time planes. For this reason in this report a mineralogic datum--the top of the biotite zone--is used (fig. 3).

Heavy mineral zones recognized are the staurolite zone, the tourmaline-garnet-zircon zone, the epidote zone, and the biotite zone. Clay mineral zones are also employed (fig. 3).

Comparison of the mineral zones at Sanostee and Todilto Park reveals marked similarities up to the base of the upper Mancos Shale (fig. 3). Above that the relationships become confused.

Quaternary Alluvium

Material mapped as Quaternary alluvium is restricted to the present channels of Pena Blanca and Pajarito creeks and their tributaries. It consists chiefly of unconsolidated sand, silt, and gravel derived from exposed Cretaceous formations. A thin veneer of basalt fragments caps most of the pediment surfaces in this area but was not differentiated on the map.



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u
v
EXPLANATION
Qal
Alluvium
Kg
Gallup Sandstone
Exposed mineral lenses
a to v
Sample localities
Cross sections
Radioactive intensity
GEOLOGIC AND RADIOMETRIC MAP
OF THE SANOSTEE DEPOSIT
200
0
200
400 Feet

PLATE 7

Structure

The structural relationships in the Sanostee area are singularly uncomplicated. Gently dipping limbs of shallow synclines and anticlines form prominent bluffs and low-angle dip slopes. With the exception of the Dakota (?) outcrops in the extreme southwestern part, recorded dips seldom exceed ten degrees. The minor warps which are present in the map area are probably due to the peripheral effects of two major positive tectonic features: the Defiance uplift and the Hogback monocline.

The Defiance uplift is a northerly trending monocline whose trace is extremely irregular and sinuous (Kelley, 1957). Its western flank is gentle compared to the steeply dipping eastern border. It is primarily a Laramide feature but may have been active prior to late Cretaceous time. At Toadlena, 25 miles south of Sanostee, Paleozoic and Mesozoic sediments have been severely deformed into an anticlinal arch which has been subsequently eroded to leave the eastern flank of the anticline as a prominent hogback in that area. Northward between Toadlena and Sanostee the dips flatten considerably. The lack of parallelism between the northern part of the syncline, where it borders upon Beautiful Mountain, and the axis of the Defiance uplift suggest that no direct relationship exists between these two structures (Beaumont, 1954). In fact, Kelley suggests in his tectonic map of the San Juan basin that the shallow trough to the west of the Beautiful Mountain anticline may be an extension of the Nakaibito syncline.

The Hogback monocline is a northeast-southwest-trending flexure which bounds the structural San Juan basin on its northwest flank. In a southwesterly direction, it is decreasingly prominent and disappears altogether near the southern part of the Chuska Mountains.

The minor flexure of which the Beautiful Mountain anticline and the adjacent syncline to the west are a part are possibly a result of these two regional structural features. The folding of the sediments took place during the Laramide revolution when both the Defiance uplift and Hogback monocline were active. Deformation ceased probably by middle Tertiary time and subsequent erosion leveled the pre-Chuska surface. A few minor slips in the lower Mancos Shale constitute the only adjustments by fracture. The scarcity of faults in the western part of the San Juan basin is a characteristic noted by Beaumont.

MINERAL DEPOSITS

The lenses of heavy minerals which together constitute the Sanostee deposit crop out in a prominent cuesta formed by the Gallup Sandstone. This area is designated the Sanostee prospect (pl. 3). It is four miles west-northwest of the Sanostee Trading Post and three miles northwest of the village of Sanostee.

The deposit is composed of six en echelon lenses. A plane table map of the cuesta top was constructed at a scale of 200 feet to 1 inch (pl. 7). This map indicates the exposed positions of the mineral lenses and was utilized as a base for a radiometric survey of the deposits. The radiometric data were contoured and an interpretation made which indicates the presence of a buried mineral lens.

Two sampling plans were followed. First, the mineral lenses were sampled at approximately 100-foot intervals along the trace of the outcrop. (The positions are indicated by a lower-case letter and circle on the plane table map.) These samples were used for X-ray spectrographic analyses of the deposits. Second, chip samples were taken at 5-foot intervals along the outcrop length and were used in studying the mineralogy of the deposit. The three lenses sampled are designated A, B, and C on Plate 7.

Structural and Stratigraphic Relationships

As mentioned, the Gallup Sandstone is composed of three units: an upper unit of intercalated fine-grained to conglomeratic sandstones and shales, a medial unit of coal beds and carbonaceous shales, and a lower, thick, fine-grained, massive unit gradational into the underlying lower Mancos Shale. The heavy mineral lenses lie entirely within and at the top of the lower unit. The lenses are relatively uniform in thickness but vary considerably in their other dimensions. Average thickness is about six feet, but thicknesses of twelve feet are exposed locally. Thickness is estimated on the basis of the magnitude of a purplish black zone which extends down the cliff faces. Since this colored zone may be due to iron transported in solution, the reported thickness may be too great. The east cliff face of Sanostee cuesta represents the only complete vertical section through a lens. Inasmuch as the cliff face does not cut the mineral lenses in a direction normal to their strike, the outcrop length varies over a wide range; the length of a lens exposed in the cliff face directly beneath lens C is 160 feet. In contrast, lens A is exposed along the western edge of Sanostee cuesta for a distance of 1600 feet. Other lenses exposed in the area have been partly eroded and have outcrop lengths between these extremes. No absolute dimensions can be assigned to any of the mineral lenses because no single lens has been exposed in its entirety.

The Gallup Sandstone in the vicinity of the Sanostee prospect forms the westward-dipping flank of the Beautiful Mountain anticline. The average dip of the formation in the vicinity of the deposit is between two and three degrees west and the strike ranges from N. 20° E. to N. 20° W. The strike of the exposed lenses is similar to that of the Gallup Sandstone, but the dip is to the east and ranges between two and five degrees. The top of the littoral marine unit of the Gallup Sandstone was essentially a horizontal surface during deposition, and hence the initial dip angle of the mineral lenses can be determined either graphically or by addition of the dip values. The initial dips of the lenses are ten, four, and five degrees. These angles of initial dip are similar to ones reported by Griggs (1944) on recent chromiferous black sand deposits along the Oregon coast.

The heavy mineral lenses exposed on the eastern face of the cuesta are gradational in the area of lens B downward and eastward into quartz sandstone. In these places, typical Gallup Sandstone and dark heavy mineral layers interfinger. The light bands may pass almost entirely through the mineral lenses. The tops and westernmost boundaries of the lenses are generally sharp and well defined against the lighter quartz sandstone. Exposures of adjacent mineral lenses suggest an en echelon arrangement of the concentrations (fig. 5). From these stratigraphic and structural relationships it is concluded that the heavy mineral lenses represent beach placers which were formed in the littoral zone. In view of such an origin the mineral lenses are quite likely to be (1) discontinuous along the strike, (2) variable in heavy mineral content, and (3) regular or sinuous depending upon the configuration of the Upper Cretaceous shoreline during deposition of the Gallup Sandstone. Because of the attitude of the deposits, their relation to each other, and the proposed mechanics of deposition, it is concluded that the lenses become younger to the east and that the distributive province lay somewhere to the west.

Radiometric Survey

A radiometric survey of portions of the Sanostee cuesta was made with a Precision Model 111 "Scintillator." This instrument has a dry-cell power supply which can be fastened to the operator by belt loops and a hand-held "gun" which contains the detecting crystal. Attached to the detector is a meter which reads in milliroentgens per hour (mr/hr). The Scintillator can detect radiation of less than 0.005 milliroentgen per hour, which is well below the background intensity of about 0.05 milliroentgen per hour in parts of the cuesta not containing mineral lenses. Radioactivity readings were taken at 50-foot intervals along east to west lines that start at the mesa edge and are spaced 100 feet apart along the outcrops of the mineral lenses. Readings were taken at observation points by holding the detector at waist height for at least two minutes, thus allowing the meter reading to reach a stable position, and were made at 50-foot intervals along the east to west traverses until the intensity remained at background level for at least two successive observations. Observed intensities were recorded on the plane table map of the cuesta surface. The radioactive intensities were contoured using a contour interval of 0.04 milliroentgen per hour. The result is illustrated on Plate 7.

Heavy mineral concentrations determined by field measurements and mineralogy can be correlated directly with areas of high and low radioactive intensity. The contoured area generally parallel to lens A(pl. 7) is interpreted as indicating the presence of a buried heavy mineral lens adjacent to lens A. It is also possible, but less likely, that the areas of high intensity opposite sample localities a, and j may represent local concentrations of radioactive zircon within lens A. The inferred mineral lens is referred to as lens A'. The generally higher intensity near sample locality m is probably the result of the increased thickness of lens A at that point. The crowding of contour lines is probably a result of the increase in amount of overburden near the cuesta edge. Section I of Figure 5 is a schematic interpretation of the inferred relationship between lenses A and A'.

The contour diagram near sample localities t, u, and v (pl. 7) can be correlated with the position of lens B and a second lens which is buried under a thin veneer of alluvium but which crops out in the cliff face. The area of high intensity west of sample locality t is caused by the buried lens (lens B'). Section II of Figure 5 illustrates the inferred special relationship between lenses B and B'.

A prominent change in intensity is exhibited along the eastern cuesta face near lens C. This pronounced change is due to the cropping out of portions of two distinct lenses of differing heavy mineral concentration. The northernmost part of the contoured area (near sample locality o) yielded an intensity level of 0.70 milliroentgen per hour, the highest for any lens. This lens also has the highest per cent of heavy minerals of any lens sampled. The lens opposite sample designations q, r, and s has a much higher quartz to heavy mineral ratio and has a correspondingly lower radioactive intensity. The relationship between the two is illustrated in section II of Figure 5.

Megascopic Features

The heavy mineral lenses of the Sanostee deposit are characterized by a wide range in color, density, degree of alteration, degree of cementation, and composition. Minor features such as spots, pits, cross-stratification, and desert varnish are well developed. Many of these features are related; for example, color varies with degree of alteration and heavy mineral content, as does the degree of cementation.

Exposures of the mineral lenses are dark brown to black in contrast to the light buff-colored Gallup Sandstone (pl. 5). This striking dark color is due in part to the presence of black opaque minerals and in part to the presence of brown iron-rich cement. The dark brown is also due in large part to the development of desert varnish on most exposed surfaces of the mineral lenses. The "varnish" consists of a glossy, brownish black film which varies in thickness from one to three millimeters. Desert varnish is a common phenomenon and characteristic of iron-rich rock in a desert climate.

The exposed surfaces of heavy mineral lenses, where not obscured by desert varnish, are multicolored and at many places mottled. Marked color changes occur in short distances. The most striking color changes are present in lens A, which may be due to the fact that it is the most highly altered lens. However, lens A contains the lowest weight per cent of heavy minerals, and hence the observed color range may be a primary characteristic. Lens C is strikingly mottled in shades of lavender, yellow or green, and tan. This mottling is not related in pattern to any obvious sedimentary feature. The differences are most obvious on the fresh surfaces of hand specimens.

The upper surface of the exposed lenses is commonly nodular and pitted. Individual pits and nodules seldom exceed half an inch in diameter. They appear to represent organic material deposited with the heavy minerals that subsequently was removed from the body of the rock during post-depositional alteration. It is also possible that the pattern, blotchy color variations, and nodular and pitted surfaces are the result of differences in the degree of cementation.

Samples from lens A are commonly mottled. There are generally three different colors present. Blotchy areas which range from grayish red (5R412) to pale red (5R612) are rimmed by a thin band about one millimeter wide which ranges from grayish yellow green (5GY7/2) to pale yellowish orange (10YR8/6). The remaining parts of the rock surface are generally a dark yellowish orange (10YR6/6). In some specimens the colors are arranged in

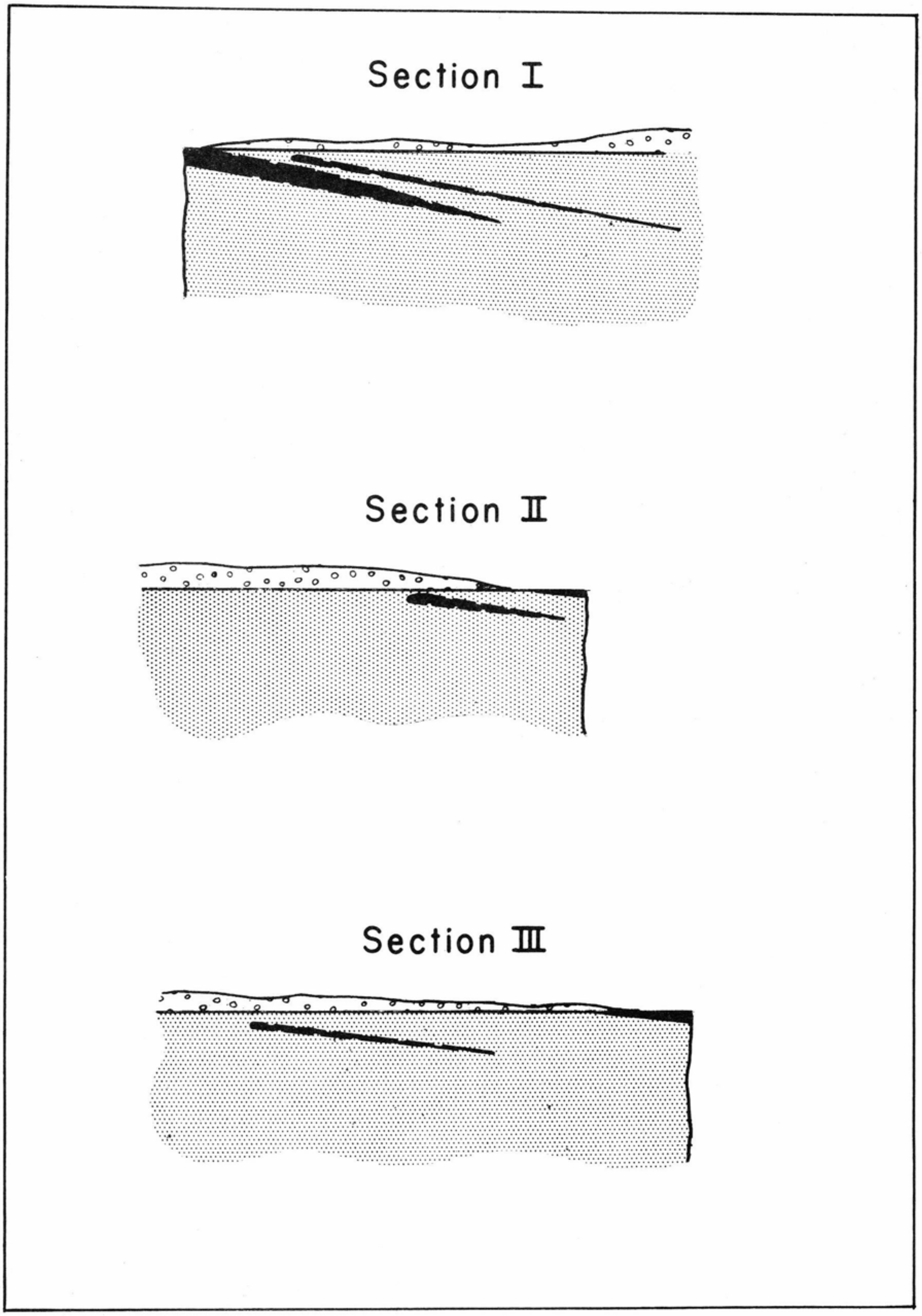

Figure 5 Schematic representation of the inferred structural relationship of the mineral lenses. *Stippled area - Gallup Sandstone, black area - heavy mineral lenses, circles - alluvium.*

streaks but in general they form dendritic blotchy patterns. Color variation is not limited to exposed surfaces throughout the body of the lenses. This suggests that the alteration that produced the coloring is not related to surface weathering. A few samples contain small (less than one centimeter) areas of red coloring, surrounded by a band of light green color which in turn passes into the yellowish brown matrix of the rock. This color sequence in hand specimens is the expected sequence if the colors are the result of oxidation and hydration of low valence iron.

Megascopically, the heavy mineral lenses commonly appear spotted. The spots are grayish yellow (5Y8/4) circular areas seldom in excess of two millimeters in diameter which stand out boldly against the darker rock. These spots may be due to the presence of small particles of organic matter or to a tendency of amorphous iron or titanium oxides to segregate into concretionary forms. The exact determination of chemical or mineral phases present in the spots is a difficult task which could be accomplished only through careful chemical and X-ray analysis. A detailed determination of the alteration mechanisms and products is beyond the scope of this paper, but deserves further study.

Small-scale cross-stratification is present at places in the lenses and is the result of the segregation of thin, discontinuous streaks or layers of quartz grains. These thin quartz-rich layers are seldom more than three millimeters thick.

Sampling and Laboratory Methods

Composite chip samples were taken of heavy mineral lenses A, B, and C. Approximately 100 pounds were collected from each lens. These composite samples were utilized in the collection of all the mineralogic and mechanical data. Most of the samples were obtained by breaking small chips off the upper surface of the lenses along their outcrop length, but where nearly vertical joints and exfoliation fractures were developed, samples were taken through a vertical section. Because of the lack of exposures, no samples were collected in a direction normal to the long axis of the lenses.

Samples were also collected at 100-foot intervals along the outcrop trace of the lenses. The sample localities are indicated by a lower-case letter and small circle on the plane table geologic map (pl. 7). From this second set of samples, data were collected regarding the distribution of niobium.

The laboratory operations are outlined in Figures 6 and 7. Each sample was blown free of adhering dust and soil by compressed air, examined megascopically, and crushed in a Brown Chipmunk jaw crusher to chips three-eighths-inch across. A 500-gram sample was obtained through splitting in a Jones splitter and was weighed and placed in a one-liter beaker containing 1:20 HCl for about three weeks, during which it was stirred at least once a day. At the end of the three-week period, the solution had taken on a deep amber color due to the presence of dissolved iron. It was found that this leaching did not completely disaggregate the larger rock fragments, but it did weaken them so that mechanical disaggregation could effectively complete the process. Samples were thoroughly washed to remove any traces of HCl and $FeCl_3$, and the disaggregation process was completed by gentle grinding in a

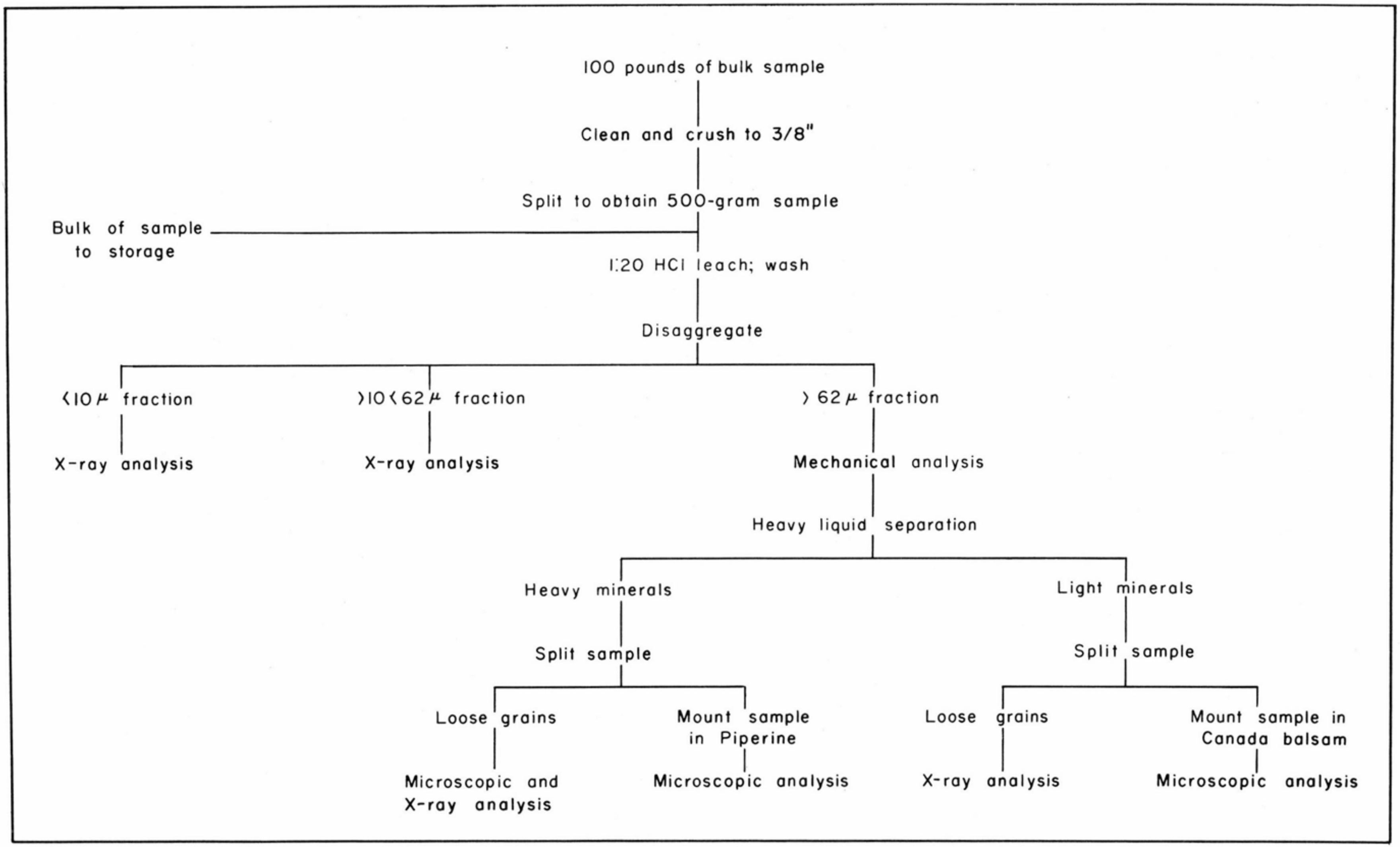

Figure 6 Flow sheet for mineralogic analysis

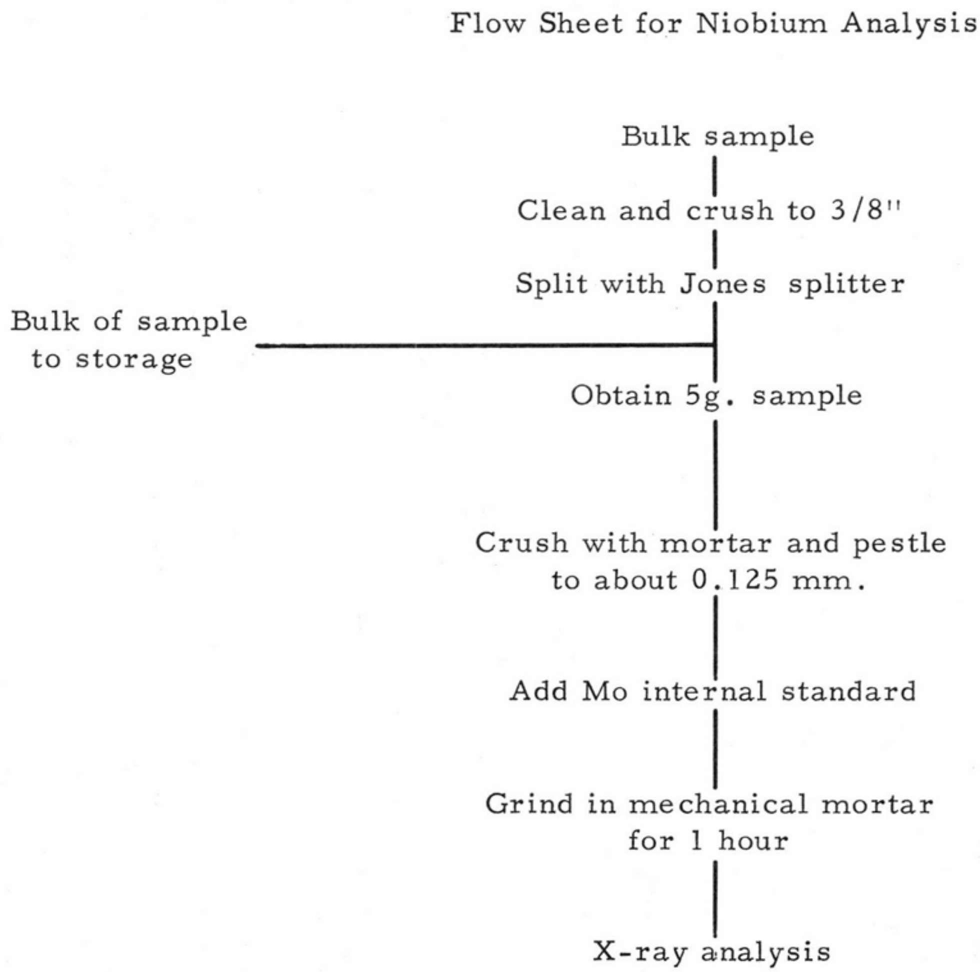

Figure 7 Flow sheet for niobium analysis

porcelain mortar with a rubber-covered pestle. A large amount of cement was removed in suspension and placed in a gallon jar. The suspension was allowed to stand for at least one hour to allow all particles larger than 10 microns to settle to the bottom of the jar. The liquid was then siphoned out and passed through a supercentrifuge which deposited all solid material on a celluloid sheet. The less-than-10-micron fraction was then dried and set aside for X-ray analysis. In all samples, this fraction constituted less than one per cent by weight of the total sample. The residue in the glass jar was removed, dried, and later added to the pan fraction of the sieve analysis. The bulk of the sample after disaggregation was dried, weighed, sieved with a set of U. S. Standard sieves, sizes 2000, 1000, 500, 250, 125, and 62 microns. Each fraction was then weighed and a heavy liquid separation was made utilizing acetylene tetrabromide which has a specific gravity of 2.89 at 25°C. Each fraction from the heavy liquid separation was washed with acetone, dried, and weighed. The light fraction of the material between 250 and 125 microns and between 125 and 62 microns in diameter was mounted on a glass slide in Canada balsam. Mineral data, angularity measurements, and type of inclusions in quartz were obtained from this portion of each sample. The heavy mineral fractions of the same size groups were split using a microsplitter into three fractions. The first was mounted on a glass slide in Piperine, a low-melting alkaloid which has a refractive index of l. 68. The identity and quantity of heavy mineral species present were determined from this part of the sample. The second part was stored in a glass vial. Individual mineral species were later picked from this part of the sample for analysis with an emission spectrograph. The third fraction was run through a Carpco magnetic separator and separated into six fractions according to degree of magnetic susceptibility. Each of these six fractions was analyzed by X-ray diffraction and examined in polished section.

X-ray diffraction techniques were utilized to determine mineralogic composition, presence or absence of clay minerals, and the degree of crystallinity. A Norelco high-angle X-ray diffractometer employing Ni-filtered Cu radiation was used. All samples for analysis were first ground in an agate mortar. The sample was then mounted in an aluminum sample holder which contains a window measuring 1 centimeter by 2 centimeters by l-l/2 millimeters. The diffraction spectrum is traced on a moving chart by a Brown recorder which receives an amplified pulse from a Geiger tube detector. Samples containing clay minerals were analyzed twice, first in the dry state as described above and second in an expanded state. The expanded sample is prepared by adding a few drops of glycerol to a small portion of the sample. The powder plus glycerol mixture is allowed to stand for at least half an hour. The mixture is then smeared on a glass slide and placed in the diffractometer for analysis.

For routine identification, the positions of reflections recorded on the X-ray diffraction charts were measured and the value for each reflection was converted to interplanar spacing, d. Values of d were then compared with the data on American Society for Testing Materials cards for known minerals. For identification of the clay minerals, known standards supplied by the New Mexico Bureau of Mines and Mineral Resources were analyzed. Diffraction data from Sanostee samples were then compared with the standard charts. Relative amounts of the clay minerals in the Sanostee samples were estimated by comparing their peak amplitudes to those of the standard charts.

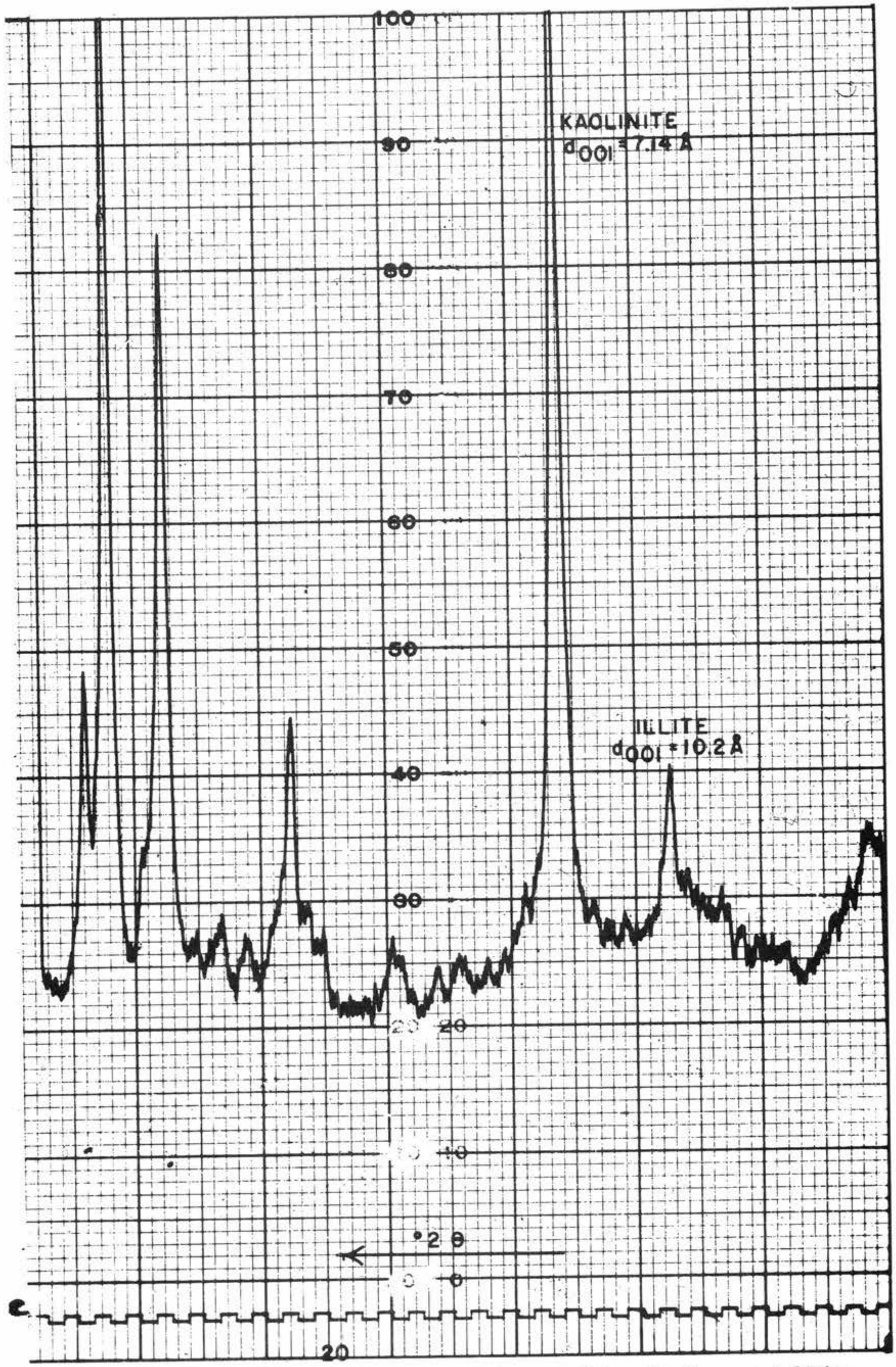

Figure 8 X-ray diffraction pattern of kaolinite and illite

The four common clay minerals in sediments are kaolinite, illite, montmorillonite, and mixed-layer clay. Kaolinite and illite do not have expandable lattices, whereas montmorillonite and mixed-layer clays do. Kaolinite and illite are identified by the presence or absence of the 7A and 10A (001) reflections (fig. 8). These reflections do not shift when the sample is glycolated. The (001) reflection of montmorillonite varies with the nature of interplanar adsorbed material (Brindley, 1951). For this reason, the samples were treated with glycerol, which expands the lattice to a fixed position. Glycolated montmorillonite has a characteristic (001) spacing at 17.7A (fig. 9).

Randomly interstratified illite-montmorillonite is in some samples and was recognized from the position of the 001/002 peak after treatment with glycerol (fig. 10). The position of the 001/002 reflection, after glycolation, is directly proportional to the ratio of illite to montmorillonite in the mixed-layer clay.

Samples of the heavy mineral lenses collected for niobium analysis were handled in a different manner from those taken for mineralogic analysis (fig. 7). The crusher was dismantled and carefully cleaned with a wire brush and compressed air between each crushing to avoid contamination.

Size frequency curves based on the collected mechanical data have been prepared. Size is plotted along the abscissa and weight per cent is plotted along the ordinate. An arithmetic scale is used for both axes. Figure 11 shows that the curves of the bulk sample for lenses A and B are bimodal, whereas the curve for lens C has only one maximum. The curve for lens C with only one maximum is characteristic of a well-sorted marine beach deposit. The bimodal character of lenses A and B may be the result of alteration after deposition. The frequency curves of the heavy mineral fractions all show one maximum which in all instances is displaced toward the finer grain sizes. This relation is expectable because, due to hydraulic factors (Krumbein and Pettijohn, 1938), light minerals such as quartz and feldspar will be deposited with heavier minerals of smaller diameter. The difference in density is balanced by a proportional difference in average diameter.

The median diameter (Md), first quartile (Q1), and third quartile (Q3) measurements were determined. From these data, the Trask sorting coefficient (So = Q1/Q3) and the geometric skewness ($Skg = \frac{Q_1 Q_3}{(Md^2)}$) were calculated (fig. 12). In all instances, the median diameter of the heavy minerals is less than the median diameter of the bulk sample. This again is due to hydraulic factors. All the sorting coefficients determined are less than 2.5, which indicates that the lenses are well sorted according to Trask's classification (Krumbein and Pettijohn). A value of unity for So would indicate perfect sorting; all the mineral lenses are very close to this optimum. Values of the geometric skewness less than unity indicate that the size spread is greatest on the coarse side of the median diameter and conversely a value greater than one indicates that the size spread is greatest on the high side. Values of skewness for the samples from lenses A, B, and C are very close to unity, indicating that the asymmetry of the size curves is low. The skewness for the heavier mineral concentrates from lenses B and C is higher than the skewness for the bulk samples, which reasserts the fact that the heavier mineral fraction occurs in a smaller size fraction than the bulk of the sample.

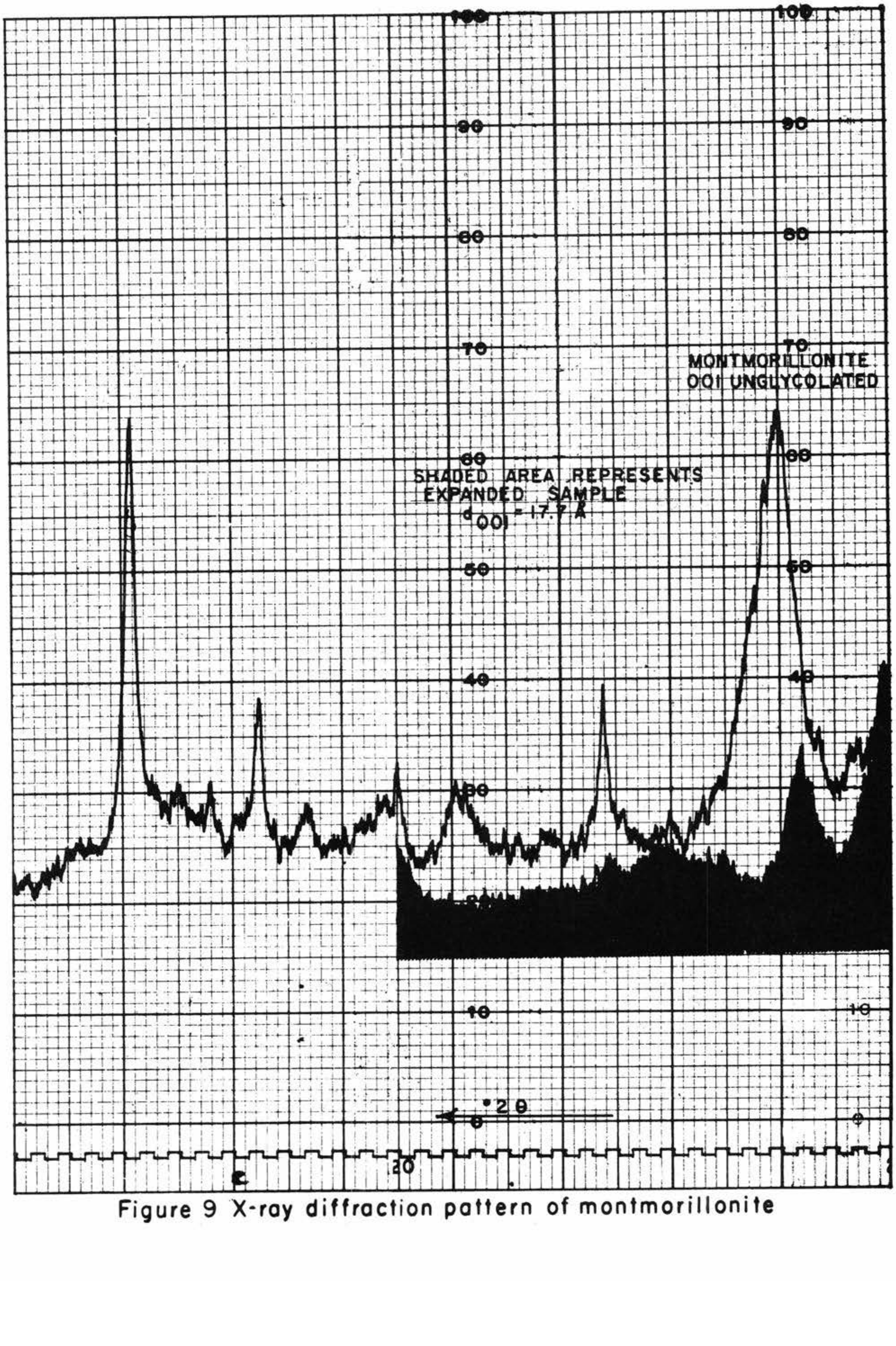

Figure 9 X-ray diffraction pattern of montmorillonite

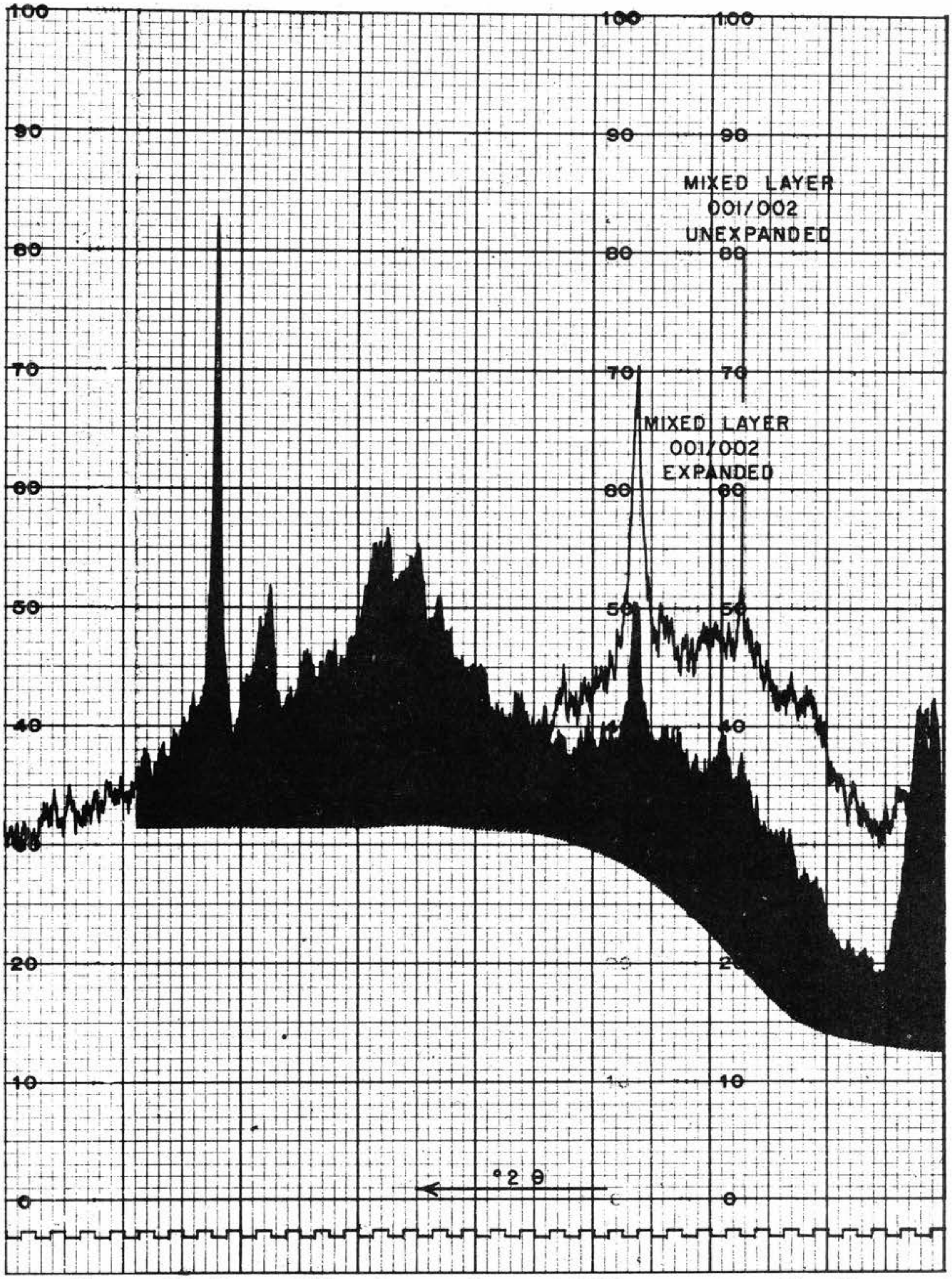

Figure 10 X-ray diffraction pattern of illite – montmorillonite mixed-layer clay

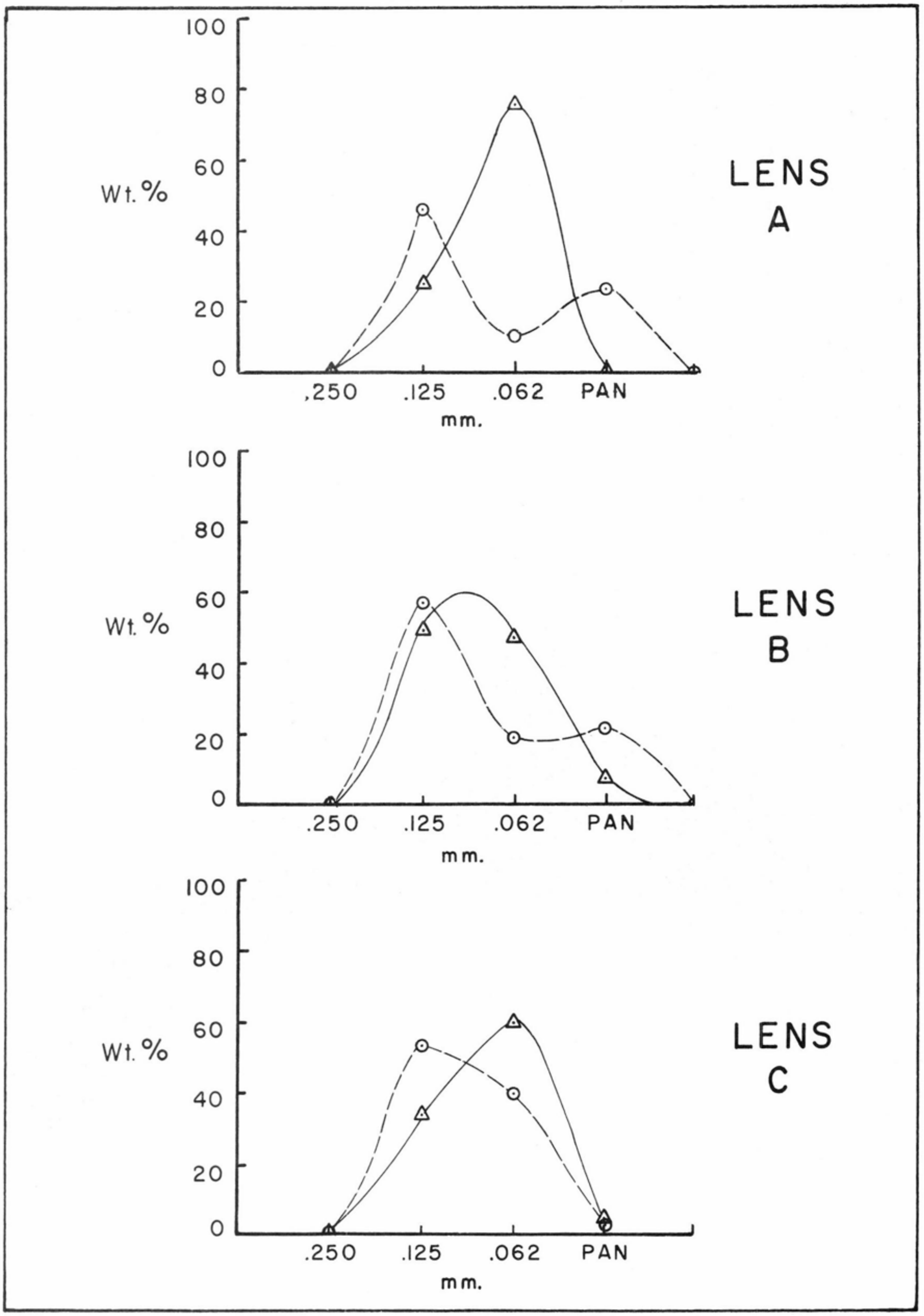

Figure 11 Size frequency curves of heavy and light fractions of the mineral lenses. *Dashed line connecting circles represents light fraction, solid line connecting triangles represents heavy fraction.*

Statistical Parameters

	Lens A		Lens B		Lens C	
	Bulk comp.	Heavy minerals	Bulk comp.	Heavy minerals	Bulk comp.	Heavy minerals
Md (mm)	0.132	0.112	0.148	0.125	0.168	0.112
So (Trask)	1.30	1.63	1.67	1.18	1.75	1.09
Skg	1.00	0.99	0.82	0.95	0.68	1.03

Figure 12 Table of statistical parameters for the heavy mineral lenses

Mineralogy

A system of mineral analysis was followed utilizing the petrographic microscope, X-ray diffractometer, and emission spectrograph. The results of the analyses and their meaning are discussed under three separate headings: allogenic minerals, authigenic minerals, and source. These topics are separated in the text, but each is an integral part of the complete geologic picture reconstructed according to recognized principles of sedimentation, diagenesis, and weathering.

Allogenic Minerals

The allogenic constituents of the mineral lenses are largely the common rock-forming minerals: quartz, zircon, garnet, tourmaline, and ilmenite. Inasmuch as allogenic minerals are derived from some pre-existing rock and have been transported an unknown distance and deposited, they would be expected to show characteristics related to that history. Hence, knowledge of the composition of the mineral suite, abrasion effects (roundness, angularity, sphericity), surface characteristics (polish, frosting), and the nature of primary textures and structures (bedding, etc.) is essential in the study of these sedimentary deposits.

Quartz. Quartz is the only light mineral present and makes up more than twenty per cent of the lenses sampled. Angularity of the quartz grains ranges from 0 to 100 per cent, but an average for A, B, and C is given in Plate 4, Table 3. Inclusions in quartz were noted and their frequency determined according to Mackie's classification (Krumbein and Pettijohn) in which inclusions are placed into one of four groups: (a) irregular, anhedral blebs, usually gas or liquid inclusions and vacuoles, (b) regular, mineral inclusions such as micas, rutile, zircon, apatite, and black iron ores, (c) acicular, needlelike or hairlike mineral inclusions, rutile in many instances, and (d) no inclusions.

Authigenic overgrowth of quartz on clastic quartz grains are common but not widespread. In addition, all the very fine size fractions contain some quartz as identified by X-ray analysis. This clay-size quartz is not abundant and is probably authigenic.

The quartz from the 125- to 250-micron size fraction was analyzed with both the emission and X-ray fluorescent spectrograph; no niobium was present.

Zircon. Zircon is the dominant mineral in the heavy mineral suites. It is euhedral, subrounded, or angular (pls. 8 and 9). The dominant crystal form is a combination of first order prism with dipyramidal terminations; elongation parallel to c is variable producing long, slender, needlelike forms and short, stubby, practically equidimensional forms. A few crystals show a combination of first and second order prisms with ditetragonal dipyramidal terminations. Colorless and pinkish varieties are most abundant, but a great many of the grains are very pale (light) green. Zoned zircons are common and are generally some shade of pink. Zoning appears to be the result of the inclusion of a fine dust on the faces of the crystal during growth. Metamict zircon was noted in all the mineral concentrates. It appears almost opaque in transmitted light and a milky white in reflected light. Several pink zircon crystals exhibit

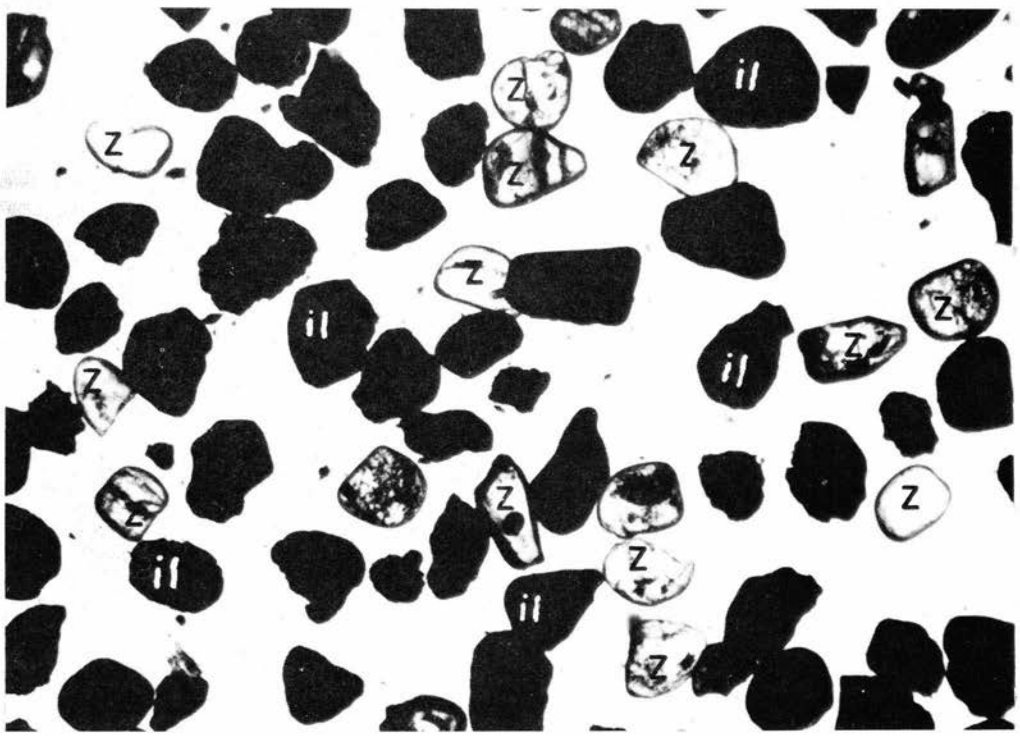

Plate 8

Photomicrograph of lens A heavy mineral fraction

Plate 9

Photomicrograph of lens A nonmagnetic residual of heavy mineral fraction.

partial metamictization with the milky white alteration product concentrated within the dipyramidal terminations or around inclusions of opaque material. Almost all inclusions were of the "regular" type. "Irregular" inclusions were less common and acicular inclusions rare (pl. 4, table 3). The shape of zircon grains ranges from euhedral to beadlike. All pale green grains are highly rounded to beadlike. Pink zircons tend to be fragmental. This trend is best exhibited in lenses A and B (pl. 4, table 3).

A zircon concentrate was collected from the nonmagnetic fraction of the heavy mineral suite from lens C. This concentrate was then analyzed qualitatively with the X-ray spectrograph. Ten zircon crystals were also picked individually from the same concentrate and analyzed with the emission spectrograph. Both samples contained substantial amounts of yttrium. Hafnium, a common trace constituent of zircon, was not present (Rankama and Sahama, 1950). In view of the absence of common trace elements such as hafnium, cerium, and uranium, it is concluded that the radioactive nature of the zircon from the Sanostee deposit is due to yttrium. Because of the diadochy which exists between zircon and niobium, the concentrate was carefully examined for the presence of niobium. None was present.

Zircon is the dominant heavy mineral in all size fractions except the 125-micron fraction of lens C (fig. 13). The ratio of zircon to opaque minerals increases in the finer-grained size fractions.

Tourmaline (Schorlite). All the observed tourmaline consists of an iron-bearing, brownish black, strongly dichroic variety known as schorlite. Tourmaline constitutes less than one per cent of the bulk sample of each lens and is found only in the 250- to 125-micron fraction (fig. 13). Euhedral prisms, angular equidimensional fragments, and polished beadlike grains are present. Grain shapes intermediate between these extremes are not present. Inclusions are rare and when present are of the regular type. The nonmagnetic fractions of the heavy mineral concentrates contained several grains of tourmaline, and inasmuch as this fraction was free of niobium, it is concluded that no niobium is in the tourmaline structure.

Rutile. Deep red, highly rounded grains of rutile are a common accessory mineral in all the lenses. Rutile is characterized by its deep, blood-red color, high dispersion, and striations parallel to the long axis of the grains. It is equally common in the 62- to 125- and 125- to 250-micron fractions. Ten grains were hand-picked and analyzed with the emission spectrograph; none contained detectable niobium.

Sphene. Two highly rounded sphene grains were observed in the heavy mineral fraction of lens A. Because of the extremely small amounts of this mineral present, it was not analyzed for the presence of niobium.

Garnet. One angular fragment of colorless garnet, probably grossularite, was noted in the heavy mineral suites.

Ilmenite. The black opaque fraction of the mineral deposit is largely ilmenite. Individual grains vary in size from less than 250 microns to about 40 microns. The ilmenite ranges from black through purplish black to chocolate brown. The change in color probably represents a progressive leaching of iron.

The majority of the ilmenite grains are subrounded to highly rounded (pls. 10 and 11). The euhedral grains are tabular with rhombic truncations, the commonest form of ilmenite (Palache, Berman, and Frondel, 1944). Many of

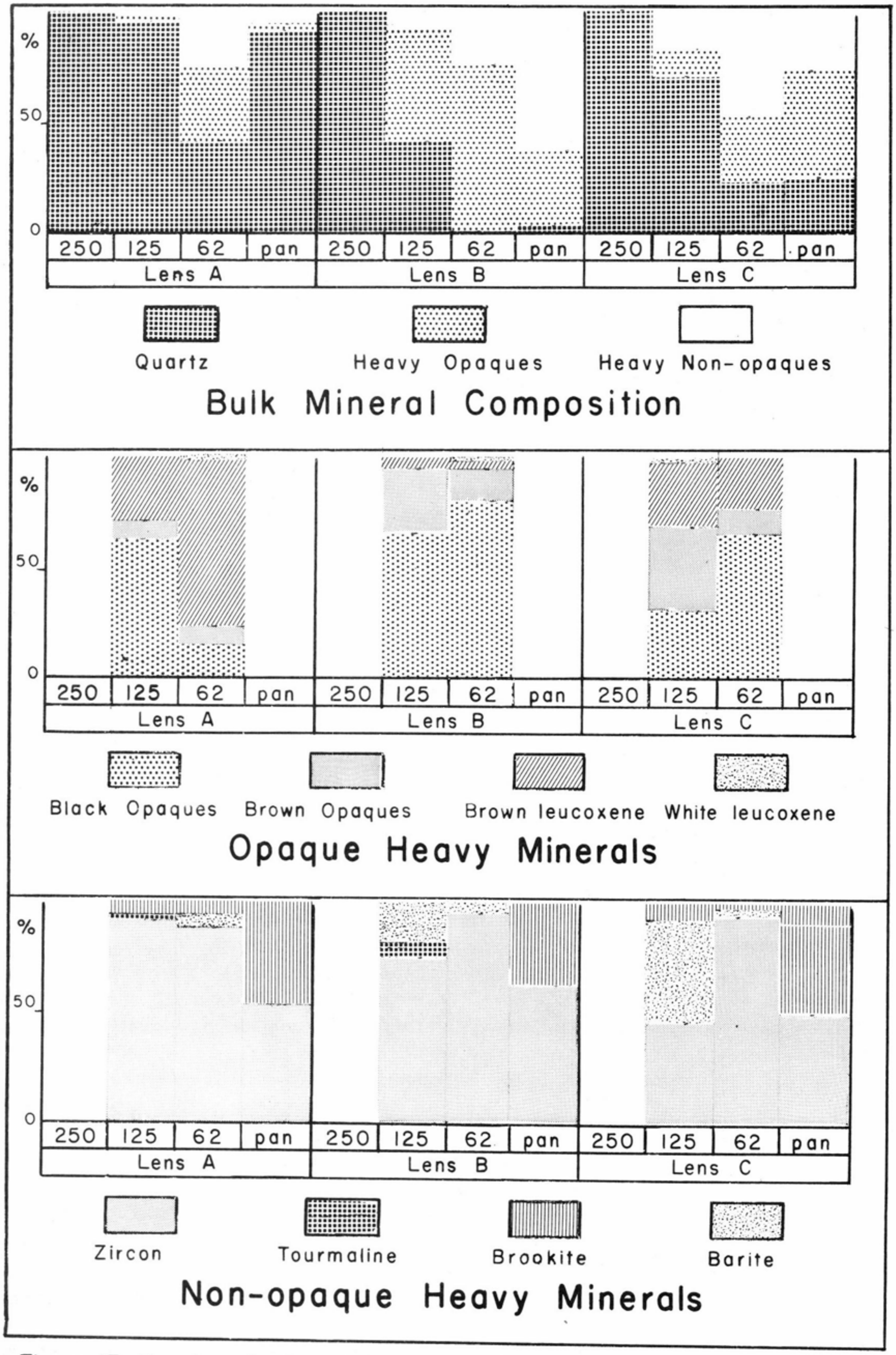

Figure 13 Graphs of mineral frequency for the heavy mineral lenses
All sizes fractions are in millimeters

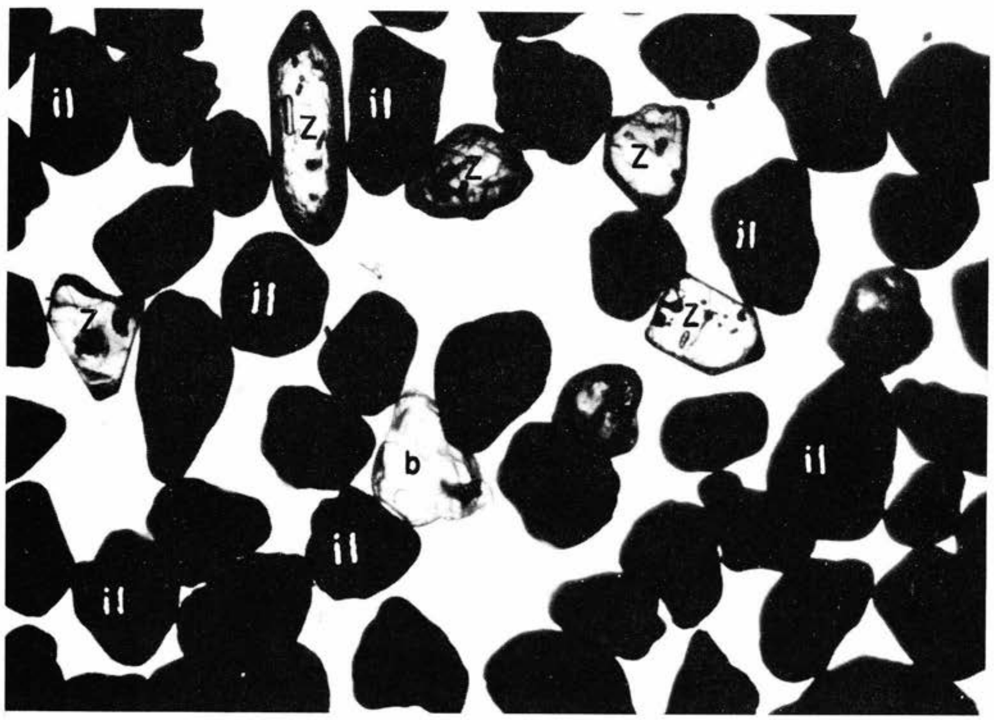

Plate 10

Photomicrograph of lens B heavy mineral fraction

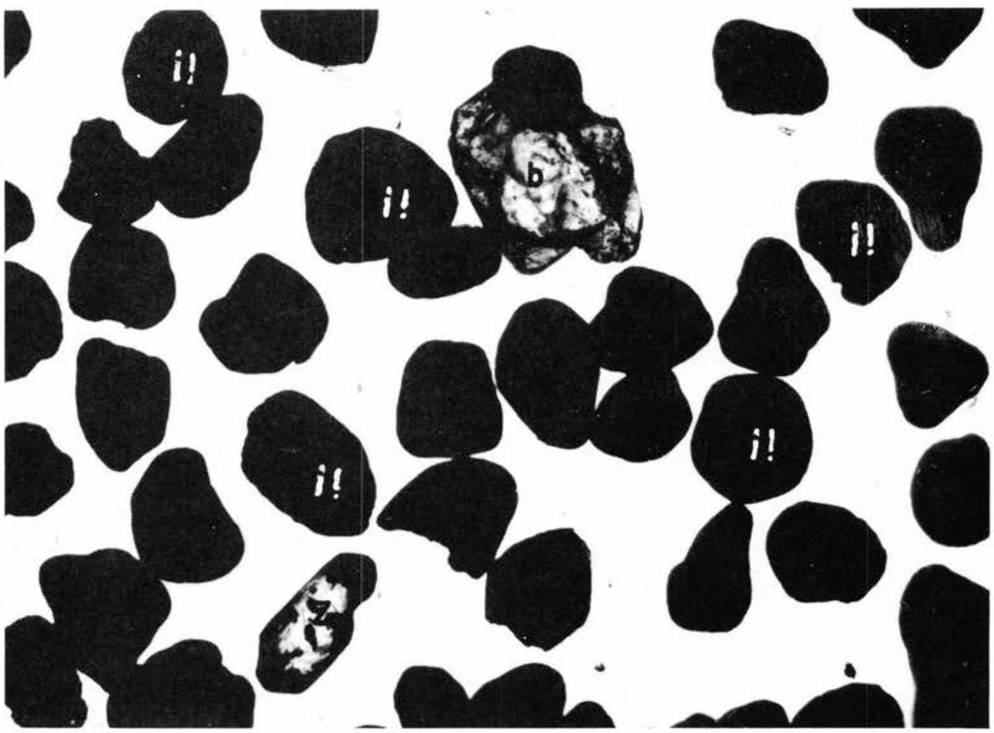

Plate 11

Photomicrograph of lens C heavy mineral fraction the subhedral grains have small triangular pits in their surfaces. These pits are probably primary impressions produced by the interference of adjacent grains during crystallization of the ultimate source rock. Ilmenite grains in lens A are concentrated in the coarser size grade of the heavy mineral suite because of their relative lightness. The reverse is true in the heavy mineral suites of lenses B and C and is most likely due to the effects of the disaggregation method utilized; it is not characteristic of these lenses.

Six magnetic separations were made according to decreasing magnetic susceptibility of the 125- to 250-micron size fraction of the heavy mineral suite. Fractions one through four, when examined with the binocular microscope, were found to consist of ninety per cent plus opaque minerals. Fraction five contained more than fifty per cent nonopaque heavy minerals, the majority of which consisted of pale green zircon. The sixth fraction was almost 100 per cent nonopaque heavy minerals, largely colorless, and pink zircon. Magnetic fractions one to four were analyzed by X-ray diffraction utilizing manganese-filtered iron radiation. It was found that there is a direct relationship between magnetic susceptibility and degree of crystallinity. In all instances, the poorer crystallized ilmenite has a lesser magnetic susceptibility. Bailey et al. (1956) record the same phenomenon in the ilmenite of recent beach sands from Mozambique, Florida, Ceylon, and Brazil. It was also noted that the ilmenite grains of fraction one had a fresher, blacker appearance and small white patches of extremely fine-grained material adhering to their surfaces. In contrast, the ilmenite grains of the intermediate fractions contained small yellow patches of fine-grained material.

The alteration of ilmenite is considered by Bailey et al. to consist of three stages. The leaching out of iron, destruction of crystallinity, and the reduction of magnetic susceptibility take place during stage one. The end product of this first stage is an amorphous mixture of iron and titanium oxides. Recrystallization of titanium oxide takes place during the later stages of alteration. Ilmenite from the Sanostee deposit shows the characteristics of all three stages. The theory of alteration requires the presence of an oxidizing leaching environment, and this could have been provided several times during or subsequent to the deposition of the Sanostee heavy minerals. The removal of iron during alteration is economically important in that it results in an upgrading of the deposit in TiO2. Titanium, as established by Rankama and Sahama, is not mobilized and is classified by them as a hydrolyzate; that is, an element which is immediately hydrolyzed and precipitated in an aqueous environment after it has been freed from the parent mineral by alteration.

Alteration of ilmenite results in dendritic to patchy intergrowths of leucoxene which are apparently controlled by either crystallographic planes or an (0001) parting in the original grain (pls. 12 and 13). All stages were observed between fresh ilmenite and grains which had been completely converted to a fine-grained yellowish white opaque material. This material has a gray metallic luster in plane polarized reflected light, and high internal reflections under crossed nicols. Similar materials from other localities have been identified as finely crystalline rutile, anatase, brookite, pseudobrookite, leucoxene, amorphous iron titanium oxide, or combinations of these (Karkhanavala et al. , 1959; Bailey et al. ; Allen, 1956). The writer prefers the terms suggested by Lynd (1960). Any finely divided amorphous (optically and to X-ray diffraction) alteration product of ilmenite he calls amorphous leucoxene. Any

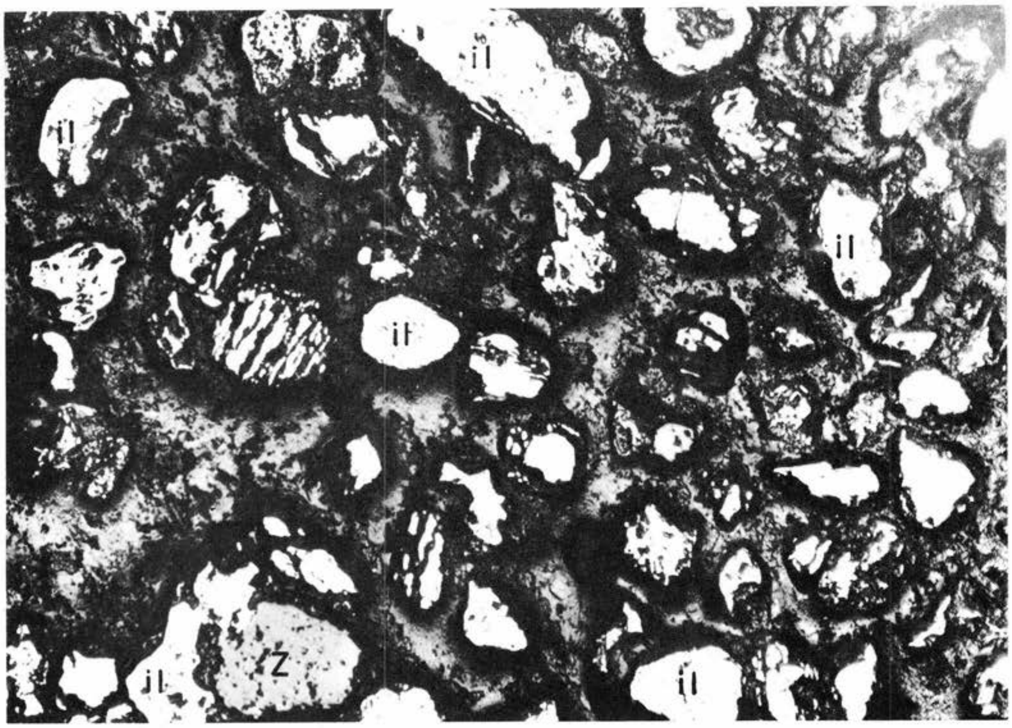

Plate 12

Polished section of magnetic part of lens A

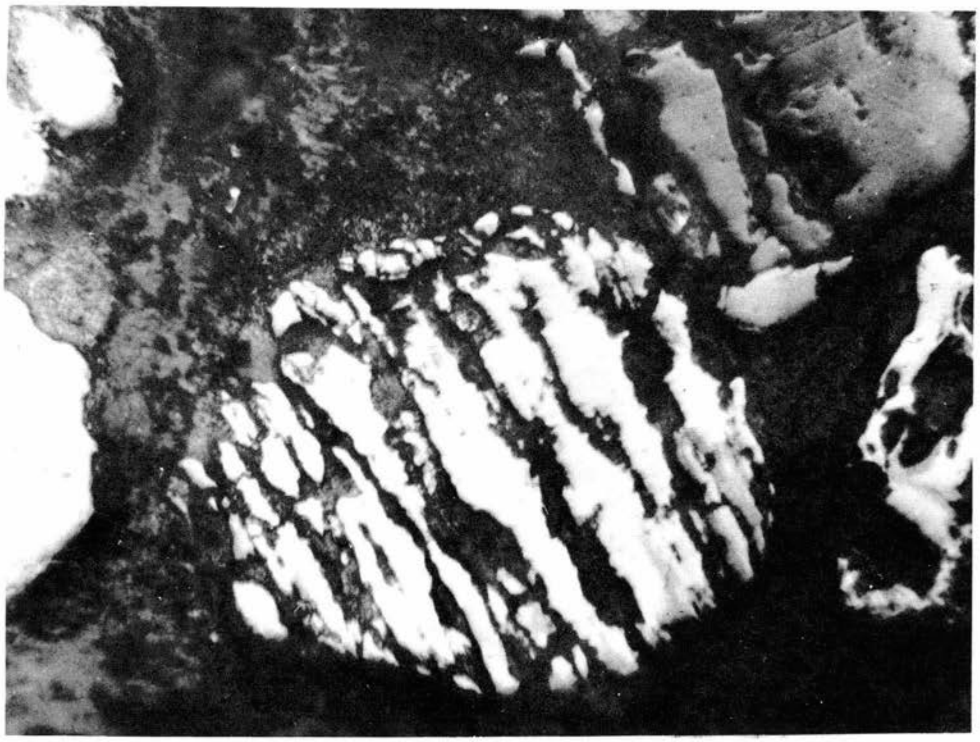

Plate 13

Enlarged view of one ilmenite grain

alteration product of ilmenite which appears amorphous under the microscope but which has a recognizable diffraction pattern he designates as crystalline leucoxene regardless of whether more than one polymorphic form of TiO_2 is present. Both crystalline leucoxene and its microscopically recognizable derivatives are considered authigenic and are discussed under that heading. Serious objection to the use of the term leucoxene to describe the alteration products of ilmenite has been raised by Flinter (1960). He contends that leucoxene implies 100 per cent TiO_2 and therefore may not be applied to ilmenite alteration products because they invariably contain some iron. He prefers the term Arizonite, ferric metatitanate, for the alteration products of ilmenite. However, the term Arizonite is even more controversial than the term leucoxene (Lynd) and hence is not used here.

Ilmenite, analyzed with the X-ray and emission spectrographs, contains substantial amounts of niobium. For X-ray analysis, a portion of each of the first four magnetic fractions was combined into one sample. This composite sample of nearly 100 per cent black opaque minerals was analyzed. In addition, ten grains from each 125- to 250-micron heavy mineral suite were analyzed with the emission spectrograph. Niobium was present in all the Sanostee ilmenite samples. These findings are expectable in view of the diadochic nature of the titanium: niobium pair (Rankama and Sahama). Fleischer et al. (1952) have also firmly established the common association of niobium and titanium.

Authigenic Minerals

Authigenic minerals are those which have not been transported but which have formed *in situ*. The authigenic minerals in the lenses of the Sanostee deposit are quartz, barite, amorphous and crystalline leucoxene, and brookite.

Quartz. Watery clear quartz overgrowths on clastic quartz grains were noted in the three lenses sampled. The overgrowths are bounded by crystal faces and in all instances were in optical continuity with the clastic quartz core. The secondary quartz could have many sources. Three of the most probable sources of the silica are silica introduced by circulating ground water, silica dissolved from the quartz grains in the lenses and reprecipitated locally, or silica supplied by the alteration of volcanic ash which is common in the Cretaceous section and in the Tertiary Chuska Sandstone. The total amount of authigenic quartz is estimated at less than one per cent of the bulk of the deposit.

Barite. Barite is a colorless mineral in the heavy mineral concentrate characterized by the presence of many dustlike inclusions. It is always found as sharply angular grains and is concentrated in the larger size fraction of the heavy mineral suite (fig. 13). Barite in sediments is considered to be, almost without exception, of authigenic origin (Krumbein and Pettijohn; Milner, 1911). The source of the barium ion is not known, but the alteration of barium-bearing feldspar and barium-rich interstitial solutions is a possible source. Sulfate-rich circulating ground waters are common and may be the result of the solution of gypsum or the oxidation of H_2S-bearing solutions (Austin, 1960). The barite analyzed spectroscopically with zircon contained no detectable niobium.

Leucoxene. Leucoxene is a nonstoichiometric mineral which forms as an alteration product of titanium-bearing minerals. In the Sanostee deposit it occurs as an alteration product after ilmenite. Along with hematite and polymorphs of TiO_2, it is the principal constituent of the rock cement (pl. 14). It is an opaque, dull, white to yellowish white, finely divided material. Because of its small grain size and interstitial nature, it is very difficult to study. Its composition was determined by X-ray diffraction and X-ray spectroscopic techniques. Samples for analysis were prepared by size separation based upon settling velocity in water. Two size fractions, 44 to 5 microns and less than 5 microns, were analyzed. The larger size consists of a mixture of anatase, brookite, and amorphous material. The less-than-5-micron size fraction consisted of anatase and amorphous material. Consistently high background counts were interpreted as the products of diffuse scattering by amorphous TiO_2 and iron. The presence of brookite was confirmed by the presence of a

2. 90Å reflection and anatase by the 3. 51Å and 1. 89Å reflections. The maximum intensity reflection of brookite is at 3. 47Å but because of its proximity to the 3.51Å. reflection of anatase, it could not be considered diagnostic. According to these data, the fine-grained crystalline TiO_2 is in the form of anatase. This mineral is considered the first crystallization product of amorphous TiO_2. Pseudobrookite was not found in the analyzed samples, although reported in similar associations elsewhere. It must be concluded that the chemical environment during the alteration process favored the formation of anatase over other polymorphic forms of TiO_2.

Spectroscopic analyses of leucoxene reveal the presence of a substantial amount of niobium. The similarities between titanium and niobium are such that they react in much the same way during alteration and recrystallization.

Brookite. Brookite is a polymorph of titanium dioxide. It occurs as dark yellow-brown tabular plates and subhedral grains (pl. 15). Pleochroism usually is distinct. Penetration twins are common. Its appearance under crossed nicols is distinctive because of its anomalous orange and violet interference colors and extinction. Striations on crystal faces, commonly reported for brookite (Krumbein and Pettijohn), are absent.

Brookite occurs in crusts lining geodelike cavities in leucoxene and as felted masses between clastic grains. Its position in the rock fabric leaves no doubt that some genetic relationship exists between it and leucoxene. Whether brookite has crystallized directly from amorphous TiO_2 or has originated by the polymorphic inversion of anatase is not known. Brookite has been reported as an authigenic mineral in a heavy mineral deposit near Gallup, New Mexico (Sun and Allen), and is there interpreted as being derived from amorphous titanium dioxide. Several samples of a brookite concentrate were analyzed and found to contain niobium.

Hematite. A small percentage of the opaque authigenic cement is hematite. It consists of dark red flakes and thin red films on leucoxene.

Origin of the Deposit

The heavy mineral lenses which occur within the Gallup Sandstone on Sanostee cuesta are interpreted as beach placers formed in the littoral zone by the sorting action of waves and currents impinging upon the late Cretaceous

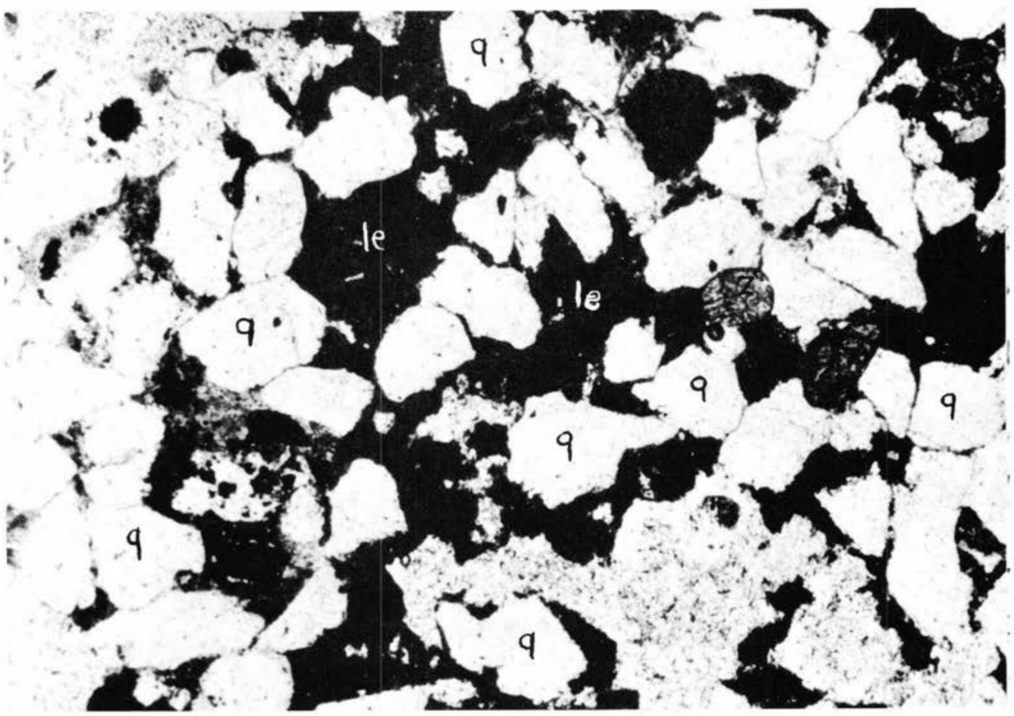

Plate 14

Thinsection of sample from lens A

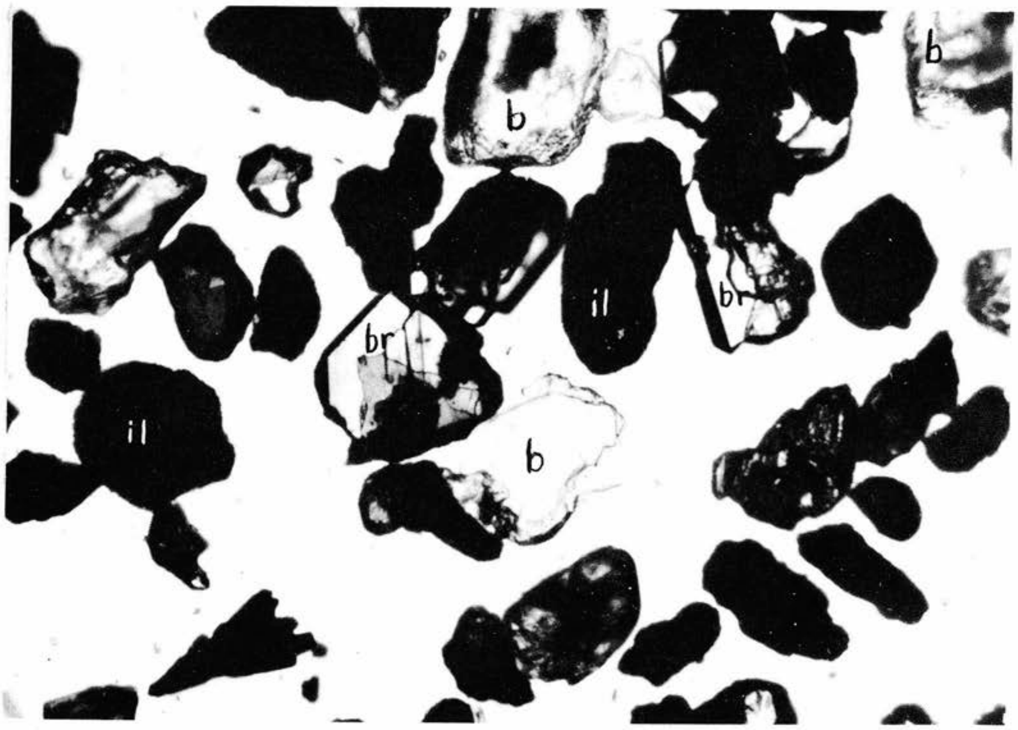

Plate 15

Pan fraction from lens A

REWORKED SEDIMENTS

Quartz	Leucoxene	Zircon, rounded
Chert	Tourmaline, rounded	

METAMORPHIC

Low-Rank	High-Rank
Slate and phyllite fragments	Quartz, metamorphic variety
Quartzite and quartz fragments	Garnet
Brown tourmaline	Blue-green hornblende
	Kyanite
	Sillimanite
	Staurolite
	Epidote
	Zoisite

IGNEOUS

Acid	Basic
Apatite	Augite
Biotite	Hypersthene
Hornblende	Ilmenite
Zircon, euhedra	Rutile
Quartz, igneous variety	

Figure Common detrital minerals characteristic of source rock type (After Pettijohn, 1957)

Figure 14 Common detrital minerals characteristic of source rock type (After Pettijohn, 1957)

shoreline. Several lines of evidence indicate the marine origin of these lenses. First, the heavy minerals occur entirely within and at the top of the littoral marine unit of the Gallup Sandstone. Second, the uniform width (measured normal to the strike of the lens), thickness, dip, and interfingering nature of the lenses is similar to recent beach placers in Florida and Oregon. The uniform eastward dips of the lenses reflect a marine beach profile which dipped eastward. The high degree of sorting of the elastic constituents (average So = 1.43) and the skewed size frequency distribution suggest deposition in a beach environment.

Mineral frequency variations in the lenses and interstratified tongues of quartz sandstone reflect variations in the form of the shoreline and angle of impingement of currents. Inasmuch as the heavy minerals are concentrated by a winnowing out of quartz in the zone of wash and backwash, any factor such as changing current direction or an obstacle to the circulation of waves will tend to alter the position of heavy mineral concentrates.

Origin of Heavy Minerals

Inclusions in quartz, grain morphology, and mineralogy furnish clues to the nature of the provenance. The genetic implications of inclusions in quartz are apparent from Mackie's classification; that is, an abundance of irregular and acicular inclusions indicate an igneous source rock, whereas an abundance of regular inclusions or the absence of inclusions indicate a metamorphic source rock. Inclusions in the quartz grains of a sedimentary rock indicate the nature of the ultimate source. A pronounced change in the relative proportions of type of inclusions is noted in the heavy mineral lenses at Sanostee (pl. 4, table 3). In lens A, 58 per cent of the quartz grains with an angularity of less than 50 per cent contain irregular and acicular inclusions (igneous source rock). Inasmuch as mineral grains which show a pronounced rounding have probably been recycled, it would seem that the ultimate source of the recycled quartz was largely igneous rock. The presence of large amounts of highly rounded and beadlike zircon also suggests that the ultimate source rocks were largely igneous.

Grain morphology and mineralogy indicate the nature of the immediate source of elastic material. The genetic implications of rounding have been discussed in a preceding section. It is re-emphasized at this point, however, that highly rounded or beadlike zircon is an unqualified indication of derivation from a pre-existing sedimentary rock. Ample evidence is offered in the literature that one cycle of erosion, transportation, and deposition is not sufficient to cause appreciable rounding of the stable minerals zircon and tourmaline. It is also unlikely that initially angular grains of the same size will develop various degrees of rounding during one transportation cycle. The mineralogy of some allogenic minerals may be diagnostic of igneous or metamorphic source rocks (fig. 14) (Pettijohn, 1957).

The zircon and ilmenite morphologies reflect both the sedimentary and crystalline natures of the immediate source. Based on the degree of rounding, the light green variety of zircon was derived entirely from sediments, whereas the immediate source of the pink and colorless varieties was dominantly crystalline rock. The highly rounded to beadlike character of ilmenite suggests that it has been recycled. Some euhedral ilmenite is present and attests to an immediate igneous source rock in part.

The heavy mineral suite (zircon-tourmaline-ilmenite) is characteristic of sedimentary rocks and suggests that they were the immediate source. This stable suite of heavy minerals, characteristic of both the lenses and the normal Gallup Sandstone, evidently was derived from the same source. Unstable minerals, although absent in the lenses and Gallup Sandstone, are present in recent beaches and in some Upper Cretaceous littoral sandstones in the San Juan basin. Hence, it is clear that they can survive deposition in that environment. It seems likely that a large percentage of the minerals contained in the heavy mineral lenses at Sanostee was derived from an immediate source in which sedimentary rocks predominated. The specific formations from which they were derived are not so clearly indicated. Two possibilities exist: older Cretaceous or Jurassic rocks. These older sedimentary rocks are the most logical source of heavy minerals for the Gallup Sandstone and for the beach placers. The Dakota (?) Sandstone and older Jurassic rocks contain the same stable mineral suite present in the mineral lenses and in the Gallup Sandstone. They also contain small amounts of unstable minerals, but these would not be expected to survive recycling. It is highly improbable, however, that the heavy minerals of these older rocks would be released from the source area to intermittent floods to produce the stratigraphically distinct concentrations which crop out in the Sanostee cuesta. Instead, it is suggested that the heavy minerals were released from Jurassic and/or pre-Gallup Upper Cretaceous rocks, and those stable heavy minerals which survived this cycle of transport were deposited along with large amounts of quartz as the littoral marine facies of the Gallup Sandstone. During deposition, a slight decrease in the rate of sedimentation or a still stand of the sea would allow normal marine erosion to establish a new profile of equilibrium. Such erosion would rework sediment deposited in the beach zone and would effectively concentrate disseminated heavy minerals near the high tide mark. A slight change in the angle of impingement of currents upon the beach or a return to a substantial rate of sedimentation would shift the position of established placers or bury them completely. It is seen then that accessory heavy minerals disseminated in sediments entering the basin of deposition during the accumulation of Gallup Sandstone sediments could be concentrated into lenses similar to those exposed at Sanostee. Therefore, it seems likely that the Sanostee heavy mineral lenses are local concentrations of accessory minerals derived from preexisting Jurassic and/or Cretaceous sedimentary rocks and that concentration occurred during deposition of the Gallup Sandstone sediments.

Niobium Content and Distribution

Niobium is commonly associated with titanium (Fleischer et al.) and, although many titanium-bearing heavy mineral deposits are known in the San Juan basin, the presence of niobium in these deposits has never been investigated. The presence of substantial amounts of niobium in these placers may be of economic significance.

The heavy minerals in the Sanostee deposit have been separated and analyzed for niobium, and the per cent of niobium in the lenses has been calculated. The mineralogic distribution of niobium is of importance in working out the metallurgy of this deposit. An estimate of the amount of zircon and titanium was also made.

Distribution of niobium. The distribution of niobium in the various mineral species present in the Sanostee deposit was determined by qualitative X-ray and emission spectrographic analyses. In view of the titanium:niobium diadochy (Rankama and Sahama) and the data presented by Fleischer et al., it was suspected that niobium might be found in the titanium-bearing minerals ilmenite, leucoxene, brookite, and anatase. This hypothesis was confirmed by analysis. Not only is it present in the allogenic ilmenite but also in the authigenic leucoxene and polymorphs of Ti02. This indicates that during the alteration of the Sanostee deposit niobium has followed titanium, at least in part. No direct data are available which would allow an estimate of the amount of niobium present in each mineral species. Since the niobium is held in solid solution in the titanium mineral lattice, it is most probable that niobium is present in nonstoichiometric amounts. Not only may it vary in amount in a single mineral species, but it may also vary from mineral to mineral. Fleischer's data indicate that brookite may retain more niobium in solid solution than ilmenite. However, these data are based on igneous as well as sedimentary occurrences, and may be misleading with regard to titanium minerals formed by an authigenic process.

A niobium-titanium intensity (proportional to concentration) ratio was calculated in an attempt to evaluate the niobium-titanium relationship in the mineral lenses. If niobium were present in stoichiometric amount in all the ilmenite and if it followed titanium during alteration of ilmenite, the calculated ratio should remain constant. The results of niobium analyses (fig. 15) show the niobium:titanium ratio for each sample analyzed. Inasmuch as the ratio is not constant it appears that ilmenite does not contain fixed amounts of niobium or that niobium does not completely follow titanium during the alteration.

Limited data are available regarding the presence of niobium in other heavy mineral deposits throughout the San Juan basin. Grab samples were obtained from deposits near Gallup, New Mexico (Gallup Sandstone), Standing Rock, New Mexico (Point Lookout Sandstone), and Farmington, New Mexico (Hogback deposit in the Crevasse Canyon formation). These samples were analyzed qualitatively with the X-ray spectrograph, and it was found that neither the Standing Rock nor the Hogback deposit contained detectable niobium, whereas the Gallup deposit contained niobium in approximately the same amounts as the Sanostee deposit. The absence of niobium in rocks younger than the Gallup Sandstone is probably due to a change in the source rocks. As already noted, this change in source rock is also indicated by a general change in the heavy mineral assemblage above the Gallup Sandstone. In view of these findings, any search for niobium-bearing heavy mineral deposits would best be directed within or below the Gallup Sandstone.

Niobium content. The niobium content of the Sanostee deposit has been calculated from the quantitative analysis of representative samples of the heavy mineral lenses and an estimate of the amount of lens material present in the deposit. Niobium content is expressed as Nb205-the most common commercial form—and is calculated by multiplying the assay in weight per cent times the total tonnage of lens material. Figure 15 shows the average per cent by weight of Nb_2O_5 for each lens and for the entire deposit.

Sample	Nb/Ti	I_{Mo}/I_{Nb}	% Nb_2O_5
a	0.68	0.0121	0.10
b	0.98	0.0125	0.11
c	0.71	0.0128	0.11
d	0.80	0.0124	0.10
e	0.66	0.0173	0.14
f	0.74	0.0122	0.09
g	0.69	0.0110	0.09
h	0.45	0.0150	0.13
i	0.91	0.0112	0.09
j	0.87	0.0116	0.10
k	---	---	---
l	0.85	0.0136	0.11
m	0.76	0.0119	0.10
n	1.41	0.0158	0.13
o	1.50	0.0183	0.15
p	0.47	0.0183	0.15
q	0.57	0.0120	0.10
r	1.04	0.0140	0.12
s	0.21	0.0144	0.12
t	0.51	0.0102	0.09
u	0.80	0.0128	0.11
v	0.54	0.0101	0.09
Lens A (Average)			0.11
Lens B "			0.09
Lens C "			0.13
Deposit "			0.11

Figure 15 Results of niobium analyses

Three tonnage estimates of available lens material have been made. They are designated respectively, "probable," "possible," and "maximum possible." Lens material is defined as that portion of the Gallup Sandstone which contains more than ten per cent heavy minerals and which is a characteristic dark brown color in outcrop. All samples of lens material were found to contain niobium in excess of 0.09 per cent Nb2O5.

"Probable" lens material is defined by the outcrop length of each exposed lens, an assumed width in the cuesta of 50 feet, and an average thickness of 6 feet. On the east face of Sanostee cuesta, two lenses are exposed beneath lenses B and C. These are designated B' and C' and are included in the estimate of probable lens material. The buried lens indicated by the radiometric survey is designated A' but is not included in the probable class. On the basis of an outcrop length of 1600 feet for lens A and an outcrop length of 160 feet for lenses B, B', C, and C', the probable volume of lens material is 672, 000 cubic feet. Using the density of lens A (171. 68 pounds per cubic foot), lens B (168.56 pounds per cubic foot), and lens C (167.94 pounds per cubic foot) as determined by the water displacement method, the total "probable" tonnage is estimated to be 57, 400 tons of lens material. Utilizing the average assay for lenses A, B, and C and the average assay of the deposit for lenses B' and C' (fig. 15), the niobium content amounts to 60.7 tons. The value of contained niobium pentoxide in the ground is $148, 600. Inasmuch as the fifty-foot assumed width is an arbitrary cut-off point which is unrealistic in view of geologic evidence, the "probable" tonnage and value estimates are very conservative.

A second estimate of tonnage is designated "possible." As defined, it includes all lens material within the exposed dimensions but with the unexposed portions of lenses B, B', C, and C' estimated to be 150 feet, the inference being that their long dimension is at least as great as their outcrop length. Because a part of lens A has been removed by erosion, its width is estimated to be 100 feet. The presence of lens A' is recognized, and it is estimated to be 1600 feet long, 160 feet wide, and 6 feet thick. All lenses are considered as having an average thickness of six feet. Total "possible" volume estimated for lenses A, A', B, B', C, and C' is 3,110, 000 cubic feet. Using average densities, the total "possible" tonnage of lens material is calculated to be 265, 950 tons.

Inasmuch as the Sanostee cuesta is bounded on three sides by cliffs which limit the extent of the mineral lenses, a maximum strike length can be calculated. An arbitrary cut-off point for the lenses of 200 feet from the cuesta edge is used. Also, if the assumption is made that no more than six lenses are present and that they are all continuous along the strike, then a "maximum possible" tonnage can be calculated. The length of the cuesta parallel to the strike of the mineral lenses is 8000 feet and the total length of lenses A and A' is assumed to be 5600 feet and 7600 feet, respectively. On the eastern margin of the cuesta, the strike length of lenses B and B' is estimated to be 3800 feet and of C and C' to be 2600 feet. Using density and grade values as in the first two estimates, the maximum possible tonnage of lens material is calculated to be 2, 064, 500 tons. Total tonnage of Nb2O5 is 2160 tons.

Economic Potential

From the discussion of the niobium content, it is obvious that the Sanostee deposit is potentially an economic source of niobium. Two factors which are significant in the economic consideration of this deposit are ease of concentration of niobium and value of associated minerals.

The ease of concentration of niobium is based upon the constant association of titanium minerals and niobium. Desliming and a simple magnetic separation yield a concentrate (slimes plus magnetic fraction) which contains all the niobium and essentially all the titanium in the lens material. If the nonmagnetic fraction is processed to remove quartz, an essentially pure zircon concentrate is made.

The combined value of the zircon, titanium, and niobium increases the economic potential of the Sanostee deposit. No detailed analysis of the titanium content has been made. However, several assays were run on grab samples and they contained in excess of 20 per cent TiO_2. An average grade of 10 per cent TiO_2 for the lens material would probably not be unreasonable. Using this estimate of grade and the calculated tonnage for "probable, " "possible, " and "maximum possible" lens material, the estimated tonnages of titanium metal in the deposit are 3440 tons, 15,960 tons, and 123, 800 tons.

Because of ease of separation as a by-product, zircon tonnages are also calculated. A more accurate estimate of the amount of zircon present can be made than was possible for titanium because mineral percentages have been calculated for lenses A, B, and C from optical data (fig. 13). Using these percentages and the three classifications of available tonnages, the probable, possible, and maximum tonnage estimates of zircon are 3422 tons, 13, 571 tons, and 153, 950 tons.

It is interesting to note that substantial amounts, probably about equal to niobium, of yttrium are present in the deposit. Unfortunately, this element is present in solid solution in zircon which renders recovery difficult. However, should a process be devised for recovering yttrium from zircon, this deposit could become an economic source of that element.

One aspect of the niobium content which is of interest is that no tantalum is present. Consequently, the usual technological difficulties involved in removing tantalum from niobium concentrates would not be involved in processing the lens material.

Summary

Rocks of Jurassic, Upper Cretaceous, and Tertiary ages are exposed near Sanostee, New Mexico. The Jurassic rocks consist of red and green variegated shales and siltstones which are undifferentiated in this report. Five formations, the Dakota (?) Sandstone, the lower Mancos Shale, the Gallup Sandstone, the upper Mancos Shale, and the Point Lookout Sandstone constitute the Upper Cretaceous rocks. Tertiary units include the Chuska Sandstone and both sedimentary and crystalline volcanic rocks. A composite stratigraphic section was measured and sampled which includes all the above units except the Point Lookout Sandstone. This section was found to contain heavy mineral and clay mineral zones which correlate with similar zones from Todilto Park, New Mexico.

The stratigraphy, sedimentary petrology, and mineralogy of the Gallup Sandstone indicate that it is composed of three distinct facies, littoral, lagoonal, and nonmarine. Heavy mineral and grain morphology data suggest that during deposition of the littoral sediments the source rocks were largely sedimentary, whereas during deposition of the lagoonal and nonmarine facies in the same area, the source rocks were largely crystalline.

Six en echelon heavy mineral lenses occur within and at the top of the littoral facies of the Gallup Sandstone. Structurally and stratigraphically, they are similar to recent beach placers exposed along the Oregon and Florida coasts. In addition, both the mineral lenses and the normal Gallup Sandstone contain similar mineral suites including niobium-bearing heavy minerals. It is concluded that the heavy mineral lenses were formed by local concentration of heavy minerals in the beach zone during deposition of Gallup Sandstone sediments. The en echelon nature of the lenses is probably a result of shifts in current direction or changes in the rate of sedimentation.

Postdepositional alteration of the ilmenite in the lenses has resulted in the formation of a leucoxene cement and produced an upgrading in titanium and niobium. The titanium polymorphs, brookite and anatase, have crystallized authigenically in the leucoxene host.

The niobium distribution and content of the Sanostee deposit has been studied. Qualitative analysis by emission spectroscopy indicates that niobium occurs only in ilmenite, leucoxene, anatase, and brookite. Twenty-two quantitative X-ray fluorescent analyses of lens material reveal that the niobium content ranges from 0.09 to 0.15 weight per cent niobium pentoxide. Three tonnage estimates of 57, 400, 265,950, and 2, 064, 500 are made based upon the inferred limits of concealed lenses.

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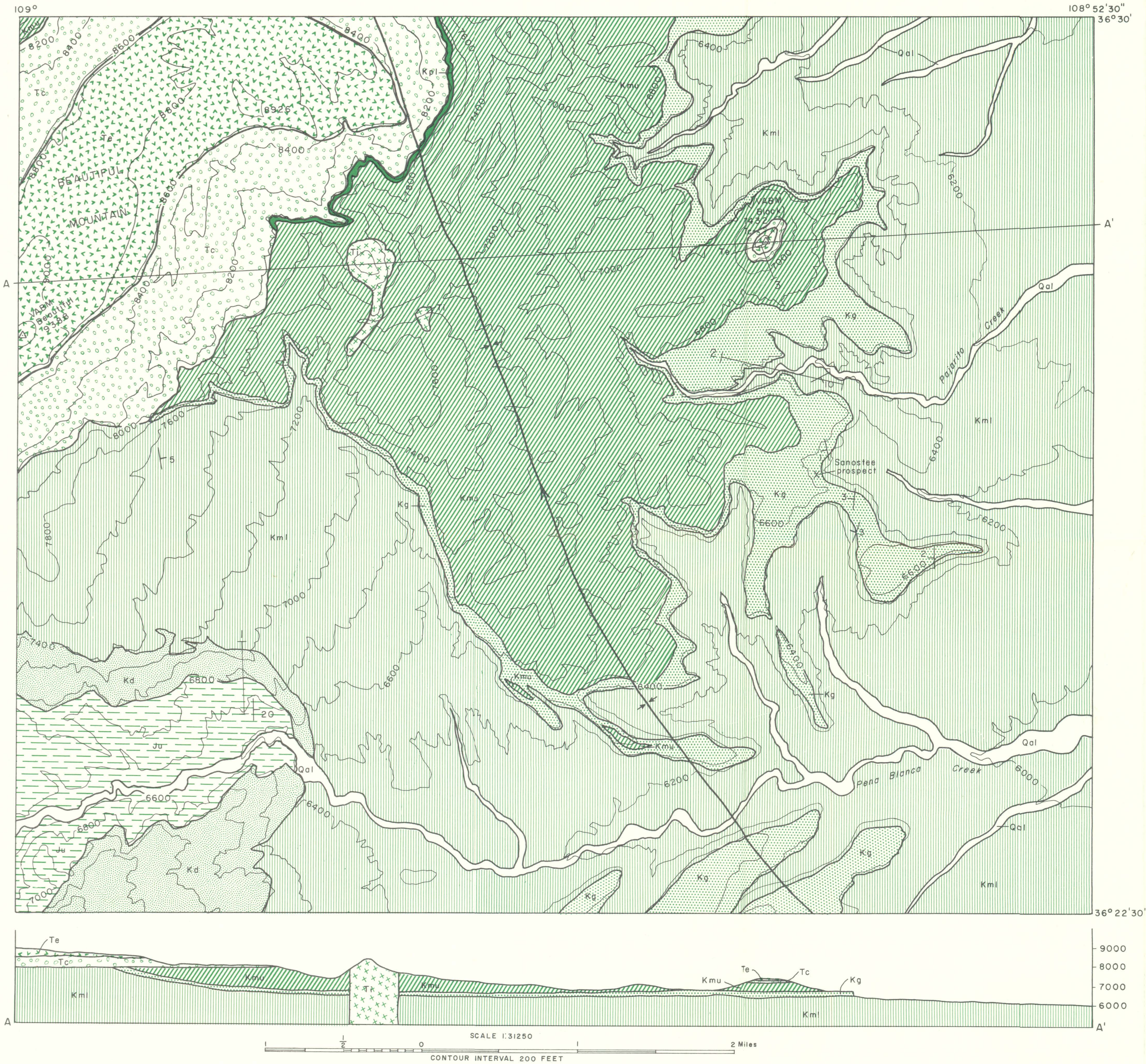


EXPLANATION

QUATERNARY

Qal
Alluvium

TERTIARY

Ti
Intrusive volcanic plug and associated dikes.

Te
Extrusive sequence of basalt and intertonging pyroclastic units. Basalt contains numerous quartzite inclusions.

Tc
Chuska sandstone
White, massive, fine to medium-grained, friable sandstone.

UNCONFORMITY

CRETACEOUS

Kpl
Point Lookout sandstone
Massive light-gray to yellow sandstone.

Kmu
Upper Mancos shale
Buff to gray, thinly laminated shale and siltstone. Contains ferruginous foraminifera tests.

Kg
Gallup sandstone
White, buff, and pink fine to coarse-grained sandstones and gray to buff carbonaceous shales. One four inch coal bed near top. Lower massive fine-grained unit forms prominent cliffs and grades into underlying shale.

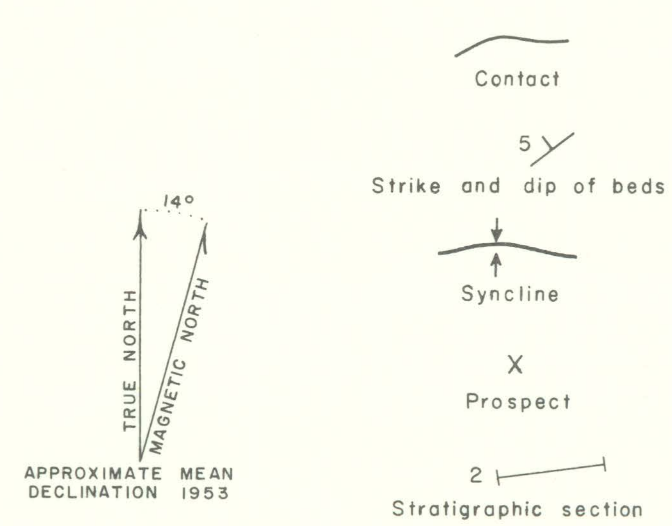
Kml
Lower Mancos shale
Gray, bluish-gray, and brown, thinly laminated shale.
Upper part- Gray to bluish gray, bentonitic, limy, calcareous concretions common.
Lower part- Brown, fissile shale with warped bedding planes.

Kd
Dakota (?) sandstone
Yellow to tan, fine to coarse-grained, massive and iron-stained sandstones with intercalated gray, carbonaceous siltstones and shales. One thin coal bed. Many of the sandstones are highly crossbedded and some weather to a nodular surface.

UNCONFORMITY

JURASSIC

Ju
Jurassic undifferentiated
Variegated pink, gray, and green shales, siltstones, and sandstones. Sandstones are massive, even-bedded, and everywhere gradational into the underlying fine-grained units.



GEOLOGIC MAP AND SECTION OF SANOSTEE AREA, NEW MEXICO