THE INVESTIGATION AND INTERPRETATION OF THE
NIOBium-BEARING SANGSTEE HEAVy MINERAL DEPOSIT
SAN JUAN BASIN, NORTHWESTERN NEW MEXICO

by Edward C.
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degree of Master of Science in Geology

The New Mexico Institute of Mining and Technology
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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 non-marine facies are represented in the Gallup sandstone. Mineralsologic 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 echelon 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 minerals 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 percent niobium. The deposit is estimated to contain 9 weight percent zircon and 10 weight percent titanium. Probable (57,400 tons), possible (266,100 tons), and maximum possible (2,064,500 tons) tonnage estimates are made.
The Investigation and Interpretation of the
Niobium-Bearing Sanostee Heavy Mineral Depo-
sit, San Juan Basin, Northwestern New Mexico

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 have 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 consisting of the preparation of a reconnaissance geologic map encompassing several tens of square miles surrounding the deposit, the preparation of a plane table geologic map of the deposit, and an organized sampling program was carried out during the summer of 1960. Laboratory work consisting largely of microscopic and X-ray analysis of the samples from the deposit 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, p. 9) with special regard to its potentialities as a source of titanium. A similar deposit near Gallup, New Mexico has received attention by Sun and Allen (1957, p. 265). Chenoweth has published a compilation of the known heavy mineral deposits within the San Juan Basin but little detailed data is furnished.

In this report, data is 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.
LOCATION AND ACCESSIBILITY

The region mapped on a reconnaissance scale of 1:31,250 comprises an area of 40.3 square miles wholly within the Navajo reservation along the western margin of San Juan county, New Mexico (Figure 1). It is bounded by meridians 109°00' and 108°52'30"W and by parallels 36°30' and 36°22'30"N. The Sanostee Trading Post which is one and one-half miles east of the area is 28 air miles southeast of Shiprock, New Mexico and 68 air miles northwest of paved U.S. Route 666; the trading post may be reached from that highway 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 of these traverse lower Mancos shale any rainfall renders them extremely treacherous if not impassable to conventional motor vehicles.
FIGURE 1

Index map of northwestern New Mexico. Shaded portion represents area of reconnaissance mapping.
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 $95^\circ$F, but the temperature may fall to as low as $40 - 45^\circ$F at night. Daytime winter temperatures often border on $32^\circ$F and nighttime extremes may drop to below $0^\circ$F. The mean annual rainfall of about 7 inches, coupled with the temperature extremes, produces an inhospitable panorama of arid desert land which nonetheless has an intrinsic beauty. Violent local thunderstorms are common midafternoon occurrences during the summer months.

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

The character of the vegetation changes from place to place and is controlled by topography. Sagebrush and a few scattered piñons are the principle 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 piñon and juniper. Beautiful Mountair, parts of which are at an altitude in excess of 9,000 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.
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 made up largely of Tertiary Chuska sandstone capped by volcanics, and the latter composed chiefly of Upper Cretaceous shale with a thin veneer of Tertiary rocks. Desert forms such as mesas, cuestas, rincons, canyons, and dry washes are common. Topography is closely controlled by structure and lithology—sandstones form mesas and cuestas; shale and siltstones form broad subsequent valleys.

Maximum relief is over 3,000 feet between the valley bottom near Sanostee Trading Post and the summit of Beautiful Mountain. The area is well drained by two intermittent consequent streams—Peña Blanca and Pajarito Creeks.

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 (denoted Black Peak) is exposed at an elevation of about 7,300 feet. On the east flank of Beautiful Mountain it occurs between 8,000 and 8,200 feet. A similar surface has been described by Cooley (1958, p. 148) in the
Black Mesa Basin area and is there 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. From a limited number of elevation checks these two surfaces apparently slope to the east but at slightly different angles.

Pedicent surfaces are developed upon the upper and lower Mancos shales as represented by the tops of erosional remnants at elevations of 7,100 feet (average) and 6,400 feet (average). The largest remnant of a preexisting pediment surface is located at the mouth of the canyon developed in the Gallup sandstone by Pajarito Creek. The surface is about 0.4 miles wide and about 1½ miles long. It is elongated in an east-west direction and has an eastward gradient of about 160 feet per mile. Erosion which produced the canyon in the eastward facing cuesta 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

General Relationships

The consolidated sedimentary rocks of the Sanostee area are chiefly of Jurassic and Upper Cretaceous age. 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 Peña 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 over 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, p. 2156). All pre-Upper Cretaceous rocks were mapped as Jurassic undifferentiated and since no visible unconformity exists, the boundary between Upper Cretaceous
FIGURE 2

Measured stratigraphic section.
Index map showing location of mapped area
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 upon the Udden grade scale as modified by Wentworth (1922, p. 377).

Jurassic Formations (undifferentiated)

Pre-Upper Cretaceous sediments of Jurassic age occur in one small area in the extreme southwestern part of the Sanostee area. Viewed from a distance they are pink and are conspicuous against the more neutral buffs and grays of the Upper Cretaceous rocks which overlie them. Pre-Upper Cretaceous rocks of similar color and lithology which crop 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, p. 55).

The Jurassic rocks exposed at Sanostee consist of variegated pale yellowish green (10GY7/2) to light brownish gray (5YR5/1) 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 floodplain, origin.

Although the sediments immediately above the Jurassic sequence are of late Cretaceous (Beaumont, 1954, map) 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 however that the contact between Jurassic and post-Jurassic rocks may occur anywhere between the multi-colored shale at the base of the section and the first appearance of what is unquestionably Mancoos shale.

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; 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 is rounded, but the presence of some euhedras 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 of Table 2) while 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 of 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 (?) sandstones form the upper edge of the canyon cut by Peña Blanca Creek.

Rocks of Dakota (?) age form a composite sequence at Sanostee which is similar to described exposures elsewhere in Northwestern New Mexico (Reeside, 1924, p. 9; Gregory, 1917 p. 12; Dane and Eachman, 1957, p. 97). The basal unit of the Dakota (?) sandstone consists of a grayish yellow (5Y8/4), thick, cross-bedded, locally banded, quartz sandstone. Overlying this unit is a zone of pale greenish yellow (10Y8/2) interbedded shale and siltstone which becomes coarser grained and thicker bedded upward until it finally grades into a 35 foot thick, fine-grained, crossbedded 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, 2-3 feet thick fine-grained quartz sandstones, and moderate (10YR5/4) to dark yellowish orange (10YR6/6) thin, crossbedded 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 is illustrated in the exposures at Sanostee on a minor scale. That 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 clastic 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 of the distinct lithologic 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 this 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 in part for the Dakota (?) sandstone.

The heavy mineral suite makes up less than 1% 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 Peña Blanca and Pajarito Creeks (Illustration 1). Its base is exposed only in the southwestern part of the area where the underlying Dakota (?) sandstone crops out.

The lower Mancos shale at Sanostee, New Mexico 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 (Illustration 2) with numerous septarian concretions. In section traverse #2 (See Plate 1) a one foot thick bentonitic bed was found at the contact between these two units, but in most examined exposures of the contact 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 and the maximum exposed thickness is about 500 feet. The stratigraphic thickness of this unit, as determined from the well record of the Navajos Company's Raymond #1 well located at Sanostee and barometric measurements, is 600 feet of which only about the top 20 feet was sampled. The
Illustration 1

Slopes of lower Mancoo shale in the foreground capped by prominent cliffs of Gallup sandstone. Chuska Mountains on the skyline.

Illustration 2

Southern margin of Sanostee cuesta. Upper cliffs are of Gallup sandstone. Prominent cliffs at the base of the cuesta are produced by the limy zone in the lower Mancoo.
buff unit of the lower Mancos thins westward from the maximum thickness of 600 feet near the center of the Beautiful Mountain anticline, the axis of which lies just east of the mapped area, to an indeterminate thickness where the Chuska sandstone directly overlies the lower Mancos on the eastern flank of Beautiful Mountain.

The Mancos shale is generally considered to be 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, p. 29). The bluish gray and buff units within the lower Mancos shale form very distinctive units in the Sanostee area. This difference may have important genetic implications and deserves further study.

Samples 14, 15, and 15a (See Plate 3, 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 foot thick
bentonite bed of white to moderate orange pink (5YR8/4) 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 (See Figure 4).

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 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 (Illustration _ and _).

The lowermost unit of the Gallup sandstone is a thick, massive, medium- to fine-grained quartz sandstone. It varies in thickness from 60 to 80 feet. In general it is a grayish (10YR7/4) to dark yellowish orange (10 YR6/6), but 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
(Illustration 4). 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 (Illustration 3). This succession
varies in thickness from a maximum of about 6 feet to
a minimum of about 1 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 (5Y8/4)
to moderate yellowish brown (10YR5/4) siltstones which
grade upward into the upper Manos shale. The coarser
grained parts of this upper unit contain interfingering
conglomeratic lenses composed of elastic quartz, chert,
and rock fragments in excess of 5 mm. in diameter. Many
of the sandstones contain plant fragments and one
Illustration 3

A portion of the upper part of the Gallup sandstone as exposed on Sanostee cuesta.

Illustration 4

East face of the Sanostee cuesta. Dark streaks dipping to the east are exposed heavy mineral lenses. Black Peak in background.
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, 1947, p. 28), transgressive sediments derived in part by the reworking of a portion of the Gallup sandstone (Beaumont, 1947, p. 116), and as a regressive deltaic facies of the Gallup sandstone (Budd, 1957, p. 123).

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 coefficient of the lower unit is 1.40 as 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 fluvial (in part) 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 suggest 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 three-fold 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, p. 65). 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 well and poorly sorted units and abrupt lateral variations in thickness.

A vertical section of the Gallup sandstone as exposed on Sanostee cuesta is shown in Figure 3.
FIGURE 5

Petrography of the Gallup sandstone.
<table>
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<tr>
<td>S</td>
<td>58.03</td>
<td>53</td>
<td>X</td>
<td>&quot;</td>
<td>&quot;</td>
<td>Thiny laminated brown mudstone. Poorly exposed.</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>57.09</td>
<td>21</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>Brown siltstone. Poorly exposed.</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>57.09</td>
<td>21</td>
<td>X</td>
<td>&quot;</td>
<td>&quot;</td>
<td>Even-bedded, flaggy, brown mudstone.</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>126.96</td>
<td>18</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>Medium-grained, gray quartz sandstone. Iron-stained, nodular surface, highly cross-bedded. Feldspar uncommon. Heavy minerals rare. Fills channels cut in the underlying shale.</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>126.96</td>
<td>18</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>Thinly laminated to flaggy, gray to brown siltstone and shale.</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>123.00</td>
<td>18</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>Thin bedded gray to brown ss. Large amounts of muscovite. Authigenic quartz very common.</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>123.00</td>
<td>18</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>Med-grnd. gray quartz ss. Feldspar up to 20% Chert fragments common. Angular quartz grains.</td>
<td></td>
</tr>
</tbody>
</table>

**Environment of Deposition**
- Non-marine
- Lagoonal
- Littoral Marine

**Petrography of the Gallup Sandstone**
Compositional, mechanical, and mineralogic parameters for each lithology are also shown in Figure 3. The sequence is then divided into environments of deposition based upon the classification by Krumbein and Sloss (1951, p. 204). All of the rock units which comprise 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 (Figure 3) 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. Non-marine deposits eventually encroach upon and completely bury the lagoonal deposits. Lithologies N to T represent non-marine 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 K, is interpreted as the direct result of proximity to the source rocks. The interval between lithology X and Z represents that part of the beach exposed to subaerial erosion and as such represents a diastem.

Upper Mancos shale

The thick silty very pale orange (10YR6/2) shale which overlies the Gallup sandstone is designated the upper Mancos shale (Beaumont, et al, 1956, p. 2156). 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 in Figure 2). Slopes composed of upper Mancos shale are invariably covered with a dense growth of grass and bushes; consequently good exposures of fresh material 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 is available to assign a marine or non-marine origin to this formation; however, it has been designated the Mulatto tongue of the Mancos formation by Pike (1947, p. 17), the marine equivalent of the "stray" sandstone.

Two samples were taken of this formation. Sample 19a is representative of the entire thickness where measured and Sample 19b was 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 minerals 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 highly rounded as contrasted with the non-opaque suite which is characterized by high 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, 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) it may have been inherited from the provenance. A marine environment is necessary for the first two, and a non-aggressive non-marine environment for the last.

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 (1951, map), 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 (1917, p. 80). It crops out in subdued bluffs along the eastern flanks

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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 (Illustration 4).

The Chuska sandstone where it crops out in Black Peak is a massive, medium- to fine-grained, friable, grayish orange pink (10R8/2) sandstone. The measured section at Black Peak is only 12 feet thick, but in the Beautiful Mountain exposures less than 3 miles away, approximately 300-400 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 Gregory (1917, p. 80) and Wright (1956, p. 416) report that differential cementation is common in this formation.

Wright (1956, p. 418) 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 respectively to be 1.39, 0.235 mm., and 0.92. 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 10% 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 non-marine environment during a time when the climate was notably arid (Wright, 1956, p. 432). Montmorillonite is a characteristic product of the weathering of volcanic ash in a "non-aggressive" 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, 1956, p. 432). 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 (10YR8/2) matrix.
Included within this unit is a 20 to 30 foot thick lens
of pale red (5R6/2) 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 sed-
iments. Numerous inclusions of quartzite from 1/2 to 2
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, pl. 22) 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 they could be correlated with zones recognized in the Todilto Park section reported by Willard (Allen & Balk, 1954, p. 139). 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, 1947, pl. 11). 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 to approximately parallel time planes. For this reason in this report a mineralogic datum - the top of the biotite zone - is used (See Figure 4).

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 (See Figure 4).
FIGURE 4

Correlation of Upper Cretaceous rocks based upon heavy mineral and clay mineral zones.
Comparison of the mineral zones at Sanostee and Todilto Park reveals marked similarities up to the base of the upper Manoos shale (See Figure 7). Above that the relations become confused.

Quaternary Alluvium

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

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 dips slopes. With the exception of the Dakota (?) outcrops in the extreme southwestern part, recorded dips seldom exceed 10°. 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, p. 44). Its western flank is gentle as 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 parallax 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, map). In fact, Kelley (1957, tectonic map) 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 increasingly 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 and Hogback Monocline were active. De-
formation 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 (1954, map legend).
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 (See Plate 1). It is located 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. (See Plate 1). 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 was contoured and 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 sample positions are indicated by a lower case letter and circle on the plane table map. These samples were used for X-ray spectrographic analysis 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 in Plate 2.

Structural and Stratigraphic Relationships

As mentioned previously, the Gallup sandstone is composed of three units; an upper unit composed of intercalated fine-grained to conglomeratic sandstones and shales, a medial unit made up of coal beds and carbonaceous shales, and a lower thick, fine-grained, massive unit which is 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 was 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 outcrop length of a lens exposed in the cliff face directly beneath Lens C is 160 feet. In contrast Lens A is

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exposed along the western edge of Sansotée cuesta for an outcrop length 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 Sansotée prospect forms the westward dipping flank of the Beautiful Mountain anticlone. The average dip of the formation in the vicinity of the deposit is between 2 and 3° west and the strike ranges from 0° N20°E to N20°W, south. The strike of the exposed lenses is similar to the strike of the Gallup sandstone, but the dip is to the east and ranges between 2 and 5°. The top of the lower 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 10°, 4°, and 5°. These angles of initial dip are similar to ones reported by Griggs (1944, p. 45) on recent chromiferous black sand deposits along the Oregon coast.

Two of the heavy mineral lenses exposed on the eastern face of the cuesta are gradational downward and eastward into quartz sandstone. In these places:
typical Gallup sandstone and dark heavy mineral layers interdigitate. 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 (See Figure 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 Sandstone cuesta was made with a Precision Model Ill "Scintillator" manufactured by Precision Radiation Instruments, Inc. This instrument consists of a dry cell power supply
FIGURE 5

Schematic representation of the inferred structural relationships of the mineral lenses. Stippled area—Gallup sandstone, black area—heavy mineral lenses, circles—alluvium.
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.). This instrument can detect radiation of less than 0.005 milliroentgens per hour which is well below the background count of about 0.05 milliroentgens per hour in parts of the cuesta not containing mineral lenses. Radioactivity readings were taken at 50 feet 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. Readings were made at 50 foot intervals along the east to west traverses until the count 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 milliroentgens per hour. The result is illustrated in Plate 2.

Heavy mineral concentrations as 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 (Plate 2).
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, g, 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 and crowding of contour lines near sample locality m is probably the result of the increased thickness of Lens A at that point and also the increase in amount of overburden near the cuesta edge. Section I of Figure 5 is a schematic interpretation of the inferred relationship between Lens A and A'.

The contour diagram near sample localities t, u, and v (Plate 2') 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 spatial 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 c) yielded a radioactivity count of 0.70 milliroentgens per hour - the highest for any lens. This lens also has the highest percent 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 radioactivity count. The relationship between the two lenses is illustrated in section III of Figure 5.

Megasopic Features

The heavy mineral lenses of the Sandstone 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 (Illustration). This striking dark color is due in part to the presence of black opaque minerals and iron in part to the presence of brown rich cement. The striking dark brown color is also in large part due 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
1 to 3 millimeter. 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 percent heavy minerals and hence the
observed color range may be a primary characteristic.
Lens C is strikingly mottled. This mottling is 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 $\frac{1}{4}$ inch in diameter. Pits on exposures
near sample locality c are about $\frac{1}{8}$ inch in diameter
and randomly scattered on the exposed upper surface of
the lens. They appear to represent the preferential
removal of some substance. They may represent organic
material deposited with the heavy minerals that sub-
sequently was removed from the body of the rock during
post depositional alteration. It is also possible that
the pattern is the result of differences in the degree of cementation. The blotchy color variations and the nodular and pitted surfaces could also be the result of variation in cementation.

Variations in color, composition, and cementation are much more striking on freshly broken surfaces of the mineral lenses and enclosing rocks. Colors range from brownish black (5YR2/1) to grayish orange (10YR7/4) between lenses.

Samples from Lens A are commonly mottled. There are generally three different colors present. Blotchy areas which range from grayish red (5RA/2) to pale red (5R6/2) are rimmed by a thin band about 1 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 streaks but in general they form dendritic or 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 1 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.

\[
\text{Ilmenite (black) + Oxygen } \rightarrow \text{Hematite (red)} \rightarrow \text{Goethite (brown)}
\]

\[
\begin{align*}
4\text{Fe TiO}_3 + 0_2 & \rightarrow 2\text{Fe}_2\text{O}_3 + 4\text{TiO}_2 \\
\text{Hematite (red)} + \text{Water} & \rightarrow \text{Goethite (brown)}
\end{align*}
\]

\[
\begin{align*}
\text{Fe}_2\text{O}_3 + \text{H}_2\text{O} & \rightarrow 2\text{HFeO}_2
\end{align*}
\]

From this it appears that the different proportions of red to brown material represent various stages of alteration.

Megascopically the heavy mineral lenses commonly appear spotted. The spots are grayish yellow (5Y8/4) circular areas seldom in excess of 2 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 for 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. This stratification is the result of the segre-
ation of thin discontinuous streaks or layers of quartz grains. These thin quartz-rich layers are seldom more than 3 millimeters thick.

Sampling and Laboratory Methods

Composite chip samples were taken of heavy mineral lenses A, B, and C. (See Plate 2.) Approximately 100 pounds of sample was collected from each lens. These composite samples were utilized in the collection of all of 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 (Plate 2). From this second set of samples data was collected regarding distribution of niobium.

The laboratory operations are outlined in Figures 6 and 10. Each sample was crushed to chips 3/8 inch across and blown free of adhering dust and soil by compressed air.
FIGURE 6

Flow sheet for mineralogic analysis.
FLOW SHEET FOR MINERAL ANALYSIS
after megascopic examination and further crushing in a Brown Chipmunk jaw crusher. A 500 gram sample was obtained through splitting in a Jones splitter. The 500 gram portion was weighed and placed in a 1 liter beaker containing 1:20 HCl for about three weeks. During this time the sample 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 FeCl₃ and the disaggregation process was completed by gentle grinding in a porcelain mortar with a rubber covered pestle. A large amount of cement was removed in suspension and placed in a 1 gallon jar. The suspension was allowed to stand for at least one hour in order to allow all particles larger than 10 microns to settle to the bottom of the jar. The supernatant liquid was then siphoned out and passed through a super centrifuge which deposited all solid material on a celluloid sheet. The 10 micron fraction was then dried and set aside for X-ray analysis. In all samples this fraction constituted less than 1 percent 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. The sieve sizes were 2,000; 1,000; 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. 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 1.68. 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 analysed 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 and pestle in order to reduce the possibility of establishing a preferred orientation in the sample. The sample was then mounted in an aluminum sample holder which contains a window measuring 1 centimeter by 2 centimeters by 1/2 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 analysed 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 one-half 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 converted to interplanar spacing \( d \) using Bragg's equation, \( n\lambda = 2d\sin\theta \). 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 analysed. 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 and the peak amplitudes of the standard charts.

There are four common clay minerals in sediments: 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 (Figure 7). No position of these reflections does not shift when the sample is glycolated. The (001) reflection of montmorillonite varies with the nature of interplanar adsorbed material (Brindley, 1951, p. 124). For this reason the samples were treated with glycerol, which expands the lattice to a fixed position. Glycolated

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FIGURE 7

X-ray diffraction pattern of kaolinite and illite
FIGURE 8

X-ray diffraction pattern of montmorillonite
MONTMORILLONITE
001 UNGLYCOSATED

SHADED AREA REPRESENTS EXPANDED SAMPLE
d_{001} = 17.7 Å

2θ
X-ray diffraction pattern of illite;montmorillonite mixed layer clay.
montmorillonite has a characteristic (001) spacing at 17.7Å (See Figure 8).

Randomly interstratified illite-montmorillonite is present in some samples and was recognized from the position of the 001/002 peak after treatment with glycerol (See Figure 9). 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 (See Figure 9). 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 percent 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.
FIGURE 10

Flow sheet for niobium analysis
Flow Sheet for Niobium Analysis

Bulk sample

Clean and crush to 3/8"

Split with Jones splitter

Bulk of sample to storage

Obtain 5g. sample

Crush with mortar and pestle to about 0.125 mm.

Add Mo internal standard

Grind in mechanical mortar for 1 hour

X-ray analysis
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.
The frequency curves of the heavy mineral fractions all show one maximum which in all cases is displaced toward the finer grain sizes. This relation is expectable because due to hydraulic factors (K & P, 1938, p. 319) 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.

Cumulative curves of the bulk lens material and the heavy mineral concentrates are shown in Figure 12. Because of the limited particle size range in the lens material these data were plotted on two cycle semi-log paper. Cumulative curves for the clastic sediments of the stratigraphic section were plotted on four cycle semi-log paper. The curves of Figure 12 amply illustrate that the heavy minerals are better sorted than the bulk material.

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 = Q1Q3/(Md^2)) were calculated. In all cases 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 of the sorting coefficients
FIGURE 12

Table of statistical parameters for the heavy mineral lenses.
determined are less than 2.5, which indicates that the lenses are well sorted according to Trask's classification (K. & P., 1938, p. 232). A value of unity for So would indicate perfect sorting and 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, E, 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.

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 preexisting 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 percent (20%) of the lenses sampled. Angularity of the quartz grains ranges from 0 to 100 percent, but an average for A, B, and C is given in Table 3, Plate 3. Inclusions in quartz were noted and their frequency determined according to Mackie's classification (K & P, 1938, p. 373). In this classification 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 - needle-like or hair-like mineral inclusions, rutile in many cases, and d) no inclusions.
Authigenic overgrowths of quartz on clastic quartz grains are common, but not widespread. In addition, all of 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 analysed with both the emission and X-ray fluorescent spectrophotograph; no niobium was present.

Zircon: Zircon is the dominant mineral in the heavy mineral suites. It is euhedral, subrounded, or angular. The dominant crystal form is a combination of first order prism with dipyramidal terminations. Elongation parallel to c is variable producing long, slender needle-like forms and short, stubby, practically equidimensional forms. A few crystals show a combination of first and second order prisms with dipyramidal 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 of the mineral concentrates. It appears almost opaque in transmitted light and a milky white in reflected light. Several pink zircon crystals exhibit
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 (See Plate 3, Table 3).

The shape of zircon grains ranges from euhedral to bead-like. All pale green grains are highly rounded to bead-like. Pink zircons tend to be fragmental. This trend is best exhibited in Lenses A and B (Plate 3, Table 3).

A zircon concentrate was collected from the non-magnetic fraction of the heavy mineral suite from Lens C. This concentrate was then analysed qualitatively with the X-ray spectrograph. Ten zircon crystals were also picked individually from the same concentrate and analysed with the emission spectrograph. Both samples contained substantial amounts of yttrium, a rare earth element. Hafnium, a common trace constituent of zircon, was not present (Rankama & Sahama, 1950, p. 568). 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 Sandstone deposit is due to yttrium. Because of the diadochy which exists between zircon and niobium the concentrate was carefully
Illustration 5

Lens A. 0.125 mm. heavy mineral fraction. X 75
Il - ilmenite, Z - zircon

Illustration 6

Lens A. 0.125 mm. magnetic residual of heavy mineral fraction. X 75 il - ilmenite, Z - zircon
examined for the presence of niobium. None was present.

Zircon is the dominant mineral in all size fractions except the 125 micron fraction of Lens C (Figure 13). The ratio of zircon to opaque minerals increases in the finer grained size fractions. This is expectable in view of the density difference between ilmenite and zircon (Pettijohn, 1949, p. 427).

Tourmaline: (Schorlrite) - All of the observed tourmaline consists of an iron bearing, brownish-black, strongly dichroic variety known as schorlrite. Tourmaline constitutes less than one percent (1%) of the bulk sample of each lens and is found only in the 250 to 125 micron fraction (Figure 13). Euhedral prisms, angular equidimensional fragments, and polished bead-like grains are present. Grain shapes intermediate between these extremes are not present. Inclusions are rare and when present are of the regular type. The non-magnetic fractions of the heavy mineral concentrates contained several grains of tourmaline and in as much as this fraction was free of niobium, it is concluded that no niobium is present 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
FIGURE 13

Graphs of mineral frequency for the heavy mineral lenses. All size fractions are in millimeters.
<table>
<thead>
<tr>
<th>Lens</th>
<th>Heavy minerals</th>
<th>Bulk comp.</th>
<th>Md (mm.)</th>
<th>So (Trask)</th>
<th>Skg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens A</td>
<td>0.132</td>
<td>1.30</td>
<td>1.00</td>
<td>0.99</td>
<td>1.03</td>
</tr>
<tr>
<td>Lens B</td>
<td>0.148</td>
<td>1.67</td>
<td>0.82</td>
<td>0.95</td>
<td>1.03</td>
</tr>
<tr>
<td>Lens C</td>
<td>0.168</td>
<td>1.75</td>
<td>0.68</td>
<td>0.95</td>
<td>1.03</td>
</tr>
</tbody>
</table>
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 analysed with the emission spectrograph;
detectable
none contain 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 analysed for the presence of niobium.

Carnet: 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
well to highly rounded. The euhedral grains are tabular with
rhombic truncations, the commonest form of ilmenite
(Palache, Berman, and Frondel, 1944, p. 536). Many of
the subhedral grains have small triangular pits in their
surface. These pits are probably primary impressions
produced by the interference of adjacent grains during
crystallization of the ultimate source rock. Ilmenite
Illustration 7

Lens E. 0.125 mm. heavy mineral fraction. X 75
l - ilmenite, Z - zircon

Illustration 8

Lens C. 0.125 mm. heavy mineral fraction. X 75
l - ilmenite, Z - zircon, b - barite
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. The reversal is most likely due to the effects of the disaggregation method utilized and is not characteristic of these lenses.

A magnetic separation of the 125 to 250 micron size fraction of the heavy mineral suite was made. Six separations were made according to decreasing magnetic susceptibility. Fractions one through four when examined with the binocular microscope were found to consist of ninety percent plus opaque minerals. Fraction five contained more than fifty percent non-opaque heavy minerals, the majority of which consisted of pale green zircon. The sixth fraction was almost 100 percent non-opaque heavy minerals, largely colorless and pink zircon. Magnetic fractions one to four were analysed 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 cases the poorer crystallized ilmenite has a lower magnetic susceptibility. Bailey, et al (1956, p. 276) records 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 A had
a fresher, blacker appearance, and had small white
patches of extremely fine-grained material adhering to
their surface. 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, (1956, p. 256) 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 (1950, p. 193), is not mobilized
and is classified by them as a hydrolazate, 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. 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 lustre in plane polarized reflected light, and intense 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 (Markkanavala, et al, 1959, p. 915; Bailey, et al, 1956, p. 278; Allen, 1956, p. 832). The writer prefers the terms suggested by Lyakh (1960, p. 1068). Any finely divided amorphous (optically and to X-ray diffraction) alteration product of ilmenite he calls amorphous leucoxene. Any 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 TiO₂ 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
Illustration 9
Polished section of magnetic part of the .125 size fraction of Lens A. Black streaks and blebs in many of the ilmenite grains represent leucoxene forming as an alteration of ilmenite. X 100 11 - ilmenite, 2 - zircon

Illustration 10
Enlarged view of one ilmenite grain from above photograph showing detail of the alteration. White - ilmenite, gray - leucoxene. Alteration is probably proceeding along (0001) parting planes. X 470
the alteration products of ilmenite has been raised by Flinter (1960, p. 1069). He contends that leucoxene implies 100 percent TiO₂ and therefore may not be applied to ilmenite alteration products because they invariably contain some iron. He prefers the term Arizonite, ferric meta titanate, for the alteration products of ilmenite. However, the term Arizonite is even more controversial than the term leucoxene (Lynd, 1960, p. 1065) and hence is not used here.

Ilmenite was analysed with the X-ray and emission spectrograph and it 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 nearly 100 percent black opaque minerals was then analysed. In addition, ten grains from each 125 to 250 micron heavy mineral suite were analysed 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 & Sahama, 1950, p. 606). Fleisher, et al (1952, p. 3) has also firmly established the common association of niobium and titanium.

**Authigenic minerals** - Authigenic minerals are those which have not been transported but which have been 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 cases 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: 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 percent of the bulk of the deposit.

Barite: Barite is a colorless mineral in the heavy mineral concentrate characterized by the presence of many dust-like inclusions. It is always found as sharply angular grains and is concentrated in the larger size fraction of the heavy mineral suite (Figure 7). Barite in sediments is considered to be, almost without exception, of authigenic origin (K & P, 1938, p. 420; Wilner, 1911, p. 249).

The source of the barium ion is not known but the
alteration of solution or barium bearing feldspar and
barium rich interstitial solutions are possible sources.
Sulfate-rich circulating ground waters are common and may be the
result of the solution of gypsum or
generally are the result of the oxidation of base metal
sulphide H₂S bearing solutions (Austin, 1960, p. 1758).

The barite analyzed spectroscopically with zircon
contained no niobium.

Leucoxene: Leucoxene is a non-stoichiometric
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 TiO₂ it is the principle constituent
of the rock cement. 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 analysed. 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 TiO₂ 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.

NoP. 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 TiO₂ is in the form of anatase. This mineral is considered to be the first crystallization product of amorphous TiO₂. Pseudobrookite, although reported in similar associations elsewhere, was not found in the analysed samples. It must be concluded that the chemical environment during the alteration process favored the formation of anatase over other polymorphic forms of TiO₂.

Spectroscopic analysis of leucoxene reveals the presence of substantial amounts 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 (T || 012, X || a) and subhedral grains. Pleochroism is usually distinct. Penetration twins are common. Its appearance under crossed nicols is distinctive owing to its anomalous
Illustration II

Thin section of sample from Lens A. Interstitial opaque material is leucoxene. White grains are quartz and rounded gray grains in upper right quarter are zircon. X 60 q - quartz, le - leucoxene, Z - zircon.

Illustration 12

Pan fraction from Lens A. Euhedral grains in center and upper right are brookite. X 160 br - brookite, il - ilmenite, b - barite
orange and violet interference colors and extinction.

Striations on crystal faces, a phenomenon commonly reported for brookite (R. & P., 1938, p. 422) are absent.

Brookite occurs in crusts lining geode-like 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 & Allen, 1957, p. 268) and is there interpreted as being derived from amorphous titanium dioxide. Several samples of a brookite concentrate were analyzed and contain niobium.

Hematite, a small percentage of the opaque authigenic cement, consists of dark red flakes and thin red films on leucoxene.

Origin of the Deposits

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 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 interfingerling nature of the lenses is similar to recent beach placers in Florida and Oregon. The uniform eastward dip of the lenses reflect a marine beach profile which dipped eastward. The high degree of sorting of the clastic 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. In as much as the heavy minerals are concentrated by a winnowing out of quartz in the zone of swash 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 Mackies 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 Samostee (Plate 3, Table 3). In Lens A 58 percent of the quartz grains with an angularity of less than 50 percent contain irregular and acicular inclusions (igneous source rock). In as much 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 bead-like zircon also suggests that the ultimate source rocks were largely igneous.

Grain morphology and mineralogy indicate the nature of the immediate source of clastic material. The genetic implications of rounding have been discussed in a preceding section. It is reemphasized at this point, however, that highly rounded or bead-like 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 will develop various degrees of rounding during one transportation cycle. The mineralogy of some alloogenic minerals may be diagnostic of igneous or metamorphic source rocks (See Figure 14) (Pettijohn, 1957, p. 97).

The zircon and ilmenite morphology reflect both the sedimentary and crystalline nature of the immediate source. Based on the degree of rounding the light green variety of zircon was derived entirely from sediments whereas the pink and colorless varieties were dominantly crystalline. The highly rounded to bead-like character of ilmenite suggests that it has been recycled. Some subhedral ilmenite is present and attests to an immediate igneous source 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 is characteristic of the lenses and the normal Gallup sandstone and evidently was derived from the same source. Unstable minerals, although present in the lenses and Gallup sandstone, are present in recent beaches and in Upper Cretaceous littoral sandstones in the San Juan Basin. Hence it is clear that they can
FIGURE 14

Minerals characteristic of source rock type.
REWORKED SEDIMENTS

Quartz
Chert
Leucoxene
Tourmaline, rounded
Zircon, rounded

METAMORPHIC

Low-Rank
Slate and phyllite fragments
Quartzite and quartz fragments
Brown tourmaline

High-Rank
Quartz, metamorphic variety
Garnet
Blue-green hornblende
Kyanite
Sillimanite
Staurolite
Epidote
Zoisite

IGNEOUS

Acid
Apatite
Bi, coarse
Hornblende
Zircon, euhedra
Quartz, igneous variety

Basic
Augite
Hypersthene
Ilmenite
Rutile

Figure
Common detrital minerals characteristic of source rock type (After Pettijohn, 1957)
survive deposition in that environment. It seems likely that a large percentage of the minerals contained in the heavy mineral lenses at Sanostee were derived from an immediate source in which sedimentary rocks predominated. The specific formations from which they were derived are not as clearly indicated. Two possibilities exist: 1) 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 stable suite of minerals 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 in 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 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 pre-existing 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, 1952, p. 1) 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 analysed for niobium, and the percent 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 made and this together with the percent niobium suggests the possible "in the ground" value of this deposit.

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 analysis (See Appendix for the details of theory and method). In view of the titanium:niobium diadochy (Rankama and Sahama, 1950, p. 606) and the data presented by Fleischer (1952, p. 8) it was suspected that niobium might be found in the titanium-bearing minerals ilmenite, leucoxene, brockite, 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 TiO$_2$. This indicates that during the alteration of the Sanostee deposit niobium has followed titanium, at least in part. No direct data is 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 non-stoichiometric amounts. Not only may it vary in amount in a 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 was present in stoichiometric amounts in all the ilmenite, and if it followed titanium during alteration of ilmenite, the calculated ratio should remain constant. The results of niobium analyses (Figure 15) shows the Nb:Ti ratio for each sample analysed. In as much 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 is available regarding the presence of niobium in other heavy mineral deposits throughout the San Juan Basin. Cabot samples were obtained from deposits
FIGURE 15

Results of niobium analysis
### Results of Niobium Analyses

<table>
<thead>
<tr>
<th>Sample</th>
<th>Nb/Ti</th>
<th>(I_{\text{Nb}}/I_{\text{Mo}})</th>
<th>% (\text{Nb}_2\text{O}_5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.68</td>
<td>0.0122</td>
<td>0.10</td>
</tr>
<tr>
<td>b</td>
<td>0.98</td>
<td>0.0125</td>
<td>0.10</td>
</tr>
<tr>
<td>c</td>
<td>0.71</td>
<td>0.0129</td>
<td>0.10</td>
</tr>
<tr>
<td>d</td>
<td>0.80</td>
<td>0.0124</td>
<td>0.10</td>
</tr>
<tr>
<td>e</td>
<td>0.66</td>
<td>0.0173</td>
<td>0.13</td>
</tr>
<tr>
<td>f</td>
<td>0.74</td>
<td>0.0112</td>
<td>0.09</td>
</tr>
<tr>
<td>g</td>
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</tr>
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<td>h</td>
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<td>j</td>
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<tr>
<td>l</td>
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</tr>
<tr>
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**Lens A (Average)**

- 0.10

**Lens B**

- 0.09

**Lens C**

- 0.13

**Deposit**

- 0.11
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 analysed qualitatively with the X-ray spectrograph and it was found that neither the Standing Rock nor the Hogback deposit detectable contained 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 $\text{Nb}_2\text{O}_5$ - the most common commercial form, and is calculated by multiplying the assay in weight percent times the total tonnage of lens material. Figure 15 shows the average percent by weight
of Nb₂O₅ for each lens and for the entire deposit.

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 percent 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 0.07 percent Nb₂O₅.

Probable lens material is defined by the outcrop length of each exposed lens, an assumed width in the cuesta of fifty feet, and an average thickness of six feet. On the east face of Sanostee cuesta two lenses are exposed beneath Lenses B and C. These lenses 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 (171.66 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 Lens A, B, and C and the average assay of the deposit for Lenses B', B, C, and C' (See Figure 13) the niobium content amounts to 60.7 tons. At the market price of $1.20 per pound (Engineering and Mining Journal, 1961, p. 92) the value of contained niobium pentoxide in the ground is $148,600. If the 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 1,600 feet long, 160 feet wide, and 6 feet thick. All lenses are considered as having an average thickness of 6 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. Considering Lens A' to be of the same grade as Lens A and using the same assays for Lenses B, B', C, and C' as in the "probable" estimate, the total value of Nb₂O₅ in the ground is $690,000.

Inasmuch as the Sanostee cuesta is bounded on three sides by cliffs which limit 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 and value 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 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 5,160 tons with an in the ground value of $5,160,000.
Economic Potential

From the discussion of the niobium content it is obvious the Sanostee deposit is potentially an economic source of niobium. Two factors which are significant in the economic consideration of this deposit are the ease of concentration of niobium and the 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 of the niobium and essentially all of the titanium in the lens material. If the non-magnetic fraction is processed to remove quartz, an essentially pure zircon concentrate is made. Each of the concentrates should be marketable items.

The combined value of the zircon, titanium, and niobium increase 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 percent $\text{TIO}_2$. Average grade of 10 percent $\text{TIO}_2$ 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. At the current unit price of titanium metal $11,600,000; $51,100,000; and $396,000,000 respectively. The unit price for titanium metal is used because the metal would be formed during the recovery of niobium.

Because of ease of separation as a byproduct, zircon values 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 (See Figure 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. In the ground zircon values are $157,400; $624,000; and $7,080,000 respectively at the unit price of $46 per ton. These values are based upon grade estimates of 3.65 weight percent zircon for Lens A, 12.00 weight percent for Lens B and 10.27 weight percent for Lens C.

Summing up the value of the three readily concentrated elements discussed above the total value of the Sanostee deposit ranges somewhere between $11,306,000 and $408,245,000. From the sum total of the writer's knowledge of the Sanostee deposit the best single estimate of available tonnage would be a little greater than 500,000
tons of lens material (plus 0.17 percent Nb₂O₅; plus 10 percent TiO₂; plus 3.65 percent zircon), $60,000,000. In the writer's opinion this is a conservative estimate; value of about $65,000,000. It is interesting to note that substantial amounts, probably about equal to niobium, of yttrium are present in the deposit. Assuming a grade of 0.20 percent yttrium and using the estimates of 300,000 ton of lens material, the gross value of yttrium is about $60,000,000. Unfortunately this element is present in solid solution in zircon and 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 technological difficulties involved in removing tantalum from the usual niobium concentrates would not be involved in processing the lens material.
SUMMARY

Rocks of Jurassic, Upper Cretaceous, and Tertiary age are exposed near Sanostee, New Mexico. The Jurassic rocks consist of red and green variegated shales and siltstones which are undifferentiated in this report. Six 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 of 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 non-marine. 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 non-marine 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.

Post-depositional 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 analyses by emission spectroscopy indicate 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 0.17 to 0.30 weight percent niobium pentoxide.
Three tonnage estimates 57,400 tons; 261,950 tons; and 2,054,500 tons are made based upon the inferred limit of concealed lenses. The value of the niobium content of the Sanostee deposit, based upon average grade and tonnage estimates and the 1961 unit price of Nb₂O₅ (5.00 per pound) is $148,000; $690,000; $2,185,000. In addition, estimates of titanium and zircon content are made. The probable "in the ground" value of the deposit based upon three commodities and 1961 prices is estimated to be about $60,000,000 dollars.
X-ray fluorescent spectroscopy

X-ray fluorescent spectroscopy is particularly well adapted to determining elemental concentrations in mixtures of chemically similar elements. A few examples are the determination of niobium in tantalum, thorium in uranium, and hafnium in zircon.

The basic theory of X-ray fluorescent spectroscopy was developed from experiments carried out independently by Barkla and Moseley in the period between 1908 and 1914. According to the Bohr model of the atom electrons are arranged around the nucleus in shells which correspond to energy levels. When an atom is bombarded by primary X radiation an electron from an inner orbit is driven out of the atom and its place is taken by an electron from an outer shell. Each time an electron jumps from an outer shell to an inner shell a quantum of energy in the form of secondary X radiation is emitted. The energy differences between the electron shells give rise to emission spectra characteristic of a given element (Parrish, 1956, p. 24; Moore, 1955, p. 268).

The spectra of an element consist of emission and absorption spectra. Emission spectra arise when a photon or quantum of energy is released by the atom. The total amount of energy released by a sample is proportional to the number of atoms present. Absorption
spectra are produced when an inner shell electron is removed by photoelectric absorption of an X-ray photon (Friedman, et al, 1953, p. 5). This phenomenon is accompanied by a sharp increase in the absorption coefficient of the fluorescent material at the critical excitation potential. This absorption discontinuity is called an "absorption edge". Two characteristic emission frequencies are produced by the transition L - K and are designated K_{el} and K_{e2}. This doublet arises because the L shell has three slightly different energies. The K_{el}, K_{e2} doublet and the K_{e2} line are produced by M - K transitions.

The frequencies of X-ray emission spectra and the critical excitation potential are related to the atomic number of elements in a systematic manner. With increasing atomic number the electrons of the innermost K orbital are more tightly held to the nucleus and progressively higher potentials must be applied in order to ionize the K shell electron. The critical excitation potential of an emission line of known frequency can be calculated from the Einstein equation

\[ eV = h\nu \]

where \( e = 1 \) electron volt, \( h \) is Planck's constant, \( \nu \) is the frequency of the emission line and, \( V \) is the excitation potential in kilovolts. Substituting the values for \( e \) and \( h \), and letting the frequency equal the
velocity of light divided by the wavelength of the emission line, the excitation potential can be calculated. Using this relationship, the excitation potentials of a number of K and L lines of a few elements were calculated (See Figure 16). From these data it is seen that in order to excite the K line spectrum of aluminum, At. No. 13, only 1.48 kilovolts are required, but to excite the K spectrum of uranium, At. No. 92, 98 kilovolts are required. Because the maximum potential which may be applied to the X-ray tube emitting primary X-radiation in conventional equipment is 50 kilovolts, the L spectra are used in studying elements above atomic number 64. In general qualitative work the maximum allowable potential should be applied in order to excite all the possible elements which might exist in an unknown mixture. In some cases where emission spectra of an element with high atomic number interfere with the analysis of an element of low atomic number, the interfering element can be avoided by utilizing a potential slightly less than the critical excitation potential of the interfering element.

One of the drawbacks to X-ray fluorescent spectroscopy is that elements of atomic number less than 20 cannot be detected. The secondary radiation of these elements is so soft that air molecules in the path from source
FIGURE 16

Table of excitation potentials (After Cope)
to detector block the transmission of the secondary radiation. Use of a helium atmosphere allows the analysis of elements down to aluminum At. No. 13, but this process requires special equipment.

Secondary X-radiation emitted from the sample is collimated and diffracted by a crystal of known interplanar spacing. Since the radiation consists of a number of different wavelengths a diffraction grating must be used to separate the characteristic wavelengths. In view of the extremely small wavelengths of the X-radiation a crystalline substance is used. The crystal is oriented in such a way that the collimated beam is diffracted from one set of atomic planes. Diffraction by the analysing crystal is governed by Bragg's Law, \( n\lambda = 2d \sin \theta \), where \( n \) is the order of the "reflection", \( \lambda \) is the wavelength of the characteristic line spectra, \( d \) is the interplanar spacing, and \( \theta \) is the angle of incidence when "n" order reflections are in phase.

Although the methods of X-ray diffraction and X-ray spectroscopy are similarly instrumented they are different in principle and results. In X-ray diffraction filtered radiation of one known wavelength is diffracted by a crystalline substance. The diffraction picture is representative of the structure of the crystalline material. In X-ray spectroscopy atoms are bombarded by
primary polychromatic radiation and the atoms give off a spectrum of energy wavelengths which is analyzed by a crystal of known interplanar spacing. This technique supplies information regarding the elemental composition of a sample but nothing about its structure.

Details of the technique

In this study, a Norelco X-ray fluorescent spectrometer was used with wide angle goniometer and a photomultiplier detector. A single sodium chloride crystal with a 2d spacing of 5.344 was utilized to analyze the X-ray spectrum. Impulses from the detector were amplified, counted by an electronic circuit, and the resulting signal fed to a Brown automatic recorder. All qualitative analyses were made at a scanning rate of 1°2θ per minute. For quantitative work the goniometer was set at a predetermined 2θ position and the number of counts per unit time recorded. Intensities in counts per second were determined for Nb Kα1 and Mo Kα1, the internal standard. A calibration curve was constructed by plotting \( I_{\text{Nb}} / I_{\text{Mo}} \) against percent Nb₂O₅. All of the samples were then analyzed and their niobium content determined within a known experimental error. Since the ratio of intensity for the same emission line of any two elements will be directly proportional to their relative amounts in the sample, the Kα1 line of
titanium was also measured. A niobium : titanium ratio was then calculated for each sample and recorded along with the amount of niobium present (Figure 15).

**Internal standard** - An internal standard is often used in quantitative X-ray spectroscopic analysis because it reduces the number of potential accidental errors. Such errors may be produced by disturbing effects of the matrix, particle size of the sample, density differences produced by variations in degree of sample packing, or by X-ray tube potential settings which are not exactly reproducible. Selective absorption or enhancement of secondary radiation by the sample matrix may also affect the analysis. These errors are minimized by use of an internal standard. Since weight percent is plotted versus an intensity ratio any factor which affects the desired results from the element being analysed will also affect the internal standard and to the same degree.

Care must be taken in the selection of an internal standard. If an element is chosen that is a "disturber", (defined as an emission line or absorption edge, which lies between the reference line of the element being analysed and the reference line of the internal standard), selective absorption or enhancement will take place (Cope, 1956, p. 42). Figure 17 illustrates the principle
FIGURE 17

Principal emission lines and absorption edges in the vicinity of niobium.
lines and edges in the vicinity of Nb$_{X1}$ and Mo$_{X1}$. According to Figure 17, the K$_{β1}$ line of yttrium causes a disturbing effect. This element is present in all samples in about equal amounts, but the K$_{β1}$ line is so weak it probably does not cause any major error in the niobium determinations. A molybdenum internal standard was chosen as the standard for this series of determinations.

The calibration curve was prepared by adding 10 percent by weight MoO$_3$ to a series of samples containing 5, 3, 1, 0.5, and 0.1 weight percent Nb$_2$O$_5$. The intensity of Nb$_{X1}$:Mo$_{X1}$ was calculated and plotted versus weight percent Nb$_2$O$_5$. The resulting curve is an hyperbola, but for practical purposes in a limited composition range it may be treated as a linear function (Sherman, 1953, p. 33). Using the method of least squares (Steinback, and King, 1950, p. 13) values for m and b in the general equation $y = mx + b$ were calculated to be $m = 0.122$ and $b = 0.019$. In this method of formulating a working curve the internal standard may be added to either an artificial mixture which approximates the composition of the sample, or to a sample of the ore itself. For this study the second procedure was adopted. Coming back to the general equation of the working curve it is seen that the y intercept is the amount of niobium in the sample before any pure Nb$_2$O$_5$ was added. By equating the y intercept to zero, the intensity ratio
becomes directly proportional to weight percent $\text{Nb}_2\text{O}_5$ with $m$ being a constant of proportionality. By substituting data for the intensity ratio the niobium content was calculated directly by the formula:

$$\text{wt.\% Nb}_2\text{O}_5 = \frac{(I_{\text{Nb}})}{(I_{\text{Mo}})} \times 0.122$$

A similar procedure was also utilized to measure the lower limit of detection of the equipment. A sample of quartz sandstone was used as a matrix. The goniometer was set at the proper $2\theta$ position for the NbK$_{\alpha1}$ line and the intensity recorded in counts per second. Niobium oxide was added until a reproducible positive change in the intensity was recorded. A 0.001 weight percent concentration of $\text{Nb}_2\text{O}_5$ produced such a change and is considered to be the lower limit of detection. This value compares favorably with a figure of 0.005 percent $\text{U}_3\text{O}_8$ obtained by Cope with a lithium fluoride analysing crystal (1956, p. 43).

**Discussion of Error**

Conclusions based on results of any quantitative process are only as reliable as the accuracy and precision allows. The precision of a result is a measure of its concordance within a series of similar measurements. The accuracy of a result is an indication of the divergence between a measurement and the true value.
Both precision and accuracy of a result are a function of systematic and accidental errors and in most instances can be approximated. Accidental errors are the result of mistakes in procedure and can be avoided by careful laboratory technique. Systematic errors affect all results to the same degree and are the result of instrumental error, chemical or physical shortcomings of the quantitative technique, and derived results. In most cases their magnitude can be approximated by statistical treatment, or they can be avoided by changes in technique. Many results may be precise but highly inaccurate because of the influence of unknown variables. Therefore in order to determine the accuracy of a result it must be compared with a presumably true value, in most cases a chemical analysis of the lens material was prohibitively costly, the accuracy of the spectrographic method could not be determined. However, the niobium content of the deposit is of the same order of magnitude as that obtained by Chenowith (1957, p. 212) for similar occurrences in the San Juan Basin.

All of the recognized instrumental errors are obviated by the use of an internal standard. Such sources of error are non-reproducible kilovolt settings, temporary power surges, variation in sample packing, and differences in grain size from sample
to sample. Non-instrumental sources of error which can be avoided by the careful application of standard laboratory procedures are errors in weight caused by failure to dry samples and internal standard in an oven, and failure to create an intimate mixture of sample and internal standard. Mixing of the standard and sample was accomplished by grinding the two powders together in a mechanically operated agate mortar for at least one hour. This is a standard technique which is excelled only by adding the internal standard in liquid form and grinding to dryness.

Error inherent in setting the goniometer and recording intensities in counts per second were evaluated by making twenty determinations on a single sample. The percent error involved in recording the intensity of a given peak was found to be 0.67 percent. This error varies with the number of counts recorded and was established on the basis of 12,400 counts recorded. For each sample analysed the time required to accrue 12,400 counts was recorded in order that the error remain constant. All weighings of sample and internal standard were performed with an automatic analytical balance with an allowable error of ± 0.05 milligrams. Since no amount of substance less than 0.2 grams was weighed in the preparation of samples the resulting maximum
percent error of 0.025 percent is considerably less than the error due to counting. The derived error is illustrated by the following example.

$I_{\text{Nb}} = 152 \pm 1.20 \text{ counts/sec.} \quad I_{\text{Mo}} = 4130 \pm 27.6 \text{ counts/sec.}$

$$\%\text{Nb}_2\text{O}_5 = \frac{(152/4130)}{0.122} = 0.302$$

$$\%\text{Nb}_2\text{O}_5 = \frac{(152/4130)}{0.122} = 0.306$$

$$\%\text{error} = \frac{0.006(100)}{0.302} = 2.0\%$$

Expressed in percent Nb$_2$O$_5$ the maximum error is $\pm 0.006$ percent Nb$_2$O$_5$. As the concentration of Mo in the standard increases the counting time decreases. With shorter counting time the error in counts per second increases. Consequently, the percent error in niobium content could effectively be decreased by adding less Mo internal standard to the samples. For samples containing less than 0.01 percent Nb$_2$O$_5$ this would be a necessary adjustment.
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### Heavy Mineral Data, Sanostee Deposit

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