BUREAU OF ECONOMIC GEOLOGY
The University of Texas
Austin, Texas 78712

Peter T. Flawn, Director

Report of Investigations — No. 53

Potential Low-Grade Iron Ore and Hydraulic-Fracturing Sand in Cambrian Sandstones, Northwestern Llano Region, Texas

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VIRGIL E. BARNES AND DANIEL A. SCHOFIELD

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Virgil E. Barnes and Daniel A. Schofield

ABSTRACT

The red upper unit of the Hickory Sandstone is a hematitic and goethitic sandstone containing a large reserve of potential low-grade iron ore. It is estimated that about 7 million long tons of elemental iron is locked up in each square mile of the upper 30 feet of this deposit in sandstone averaging about 12.4 percent elemental iron. At least 175 square miles of the deposit is under less than 800 feet of cover, and reserves in the upper 30 feet in this area total about 650 million long tons if 75 percent of the potential iron ore is minable and two-thirds of the iron in the mined ore is recoverable. Beneath this level another 50 or 60 feet of poorly exposed iron-bearing sandstone is probably equally as iron-rich, and if this is true, total potential reserves may be as much as 1.6 billion long tons of elemental iron in 23 billion long tons of rock or about 6 billion tons of concentrates. No part of the deposit can be regarded as direct shipping ore. Iron oxide from the red unit of the Hickory Sandstone, except for high carbonate mineral content, is of paint pigment quality.

Hydraulic-fracturing sand production from the lower unit of the Hickory Sandstone is well established in the Voca area, McCulloch County, and within the area of this report the amount of such sand is very large.

The middle unit of the Hickory Sandstone, the Lion Mountain Sandstone, the Welge Sandstone, and the sandstone zones in the San Saba Member appear to be devoid of deposits of value.

INTRODUCTION

A long-term stratigraphic study of Cambrian and Ordovician rocks in the Llano region sparked by Josiah Bridge (1937; Bridge, Barnes and Cloud, 1947) and continued by Cloud and Barnes (1948) is approaching completion (Barnes and Bell, MS.). A product of this investigation was the recognition of the potential value of the Hickory Sandstone for hydraulic-fracturing sand and recognition that the red upper part of the Hickory Sandstone in the northwestern part of the Llano region constitutes a large potential reserve of low-grade iron ore. This material is not *ore* in the strict sense of a mineral aggregate that can be economically exploited under existing or immediately foreseeable economic conditions. It is potential ore in that it can be added to the nation's inventory as a resource for the future. In the United States, iron ore reserves are estimated as 10 billion long tons of crude ore equal to 5.5 billion long tons of direct shipping ore and concentrates containing 3 billion long tons of iron. These are measured, indicated, and inferred reserves (deposits that can be reasonably assumed to exist under existing economic conditions and with known technology) . Potential ore which might become usable in the future is estimated at 65 billion long tons which might yield 25 billion long tons of concentrates and some direct shipping ore (Carr and Dutton, 1959, pp. 85–86). If this central Texas deposit is assessed as potential ore, the United States' potential domestic iron resources are substantially increased.

Although basic field work on Cambrian stratigraphy was essentially completed prior to 1951, intervention of other projects delayed a study of the commercial possibilities of the sandstone. Sampling, mapping, testing, and preparation of manuscript were finally completed in 1963. Exploitation of the lower unit of the Hickory for hydraulic-fracturing sand was begun in the meantime (1958), and at the time of publication of this report two plants are in operation.

The area covered is in the northwestern part of the Llano region and extends from just east of Valley Spring in Llano County, westward and from just south of Mason in Mason County, northward to include all exposed bodies of Cambrian sandstone in these directions (Pls. I and II, in pocket). This study is limited to most of the outcrop area of the red upper unit of the Hickory Sandstone. Hydraulic-fracturing sand is produced from the lower unit of the Hickory near Voca, McCulloch County.

All field work and preparation of manuscript were the responsibility of Barnes; testing was done under the direction of Schofield.

GENERAL STRATIGRAPHY

LIST OF STRATIGRAPHIC UNITS

Cambrian and Ordovician units shown on Plates I and II and their normal range of thicknesses, where not truncated by the unconformity at the top of the Ellenburger, are as follows:

STRATIGRAPHIC UNIT	NORMAL RANGE OF THICKNESS *(feet)*
Honeycut Formation	679+
Gorman Formation	426–490
Calcitic facies	237–383
Dolomitic facies	91–244
Tanyard Formation	523–658
Staendebach Member	229–481
Calcitic facies	0–176
Dolomitic facies	0–481
Threadgill Member	202–294
Dolomitic facies	0–260
Calcitic facies	0–294
Wilberns Formation	560–619
San Saba Member	193–324
Dolomitic facies	0–277
Calcitic facies	0–299
Point Peak Member	25–214
Morgan Creek Limestone Member	113–143
Welge Sandstone Member	11–27
Riley Formation	520–860
Lion Mountain Sandstone Member	29–78
Cap Mountain Limestone Member	165–497
Hickory Sandstone Member	276–470

The thickness given for the Honeycut Formation is its measured thickness in the southeastern part of the Llano region at Honeycut Bend. Everywhere it is present in the Llano region, the upper surface is an erosional unconformity. The Honeycut is missing in the northwestern part of the Llano region except possibly in a collapse structure along Ranch Road 1311 north of San Saba River. Locally, all other Ordovician units were also removed by erosion; north of Hext, Canyon sediments were deposited directly on San Saba rocks.

The stratigraphy of Cambrian and Ordovician rocks in the Llano region is treated in references cited above and in others by Barnes and Bell (1954a, 1954b), Barnes, Bell, and Pavlovic (1954), and Barnes (1956, 1959). The Cambrian-Ordovician boundary is within the upper part of the San Saba Member in the western part of the Llano region; to the east where dolomitic facies of the Threadgill and San Saba Members are in contact, the boundary locally is in the Threadgill Member.

Stratigraphic units shown on Plates I and II in addition to those listed above include:

Precambrian—
- Valley Spring Gneiss and Packsaddle Schist (Paige, 1911)
- Lost Creek Gneiss (Ragland, 1960)
- Town Mountain Granite and Oatman Creek Granite (Stenzel, 1932)

Mississippian—
- Ives (Conglomerate) Breccia (Bullard and Plummer, 1939)
- Chappel (Formation) Limestone (Sellards, 1933)
- Barnett (Shale) Formation (Plummer and Moore, 1922)

Pennsylvanian—
- Marble Falls Limestone (Hill, 1889)
- Canyon Formation or Group (Cummins, 1891)

Lower Cretaceous—
- Hensell Sand (Hill, 1901)
- Walnut Clay (Hill, 1891)
- Comanche Peak Limestone (Hill, 1889a)
- Edwards Limestone (Hill and Vaughan, 1898)

Quaternary—
- Terrace deposits, travertine and alluvium

All of the above units, except the Lost Creek Gneiss, have long established usage. The Lost Creek Gneiss was named by Ragland (1960) in a Rice University thesis. Plate I of the present publication is the first published map which includes this unit. The first sample of this augen gneiss was described by Barnes, Dawson, and Parkinson (1947, p. 121). It was brought to the attention of Mr. Ragland by Barnes, who suggested that it might correlate with the meta-igneous Red Mountain Gneiss of the southeastern part of the Llano region. Ragland, however, determined that the Lost Creek is a metasedimentary gneiss; because it is distinct from the underlying Valley Spring Gneiss, he proposed the name Lost Creek Gneiss after Lost Creek along which it crops out. The Lost Creek Gneiss grades Upward through a sequence of alternating beds of augen gneiss and schist to Packsaddle Schist. The Lost Creek Gneiss on Plate I was mapped by Ragland. Elsewhere the Lost Creek Gneiss is included with the Valley Spring Gneiss.

The geologic maps (Pls. I and II) were compiled from published material, manuscript maps by Barnes and Bell (MS.), theses maps supervised by Barnes and Bell (R. H. Alexander, 1956; Winston, 1957; Ragland, 1960), and aerial photographs, with a minimum of field checking for the remaining area by Barnes. The final compilation was then checked against modern Texas Agricultural & Mechanical College theses. Theses that proved to be especially helpful were by Sweet (1957), Grote (1954), Mangum (1960), and Fritz (1954). However, whether or not they were used in the compilation, all theses areas are shown in the insets on Plates I and II.

RÉSUMÉ OF SANDSTONE UNITS

HICKORY SANDSTONE

The thickness of the Hickory Sandstone is controlled by the irregularity of the Precambrian floor, which rises in a general northwestward direction, and by lateral gradation between the Hickory Sandstone and Cap Mountain Limestone. Because of this gradation, the thickest outcrop of Hickory Sandstone is not in the thickest known section of the Riley Formation. The greatest thickness of Hickory Sandstone measured, 530 feet, was found by Barnes (1959) in Phillips Petroleum Company No. 1 Spiller, Kimble County; the Riley in this well totaled 740 feet, which is 120 feet less than in the Threadgill section where the Hickory is only 364 feet thick. The Threadgill section is about 15 miles south of the area of this report. The thickest surface section of Hickory Sandstone, 470 feet, was measured in the Pontotoc section (Pl. II) ; within a mile of this section the Hickory thins to a feather edge against a sharp ridge of Precambrian Valley Spring Gneiss.

The Hickory is mostly quartz sandstone; cross lamination is present throughout the member; locally quartz pebble conglomerate occurs at the base. Feldspar is important in the basal part in only a few places and where present is usually indicative of a nearby buried granite hill.

The Hickory Sandstone in the area under consideration is divisible into three units. The top unit is a very distinctive dusky red, iron-oxide-cemented, friable, medium- to coarse-grained sandstone with exceptionally well-rounded sand grains. Southeastward, the upper part grades laterally into Cap Mountain Limestone. Topographically, the upper part of this unit is mostly in the lower part of a scarp beneath Cap Mountain Limestone; the lower part mostly occupies a cultivated bench astride the boundary between the upper and middle units.

The middle unit, mostly not cultivated, forms a low, hilly belt which on aerial photographs is distinct from the units above and below. The only known well exposed part of the middle unit is the 40-foot exposure sampled along San Saba River. In the Pontotoc section (Appendix, pp. 40–44) the middle and lower parts of the Hickory are poorly exposed. In exposures of the middle unit, the rocks are commonly thinly bedded, argillaceous, silty, and in places micaceous. The presence of mesquite confirms its argillaceous nature; deciduous oaks are common.

The lower unit of the Hickory Sandstone containing poorly sorted, rounded to subrounded and mostly smooth sand is friable, mostly cultivated and forms gently rolling topography; the upper boundary is indistinct. On aerial photographs the boundary between the middle and lower units can be traced approximately; however, the less the slope, the higher stratigraphically the boundary is likely to be drawn.

LION MOUNTAIN SANDSTONE

The Lion Mountain Sandstone Member of the Riley Formation consists of quartzose greensand, glauconitic quartz sandstone, sandy limestone, trilobite coquinite lenses, impure limestone beds containing phosphatic brachiopods, and minor shale and siltstone. It is characteristically dusky green to grayish olive green where fresh and in the lower part is studded by contrasting white to yellowish-gray, cross-bedded trilobite coquinite lenses. The upper boundary is sharp and the lower gradational boundary is mostly ill defined. In mapping, the lower boundary is most conveniently located at the lower edge of a sparsely vegetated bench.

WELGE SANDSTONE

The Welge Sandstone Member of the Wilberns Formation is a coarse- to medium-grained, mostly pate to dark yellowish-brown, typically nonglauconitic, sparsely fossiliferous, well-sorted, quartz, marine sandstone. The grains characteristically have quartz overgrowths and glitter in the sunlight. The basal part is characterized locally by 2 or 3 feet of earthy, reworked Lion Mountain Sandstone or by poorly sorted granule beds marking the surface of disconformity on which the Welge was deposited. Its boundary with the overlying and more distinctly bedded Morgan Creek Limestone is gradational within narrow limits.

SANDSTONE IN SAN SABA MEMBER

Sandstone in the San Saba Member, found only in western Mason County and adjacent parts of Menard and Kimble counties, continues westward in the subsurface, where it thickens. From subsurface data it seems likely that this extensive sandstone body is sharply terminated eastward by a north-south-oriented barrier reef exposed, so far as is known, only in northwestern Mason County (Barnes, Bell, and Pavlovic, 1954; Barnes, 1959). From 55 to 70 feet of calcareous sandstone has been measured; the grains are mostly of medium size and well rounded. Plummer (1943) described Cambrian quartz sand in western Mason County which he termed the Erna Sand. Later it was found that this sand was in the San Saba Member, but in view of the varied number and local character of the sandy zones in the member in this area, Bridge, Barnes, and Cloud (1947, p. 121) thought it undesirable that any of them be formally named.

STRUCTURE

The area under consideration is situated high on the northwestern side of the Llano uplift, and the beds, where not disturbed by faulting and local structure, dip gently from northward in the Pontotoc area to westward in the Streeter area. The faults are normal. The major trends, ranging from north-south to east-west, are all in the northeast quadrant; a minor set trends northwest-southeast. Pennsylvanian Strawn rocks are displaced but Pennsylvanian Canyon rocks are not. Folds are chiefly incidental to the faulting; locally in the vicinity of Streeter, solution of Precambrian marble has resulted in collapse of the entire 2,500-foot thickness of the Cambrian-Ordovician sequence producing sinks, in one of which Pennsylvanian Marble Falls Limestone was deposited at the level of the Hickory Sandstone—Cap Mountain Limestone contact.

The intricate faulting is shown in Plates I and II; however, some areas, such as the one between the Fredonia fault zone and the Cold Creek fault zone (Pl. II) in the Pontotoc area, are little disturbed. Additional faults, not readily detected and not shown herein, occur in Precambrian rocks.

The zone of faulting marked by the north-south-trending Fredonia fault zone and the northeast-southwest-trending Mason fault zone is the most prominent zone of faulting in the area of Plate I. Both zones are marked by eastward-tilted blocks on their downthrown western sides and relatively large displacement along the main fault in each area. Where these two zones meet, a third zone of faults trends eastward.

The narrow north-south fault zone which forms the western border of the Voca anticline continues southward and passes beneath Cretaceous rocks of Mason Mountain. In line with the continuation of this zone on the south side of Mason Mountain, a narrow graben bounded by northeast-southwest faults dips steeply northeastward. This graben may be an extension of the northeast-southwest fault zone south of Streeter. If these two zones do connect through the intervening area of Precambrian rocks, this zone is roughly parallel to the Mason-Fredonia fault zone.

The north-south-trending Cold Creek fault zone bounds the western side of a graben with southward-pointing apex and weaker faulting on the southeastern flank. Spring Creek fault, a prominent north-south fault with increasing throw northward, crosses San Saba River in northwestern Mason County.

ECONOMIC GEOLOGY

INTRODUCTORY REMARKS

The primary purpose of this report is to record the presence of deposits of potential low-grade iron ore and deposits of hydraulic-fracturing sand of present economic importance in Cambrian sandstone units of the northwestern part of the Llano region. Carr and Dutton (1959, p. 84) have defined potential iron ores as including (a) material of lower iron content than that which is now being mined, (b) material of usable grade in deposits of less than minable size, (c) deposits of minable size which contain excessive quantities of impurities, and (d) deposits technologically satisfactory but too remote from transportation and metallurgical plants for present use. As far as is known, the central Texas deposit described herein falls in the category (a) above—the grade is substantially lower than the grade of ores currently being mined. No metallurgical data are as yet available for these potential ores.

Many of the factors involved in determining if a deposit is of economic value change with the economic climate and national needs. For this reason a deposit that is not commercial now may be so in the future and vice versa. Geological factors which do not change, such as grade, tonnage, areal extent, stratigraphic position, and petrographic character, are stressed in this report.

Fuel in the form of natural gas is currently available in large supply in Brown County adjoining McCulloch County on the north. Water is present in the lower unit of the Hickory Sandstone in sufficient quantity to provide water for irrigation of the outcrop area of this unit and for municipal water supply; the capacity of this reservoir has not been determined but the supply is presumably large. The area is served by a network of highways. The towns of Menard, Brady, and San Saba are on the Santa Fe railroad, and Llano is on the Southern Pacific.

LOW-GRADE IRON ORE IN RED UPPER UNIT OF HICKORY SANDSTONE

The red unit of the Hickory Sandstone crops out in normal stratigraphic sequence throughout the area of Plates I and II. The continuity of its outcrop is interrupted by numerous faults. The red unit is absent in the Little Llano River section 12 miles northeast of Valley Spring; due north of Valley Spring the bench usually found at this level is very narrow. As the beds are nearly horizontal, this indicates that the unit is thin. Southward, the red zone of the Hickory passes laterally into the Cap Mountain Limestone. In this direction sand is progressively less abundant but retains its extremely well-rounded shape and polished appearance.

The red unit of the Hickory in its normal topographic expression forms a scarp in its upper part held up by the Cap Mountain Limestone and in its lower part slopes into a bench straddling the boundary between the middle and upper units. Exposures of the red unit are mostly of the upper part in road material pits; however, in the Pontotoc section the red unit is well exposed along an abandoned road.

STREETER-HOFFMAN RANCH AREA, MASON COUNTY

The upper unit of the Hickory Sandstone crops out about 1.5 miles west of Streeter and extends for about 6.5 miles in a roughly north-south direction. The northern 3.5 miles, a north-south outcrop belt, dips very gently westward and averages about 0.75 mile in width. Southward, the outcrop narrows to about 0.25 mile and in the vicinity of U.S. Highway 377 is interrupted by collapse structures and faulting. In the first fault block south of the highway, red Hickory Sandstone crops out for 1.5 miles along the strike and the outcrop narrows southward. In the two succeeding fault blocks, which include the crest of an anticline, dips are steeper, outcrops are narrower, and the red unit in the southern fault block is mostly obscured by alluvium.

During 1950, at the time the Streeter section was measured, the top 116 feet of the Hickory was exposed mostly in ditches along U.S. Highway 377. Seven years later the highway had been widened and the ditches mostly swabbed with tar to arrest erosion. Only the interval from 20 to 27 feet was available for sampling. A generalized description of the upper 116 feet of the Hickory Sandstone made by Barnes in 1950 is given in the Appendix (p. 36).

A highway material pit north of State Highway 29 is on property owned by William Hoffman (fig. 1). The pit, about 10 feet deep, is on the northwest upper slope of a flat-topped hill. Similar flat-topped hills and ridges reaching a common level in the area are capped by a thin silicified layer of Hickory Sandstone with a few adhering patches of Cretaceous conglomerate. This erosional surface (paleoplain) truncated the Cambrian rocks prior to Cretaceous deposition, and silicification followed deposition of the Cretaceous rocks. This silicified surface resists erosion; consequently, during the present cycle considerable areas of the paleoplain became exposed. Cuneiform markings present in some beds, once interpreted by Barnes (1958) as ice crystal markings, are possibly of organic origin.

The Hoffman highway material pit exposes 20 feet of the lower part of the red unit; however, its position in reference to the top of the Hickory Sandstone cannot be readily determined. Ten feet of red Hickory exposed in a drain to the north of the pit is near the base of the red unit. The outcrop in the drain is followed by a 25-foot covered interval; consequently, only 30 feet of the red unit could be sampled in this area. Sieve analysis, moisture and iron content, and ignition loss data are given in table 1.

Binocular microscope examination of the fraction larger than 60 mesh reveals that the lower 10 feet and upper 5 feet contain an estimated 5 percent of aggregated grains and ooids. In the lower 10 feet calcite, the cementing agent, dissolves readily in acid and releases the grains. In the upper 5 feet the chief contaminant is iron oxide ooids mostly with centers of quartz, and the few aggregates present are cemented by iron oxide.

Brown sandstone beneath the red unit is exposed 1,000 feet east of the Hoffman pit in a steep slope. Except in the upper few feet of this exposure, where the sand grains are well rounded and polished, the grains are mostly rough, although fairly well rounded. Toward the base of the exposure one thin bed is a coquinite of phosphatic brachiopods.

CENTRAL MASON COUNTY

The red unit of the Hickory Sandstone crops out in numerous fault blocks in the vicinity of Mason. Its outcrop, interrupted by faults, extends from 5.5 miles west to 2 miles south-southeast of Mason. It also crops out in two areas along Mason fault between 1.7 and 3.5 miles northeast of Mason, in a graben 5.5 miles north-northwest of Mason, and in another graben 6.5 miles north-northeast of Mason. Most of the fault blocks dip steeply and, consequently, the outcrop width is narrow; however, the outcrop in the vicinity of the highway material pit 3 miles northeast of Mason is in a less steeply tilted fault block and is about one-quarter mile wide.

The part of Mason County south of the exposure 2 miles south of Mason was not mapped; however, it is unlikely that significant amounts of the red unit are present. Barnes measured the Threadgill Creek section about 18 miles southeast of Mason where the thickened Cap Mountain Limestone incorporates the red unit. In this section the red unit is represented by reddish sandy limestone beds containing well-rounded polished grains.

CAMP AIR AREA, MASON AND MCCULLOCH COUNTIES

The outcrop of the red upper unit of the Hickory Sandstone averages about 300 yards in width, extends southwestward from the west boundary fault of the Voca

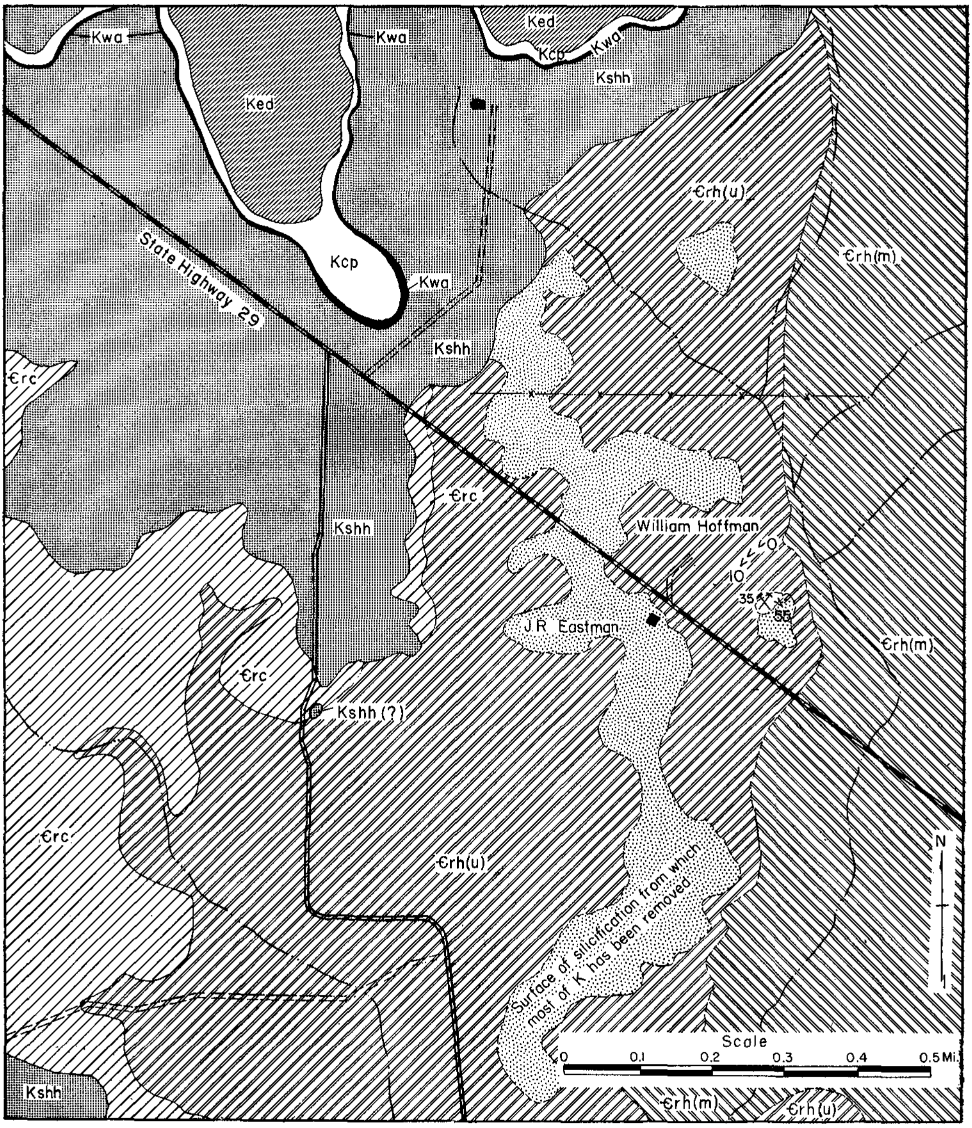

FIG. 1. Geologic map of area in vicinity of William Hoffman highway material pit, Mason County, Texas.

Stratigraphic units mapped: Cambrian, Riley Formation, Hickory Sandstone Member, middle unit, €rh(m), upper unit, €rh(u), and Cap Mountain Limestone Member, €rc. Cretaceous: Trinity Group, Shingle Hills Formation, Hensell Sand Member, Kshh, including quartzite sink filling(?), Kshh(?), and Fredericksburg Group, Walnut Clay, Kwa, Comanche Peak Limestone, Kcp, and Edwards Limestone, Ked.

Base from U. S. Department of Agriculture Soil Conservation Service, aerial photographs flown by Park Aerial Surveys, Inc., 1939–1940. Geology by Virgil E. Barnes, 1959.

TABLE 1. *Sieve analysis, iron and moisture content, and ignition loss data for samples from the upper red unit of the Hickory Sandstone, northwestern Llano region, Texas.*

			U.S. Standard Sieve Sizes															
Lab. No.	Locality	Interval *(feet)*	+10	10 to 20	20 to 40	40 to 60	60 to 80	80 to 100	100 to 140	140 to 200	200 to 270	270 to 325	325 to 20μ	—20μ	10 to 60	Fe	H_2O—	Ign. Loss
57080	Streeter	20–27	0.0	6.5	25.5	26.2	13.1	6.4	3.1	1.2	0.5	0.4	1.6	15.3	58	9.9	0.24	10.23
57081	Hoffman	0–10	0.0	0.7	12.8	14.7	12.7	12.5	11.1	3.3	6.5	1.5	8.3	15.9	28	9.7	0.19	1.74
57082	Hoffman	35–45	0.0	3.5	25.9	25.3	13.4	5.8	3.5	2.4	1.4	0.9	3.4	14.3	55	13.1	0.15	2.01
57083	Hoffman	45–55	0.0	6.0	32.3	25.0	11.0	5.2	2.2	0.1	1.7	0.5	2.1	13.8	63	15.2	0.30	3.31
57084	Sell	0–7	0.0	1.9	18.3	28.0	14.2	5.3	2.6	1.1	3.9	1.6	9.0	14.1	48	15.4	0.20	5.67
57085	Sell	7–17	0.0	1.3	18.4	30.1	14.4	6.2	3.2	0.7	2.9	1.3	8.7	12.8	50	10.8	0.18	11.02
57086	Sell	17–27	0.0	0.9	11.8	24.3	14.6	6.7	4.7	3.4	2.8	2.4	12.0	16.4	37	14.2	0.20	10.98
57087	Sell	27–32	0.0	0.4	12.4	24.2	15.4	8.7	4.3	0.5	4.4	1.8	11.0	17.0	37	12.4	0.16	15.64
57088	Sell	32–34	0.0	1.4	10.3	17.2	15.1	8.9	5.8	2.8	5.7	2.2	12.0	18.5	29	5.5	0.15	22.55
57089	Miller	0–10	0.0	1.8	9.8	19.5	20.9	14.7	6.9	1.4	4.3	1.6	9.2	9.8	31	9.7	0.17	6.86
57090	Miller	10–20	0.0	1.6	16.5	24.0	12.3	5.9	4.8	3.7	2.7	2.0	10.2	16.1	42	15.0	0.24	7.31
57091	Miller	20–30	0.0	2.6	18.0	22.9	14.9	8.3	4.2	1.8	3.3	1.5	8.8	13.7	44	13.8	0.22	5.85
57092	Highway pit	0–10	0.0	4.4	22.2	19.8	11.5	7.0	5.0	2.6	3.4	1.2	6.9	15.9	46	8.3	0.20	4.25
57093	Highway pit	10–20	0.0	4.0	21.3	22.3	13.2	6.7	4.4	2.2	1.9	1.6	8.6	13.6	48	12.2	0.12	4.86
57094	Highway pit	20–29	0.0	0.7	10.8	20.3	14.3	8.8	3.5	3.3	6.5	2.6	14.7	14.6	32	10.6	0.18	19.38
57095	Pontotoc	340–350	0.0	7.8	21.7	21.2	16.4	10.6	4.6	1.9	2.8	0.8	4.4	7.7	51	4.3	0.10	1.60
57096	Pontotoc	350–360	0.1	7.2	20.7	18.7	17.1	8.3	3.6	2.1	3.7	1.1	5.1	12.3	47	4.0	0.18	3.01
57097	Pontotoc	360–370	0.1	5.2	21.3	21.9	18.4	10.1	6.8	3.1	1.3	0.8	2.8	8.4	48	2.9	0.23	2.46
57098	Pontotoc	370–380	0.0	8.4	27.0	20.5	12.2	5.7	4.4	3.2	2.1	0.8	3.4	12.2	56	3.2	0.16	4.43
57099	Pontotoc	386–400	0.0	3.9	16.2	20.1	18.1	10.2	4.2	4.8	2.4	1.5	8.1	10.5	40	10.4	0.24	8.73
57100	Pontotoc	400–410	0.0	2.4	12.7	18.4	12.8	7.7	8.1	5.6	7.7	1.9	9.9	12.9	33	6.2	0.19	7.39
57101	Pontotoc	410–420	0.0	2.5	14.2	17.6	12.5	7.8	7.8	9.2	3.6	1.7	6.1	17.0	34	9.0	0.24	10.50
57102	Pontotoc	420–430	0.0	2.1	23.1	24.8	12.8	6.0	2.9	0.7	6.8	1.7	7.3	11.6	50	13.9	0.24	9.86
57103	Pontotoc	430–440	0.0	2.9	10.9	9.0	4.8	3.6	9.5	15.7	19.4	3.3	10.7	10.2	23	3.7	0.19	1.48
57104	Pontotoc	440–445	0.0	8.0	38.0	23.9	12.5	3.0	1.0	0.2	1.9	0.4	2.2	9.0	70	7.7	0.20	1.74
57105	Pontotoc	445–455	0.2	9.5	25.2	23.0	12.5	4.2	1.7	2.7	2.1	1.5	6.1	11.2	58	11.5	0.17	6.35
57106	Pontotoc	455–465	0.0	1.1	12.0	21.7	15.5	8.1	3.8	3.8	6.6	2.4	10.5	14.4	35	15.7	0.22	13.17
57107	Pontotoc	465–474	0.0	0.9	12.9	20.0	13.4	6.8	5.2	2.8	8.9	2.4	12.3	14.2	34	12.4	0.18	14.43

anticline 4 miles, then, because of a strike fault, gradually diminishes in width and terminates in another 1.5 miles. This unit is very poorly exposed except in the H. Sell highway material pit 1.5 miles north-northwest of Camp Air. A section measured in the northern end of the pit by Barnes and sampled by James Pegg is described in the Appendix (pp. 36–38).

Sieve analysis, iron and moisture content, and ignition loss data are given in table 1. Ignition loss is represented by carbon dioxide from carbonate minerals, combined water mostly in the mineral goethite, and to a lesser extent combined water in clay minerals. Carbonate minerals occur in all thin sections.

Binocular microscope examination of the fraction larger than 60 mesh reveals an estimated 5 percent of aggregated grains, ooids, and phosphatic brachiopod shell fragments in the lower three samples and about 20 percent in the top sample of the Hickory. The Cap Mountain Limestone sample did not yield to mechanical disaggregation and not over 10 percent of the quartz grains were freed. Acid treatment revealed carbonate minerals in all samples, and most grains were freed except in the two samples from the upper part of the unit in which fine sand and silt are cemented by goethite. After acid treatment, ooids of iron oxide remain; some have quartz grains at their centers.

The quartz grains are extremely well rounded and smooth and would be especially good for hydraulic-fracturing if the iron oxide stain on the grains is not objectionable and if the iron oxide ooids were removed.

VOCA AREA, MCCULLOCH COUNTY

The outcrop of the upper red unit of the Hickory Sandstone averages one-quarter mile in width and extends from a fault on the western flank of the Voca anticline at a point 2 miles south-southwest of Voca to another fault near the crest of the anticline at a point 4 miles northeast of Voca. From here southward along the steeply dipping eastern flank of the anticline, the outcrop narrows and in places is interrupted by faulting.

The upper part of the red unit is well exposed on the north bank of San Saba River, 2 miles north-northeast of Voca. Although not sampled, this outcrop appears to be similar in quality to others at this level in the Hickory. If the red unit should ever be exploited, the outcrops in this area are among the nearest to the railroad at Brady.

PONTOTOC AREA, SAN SABA COUNTY

The outcrop of the red unit of the Hickory Sandstone in the Pontotoc area, with one interruption by a ridge of Valley Spring Gneiss, averages about 300 yards in width and extends about 12 miles westward from the Cold Creek fault. It terminates at the eastern margin of the Fredonia fault zone (Pl. II). A sharp anticlinal flexure causes the red unit to reappear half a mile to the south. It continues south-southwestward about 4 miles where it is terminated by the same fault. Other outcrops of the red unit are in fault blocks within the Fredonia fault zone about 2.5 to 3.5 miles northeast of Fredonia.

All of the red unit is exposed 1.5 miles north of Pontotoc in the Pontotoc section measured by Barnes in 1949, and so far as known this is the only complete exposure of this unit. The description of the red unit in this section is given in the Appendix (pp. 38–40).

Sieve analysis, moisture and iron content, and ignition loss data are given in table 1. The ignition loss data indicate the presence of a substantial amount of carbonate minerals from 370 to 430 feet and above 445 feet, and a minor amount elsewhere. Iron in 53 feet of the red unit is above 10 percent, in 25 feet ranges from 5 to 10 percent, and in 50 feet is less than 5 percent. Sand larger than 60 mesh averages 46 percent (range 23 to 70 percent).

Binocular microscope examination of the fraction larger than 60 mesh shows it is composed of an estimated 1 to 25 percent of aggregates, iron oxide ooids, and phosphatic brachiopod shell fragments. Acid treatment shows the presence of carbonate minerals in all samples except in the lower 40 feet where fine sand and silt remain aggregated, perhaps from slight silica cementation, and in the upper 19 feet, where goethite is the cementing agent. In the lower 40-foot interval many grains are solution pitted and rough; however, a large proportion of the grains are well rounded and smooth. After acid treatment the more calcareous samples contain porous goethitic residues. Iron oxide ooids which are not affected by acid are present above 380 feet.

COLD CREEK AREA, LLANO COUNTY

The red unit of the Hickory Sandstone crops out in a fault block for a distance of 2 miles along the south foot of Lone Oak Mountain. Another outcrop to the west, half a mile in length, is south of Ranch Road 734 in the same fault block as Lone Oak Mountain. The upper part of the red unit is exposed in a highway material pit in the right-of-way of Ranch Road 734 at the foot of the southern end of Lone Oak Mountain.

Descriptions of thin sections from the highway material pit south of Lone Oak Mountain, Llano County, are given in the Appendix (pp. 44–45).

Sieve analysis, moisture and iron content, and ignition loss data are given in table 1. Ignition loss data show that the upper sample is very calcareous and that the lower two samples are somewhat calcareous. Sand larger than 60 mesh averages 47 percent in the lower two samples and 32 percent in the upper sample.

Binocular microscope examination of the fraction larger than 60 mesh shows that it contains less than 5 percent of aggregated grains, a few iron oxide ooids, and numerous phosphatic brachiopod shell fragments in the lower two samples and approximately 50 percent of these materials in the upper sample. Acid treatment reveals that the lower two samples are slightly calcareous and that the upper sample is very calcareous and therefore transitional to the Cap Mountain Limestone Member. The acid treatment released most of the sand grains except in the upper sample where fine sand and silt aggregates are cemented by silica and goethite.

SLICK MOUNTAIN AREA, LLANO COUNTY

The red unit of the Hickory Sandstone crops out in the vicinity of Slick Mountain on the Luther Miller property where the upper 30 feet of the unit is exposed in a highway material pit. The sandstone is predominantly deep red, a few beds are dark brown, and near the top thin lenses of ferruginous limestone are greenish gray, very sandy, and fossiliferous.

Sieve analysis, iron and moisture content, and ignition loss data are given in table 1. The ignition loss data indicate that carbonate minerals are common and fairly uniformly distributed. Sand larger than 60 mesh averages 39 percent.

Binocular microscope examination of the fraction larger than 60 mesh reveals a percent or two of aggregated grains, phosphatic brachiopod shell fragments, and a few iron oxide ooids. Carbonate minerals as revealed by acid treatment are fairly scarce and in the bottom sample amount to little more than a trace.

SUBSURFACE DISTRIBUTION

Red Hickory Sandstone is widely distributed in the subsurface (fig. 2) for a distance of about 120 miles northwestward from the line where the red zone passes laterally from Hickory Sandstone into Cap Mountain Limestone. The red zone thins shoreward, and it is unlikely that deposition of red Hickory took place near shore except around islands well off the coast (fig. 2). In Tom Green County the red zone pinches out about 50 miles from the shore of that time (fig. 2). The data used in compiling figure 2 are mostly from Barnes (1959) and Barnes and Bell (MS).

In a northeast-southwest direction the red Hickory Sandstone extends for a

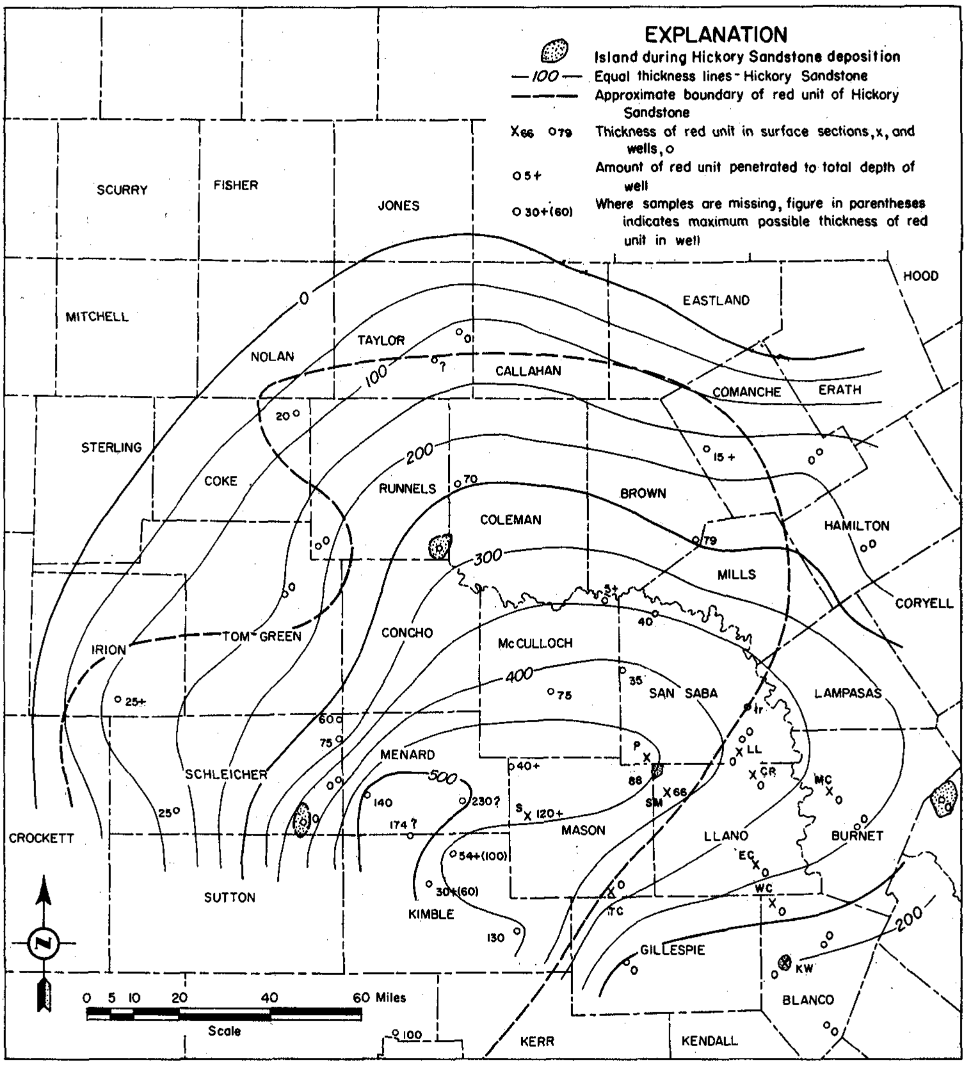

FIG. 2. Thickness map of Hickory sandstone in Texas showing distribution of red unit. Surface sections: Carter ranch, CR; East Canyon, EC; Klett-Walker, KW; Little Llano River, LL; Morgan Creek, MC; Pontotoc, P; Slick Mountain, SM; Streeter, S; Threadgill Creek, TC; and White Creek, WC.

known distance of 150 miles and may extend southwestward another 50 or so miles in the area where well control is lacking. Within this approximately 20,000 square mile area of red Hickory Sandstone, buried hills commonly interrupt its continuity. Only a few of these buried hills are shown in figure 2.

ECONOMIC POSSIBILITIES

Potential Low-grade Iron Ore

The elemental iron content of the red Hickory Sandstone is summarized in table 2 and shown graphically in figure 3. The upper 30 feet of the red Hickory averages about 12.4 percent elemental iron (range

TABLE 2. *Summary of iron (Fe) content in red Hickory Sandstone, northwestern Llano region, Texas.*

LOCALITY	INTERVAL (*feet*)	THICKNESS (*feet*)	IRON (FE) (*percent*)	AVERAGE (FE) (*percent*)
Pontotoc	445–474	29	13.2	
Pontotoc	430–445	15	5.0	10.2
Pontotoc	386–430	44	9.9	
Miller	0–30	30	12.8	
Highway pit	0–29	29	10.4	
Sell	0–32	32	13.1	
Hoffman	35–55	20	14.2	12.7
Hoffman	0–10	10	9.7	
Streeter	20–27	7	9.9	

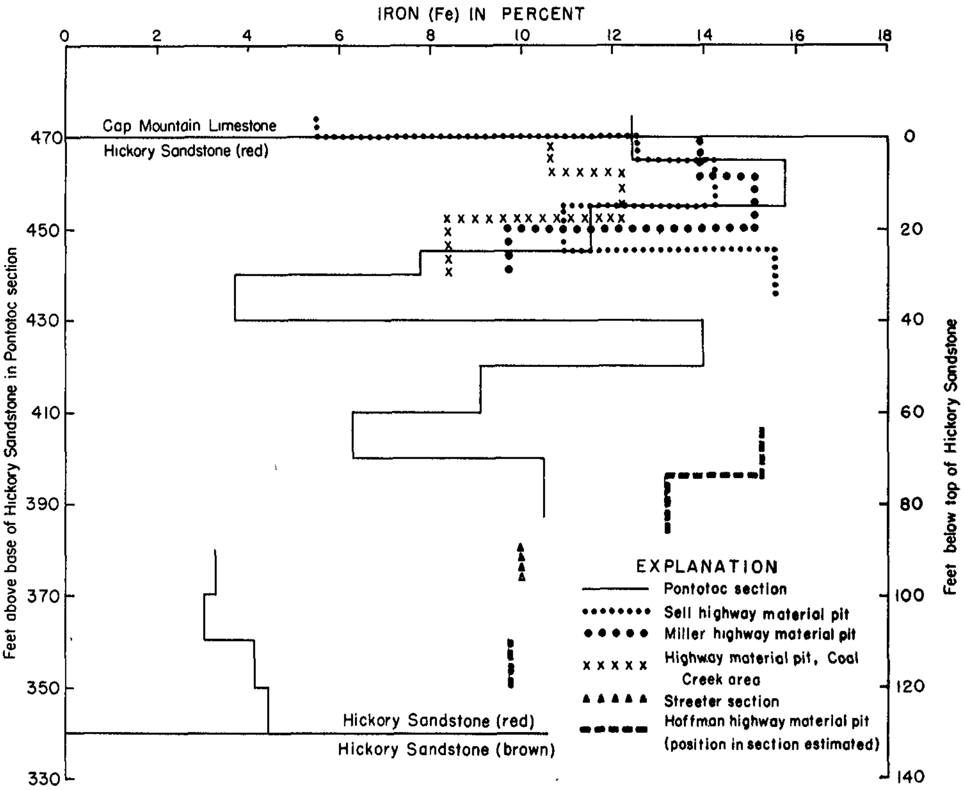

FIG. 3. Graph showing iron content of red unit of Hickory sandstone, northwestern Llano region. The Hickory Sandstone—Cap Mountain Limestone boundary is used as plane of reference, and the footages shown are for the Pontotoc section.

for four sections, 10.4 to 13.2 percent), it weighs about 156 pounds per cubic foot (14.4 cubic feet per long ton), and its outcrop length is about 53 miles. If its outcrop width averages 100 feet and if its outcrop thickness averages 12 feet, then about 3 million long tons of elemental iron is present in the outcrop area (table 3). For each additional foot laterally beneath Cap Mountain Limestone cover, an approximate additional 70,000 long tons of elemental iron is present.

The top 88 feet of the red Hickory Sandstone in the Pontotoc section averages

10.2 percent elemental iron. If this value is taken to be representative for the entire outcrop shown in Plates I and II and if the average thickness throughout the outcrop area is 20 feet and the average width of the outcrop is 500 feet, then about 20 million long tons of elemental iron are present in the outcrop area. For each additional foot laterally beneath cover, an additional 178,000 long tons of elemental iron is present if the average thickness for the red unit throughout the outcrop area is 90 feet.

Although it seems unlikely that exploitation of this deposit will be economically feasible in the foreseeable future, about 7 million long tons of elemental iron is locked up in each square mile of the top 30 feet of this deposit, and at least 175 square miles of the deposit are under less than 800 feet of cover. Dips seldom exceed 5 degrees, and the overlying Cap Mountain Limestone might furnish a stable back should economic conditions ever permit an underground operation. If half the iron in this 30-foot interval in this 175-square-mile area could be recovered, it would amount to about 650 million long tons—a substantial reserve for the future. Beneath this level, another 50 or 60 feet of poorly exposed iron-bearing sandstone is probably almost as rich, and if this is true, total reserves may be as much as 1.6 billion long tons of elemental iron.

Profiles were not made across the outcrop; however, the rate of increase of overburden can be estimated. The outcrop width of the Cap Mountain Limestone averages about 4,000 feet, and in most of the area its average thickness is about 200 feet. If the slope is uniform, the overburden thickens 1 foot for each 20 feet laterally; however, the slope of the lower part is oversteepened and as much as 20 feet of overburden may be present within 100 feet of the edge of the Cap Mountain Limestone. In the first 100 feet laterally beneath the overburden, 7 million long tons of elemental iron are estimated to be present.

If the Hoffman area (fig. 1) has been interpreted correctly, rock containing 13 percent elemental iron may be present in greater thickness there than in the Pontotoc section. If, for example, an average thickness of 40 feet of material containing 13 percent elemental iron is present, and the outcrop is 3,000 by 14,000 feet in size, then this outcrop area alone could contain 16 million tons of elemental iron.

Paint Pigment

When this study was begun, it seemed likely that the highly polished and extremely well-rounded sand grains could be used for hydraulic-fracturing sand and that some use could be found for the iron oxide. With this in mind and to avoid crushing the sand grains, the samples were disaggregated between a plastic cylinder and Lucite plate until most passed through a 20-mesh sieve. One hundred grams of the crushed material with water and sufficient

TABLE 3. *Reserves of iron (Fe) in red Hickory Sandstone, northwestern Llano region, Texas.*

	AVERAGE WIDTH (*feet*)	AVERAGE THICKNESS (*feet*)	LENGTH OF OUTCROP (*feet*)	MAXIMUM COVER (*feet*)	PERCENT IRON (Fe)	IRON (*Fe*) (*millions of long tons*)
Outcrop—						
Upper 30 feet	100	12	280,000	0	12.4	3
All of red unit (90± feet)	500	20	280,000	0	10.2	20
Hoffman area	3,000	40	14,000	0	13.0	16
Subsurface—						
Upper 30 feet—						
Adjacent to outcrop	100	30	280,000	20	12.4	7
Per square mile	5,280	30	5,280	800	12.4	7
Total 175 square miles	70,000	30	70,000	800	12.4	1,300
All of red unit (90± feet)—						
Adjacent to outcrop	100	90	280,000	20	10.2	18
Per square mile	5,280	90	5,280	800	10.2	18
Total 175 square miles	70,000	90	70,000	800	10.2	3,200

sodium hexametaphosphate "Calgon" to produce a dispersion of the colloidial part of the sample were placed in a glass jar along with a polyethylene bottle full of lead shot, then rotated at a speed of 72 rpm for 3 hours. About 80 percent of the minus 20-micron fraction was separated by decantation at a controlled rate. The rest of the 20-micron fraction was removed in a cone elutriator, set to retain particles 20 microns and larger. Conventional sieve analysis was made on the dried sand.

After this treatment the plus 60-mesh material amounted to an average of 42 percent for the top 30 feet of the red Hickory and in addition to sand included numerous aggregated grains and iron oxide ooids. Acid treatment released the aggregated grains. If the ooids can be removed magnetically, the remaining sand should be excellent for hydraulic-fracturing even though red. Indeed, for some experimental purposes where samples of rock subjected to hydraulic-fracturing are recovered by coring, this sand, because of its color and ease of identification, should be preferable to sand without color.

The finer fractions of selected samples were analyzed for iron (Fe); the data are recorded in table 4. In these samples, the portions passing the 140-mesh sieve range from 19.0 to 37.0 percent and the iron content ranges from 24.9 to 45.3 percent. The minus 140-mesh material from the Streeter and Hoffman samples contains the most iron. The yield of minus 140-mesh material is low in these samples probably because calcite, which is readily pulverized, is scarce. The Sell and Miller samples, in which calcite is abundant, yield the most minus 140-mesh material. These samples are richest in iron. However, dilution of the minus 140-mesh portion of the sample by calcite reduces the percentage of iron in the minus 140-mesh portion to almost two-thirds that in the Streeter and Hoffman samples.

Selected samples were investigated for use as paint pigment by means of chemical analyses, X-ray diffraction studies, and

Table 4. *Distribution of iron (Fe) in various size fractions of red Hickory Sandstone after disaggregation, northwestern Llano region, Texas.*

Lab. No.	Locality	Interval (*feet*)	U. S. Standard sieve sizes showing (A) percent of iron (Fe) in several size fractions, (B) percent this is of total amount of iron (Fe) in sample, and (C) iron (Fe) by difference remaining in plus 140-mesh material											Total iron (Fe) in bulk sample by analysis	Analysis of minus 140-mesh portion	
			140 to 200		200 to 270		270 to 325		325 to 20µ		−20µ					
			A	B	A	B	A	B	A	B	A	B	C		Percent of original sample	Percent iron (Fe)
57080	Streeter	20–27	35.5	0.4	41.5	0.2	42.9	0.2	40.9	0.6	44.5	6.8	1.7	9.9	19.0	43.5
57082	Hoffman	35–45	29.6	0.7	47.2	0.7	49.4	0.4	48.7	1.6	46.6	6.7	3.0	13.1	22.4	45.3
57086	Sell	17–27	18.8	0.6	20.7	0.6	22.6	0.5	23.7	2.8	40.4	6.6	3.1	14.2	37.0	30.3
57090	Miller	10–20	15.3	0.6	22.5	0.6	27.7	0.6	28.7	2.9	48.7	7.8	2.5	15.0	34.7	36.0
57093	Highway pit	10–20	21.1	0.5	24.2	0.5	22.4	0.4	28.1	2.4	42.0	5.7	2.7	12.2	27.9	31.8
57101	Pontotoc	410–420	.....	...	14.1	0.5	14.8	0.2	17.6	1.1	30.8	5.2	2.0	9.0	28.4	24.9
57105	Pontotoc	445–455	.....	...	25.4	0.5	28.2	0.4	29.6	1.8	40.1	4.5	4.3	11.5	20.9	34.5

pigmentation tests of the minus 20-micron and 20- to 44-micron fractions.

Chemical analyses of the minus 20-micron fraction of red Hickory Sandstone are compared (table 5) with an analysis of a typical New York State natural iron oxide pigment (Kirk and Othmer, 1953, p. 632). The amount of iron oxide in the minus 20-micron fraction of the red Hickory Sandstone is greater in all samples, except No. 57101, than in the sample from New York, and No. 57101 contains twice as much lime as the New York sample. Even in this sample the iron oxide content is higher than the minimum set by the American Society for Testing Materials, (1956, pp. 53–58) for mineral iron oxide pigment standards—D 85–47, D 763–48, and D 765–48. All samples, except Nos. 57080 and 57082, exceed the maximum amount for CaO, and all samples exceed the maximum amount of volatiles specified by the American Society for Testing Materials (table 6). For these samples to meet these standards, the carbonate minerals would have to be mostly removed. Because the minus 20-micron fraction was separated by sedimentation from a water suspension of the dispersed sample, and by the use of a cone elutriator, plus 325-mesh material should be well within the 2 percent maximum specified.

TABLE 5. *Chemical composition of minus 20-micron fraction of selected samples of red Hickory Sandstone, northwestern Llano region, Texas. Analysis of a typical New York State natural iron oxide pigment included for comparison.*

Lab. No.	Locality	Interval (*feet*)	Fe_2O_3	MnO	SiO_2	Al_2O_3	MgO	CaO	H_2O—	Ignition loss
57080	Streeter	20–27	63.60	0.15	14.94	6.23	0.63	3.55	0.82	7.38
57082	Hoffman	35–45	66.60	0.20	13.60	9.87	0.53	0.44	0.96	8.32
57086	Sell	17–27	57.70		12.36	4.34	1.19	9.26	0.82	12.26
57090	Miller	10–20	69.60	0.91	10.07	0.92	1.21	5.48	1.00	10.12
57093	Highway pit	10–20	60.60	1.00	12.72	8.62	1.56	5.42	0.80	9.10
57101	Pontotoc	410–420	44.00		13.67	7.27	1.28	15.74	0.82	16.62
57105	Pontotoc	445–455	57.10	0.82	13.91	6.09	1.46	5.90	0.86	11.56
New York State iron oxide pigment			56.5		17.0	7.0	3.5	8.0		8.0

X-ray diffraction patterns for the minus 20-micron fraction of samples 57080, 57082, 57086, 57090, 57093, 57097, and 57105, using copper radiation on powder packs, show strong peaks corresponding to hematite, goethite, quartz, and calcite and weaker peaks corresponding to kaolinite and hydrous mica. No relationship was discerned between the intensity of red color and the hematite/goethite ratio as determined by X-ray.

Known weights of minus 20-micron red Hickory pigment and white paint base were intimately mixed by rubbing with a spatula on a smooth glass plate. The paint produced was spread over smooth wood

TABLE 6. *American Society for Testing Materials (1956) specifications for Fe_2O_3, CaO, moisture and other volatile matter, and coarse particle content for ocher, raw umber, burnt umber, raw sienna, and burnt sienna.*

Mineral iron oxide pigment standard	D 85–47	D 763–48		D 765–48	
Mineral iron oxide pigment	Ocher	Raw umber	Burnt umber	Raw sienna	Burnt sienna
Fe_2O_3, min., percent	17	37	42	38	40
CaO, max., percent	5	5	5	5	5
Moisture and other volatile matter, max., percent	1	5	5	4	4
Particles retained on 325-mesh screen, max., percent	1	2	2	2	2

test blocks. The resulting colors, as determined by comparison with Maerz and Paul's Dictionary of Color (1930), are listed in table 7. In general, using 5 percent pigment, the colors are pink hues of medium brilliance and low saturation (moderate orange pink of Rock-Color Chart Committee, 1951) ; using 17 percent pigment, the colors are reddish-brown hues of low brilliance and medium saturation (pale red of Rock-Color Chart Committee, 1951). The color of the minus 20-micron fraction was not improved by calcination in an electric furnace at either 300°, 450°, or 600° C. When ignited at 1,050° C, all samples became dark brown and dark reddish brown.

TABLE 7. *Paint colors* produced by addition to white paint base of minus 20-micron and 20- to 44-micron fractions of red Hickory Sandstone, northwestern Llano region, Texas.*

Lab. No.	Locality	Interval (*feet*)	Minus 20-micron fraction 5 percent pigment	Minus 20-micron fraction 17 percent pigment	20 to 44-micron fraction 17 percent pigment
57080	Streeter	20–27	Pl. 4, C-9	Pl. 5, F-9	....
57082	Hoffman	35–45	Pl. 4, E-9	Pl. 5, E-9	Pl. 4, A-9
57086	Sell	17–27	Pl. 4, E-9	Pl. 5, E-9	Pl. 4, B-7
57090	Miller	10–20	Pl. 4, D-9	Pl. 5, E-9	Pl. 4, A-9
57093	Highway pit	10–20	Pl. 4, C-9	Pl. 5, D-9	Pl. 4, B-8
57101	Pontotoc	410–420	Pl. 4, B-9	Pl. 5, C-9	....
57105	Pontotoc	445–455	Pl. 4, C-9	Pl. 5, D-9	....

* Maerz and Paul (1930), Dictionary of Color.

The American natural red pigments, according to Kirk and Othmer (1953, p. 632), are less brilliantly colored than the two imported grades—Persian red and Spanish red. However, the natural American red iron oxide pigments, because of their lower cost, find wide application in paint used for barns, freight-cars, metal structures and similar uses. Much of the American natural iron oxide pigment is blended with synthetic red iron oxide pigment to increase the iron oxide content and improve the color. The minus 20-micron red Hickory might be improved as a pigment if blended in this manner.

For the 20- to 44-micron fraction of red Hickory Sandstone, the chemical analyses in table 8 show that this fraction contains less iron oxide and more lime than the minus 20-micron fraction. X-ray diffraction data for two samples (57090 and 57105) show that calcite and quartz are more abundant and clay minerals less abundant than in the minus 20-micron fraction. In the pigmentation test, table 8, the 20- to 44-micron fraction forms faint pink hues of medium brilliance and very low saturation (grayish orange pink to grayish pink of Rock-Color Chart Committee, 1951), having less than one-quarter the pigmentation value of the minus 20-micron fraction.

In the United States 45,900 tons of crude pigments valued at $453,000 were sold or used during 1961, and the combined sales of 106,500 tons of finished natural and manufactured iron oxide pigments were slightly above those for 1960 (Minerals Yearbook, 1961).

ORIGIN OF IRON

Kelley (1951), in connection with his study of oolitic iron deposits in the Cambrian Bliss Sandstone of New Mexico, reviewed the theories of origin of sedimentary iron deposits, and the reader is referred to that publication for a theoretical discussion of the origin of such deposits. The following discussion is limited to the probable origin of the red Hickory Sandstone as indicated by thin section data (Appendix, pp. 36–38, 44–45).

Thin section examination shows that goethite penetrated quartz grains along percussion fractures (Pl. III, D,E), invaded grain boundaries of composite quartz grains (Pl. IV, A), partly replaced feldspar (Pl. IV, C), and completely re-

TABLE 8. *Chemical composition of 20- to 44-micron fraction of red Hickory Sandstone, northwestern Llano region, Texas.*

Lab. No.	Locality	Interval (*feet*)	Total iron as Fe_2O_3	HCl insoluble	MgO	CaO	H_2O—	Ignition loss
57080	Streeter	20–27	58.5	......	......	.. .	0.90	9.40
57082	Hoffman	35–45	69.6	12.80	0.59	2.20	0.94	8.58
57086	Sell	17–27	33.9	......	......	.. .	0.70	23.72
57090	Miller	10–20	41.0	16.78	1.09	14.60	0.52	17.58
57093	Highway pit	10–20	40.2	16.14	1.25	15.66	0.64	18.64
57101	Pontotoc	410–420	25.2	......	......	.. .	0.30	25.14
57105	Pontotoc	445–455	42.3	16.54	0.90	15.44	0.32	19.34

placed a pelmatozoan fragment (Pl. III, D). It also coats mineral grains (Pls. III, B-D; IV, A-F) and fossil debris (Pl. IV, C). Such goethite-coated mineral grains are incipient ooids and these range, as the amount of goethite increases and the size of the quartz grains decreases, to ooids without quartz grains at their centers (Pls. III, C, D; IV, D,F). It seems likely that growth of ooids, and the various replacements, mostly took place before the grains were deposited. Coalesced ooids (Pls. III, B; IV, B) are interpreted as having grown together prior to deposition, but it is possible that growth united them after deposition.

Intraclasts derived from penecontemporaneously lithified beds, in part contain goethite ooids. Illustrated examples include (1) an intraclast composed of quartz grains and goethite ooids in a matrix of goethite (Pl. IV, D) and (2) an intraclast composed of quartz grains and goethite ooids in a calcite matrix which serves as a nucleus for a calcite ooid. The calcite ooid continued to grow after its incorporation in the sediment and included quartz grains and goethite ooids in its outer part (Pl. IV, F). Other intraclasts featured are composed of quartz grains and phosphatic brachiopod fragments in a matrix of goethite (Pl. IV, E).

Breakage of ooids during transportation is indicated by missing segments around some iron-oxide-coated grains (Pl. IV, B); otherwise, evidence for abrasion of ooids during transportation was not seen. Such paucity of evidence for abrasion indicates that the ooids either formed near their site of deposition or, if they travelled far, accretion probably balanced abrasion.

Dolomite rhombs (Pl. III, A, C) grew after the sediment accumulated; later the dolomite was mostly replaced by calcite and goethite, possibly during the present weathering cycle. In some specimens hematite fills the remaining space around dolomite rhombs and fragments of crushed ooids (Pl. III, A). Such hematite was surely introduced during diagenesis either as hematite or goethite; however, in other specimens where goethite ooids (Pl. III, E) and quartz grains are suspended in the hematite matrix, deposition was probably simultaneous. In the latter case, the matrix may have been deposited as goethite and later altered to hematite; it seems unlikely that hematite and goethite formed and accumulated in the same environment.

Poikilitic calcite is the cementing agent in most specimens (Pls. III, C; IV, B-E) and in places it surrounds fragments of goethite ooids (Pl. III, B, C). The ooids presumably were crushed by pressure from adjacent grains after burial.

The goethite in some ooids has been partly to completely replaced by very dusky red to blackish red (7R 2/2) hematite (Pl. IV, B); in others, replacement is incomplete and hematite occurs as concentric layers (Pl. III, B), as patches (Pl. III, C), and as cross-cutting septae (Pl. III, F). Replacement hematite of this type is considerably darker than the dark grayish-red-brown (10R 3/3) to very dark red (5R 2/6) matrix hematite. Finely divided mineral matter may account for the lighter color of the matrix hematite. The goethite ooids are mostly light brown (near 5YR 5/5) with some hint of yellowish orange.

Barnes and Bell (Barnes, 1959, p. 25)

stated that the Cambrian sea encroached from the southeast upon a mature, arid or semi-arid surface rising gently to the north and west. Lateritic iron oxide was probably absent, and if this is true the red Hickory could not have been derived from the land in the form of particulate iron oxide. The red Hickory Sandstone did not connect with the shore of that time so that it is unlikely that the iron oxide in the red Hickory is land derived.

Barnes (1959, p. 39) has shown that Riley rocks accumulated in a bay, and it is possible that restricted or modified circulation produced conditions favorable to precipitation of hydrous iron oxide from sea water during the period of red Hickory Sandstone deposition. The presence of fossil debris throughout the red Hickory shows that salinity was favorable for growth of phosphatic brachiopods, trilobites, and the organisms from which the pelmatozoan debris was derived. The presence of intraclasts indicates that the water was shallow and that the bottom was exposed periodically at least in some places.

Hydrous iron oxide (now goethite) was probably precipitated directly as coatings on mineral grains and fossil fragments, as replacement of mineral grains and fossil fragments, and as a pulverulent ooze. Soon after deposition, dolomite formed, and with increasing depth of burial the hydrous iron oxide ooze changed to hematite, and hematite partly replaced goethite ooids. Finally, calcite and a minor amount of goethite replaced dolomite, and calcite filled most of the remaining pore space.

Kelley (1951, p. 2205), in a discussion of the age and correlation of the Bliss Sandstone, listed a number of iron-rich zones in Middle and Upper Cambrian rocks from Wyoming to Arizona and Texas, but none of these zones are correlatives of the Bliss Sandstone. The iron deposits in the Bliss Sandstone differ in many ways from the red iron-bearing Hickory Sandstone. The Bliss deposits are considerably younger, correlating with high Morgan Creek and younger Wilberns beds of the Llano region. The Bliss iron-bearing beds are glauconitic; the red Hickory is non-glauconitic. Quartz aggregate growths and overgrowths on quartz grains are common in the Bliss; there are none in the red Hickory. Carbonate rhombs (dolomite) are replaced by hematite in the Bliss; no such replacement has taken place in the red Hickory. Carbonate veinlets cut various minerals including hematite in the Bliss; such veinlets are absent in the red Hickory. And the Bliss iron-bearing deposits were formed near shore, whereas the red Hickory Sandstone was deposited 50 miles or more from shore.

HYDRAULIC-FRACTURING SAND IN LOWER UNIT OF HICKORY SANDSTONE

Hydraulic-fracturing sand production is from the lower unit of the Hickory Sandstone, and the only other sandstone unit in the Cambrian containing sand with most of the qualities of hydraulic-fracturing sand is the upper red unit of the Hickory. Even after scrubbing, this sand remains red. The color might be a handicap in marketing, but the sand is of excellent quality and extremely well rounded and smooth. The upper red unit is described in the Appendix (pp. 36–40, 44–45).

Specifications for hydraulic-fracturing sand are outlined by Murphy (1960, p. 771). Information from the operators in the Voca area indicate that the coarser grain sizes are now more in demand. W. E. Hassebroek described the use of sand in hydraulic-fracturing of oil-bearing formations.[1]

VOCA AREA, MCCULLOCH COUNTY

The discovery of coarse, well-rounded, smooth quartz grains satisfactory for hydraulic-fracturing use was the direct result of field and laboratory study by Barnes of Cambrian rocks in central Texas

[1] "Sand Usage in Hydraulic Fracturing Oil Bearing Formations." Paper presented February 17, 1955 at annual meeting in Chicago, Illinois of Special Sands and Abrasives Section of the American Institute of Mining and Metallurgical Engineers. Unpublished.

(Barnes, 1956, 1959; Barnes and Bell, MS.). This occurrence of hydraulic-fracturing sand in Texas was called to the attention of industry by the Bureau of Economic Geology early in 1957 in response to an out-of-State industrial inquiry.

At that time there existed in the trade a strong color prejudice. The sands in use were light-colored (St. Peter and Jordan) and the Hickory sand was red and tan in color due to iron oxide coatings. It was suspected that iron oxide coatings on Hickory sand grains masked possible defects such as incipient fractures and rock particles which would result in poor performance.

Previously, hydraulic-fracturing sand was shipped into Texas from Illinois and Minnesota with consequent high freight costs. At present, Texas sand is consumed in large quantity in the State, appreciable tonnages are shipped to the neighboring oil states of New Mexico, Oklahoma, and Louisiana, and foreign export trade is increasing. During 1962, 72,380 short tons of hydraulic-fracturing sand worth $479,980 was produced in Texas.

The first knowledge that a plant was being established for the production of hydraulic-fracturing sand from the Hickory Sandstone came to the attention of Barnes in the fall of 1957 after sampling of the Cambrian sands for their economic possibilities was under way; he visited the plant site, 0.75 mile east of a road intersection 1.5 miles south of Voca, McCulloch County. Sand produced at the time was for construction purposes only while the plant was being built. About 4 feet of sandstone exposed in a pit was sampled, and a sample was taken also from the stock-pile of washed sand to determine grain size. Sieve analysis data for these samples are given in table 9. A caretaker pointed out two wells, about 130 feet deep to granite, drilled to furnish water for the operation.

This plant was visited again shortly after production started; however, little additional section was exposed in the pit. Three grade sizes were then produced.

Table 9. *Sieve analysis data for lower unit of Hickory Sandstone, San Saba Sand Company deposit, McCulloch County, Texas.*

Lab. No.	Kind of material	Interval (feet)	U. S. Standard Sieve Sizes											
			4 to 8	8 to 10	10 to 20	+20	20 to 40	40 to 60	60 to 80	80 to 100	100 to 140	—140	140 to 270	270 to 325	—325
57117	Natural	0–4	...	...	...	7.0	19.2	20.1	11.3	10.4	9.4	22.9	...	...	...
57117W	Washed	0–4	...	...	...	9.4	17.0	18.7	12.1	9.1	13.9	19.8	...	...	...
57118	Stock	Pit run	...	...	...	14.2	29.9	23.7	12.2	10.0	4.7	5.5	...	...	...
57118W	Washed	Pit run	...	...	...	19.1	29.0	22.6	13.0	7.6	6.0	2.7	...	...	...
58191	Coarse	Pit run	82.5	16.5	0.5	...	0.1	...	...	...	...	...	...	...	...
58190	Medium	Pit run	...	3.2	82.1	...	11.0	3.0	0.4	...	...	...	...	...	...
58189	Fine	Pit run	...	...	2.6	...	64.0	29.3	0.7	0.3	...	...	...	...	...
58192	Waste	Pit run	...	...	...	...	3.7	42.3	23.5	13.0	10.5	...	4.5	0.9	0.7

These as well as the waste were sampled but no information was available on the percent of the total each grade size represented. Sieve analysis data for these samples are also given in table 9; these analyses are not necessarily indicative of the quality of subsequent production.

This area was not revisited until March 1963, at which time two producers were active on opposite sides of the east-west road. The original property north of the road was acquired from the San Saba Sand Company in 1960 by the Pennsylvania Glass Sand Corporation. The present quarry face ranges from 50 to 70 feet in height and will be increased as the local ground-water level recedes. Overburden, absent in some areas, ranges up to a maximum of about 9 feet. After blasting, oversize blocks are reduced by a drop ball. The rock is then loaded by a power shovel into trucks which haul the rock to the top of the quarry where it is dumped into the hopper of a primary hammer-mill situated in the southwestern part of the quarry (Pl. V, A). Beyond the crusher and to the left (A), the sand is wet-scalped and hydraulically separated at about 40 mesh. The coarse fraction is attrition scrubbed, dewatered, and dried in a rotary kiln and then sized by screening into the various grades in demand by the oil industry. The fine fraction is washed and deslimed, dewatered, and dried for sale as foundry sand. The finished products are then hauled in closed trucks to the loading point on the railroad at Brady (Pl. V, B).

The sandstone exposed in the quarry is mostly medium to thick bedded; cross-bedding is common, the sand is poorly sorted, and thin clay beds are common. Salable sand is predominantly hydraulic-fracturing sand, graded in sizes 8–12, 10–20, and 20–40 mesh. Between 80 and 90 percent of the hydraulic-fracturing sand currently used is the 20–40 grade; a demand for the coarser grades fluctuates widely. The finer material is used for foundry sand.

South of the road, the Heart of Texas Mining Corporation quarries almost identical sandstone, which is stage-crushed by jaw and roll crushers, wet-scalped, dewatered, and attrition scrubbed. It is then roughly sized by hydraulic classifier, dewatered by screws, and stocked according to grade (Pl. VI, A). It is then trucked to the railroad at Brady where it is dried in a rotary kiln and further screened (Pl. VI, B). Sizes produced are 8–12, 10–20, 12–20, 16–30, 20–40, and 40–60 mesh. The coarser fractions are used as hydraulic-fracturing sand and the 40–60 mesh is used for blast sand.

Bottled samples of four grades tendered by the Heart of Texas Mining Corporation were examined with the aid of a binocular microscope. The 8–12-mesh sand is well rounded but rough, and impact scars are very common. No feldspar was seen. Aggregates are very scarce and consist mostly of silt grains plastered on larger grains. Broken grains and grains showing solution pitting are very scarce. The 10–20-mesh sand is similar but without aggregates. The 20–40-mesh sand is also fairly well rounded and perhaps not as rough; more grains show solution pitting, several have secondary crystal faces, and silt aggregates and feldspar are very scarce. The minus 40-mesh sand and silt is mostly angular and only the larger grains are rounded. About 6 percent of the minus 40-mesh grains are brown altered feldspar with an average grain size smaller than that of the quartz.

Extensive testing of the commercial part of the lower unit of the Hickory Sandstone in the Voca area shows that, using the Krumbein scale, the roundness factor for the sand grains approximates 0.7. The grains have high sphericity.

The two producing plants are about 2 miles west of the crest of the 9-mile wide gently northward-plunging Voca anticline. The anticline is flanked by north-south faults of variable but mostly large throw and the eastern flank is steeply dipping. Some minor faults on the flanks of the anticline are within a mile or two of the main faults.

The lower unit of the Hickory Sandstone has an outcrop width of about 1 mile, extending from 6 miles southwest of the producing plants to the crest of the anticline 2.5 miles to the northeast. Southeastward from the crest of the anticline, the outcrop width of the lower unit decreases to less than 0.25 mile in a distance of 2 miles. Still farther southward, because of steeper dips, the outcrop belt is even narrower and its continuity is interrupted by faults.

From what is known about the uniformity of the Hickory Sandstone in the subsurface from here westward and northward and its apparent uniformity of thickness in this area, it is likely that hydraulic-fracturing sand of the quality being produced is present throughout the length of the outcrop of the lower unit in this area. The present operations are about 16 miles from the railroad at Brady.

CAMP AIR AREA, MASON COUNTY

In the Camp Air area, the lower unit of the Hickory Sandstone Member, dipping gently northwestward, crops out for a width of 1 mile over a distance of 5.5 miles in a northeast-southwest direction. To the southwest it passes beneath flat-lying Cretaceous rocks and to the northeast terminates at the western boundary fault of the Voca anticline. Most of the outcrop is cultivated and exposures are few; however, the character of the soil suggests that the sand is mostly comparable in character and quality to that in the Voca area. The lower member of the Hickory Sandstone is irrigated from wells, and much could be learned about the buried topography of the Precambrian if a study were made of the depths of these wells. No samples were collected in the Camp Air area.

One feature might lower the quality of the sand locally and restrict pit locations. The surface of the Precambrian Town Mountain Granite of the Katemcy granite mass was hilly when the Cambrian sea covered this area, as evidenced by an exhumed granite hill 1 mile northwest of Camp Air (Pl. I). This hill stands at least 300 and perhaps as much as 400 feet above the surrounding Precambrian surface and cuts out almost all of the middle unit of the Hickory Sandstone. During deposition of the Hickory, the granite shed angular quartz and feldspar detritus locally. Such material is not desirable in hydraulic-fracturing sand. Before opening a pit, the area should be prospected to be sure that a sufficient thickness of suitable sand is present and that contamination by angular quartz-feldspar has not occurred.

The coincident U. S. Highways 87 and 377 cross the outcrop of the lower unit of the Hickory Sandstone 17 miles south of Brady; this distance is only 1 mile greater than the distance that sand is being hauled from south of Voca. When the area was mapped in 1957, water was judged to be plentiful enough in the Hickory Sandstone for sand processing; however, subsequent irrigation may have depleted the supply. Land values in the Camp Air area, because of irrigation, may be higher than in the Voca area; otherwise, there should be little difference in cost of production of sand in the two areas.

STREETER AREA, MASON COUNTY

The lower unit of the Hickory Sandstone in the Streeter area dips gently west-northwestward and crops out for a width of about 1 mile. The outcrop extends from 2 miles south of Streeter north-northeastward for 5 miles where the upper part of the unit passes beneath Cretaceous rocks. The lower part is exposed for another 2 miles in this direction, then it too passes beneath Cretaceous rocks to reappear in the Camp Air area. Most of its outcrop is cultivated and exposures are few; however, the character of the soil suggests that the sand in this area is probably comparable in character and quality to that in the Voca area. No samples were collected.

To the east of the outcrop the Precambrian surface on which the Hickory Sandstone was deposited had considerable relief, and in at least one place the upper red unit of the Hickory rests directly on Precambrian marble. Some relief is evident in the southern part of the area at the edge of the Hickory; elsewhere, as indicated by constant outcrop width and the lack of Precambrian inliers, relief on the Precambrian surface beneath this unit is probably slight.

State Highway 29 crosses the lower unit of the Hickory 29 miles east of the railroad at Menard and 42 miles west of the railhead at Llano. This locality is 34 miles from Brady by State Highway 29 and U.S. Highway 377. Clearly, producers of sand in this area would be at a disadvantage because of the long truck haul. Also, information on water wells in the vicinity of State Highway 29 indicates that water may be insufficient in the Hickory in this area for processing sand.

CENTRAL MASON COUNTY

The lower unit of the Hickory Sandstone is present in numerous fault blocks along the Fredonia-Mason fault zone between Fredonia and Mason (Pl. I), in fault blocks south of Mason, and other fault blocks west of Mason toward the Streeter area. The outcrop characteristics of the unit in these fault blocks are the same as elsewhere in this part of the Llano region, and, although no samples were collected, it seems likely that sand suitable for hydraulic-fracturing is present at least in some localities. However, it seems unlikely that it could be produced economically because of the long truck haul to rail.

PONTOTOC AREA, MASON, SAN SABA, AND LLANO COUNTIES

The lower unit of the Hickory Sandstone in the rather poorly exposed Pontotoc section (Barnes and Bell, MS.) is described in the Appendix (pp. 42–44).

Microcline and mica are more abundant in the lower part of the Hickory Sandstone in this section than in other sections measured in the Llano region. The granule size and larger fragments of microcline appear to be derived from Town Mountain Granite, possibly from the Smoothingiron granite mass (Pl. II). Several buried granite hills of this mass rise high into the Hickory Sandstone and could have furnished the microcline. Other buried granite hills possibly occur in the subsurface in other directions from the line of section.

The smaller grains of microcline and the flakes of mica may be in part derived from the high ridge of Valley Spring Gneiss to the east of the line of section and in part from the ridge of Valley Spring Gneiss between Fredonia and Pontotoc. Other buried ridges possibly occur in the subsurface to the north.

The larger grains of quartz above 35 feet in this section are fairly well rounded and from cursory inspection are not much different in appearance from those being produced in the Voca area. The Pontotoc area is too far from rail transportation to be of interest as an area of hydraulic-fracturing sand production but is near enough to the Valley Spring area to give some indication of the character of the sand which might be present there at equivalent stratigraphic levels.

VALLEY SPRING AREA, LLANO COUNTY

The lower unit of the Hickory Sandstone crops out in a number of fault blocks in the vicinity of Valley Spring (Pl. II), and, as in other areas, much of this unit is cultivated and exposures are scarce. However, 1.5 miles northeast of Valley Spring, 25 feet of sandstone is exposed in Phillips Rock and another 40 feet is exposed in a cliff 300 yards north-northwest. The 65 feet of section sampled is at the top of the lower unit of the Hickory Sandstone and may not be representative of the Hickory beneath this level.

Sieve analysis, moisture content, and ignition loss data for the sandstone of Phillips Rock and vicinity are given in table 10. The average content of 10- to 60-mesh sand for the 65 feet is 58 percent and for 5-foot intervals ranges from 44 to 68 percent. The sand is mostly slightly

TABLE 10. *Sieve analysis, moisture content, and ignition loss data for Hickory Sandstone from Phillips Rock and vicinity, Llano County, Texas.**

Lab. No.	Interval (*feet*)	U. S. Standard Sieve Sizes														
		+10	10 to 20	20 to 40	40 to 60	60 to 80	80 to 100	100 to 140	140 to 200	200 to 270	270 to 325	325 to 20μ	−20μ	10 to 60	H_2O—	Ignition loss
59047	0–5	0.0	5.7	25.0	23.3	12.4	7.5	9.2	0.9	10.3	0.9	1.3	3.5	54	0.13	0.42
59048	5–10	0.1	3.8	28.4	25.8	13.8	8.1	8.0	2.1	4.3	0.4	0.6	4.4	58	0.14	0.48
59049	10–15	0.0	4.2	25.7	29.2	9.3	6.7	7.8	4.6	1.7	0.7	0.8	9.0	59	0.16	0.79
59050	15–20	0.0	4.6	30.4	21.2	7.4	6.4	6.7	5.1	1.5	0.6	1.1	15.0	56	0.12	0.64
59051	20–25	0.0	12.5	34.2	20.7	10.0	6.3	6.3	0.5	4.3	0.4	1.1	3.5	67	0.12	0.53
59052	25–30	0.1	17.2	30.9	14.8	8.9	7.4	8.2	2.9	4.4	0.5	0.9	3.7	63	0.09	0.44
59053	30–35	0.2	9.2	26.6	17.7	10.3	8.7	11.5	1.2	9.1	0.5	0.9	4.1	54	0.06	0.49
59054	35–40	0.7	8.4	21.9	16.8	9.7	7.7	2.5	12.8	3.0	1.1	2.6	12.7	47	0.06	0.84
59055	40–45	0.0	9.6	25.3	19.1	11.5	8.5	8.7	1.7	6.5	0.7	2.6	5.8	54	0.23	0.78
59056	45–50	0.2	3.4	22.2	18.5	10.5	8.0	0.5	20.9	3.7	1.1	2.5	8.6	44	0.26	0.70
59057	50–55	0.3	13.8	32.9	16.4	6.9	6.8	8.9	1.3	6.4	0.4	1.2	4.5	63	0.19	0.39
59058	55–60	0.1	6.4	29.8	31.8	14.5	6.5	3.6	0.2	2.0	0.1	0.6	4.1	68	0.18	0.35
59059	60–65	0.1	6.1	31.2	28.8	18.3	5.9	1.6	0.1	1.4	0.1	1.0	5.6	66	0.19	0.59

* Samples were disaggregated, dispersed, scrubbed, washed, and elutriated. Sieve analyses were made on dried portions greater than 20μ in size.

colored in shades of yellow, brown, and pink, indicating an objectionable amount of iron for some industrial purposes. However, no chemical analyses were made and no attempt was made in the laboratory to remove the iron.

Binocular microscope examination of the fraction larger than 60-mesh revealed that disaggregation is complete and that very few grains are broken. Angular grains vary from scarce in most samples to abundant in one and common in the rest. Smooth grains are scarce to common and rough grains are common to abundant. Pitting of the type produced by etching is common to abundant; quartz overgrowth was not detected.

When the sand from Phillips Rock is compared with the sand from Voca, it is seen to be better rounded and smoother although slightly iron stained, whereas the Voca sand shows very little staining. The plus 60-mesh fraction from Phillips Rock and vicinity ranges from 44 to 68 percent, average 58 percent.

The stratigraphic level of production in the Voca area is considerably below the level sampled at Phillips Rock and vicinity. The airline distance from Valley Spring to the Voca sand-producing area is 22.5 miles. Because of intervening buried ridges and hills of Valley Spring Gneiss and Town Mountain Granite, and the presence of a formerly buried broad high area of Valley Spring Gneiss east of Valley Spring, it is unsafe to assume that the quality of sand is similar at the same stratigraphic level in the two areas. However, as mentioned in the discussion of the Pontotoc area, the coarser sand in the Pontotoc section, 10 miles from Valley Spring, is fairly well rounded, and the sand at the same stratigraphic level at Valley Spring may also be fairly well rounded. In the Little Llano River section 12.5 miles northeast of Valley Spring, on the eastern side of the broad high area east of Valley Spring, the larger grains in the lower part of the Hickory Sandstone are noticeably rougher and more angular. Because of the intervening high area this type of sand may not have been deposited in the Valley Spring area.

Because of poor exposures, drilling will be necessary to evaluate the sand beneath that exposed in Phillips Rock. Present information indicates that the Valley Spring area does contain deposits that can be used for hydraulic-fracturing sand. This area is favorably situated to furnish sand for use eastward and southward from the Llano region because of its location within 12 miles of the railhead at Llano. Deposits of hydraulic-fracturing sand have not been recognized from here eastward, nor have deposits been noted around the eastern and southern sides of the Llano region.

ECONOMIC POSSIBILITIES

The first reference to the sand-producing industry in the Voca area, so far as known, is the following statement: "Industrial sands were prepared [in 1958] ... at a new sand-processing plant near Brady" (Netzeband and Lonsdale, 1959, p. 924).

In 1957, petroleum, amounting to a value of $52,229, was the only mineral commodity produced in McCulloch County. The following year, when sand and gravel was added to the list, mineral production increased to $118,856, and in 1959, to $322,565. During 1958, petroleum production probably decreased, and some crushed limestone was produced. It is likely that production of sand from the Voca area was the main contributor to the value of mineral production in McCulloch County during 1959. For 1960, production figures are concealed.

The following statements refer to developments in 1959 (Netzeband and Girard, 1960, p. 981): "Sand for industrial uses was prepared by San Saba Sand Company." "A $500,000 plant to mine and process 24 carloads of Frac sand for the petroleum industry was built near Brady by the Heart of Texas Mining Company. A second plant in Brady was to process the sand further."

The following amplified information appeared in *Pit and Quarry* (1961):

> Heart of Texas Mining Company recently opened a two-stage silica sand processing plant with a capacity of 37½ t.p.h. The setup supplies material for the sand fracturing process of oil recovery.
>
> The primary processing operations (up to the drying stage) are located near the deposits at Voca, Texas. The second stage of the plant, near the rail line at Brady, handles all final operations, including drying, final screening and bagging. Engineering of the conveyors, elevators, screens, and belt feeders was handled by Hewitt-Robins. W. O. Ferguson is president of the company, and Clarence Wheeler is in charge of plant operations.

The lower unit of the Hickory Sandstone is now well established as a substantial producer of hydraulic-fracturing sand. As already mentioned, hydraulic-fracturing sand is probably present throughout most of the outcrop area of the lower unit of the Hickory Sandstone from south of Streeter to east of Valley Spring. The Camp Air area, at least so far as location is concerned, is in a competitive position with the Voca area. The Valley Spring area is favorably situated to furnish hydraulic-fracturing sand for use east and south of the Llano region.

OTHER CAMBRIAN SANDSTONE UNITS

All remaining Cambrian sandstone units were systematically examined for possible economic utilization. These include the middle unit of the Hickory Sandstone, Lion Mountain Sandstone, Welge Sandstone, and sandstone in the San Saba Member. Sieve and chemical analyses by Plummer (1943) indicated that the sandstone in the San Saba might be of value as glass sand. However, none of these units contain deposits of economic value.

MIDDLE UNIT OF HICKORY SANDSTONE

The middle unit of the Hickory Sandstone is widespread (Pls. I and II), poorly exposed, and in most exposures examined is fine to coarse grained and argillaceous. Two grab samples were collected from the middle unit of the Hickory Sandstone in highway cuts west of Streeter, and seven intervals were chip sampled from a 40-foot section exposed on the south bank of San Saba River on the G. G. Bratton property.

The same disaggregation techniques were used on these samples as on samples from most of the other sand units of the Cambrian; however, the response to disaggregation was poor. Although sieve analyses were made after disaggregation both before and after washing, aggregates of silt and finer sand sizes were so abundant that the data are mostly meaningless.

In the Pontotoc area a very poorly exposed section of the middle unit of the Hickory Sandstone measured by Barnes and Bell (MS.) is described in the Appendix (pp. 40–42).

LION MOUNTAIN AND WELGE SANDSTONE MEMBERS

The Lion Mountain Sandstone Member of the Riley Formation and the Welge Sandstone Member of the Wilberns Formation crop out in juxtaposition (Pls. I and II) between the overlying Morgan Creek Limestone Member of the Wilberns and the underlying Cap Mountain Limestone Member of the Riley. The Welge Sandstone, in a scarp held up by the Morgan Creek Limestone, forms a very narrow outcrop. The Lion Mountain Sandstone outcrop is wider and forms a bench controlled in width by the dip of the rocks and the topography.

From field examination neither of these sandstones appears to contain deposits of commercial sand; however, some of their characteristics are recorded to show how these sandstones differ from other sandstones in the Cambrian of this part of the Llano region.

The Lion Mountain Sandstone is mostly greensand, in part shaly in its upper part, and downward contains an increasing amount of limestone. A sample of the greensand, collected along Squaw Creek 500 feet east of a point 1,500 feet north of milepost 29 on the Mason-Gillespie County line, contains 2.99 percent K_2O and 0.69 percent P_2O_5 (Barnes, Dawson, and Parkinson, 1947, p. 122). The P_2O_5 is present in phosphatic brachiopod shell debris, and the K_2O is mostly in glauconite, calculated from analysis to be 39 percent of the sample, and microcline. The low potash and phosphate content, as well as the barren nature of the outcrop, indicates that the Lion Mountain greensand is of little value as a soil conditioner.

Samples were collected from the Lion Mountain and Welge Sandstones in the vicinity of Camp San Saba and north of Pontotoc. Just south of Camp San Saba, samples were collected from two localities along a west tributary of Katemcy Creek on the F. W. Otte property. One locality, in which the upper 5 feet of the Lion Mountain and the lower 5 feet of the Welge were sampled, is about 150 feet south of the southwest corner of a cemetery. The other locality, in which the upper 10 feet of the Welge and the lower 2 feet of the Morgan Creek were sampled, is about 1,500 feet southwest of the southwest corner of the cemetery. These outcrops in the Camp San Saba area are within about 11 miles of the railroad at Brady.

Samples were collected 2.2 miles north of Pontotoc in a cut along Ranch Road 501 from the section described in the Appendix (p. 46). The original section described by Barnes at this point is mostly under fill. Shale seen in the Welge in fresh exposures only may be more prevalent than examination of weathered outcrops indicates.

Sieve analysis and acid insoluble residue data for these sandstones are given in table 11. The uppermost part of the Lion Mountain is represented by two samples, one each from the Camp San Saba and Pontotoc areas. Acid-insoluble residues amount to 82 and 87 percent, respectively. The plus 60-mesh sand in each case is 78 percent and for the natural rock, 64 and 67 percent, respectively.

Binocular microscope examination of

TABLE 11. *Sieve analysis and insoluble residue data for Lion Mountain and Welge Sandstones, northwestern Llano region, Texas.*

Lab. No.	Locality	Interval (feet)	U. S. Standard Sieve Sizes +20	20 to 40	40 to 60	60 to 80	80 to 100	100 to 140	140 to 200	200 to 270	270 to 325	—325	+20 to 60 Residue	+20 to 60 Natural rock	Acid insoluble
59114	Otte(A)	0–5*	12.0	34.0	31.8	11.6	3.9	2.4	0.3	1.8	0.3	1.7	78	64	81.72
59115	Otte(A)	5–10	5.3	22.4	26.9	17.4	14.3	10.3	0.0	2.5	0.0	1.0	55	50	91.17
59108	Otte(B)	0–5	2.2	25.8	26.2	13.9	10.5	13.2	3.2	2.6	0.3	2.0	54	52	96.07
59109	Otte(B)	5–10	11.7	32.3	32.4	13.8	4.8	2.4	0.4	0.8	0.1	1.3	76	58	76.13
59110	Otte(B)	10–12†	9.8	25.3	36.1	15.5	5.2	2.9	0.7	1.7	0.3	2.5	71	31	43.34
59111	Pontotoc	0–3*	16.1	36.3	25.5	8.5	4.0	3.2	0.9	1.9	0.5	3.2	78	67	86.66
59112	Pontotoc	3–7	4.5	23.4	26.7	12.3	9.6	9.3	1.9	3.3	1.2	7.7	55	46	83.40
59113	Pontotoc	7–12	2.5	23.3	34.0	19.9	10.0	5.2	0.0	2.2	0.4	2.7	60	56	93.09

* Lion Mountain Sandstone.
† Morgan Creek Limestone.

the fraction larger than 60 mesh shows that aggregated grains are abundant, that individual grains are mostly secondarily enlarged, pitted, and rough, and that angular grains are common.

The Welge Sandstone is represented by three samples in the Camp San Saba area and two samples in the Pontotoc area. Acid-insoluble residues average 88 percent (83 to 96 percent) and of this amount plus 60-mesh sand averages 60 percent (54 to 76 percent), or 52 percent (46 to 58 percent) of the natural rock.

Binocular microscope examination of the plus 60-mesh fraction shows that aggregated grains are common; individual grains are mostly secondarily enlarged, pitted, and rough; angular grains are common to abundant.

The basal 2 feet of Morgan Creek Limestone yielded 43 percent acid-insoluble residue, and of this amount plus 60-mesh sand amounts to 71 percent, or 31 percent of the natural rock. Except for the scarcity of aggregated grains, the sand grains are similar to those in the Welge.

Economic Possibilities

The Lion Mountain and Welge Sandstones appear to be without economic value except that the Welge Sandstone locally is an aquifer. The amount of water that can be produced from the Welge is limited because it is thin, and locally calcite cement reduces its permeability.

SANDSTONE IN THE SAN SABA MEMBER

In the upper part of the San Saba Member in its westernmost occurrence in the Llano region, sandstone as much as 30 feet thick is interbedded with limestone. The sandstone is not mapped separately; on Plate I it is included in the outcrop of the San Saba Member in the Calf Creek and Leon Creek areas. Sandstone is also present in the San Saba Member in the James River area, southwestern Mason County. On aerial photographs some of the sandstone layers are distinct because they are marked by bands of denser vegetation.

Leon Creek Area, Mason County

Plummer (1943) reported the occurrence of sand near the middle of the Wilberns Formation southeast of Erna and proposed that the sand be named the Erna sand. Bridge, Barnes, and Cloud (1947) found that several sandstone layers are present in the upper part of the San Saba Member and recommended that none of them be formally named. A sieve analysis for a sample collected by Plummer from a bluff on Leon Creek very near the line of section sampled by Barnes on the Eckert property is given in table 12 (p. 30). These data compare most closely to data for the Eckert interval 25–31, and the lack of appreciable carbonate in the two analyses (table 13) indicates that the samples were grab samples from the most friable part of the interval sampled.

TABLE 13. *Composition of sand from bluff on Leon Creek, 1.8 miles southeast of Erna, Mason County, Texas (Plummer, 1943).*

Constituent	Sample 1 (*percent*)	Sample 2 (*percent*)
Quartz	99.961	99.976
Iron	0.039	0.024
Calcium carbonate	trace	0.000
Titanium	0.00	0.000

R. H. Alexander (1956) and Winston (1957), as part of the requirements for a master's degree from The University of Texas, mapped the geology of the Leon Creek area in detail and their maps are used in Plate I. This area was tedious to map because of the large number of normal faults. The sandy part of the San Saba Member is present in many fault blocks.

The Leon Creek section from which the samples were collected on the Eckert property is 1.8 miles airline southeast of Erna and was described by Barnes (Barnes and Bell, MS.). The section sampled on the Evans property is along a drain east of the road at a point 0.5 mile south of U.S. Highway 377 at Erna.

Sieve analysis and insoluble residue data for samples from the Eckert and Evans properties are given in table 12. The calcareous nature of these sandstones is apparent. The amount of acid-soluble material averages 33.6 percent in the sampled part of the Leon Creek section, and for each sandy unit sampled the amount is 66.4, 1.0, 16.5, and 51.2 percent, respectively. The segment with 1.0 percent of acid-soluble material is 5 feet thick, and only one other 5-foot interval has as little soluble material. The 20-foot interval of sandstone on the Evans property contains 37.0 percent (range 30.6 to 46.2 percent) of acid-soluble material.

The sand remaining after removal of carbonate appears to be of good quality. That from Eckert interval 130–140, although iron stained, consists of about 75 percent of sand larger than 60 mesh, or about 37 percent of the rock. Most of the rest of the sand is white, appears comparatively free of iron, and three intervals (Eckert 25–31 and 85–95 and Evans 5–20) contain much plus 60-mesh sand (72, 76, and 86 percent, respectively, or 71, 70, and 56 percent, respectively, of the natural rock).

Binocular microscope examination of the fraction larger than 60 mesh shows (1) a trace of aggregated grains, (2) angular grains mostly abundant to very abundant, (3) secondarily enlarged, pitted, and rough grains common to abundant, and (4) well-rounded frosted grains mostly absent to very scarce.

Hext Area, Menard County

The thickest measured section of sandstone (30 feet) in the San Saba Member is on the McSherry property 1 mile north of Hext. The base of the sandstone was not exposed; consequently, its true thickness is unknown. The map reproduced as figure 4 (Barnes, Bell, and Pavlovic, 1954, fig. 9) shows the broadest known outcrop of San Saba sandstone in the Llano region. The outcrop is cultivated except in its northern part where it is sparsely vegetated mostly by live-oak, cedar, bear-grass, and black persimmon. The onlapping limestone beds of the Canyon support

TABLE 12. *Sieve analysis and insoluble residue data for sandstone in San Saba Member, northwestern Llano region, Texas.*

Lab. No.	Locality	Interval (*feet*)	U. S. Standard Sieve Sizes +20	20 to 40	40 to 60	60 to 80	80 to 100	100 to 140	140 to 200	200 to 270	270 to 325	−325	20 to 60	Acid insoluble	20 to 60 percent of total
59095	Eckert	0–5	0.0	9.3	24.2	30.1	23.2	8.5	1.9	2.2	0.4	0.2	33	47.54	16
59096	Eckert	5–10	0.0	1.7	29.2	29.4	9.2	9.4	11.2	4.0	1.3	4.7	31	19.58	6
59097	Eckert	25–31	0.5	30.3	41.3	17.2	8.0	2.3	0.4				72	98.96	71
59098	Eckert	75–80	0.0	3.2	45.8	40.6	7.7	1.5	0.6			0.5	49	83.18	41
59099	Eckert	80–85	0.0	2.5	48.5	37.4	7.4	2.5	0.5	0.4	0.0	0.7	51	67.31	35
59100	Eckert	85–90	0.2	7.3	57.3	24.8	4.4	2.5	0.8	1.0	0.3	1.4	65	84.65	55
59101	Eckert	90–95	0.0	19.5	67.1	7.7	2.1	1.4	0.6	0.5	0.0	1.1	87	99.04	86
59102	Eckert	130–135	0.0	6.0	70.1	14.3	2.7	1.6	0.2	1.6	0.4	3.0	76	46.94	36
59103	Eckert	135–140	0.6	17.0	57.5	15.8	2.7	1.7	0.3	1.4	0.4	2.6	75	50.63	39
59104	Evans	0–5	0.0	0.4	12.5	49.9	30.3	5.2	0.4	1.0	0.0	0.3	13	53.80	7
59105	Evans	5–10	0.4	29.7	45.3	18.3	3.9	1.8	0.4	0.2	0.0	0.1	75	69.40	52
59106	Evans	10–15	0.2	43.8	47.9	5.4	1.6	0.7	0.4				92	67.39	62
59107	Evans	15–20	0.3	39.4	50.3	6.1	2.3	1.2	0.3				90	61.30	55
59116	McSherry	0–5	0.0	0.6	39.7	44.8	9.2	3.0	0.7	1.1	0.3	0.7	40	50.29	20
59117	McSherry	5–10	0.0	3.1	43.1	32.0	14.5	5.3	0.3	1.0	0.2	0.5	46	43.13	20
59118	McSherry	10–15	0.0	4.5	79.5	11.8	3.0	0.8	0.4				84	63.78	54
59119	McSherry	15–20	0.0	20.3	46.7	13.3	8.1	7.1	1.2	2.7	0.0	0.5	67	64.38	43
59120	McSherry	20–25	0.7	36.3	51.6	6.5	2.5	1.3	0.0	0.6	0.0	0.5	88	56.70	51
59121	McSherry	25–30	0.6	58.2	37.4	2.1	0.8	0.7				0.1	96	51.57	50
	Leon Creek*	?	0.6	33.0	46.3	17.7		1.7			0.6		80	100.00	100

* Plummer's (1943) sample from bluff on Leon Creek from some point in Eckert sequence, perhaps interval 25–31.

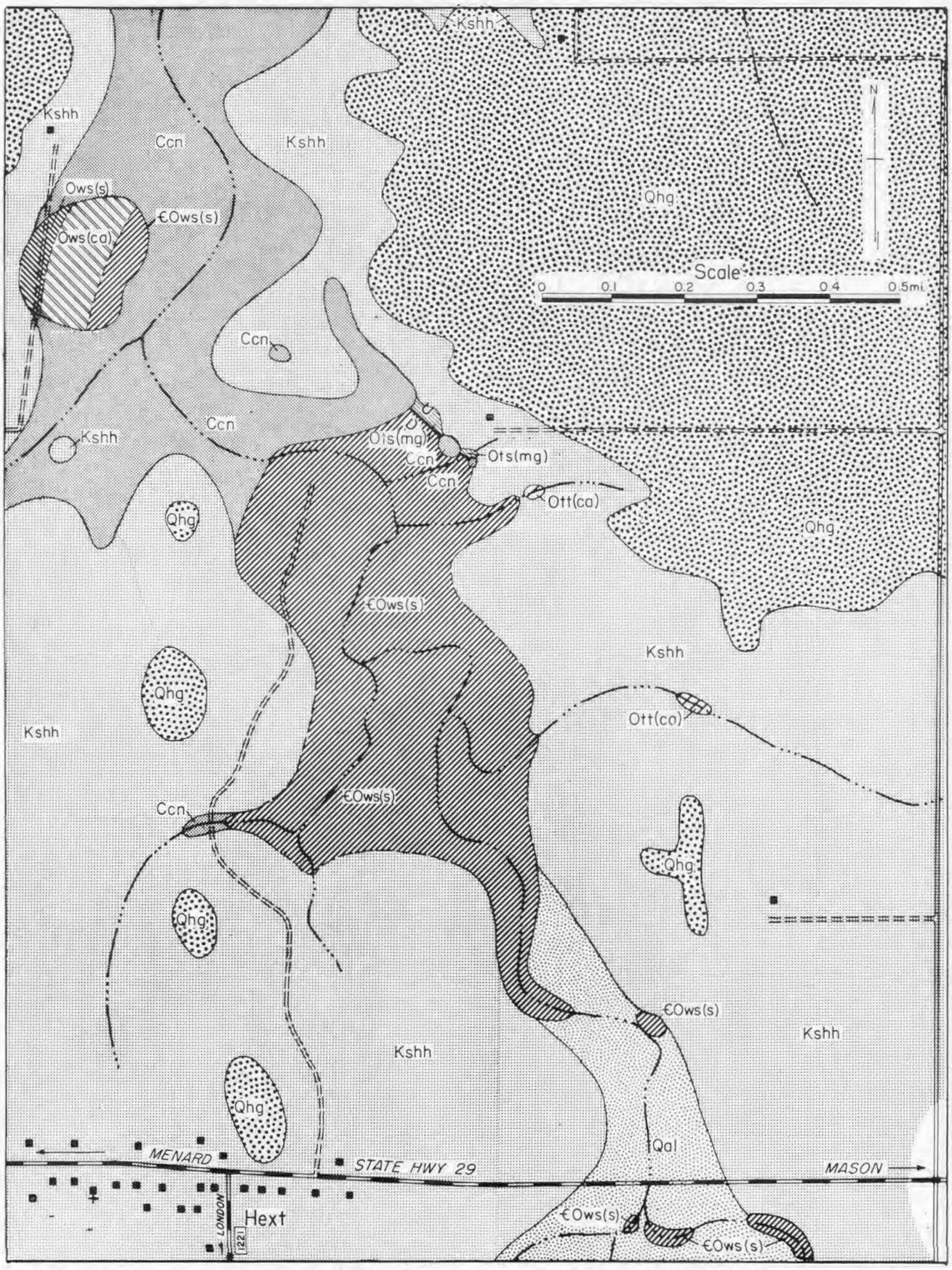

FIG. 4. Geologic map of area in vicinity of Hext, Menard County, Texas.

Stratigraphic units mapped: Cambrian-Ordovician, Wilberns Formation, San Saba Member, lower sandstone strata, €Ows(s), limestone strata, Ows(ca), upper sandstone strata, Ows(s) ; Ordovician, Ellenburger Group, Tanyard Formation, Threadgill Member, calcitic facies, Ott(ca), and Staendebach Member, dolomitic facies, Ots(mg) ; Pennsylvanian, Canyon Group limestone, Ccn; Cretaceous, Shingle Hills Formation, Hensell Sand, Kshh; Quaternary, high gravel, Qhg, and alluvium, Qal.

Base from U. S. Department of Agriculture Soil Conservation Service, aerial photographs flown by Park Aerial Surveys, Inc., 1939–1940. Geology by Virgil E. Barnes, Robert Pavlovic, and W. C. Bell, 1953.

about the same type and amount of vegetation; the overlying Cretaceous Hensell Sand is characterized by mesquite.

The section was measured near the contact where Canyon limestone beds lap out against a hill of San Saba rock; in fact, the presence of fusulinids indicates that the line of section at one point (5 to 10 feet) inadvertently included reworked sand. About half a mile northwest of the measured section, another exhumed hill of San Saba rock partly encircled by Canyon beds contains two sandstone units separated by a limestone unit. Trilobites collected from the limestone unit are Ordovician trilobites; therefore, the upper sand is Ordovician in age. This is the only area in which proven Ordovician San Saba sandstone is known. Elsewhere, Ordovician fossils are found just above the highest sandstone and Cambrian fossils are found at various levels below.

Sieve analysis and insoluble residue data for samples from the McSherry property are given in table 12. Acid-soluble material, mostly carbonate minerals, amounts to 45 percent (range 43 to 64 percent). The presence of more carbonate than needed to fill pore space indicates that the original rock framework included particulate calcite. This leaves little hope that the sandstone will be much less calcareous in the cultivated area away from the Carboniferous contact.

Grains between 20 and 60 mesh in the upper 20 feet of this deposit show a remarkable concentration (average 84 percent, range 67 to 95 percent). For the rock as a whole, because of the high carbonate content, this amounts to only 50 percent (range 43 to 54 percent).

Binocular microscope examination of the fraction larger than 60 mesh shows (1) a trace of aggregated grains, (2) secondarily enlarged and pitted grains mostly common to abundant, (3) rough grains scarce in one sample, abundant in another, and common in the rest, and (4) rounded frosted grains absent in the bottom sample, abundant from 15 to 25 feet, and scarce to common in the other three samples.

Other Localities, Mason County

A section of San Saba beds (Barnes and Bell, MS.) in the Calf Creek area, northwestern Mason County, has been measured and described by Barnes, and an area about the section was mapped by Barnes (Barnes, Bell, and Pavlovic, 1954, fig. 7). Sandstones in this section are described as follows: from 3 to 30 feet, very fine to medium grained, calcareous to dolomitic, weathers mostly yellow and brown; from 37 to 43 feet, medium to coarse grained, white in part stained yellow and brown, in part silica cemented; from 43 to 59 feet, alternates with limestone; and from 70 to 91 feet, fine to medium grained, brownish yellow to orange yellow, very calcareous. The amount of insoluble residue in the sandy units of the Calf Creek section is given in table 14.

TABLE 14. *Insoluble residue data for sandy units of Calf Creek section, Mason County, Texas.*

Feet above base	Insoluble residue in percent
85–91	56.1
80–85	52.2
75–80	39.0
70–75	36.4
55–60	18.2
50–55	33.0
45–50	38.1
40–45	68.1
35–40	47.5
25–30	54.6
15–20	55.7
10–15	49.3
5–10	58.1

A complete section of Wilberns rocks in the James River section, southwestern Mason County, has been measured and described by Barnes (Barnes and Bell, MS.). Sandstones in the San Saba Member of this section are described as follows: from 510 to 516 feet, fine to medium grained, white to pale brown, very calcitic; from 549 to 570 feet, fine to coarse grained, very pale orange to moderate reddish orange to brownish orange and pale yellowish orange, very calcitic; from 591 to 596 feet, fine to medium grained, yellowish gray, white and pinkish gray, very calcitic and dolomitic; and from 628 to 640 feet, fine to coarse grained, dark yellowish orange to moderate yellowish brown, very calcitic and slightly dolomitic. The amount of insoluble residue in the sandy units of the James River section is given in table 15.

TABLE 15. *Insoluble residue data for sandy units of James River section, Mason County, Texas.*

Feet above base	Insoluble residue in perc
635–640	33.9
630–635	66.5
625–630	58.7
590–595	31.4
565–570	86.3
560–565	77.1
555–560	53.1
550–555	46.1
510–515	45.2

Because of the high carbonate mineral content and the amount of iron discoloration, the sandstones in these sections were not further tested.

Economic Possibilities

More effort was spent on the sandstone units in the San Saba Member than was warranted in view of the information furnished by the Calf Creek and James River sections. However, two favorable chemical analyses and the one favorable sieve analysis by Plummer (1943) made it mandatory that the Leon Creek area be reexamined. The Hext area was included because of the large area of outcrop. Seventeen of the 19 samples tested contained from 16 to 80 percent of carbonate minerals and the remaining two contained about 1 percent. While the grain size of a number of the leached samples is favorable for hydraulic-fracturing sand, the grain shape and roughness of many of the grains are not favorable. Even if areas were found where leaching had removed the carbonate from large volumes of the sandstone, which seems unlikely, the railroad at Menard is 17 miles distant and the one at Brady is 25 miles distant from the nearest deposit of possible value located at Hext.

The carbonate mineral content as cement appears to have effectively eliminated most of the porosity, and if this is true these sandstones are not aquifers or oil reservoirs where buried hills similar to those in the Hext area are found beneath Carboniferous rocks in the subsurface. The present data indicate that the sandstones in the San Saba Member are without economic value.

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APPENDIX

DESCRIPTION OF STRATIGRAPHIC SECTIONS AND THIN SECTIONS

Generalized Description of Upper Red Unit of Hickory Sandstone in Streeter Section, Mason County, Texas

Description	Thickness in Feet Interval	Thickness in Feet Cumulative	Feet above base
1. Sandstone—mostly medium to fine grained, some coarse grained, grains up to 0.1 inch; grayish red to very dusky red, in part streaked moderate yellowish brown, a few fine-grained beds dark yellowish brown, others from 67 to 69 feet grayish orange mottled moderate yellowish brown, brown predominant in upper 11 feet; grains well rounded, poorly sorted, coated by hematitic iron oxide which in part is layered as in ooids; cross-beds common; a few sets of ripple marks 2 inches from crest to crest, preserved by overlying shale; shale blackish red, films and beds up to 0.25 inch, trails common; massive in lower part.	95	95	21 –116
2. Sandstone—medium to fine grained; very dusky red to grayish red, grains coated by hematitic iron oxide, some iron oxide ooids; poorly exposed.	21	116	0 – 21

Description of Rocks and Thin Sections from Section in Sell Highway Material Pit, Mason County, Texas

Description	Thickness in Feet Interval	Thickness in Feet Cumulative	Feet above base
Cap Mountain Limestone Member			
1. Limestone or sandstone—either a very sandy limestone or a very calcareous sandstone, sand very fine to very coarse, larger grains mostly well rounded, rest mostly angular, medium brown, thin bedded. Thin section at 33 and 34 feet. At 33 feet, sandstone or limestone—almost equally very fine to medium sand and fine-grained dolomite replaced by calcite and goethite; phosphatic brachiopod debris common; black dendritic mineral similar in occurrence to that at 32 feet, also forms small masses enclosing sand grains and replaces phosphatic brachiopod debris. At 34 feet, sandstone—very fine to medium grained; larger grains well rounded, others mostly angular; matrix mostly dolomite replaced by goethite and calcite similar to that at 33 feet; some calcite cement medium to coarse grained, poikilitic; phosphatic brachiopod debris common.	2	2	32 – 34
Hickory Sandstone Member			
2. Sandstone—mostly fine to coarse grained, some very coarse grained; light brown streaked by grayish red; calcareous; cross-bedded; larger grains well rounded, rest mostly angular; phosphatic brachiopods common. Thin sectioned at 28 and 32 feet. At 28 feet, sandstone—mostly fine to medium grained; grains mostly angular, a few larger ones well rounded; cemented at one end by hematite, rest by calcite, mostly fine grained, semi-poikilitic, some replaces fine-grained dolomite and contains abundant goethite; dolomite appears to have originally replaced pelmatozoan fragments and accumulated around trilobite debris; elsewhere, goethite forms very thin films around sand grains; phosphatic brachiopod debris common; a few black opaque minerals; a black, dendritic	5	7	27 – 32

Description	*Thickness in Feet* *Interval*	*Cumulative*	*Feet above base*
mineral forms at center of altered dolomite. At 32 feet, sandstone —very fine to very coarse grained; medium to very coarse, very well-rounded grains relatively scarce, rest angular; much pelmatozoan debris replaced by goethite, numerous goethite ooids up to 0.9 mm, much goethite matrix speckled by minute brown to black dendrites originally may have been dolomite which was replaced by goethite and calcite; some calcite cement, poikilitic, medium to coarse grained; phosphatic brachiopod debris abundant.			
3. Sandstone—very fine to coarse grained; dusky red, grayish red, pale reddish brown, light brown; hematitic beds both massive and burrowed interbedded with light brown calcareous beds; cross-bedded, phosphatic brachiopods abundant.	10	17	17 – 27
Thin section at 18, 20, 22, 23 and 27 feet. At 18 feet (Pl. VI, C), sandstone—very fine to coarse grained; similar to that at 15 feet, except hematite matrix is along some beds. At 20 feet, sandstone—very fine to coarse grained; similar to that at 4 feet, except for the presence of trilobite debris ghosts, that the matrix is all hematite, and that some pelmatozoan debris is invaded by goethite. At 22 feet (Pl. VI, D-F), sandstone—very fine to coarse grained; similar to that at 3 feet, except calcite matrix is mostly fine to very fine-grained, numerous ooids appear to have been entirely replaced by calcite crystals which extend beyond ooid boundaries, relative abundance of trilobite and pelmatozoan debris is reversed, some pelmatozoan debris is almost entirely replaced by goethite, and intraclasts are more abundant; intraclasts are in part composed of sand grains and phosphatic brachiopods in goethite matrix, in part of sand in goethite matrix, and one contains a goethite ooid. At 23 feet, sandstone —very fine to coarse grained; much fine-grained, irregular mosaic, calcite cement, and secondarily enlarged pelmatozoan debris; larger sand grains well rounded, smaller ones angular; goethite coats sand from merest films to thick coats, rarely occurs as ooids and replacement of secondarily enlarged pelmatozoan debris; phosphatic brachiopods common. At 27 feet, sandstone—fine to coarse grained; much goethite as matrix, ooids, and pelmatozoan replacement; hematite scarce, confined to bands in ooids; fine- to very fine-grained calcite matrix scarce; phosphatic brachiopod debris common.			
SHIFT from northernmost part of quarry to point between this part of quarry and main quarry.			
4. Sandstone—very fine to very coarse grained; grayish red, moderate brown; alternating burrowed hematitic beds and moderate brown calcitic beds; abundant phosphatic brachiopods.	10	27	7 – 17
Thin sectioned at 8, 12, 13, and 15 feet. At 8 feet, sandstone —very fine to very coarse grained; similar to that at 3 feet, except that calcite matrix is fine grained, some hematite cement is at one end of thin section, and feldspar is very scarce. At 12 feet, sandstone—very fine to coarse grained; similar to that at 4 feet, except that hematite is mostly interstitial, calcite cement is absent, and phosphatic brachiopods are numerous. At 13 feet, sandstone—very fine to coarse grained; similar to that at 3 feet, except calcite matrix is mostly fine to medium grained, ooids are more abundant, and hematite and phosphatic brachiopods are less abundant. At 15 feet (Pl. VI, B), sandstone—very fine to coarse grained; similar to that at 3 feet, except pelmatozoan debris and ooids are more abundant, the latter coalescing in some areas, and calcite matrix is mostly fine to medium grained.			
5. Sandstone—very fine to coarse grained, grayish red, burrowed, phosphatic brachiopods abundant.	3	30	4 – 7

Description	*Thickness in Feet Interval*	*Cumulative*	*Feet above base*
Thin sectioned at 4 feet (Pl. VI, 3). Sandstone—very fine to coarse grained; grains similar to those at 3 feet, except feldspar is very scarce and mostly replaced by iron oxide, composite grains more numerous with iron oxide penetrating along grain boundaries, and black opaque grains absent; matrix mostly dusky red, silty hematite in part in large patches and in part interstitial, some very fine-grained calcite; ooids up to 0.7 mm, numerous, mostly goethite, some similar to those at 3 feet; sand grains mostly coated by goethite even where matrix is hematite, suggesting that goethite coatings formed before grains came to rest; phosphatic brachiopod debris scarce.			
6. Sandstone—very fine to very coarse grained, grayish red, calcareous, cross-bedded, phosphatic brachiopods abundant.	2.5	32.5	1.5 – 4
Thin sectioned at 3 feet. Sandstone—very fine to very coarse grained; very fine and fine grains mostly angular, rest very well rounded to spherical, mostly quartz with straight extinction, some undulatory extinction, vacuole trains abundant, a few composite grains, many grains peripherally fractured with goethite penetration making the fractures visible, a few fine and very fine microcline grains, a few very fine, well-rounded, black, opaque grains; much hematite and goethite as coatings on sand grains and as concentric ooids up to 0.6 mm in size, centers commonly quartz, by reflected light mostly light brown goethite, some very dusky red hematite, some shades in between, some ooids mostly goethite, some mostly hematite, and many are alternating layers of the two; trilobite debris, mostly ghosts, with radial calcite abundant, some secondarily enlarged pelmatozoan debris, rest of calcite mostly coarse grained, poikilitic; phosphatic brachiopod shells and debris abundant; one 2-mm sandstone intraclast, sand mostly very fine, some fine, matrix dark yellowish orange, argillaceous (?) goethite; a trilobite spine contains similar material except matrix is darker brown. Microcline is very scarce to absent above this level.			
7. Sandstone—very fine to coarse grained, dark reddish brown to grayish red, massive, phosphatic brachiopods abundant.	1.5	34	0 – 1.5
Thin sectioned at 1 foot (Pl. V, E, F). Sandstone—fine to very coarse grained, poorly sorted; fine grains most abundant, angular to subrounded, coarser grains very well rounded to spherical, mostly with straight to slightly undulatory extinction, vacuole trains abundant, grains goethite coated, goethite penetrates along grain boundaries of numerous composite grains and along percussion fractures on larger grains; small microcline grains fairly numerous, in part replaced by goethite; abundant goethite ooids up to 0.8 mm in size mostly have quartz grains at their centers, some hematite replacement of goethite; matrix, hematite, in part silty; phosphatic brachiopod debris common.			

Description of Lower Part of Pontotoc Section, Llano, Mason and San Saba Counties, Texas (from Barnes and Bell, MS.)

Description	*Thickness in Feet Interval*	*Cumulative*	*Feet above base*
Cap Mountain Limestone Member			
15. Sandstone—lower half fine grained, moderate yellowish brown; upper half medium to coarse grained, moderate brown; calcareous.	4	205	470 –474
Phosphatic brachiopods abundant in upper 2 feet.			

The top of the Hickory Sandstone is arbitrarily placed at 470 feet on the basis of downward disappearance of significant calcareous content.

Description	Thickness in Feet Interval	Thickness in Feet Cumulative	Feet above base
Hickory Sandstone Member			
Upper unit			
16. Sandstone—fine to very coarse grained; alternating zones of massive, very dusky red and less massive intervals with dark brown specks in a matrix of various shades of very light brown, disturbed by organisms; grains mostly well to very well rounded, mostly polished, less well polished from 445 to 455 feet; mostly calcareous. From 432 to 436 feet, fine to very fine grained, some larger grains, moderate yellowish brown to grayish orange and very pale orange, some very dusky red near bottom, noncalcareous; from 436 to 439 feet, fine to very coarse grained, a few granules, very dusky red, mudballs common; from 439 to 440 feet, fine grained, grayish orange to dark yellowish orange; from 440 to 445 feet, medium to very coarse grained; from 445 to 470 feet, fine to very coarse grained, very dusky red, massive, upper 10 feet weathers into thin plates. Phosphatic brachiopods abundant at many levels; trilobite fragments in lower 2 feet.	38	243	432 –470
17. Shale—pale red, fissile, sandy.	1	244	431 –432
SHIFT to west road ditch; continue down in section.			
18. Sandstone—fine to very coarse grained; alternating zones of very dusky red and dark yellowish brown to moderate brown from iron oxide; grains well to very well rounded, polished; calcareous. From 395 to 405 feet, very dusky red, minor shale near bottom; from 405 to 406 feet, moderate brown; from 406 to 409 feet, fine grained, light yellowish brown, silty, slightly micaceous, thin bedded; from 409 to 412 feet, very dusky red; from 412 to 414 feet, fine grained, some larger grains, silty, pale to dark yellowish brown, thin bedded; from 414 to 424 feet, very dusky red, a dark brown bed at 417 feet; from 424 to 426 feet, pale brown, partly covered; from 426 to 430 feet, very dusky red, mudball-like objects common; from 430 to 431 feet, pale yellowish brown. Fossils at 425 and 395 feet, *Cedarina cordillerae, Kormagnostus simplex*; phosphatic brachiopods many of which are fragmental and worn from 399 to 400, 402 to 406, 409 to 412, 414 to 424, and 426 to 430 feet.	36	280	395 –431
Leave road ditch and go down in section southwestward toward drain.			
19. Sandstone—fine to coarse grained, grains well to very well rounded, polished, abundant iron oxide, calcareous; from 386 to 388 and from 391 to 395 feet, very dusky red to blackish red, cross-bedded; from 388 to 391 feet, dark yellowish brown. Worn fragments of phosphatic brachiopods common.	9	289	386 –395
20. Sandstone and shale—sandstone mostly fine and very fine grained ranging to some very coarse grained, light brown, grains fairly well to well rounded, some polished, slightly calcareous, argillaceous, beds up to 6 inches; alternates with shale pale brown, some dusky red, weathers with a purplish tint, trails common. Fossils at 385 feet, *Cedarina cordillerae.*	6	295	380 –386
Section enters drain; continue down in section mostly on west side of drain.			
21. Sandstone, shale, and covered—sandstone fine to very coarse grained; very dusky red to light brown from iron oxide; grains fairly well to well rounded, a few polished; slightly calcareous from 340 to 361 and 366 to 385 feet; some intraformational conglomerate.	32	327	348 –380

Description	Thickness in Feet Interval	Cumulative	Feet above base
From 348 to 356 feet, beds up to 2 feet; from 356 to 357 feet, covered; from 357 to 362 feet, silty, very argillaceous, slightly micaceous, thick bedded; from 362 to 364 feet, covered; from 364 to 365 feet, intraformational conglomerate; from 365 to 370 feet, sandstone beds up to 6 inches thick alternating with shaly zones, some intraformational conglomerate, poorly exposed; (cross fence); top 10 feet sandstone with numerous grains of granule size, mostly light brown, cross-bedded, beds up to 2 feet. Fossils at 354 feet, *Bolaspidella* sp., *Modocia* cf. *M. centralis*; at 350 feet, *Cedarina cordillerae*; phosphatic brachiopods at many levels.			
SHIFT downstream about 60 feet and continue down in section on bluff.			
22. Sandstone—fine to very coarse grained; very dusky red to light brown from iron oxide; grains fairly well to very well rounded, a few polished; beds up to 1 foot thick alternate with thinner bedded zones, trails common on bedding surfaces; some shale in upper part. Some phosphatic brachiopod fragments.	8	335	340 –348
SHIFT downstream about 60 feet and continue down in section along bluff on west bank of drain.			
Middle unit			
23. Sandstone and shale—sandstone in upper 5 feet very fine to very coarse grained, argillaceous, glauconitic, grains fairly well rounded; from 335 to 337 feet, light reddish brown, with dusky red shale films; from 337 to 339 feet, moderate brown to moderate yellowish brown, one bed, some intraformational conglomerate; from 339 to 340 feet, yellowish brown, beds about 4 inches thick; sandstone in middle 5 feet, fine to very coarse grained, numerous granules and small pebbles, mostly dark yellowish orange to light brown; from 334 to 335 feet, light to moderate brown, pebbles angular rough, other grains fairly well rounded, in part argillaceous, slightly glauconitic; from 330 to 331 feet and near middle, intraformational conglomerate; from 331 to 334 feet, shale dusky red, as films between sandstone beds; from 325 to 326 and from 327 to 328 feet, thin bedded, much fissile shale; from 329 to 330 feet, shale pale brown. Fossils at 326 feet, *Bolaspidella burnetensis;* phosphatic brachiopods mostly in intraformational conglomerate at 329 feet, from 330 to 331 feet, and at 333, 334, and 338 feet.	15	350	325 –340
SHIFT downstream about 100 feet and continue down in section along east bank of drain.			
24. Sandstone, siltstone, and shale—sandstone very fine to very coarse grained, in part grades to siltstone, iron stained, argillaceous, slightly micaceous, very slightly glauconitic, grains fairly well rounded, beds less than 6 inches, upper 2 feet mostly sandstone; shale weathers dusky red, forms thin films between sandstone beds, trails and burrows common. Fossils at 320 feet, *Bolaspidella burnetensis*; phosphatic brachiopods common.	10	360	315 –325
SHIFT across small fault and downstream about 100 feet; continue down in section along east bank.			
25. Sandstone, siltstone, and shale—sandstone mostly very fine grained grading to siltstone, a scattering of coarser grains, grayish orange, many 0.25-inch concretions, argillaceous, slightly glauconitic, thinly bedded, an upper 3-foot ledge and an 8-inch ledge; lower 6 inches shale, a few burrows.	4	364	311 –315

Description	*Thickness in Feet* *Interval*	*Cumulative*	*Feet above base*
SHIFT westward 100 feet to west branch of drain and continue section down east bank of drain.			
26. Sandstone and shale—mostly sandstone fine to very coarse grained, many granules and small pebbles in upper part, very fine sandstones and siltstone in lower part, dusky yellow to dark yellowish brown, argillaceous, slightly glauconitic, massive, beds up to 2 feet thick; shale greenish-gray interbeds in lower 2 feet, bedding plane films in rest of interval, a few burrows. A few phosphatic brachiopods.	11	375	300 –311
SHIFT across small fault and across stream to west bank; continue down in section along west bank.			
27. Sandstone—fine to very coarse grained, some small quartz and sandstone pebbles in upper part; dusky yellow to dark yellowish brown; mostly quartz, microcline scarce, in part glauconitic; grains mostly fairly well rounded, a few well rounded, polished; massive beds up to 3 feet. Phosphatic brachiopods at several levels.	8	383	292 –300
28. Covered.	2	385	290 –292
29. Sandstone and shale—sandstone in lower 4 feet, fine to very coarse grained, many granules, a few small pebbles, moderate yellowish brown, argillaceous, some glauconite, grains mostly fairly well rounded, a few well rounded, massive, cross-bedded, intraformational conglomerate at top; from 279 to 284 feet, upper foot mostly shale light brownish gray to purplish, rest sandstone fine to very coarse grained, argillaceous, slightly glauconitic, some siltstone, a few beds with trails on them, intraformational conglomerate in beds up to 4 inches; in upper 6 feet, sandstone, fine to very coarse grained, dark yellowish orange, argillaceous, slightly micaceous and glauconitic, grains fairly well rounded, lower half massive, cross-bedded; upper half alternating shale, siltstone, and sandstone, cross-bedded, beds up to 6 inches. Fossils at 279 feet, *Bolaspidella wellsvillensis*; phosphatic brachiopods in intraformational conglomerate from 279 to 284 feet.	15	400	275 –290
SHIFT along base of cross-bedded sandstone downstream about 250 feet and continue down in section on bluff to drain bottom.			
30. Sandstone and shale—sandstone very fine to very coarse grained, mottled in various browns and yellowish grays, grains fairly well rounded, mostly quartz, glauconite scarce, thin bedded, recessive, intraformational conglomerate abundant in lower half and upper 1.5 feet; shale beds in upper part greenish gray. Abundant phosphatic brachiopods in intraformational conglomerate.	10	410	265 –275
SHIFT about 1,700 feet downstream and continue down in section along south side of drain.			
31. Sandstone and shale—mostly sandstone and intraformational conglomerate mottled in browns and yellowish grays; some shale. Phosphatic brachiopods in intraformational conglomerate.	1	411	264 –265
SHIFT downstream about 400 feet and continue down in section down low declivity.			
32. Sandstone and shale—sandstone fine to very coarse grained, a few granules, argillaceous, glauconite common, grains fairly well rounded; lower 1.5 feet somewhat cross-bedded, beds about 4 inches; next 2 feet thin bedded with trails common on bedding surfaces, thin shale laminae; upper 1.5 feet medium to coarse grained, hard, somewhat hematitic, quartz fragments up to 0.5 inch.	5	416	259 –264

Description	Thickness in Feet Interval	Thickness in Feet Cumulative	Feet above base
Phosphatic brachiopods common in upper 1.5 feet.			
SHIFT downstream 150 feet across covered interval crossing fence.			
33. Covered.	8	424	251 -259
34. Sandstone—very fine to coarse grained; argillaceous; upper part hematitic, one bed; lower part thin bedded, conglomeratic with a few well-rounded quartz pebbles up to 1.5 inches, many grains 0.25 inch in size.	1	425	250 -251
Numerous phosphatic brachiopods.			
SHIFT downstream about 100 feet and continue down in section along east bank.			
35. Sandstone and shale—sandstone fine to very coarse grained, silty, mostly thin beds separated by shale laminae, top 6 inches hematitic, another bed 6 inches lower also hematitic, mottles and trails common.	2	427	248 -250
Phosphatic brachiopods in hematitic part.			
SHIFT downstream about 200 feet and continue down in section along north bank.			
36. Covered.	5	432	243 -248
37. Sandstone and shale—sandstone very fine to very coarse grained, a few granules; light olive gray to dark yellowish orange, some light brown; argillaceous; mostly quartz, grains fairly well rounded, some reconstitution; lower 3.5 feet mostly sandstone thin bedded, some lenticular cross-beds up to 6 inches, shale beds and partings up to 1 inch; next foot sandstone, one set of cross-beds; next 2 feet thin bedded, recessive; top 6 inches sandstone, one set of cross-beds.	7	439	236 -243
38. Covered.	1	440	235 -236
39. Sandstone and shale—sandstone very fine to medium grained, a few coarse grains, silty, argillaceous, micaceous, in part calcitic with calcite poikilitic, mostly thin bedded alternating with shale as partings and beds up to an inch in thickness, top foot essentially one bed, trails and burrows common.	7	447	228 -235
Some phosphatic brachiopod fragments.			
SHIFT about 500 feet across fence and continue down in section along south bank.			
40. Sandstone—very fine to very coarse grained, a few granules, grayish yellow to yellowish orange, in part argillaceous, mostly quartz, grains fairly well rounded, bottom part nodular perhaps from burrows, next 2 feet thin bedded with shale partings, top part thick bedded.	5	452	223 -228
SHIFT downstream about 800 feet over covered interval and continue down in section.			
Lower unit			
41. Covered.	28	480	195 -223
42. Sandstone—very fine to very coarse grained; yellowish brown to yellowish gray; mostly quartz, some microcline up to granule size; grains fairly well rounded; beds in lower foot 4 inches, next 2 feet one bed, upper 2 feet beds about 6 inches.	5	485	190 -195
SHIFT downstream about 600 feet across covered interval and continue down in section.			
43. Covered.	7	492	183 -190
44. Sandstone—medium to coarse grained, yellowish brown, cross-bedded, massive with thin-bedded zone near middle, a few small concretionary objects on weathered surface.	2	494	181 -183
45. Covered.	11	505	170 -181
SHIFT east-southeastward about 1,000 feet to side drain. This shift was made across a covered area.			
46. Sandstone—fine to very coarse grained, a few granules, some very fine grained, argillaceous in lower part, mostly quartz, some	10	515	160 -170

Description	Thickness in Feet Interval	Cumulative	Feet above base
microcline up to granule size, micaceous, grains fairly well rounded, alternating thick- and thin-bedded zones.			
Before the shift, 9 feet of section is exposed as follows: from 161 to 164 feet, massive; from 164 to 165 feet, thin bedded; from 165 to 166 feet, one bed; from 166 to 167 feet, thin bedded; from 167 to 169 feet, one bed; from 169 to 170 feet, with hackly fracture, contains coarse quartz fragments.			
After the shift, 10 feet of section is exposed as follows: from 160 to 162 feet, thick bedded; from 162 to 164 feet, thin bedded; from 164 to 166 feet, thick bedded; from 166 to 168 feet, thin bedded; from 168 to 170 feet, thick bedded, a zone of coarse quartz fragments near middle.			
47. Covered.	3	518	157 -160
48. Sandstone—fine to coarse grained, a few very coarse grains and granules some of which are microcline; some mica; grains fairly well rounded; lower 2 feet one bed with cuneiform markings on upper surface, next 3 feet thin bedded, top 2 feet massive, poorly exposed.	7	525	150 -157
A fault at 150 feet downthrown to the north is believed to be of slight displacement and has been disregarded.			
49. Sandstone—fine to very coarse grained, angular quartz fragments up to 1 inch in length and microcline cleavage fragments up to 0.25 inch in size; a thin argillaceous zone near middle, fine to very fine grained, micaceous.	2	527	148 -150
50. Covered.	2	529	146 -148
51. Sandstone and shale—sandstone yellowish gray to brownish yellow, a bed at 144 feet moderate reddish brown, in part cross-bedded, cuneiform markings common in thicker sandstone beds; shale occurs as thin films.	18	547	128 -148
From 128 to 130 feet, sandstone fine to very coarse grained, many granules, mostly quartz, some microcline, grains fairly well rounded, one set of cross-beds; from 130 to 136 feet, sandstone very fine to very coarse grained, a few granules, mostly qua tz, much microcline in finer grain sizes, mica scarce, grains fairly well rounded, lower 2 feet beds 4 to 8 inches, next foot beds 1 inch and less with shale partings, next foot one set of cross-beds thickening eastward, top 2 feet 4- to 8-inch sets of cross-beds with ripple marks on surface at 135 feet; from 136 to 140 feet, mostly fine and very fine grained, a few coarse and very coarse grains, mostly quartz, some microcline, a few flakes of mica, alternating 4- to 6-inch sets of cross-beds and thin-bedded zones of sandstone with shale partings; from 140 to 141 feet, one set of cross-beds; from 141 to 146 feet, sandstone beds 4 to 6 inches, alternate with thin-bedded intervals of sandstone with shale partings.			
52. Covered.	13	560	115 -128
SHIFT downstream about 200 feet to main drain and continue down in section.			
53. Sandstone—very fine to very coarse grained, a few granules; yellowish gray to brownish yellow, some pink, silty, argillaceous, micaceous in upper 5 feet; mostly quartz; grains fairly well rounded; much cross-bedded, bottom 5 feet one massive set of cross-beds, rest of interval cross-bed sets mostly less than 18 inches in thickness.	15	575	100 -115
SHIFT downstream about 100 feet and continue down in section along west bank.			
54. Sandstone—fine to very coarse grained, a few granules; yellowish gray; mostly quartz, some microcline and mica; grains fairly well rounded; massive, bedding indistinct.	7	582	93 -100

Description	Thickness in Feet Interval	Thickness in Feet Cumulative	Feet above base
SHIFT downstream about 250 feet and continue down in section along east bank.			
55. Sandstone—fine to very coarse grained, a few granules; mostly quartz, some microcline, mica scarce; grains fairly well rounded, some limonite cement; cross-bedded, beds average about 1 foot.	5	587	88 - 93
56. Covered.	24	611	64 - 88
SHIFT downstream across covered interval about 950 feet and continue down in section along east bank.			
57. Sandstone—mostly medium to coarse, some fine grained, a few granules; mostly quartz, some microcline and mica; grains fairly well rounded; in part argillaceous; cross-bedded, massive, little indication of bedding except in lower foot.	17	628	47 - 64
SHIFT south across fault and continue down in section.			
58. Sandstone and shale—sandstone yellowish brown to yellowish gray, argillaceous, somewhat micaceous, cuneiform markings common in some beds, beds 4 inches and less alternate with shale, light olive gray to pale red, somewhat sandy, thin beds. From 34 to 35 feet, sandstone, fine to coarse grained, a few granules, mostly quartz, about 20 percent microcline, some mica, smaller grains angular, some rounding, larger ones fairly well rounded, beds about 4 inches; from 35 to 38 feet, sandstone, very fine to granule size, micaceous, some microcline, much silt and clay, bedding indistinct, weathers with a rough surface; from 38 to 47 feet, alternating sandstone and shale, thinly bedded, sand very fine to very coarse, somewhat rounded, mostly quartz, some microcline, weathered biotite, and muscovite.	13	641	34 - 47
SHIFT across small fault and continue down in section along east bank.			
59. Covered.	6	647	38 - 34
60. Sandstone—fine to coarse grained, yellowish brown, about equally quartz and microcline, micaceous, grains mostly angular, a few of quartz slightly rounded, one bed with a peculiar vertical structure and some indication of cuneiform markings on top surface.	1	648	27 - 28
61. Covered.	19	667	8 - 27
SHIFT southwestward about 450 feet to a side drain and continue down in section.			
62. Sandstone and conglomerate—from 0 to 3 feet, angular conglomerate mostly 0.75-inch fragments of quartz and microcline, some quartz up to 2 inches in a matrix of fine to coarse-grained, angular, micaceous sand, an upper 1-foot and a lower 2-foot bed; from 3 to 4 feet, sandstone brown, micaceous, a peculiar vertical structure; from 4 to 6 feet, angular conglomerate, fragments smaller than in bottom 3 feet; from 6 to 8 feet, sandstone medium grained, brown, grains angular, micaceous, a peculiar vertical structure, markings on upper surface indistinctly cuneiform; from 3 to 8 feet, beds 6 to 12 inches.	8	675	0 - 8

Description of Thin Sections from Section in Highway Material Pit, Cold Creek Area, Llano County, Texas

CAP MOUNTAIN LIMESTONE

Limestone (HP36)[2]—very fine grained, very silty, some very fine sand; sand and silt mostly quartz, much microcline and cloudy stained feldspar, glauconite very scarce. Much goethite, some hematite. Phosphatic brachiopod debris scarce.

[2] Numeral indicates footage above base of sampled section.

Limestone (HP35)—fine grained, silty; silt mostly quartz and very cloudy stained feldspar, some microcline and glauconite. Abundant goethite, some hematite irregularly distributed in patches. Finely comminuted phosphatic brachiopod debris common.

Limestone (HP34)—very fine grained, very sandy, sand very fine, some silt; sand and silt mostly quartz and very cloudy stained feldspar, some microcline, a trace of glauconite. Goethite abundant, hematite widely distributed. Phosphatic brachiopod debris very scarce.

Limestone (HP31)—medium-grained calcite mosaic and microgranular, very silty, filled burrows(?) and intraclasts. The sharply bounded intraclasts are rounded whereas the filled burrows(?) are irregular in shape and grade gradually into the surrounding limestone. The abundant silt and small amount of very fine sand is mostly quartz and very cloudy stained feldspar, some microcline and hydrobiotite, and a trace of glauconite. Widely scattered dolomite rhombs, except for narrow margins, have been replaced by goethite and calcite. Secondarily enlarged pelmatozoan debris scarce, some radial calcite about trilobite debris.

HICKORY SANDSTONE

Sandstone (HP29)—coarse grained, well rounded down to fine grained size, below mostly angular; mostly quartz, extinction mostly straight to slightly undulatory, a few composite grains with unit boundaries invaded by goethite, bubble trains common, numerous tiny impact fractures invaded by goethite; microcline common; numerous goethite ooids, quartz nuclei abundant. Matrix, some coarse-grained calcite, mostly medium-grained dolomite replaced by goethite and calcite. Rounded goethite impregnated pelmatozoan debris common, phosphatic brachiopod debris common.

Sandstone (HP27)—bimodal, coarse grained very well rounded and fine grained angular; mostly quartz, extinction mostly straight to slightly undulatory, a few composite grains, boundaries invaded by goethite, bubble trains common, numerous tiny impact fractures invaded by goethite on larger grains, none on smaller grains; some microcline; goethite ooids very scarce. Matrix fine- to medium-grained mosaic calcite and some dolomite(?) replaced by goethite and a trace of calcite. Rounded fragments of goethite impregnated pelmatozoan debris common, phosphatic brachiopod shells and debris common.

Sandstone (HP23) (Pl. V, D)—medium grained, a few coarse grains, grains well rounded down to very fine grained size; mostly quartz, extinction mostly straight to slightly undulatory, composite grains scarce, bubble trains abundant, numerous tiny impact fractures on larger grains, none on smaller ones; some microcline; ooids of goethite containing a few hematite layers common, quartz nuclei abundant. Large intraclasts composed of fine to very fine angular sand, goethite ooids, and phosphatic brachiopod debris in a hematitic goethite matrix appear to have filled hollow trilobite fragments, then the shell dissolved before deposition of radial calcite took place around the fillings. Matrix mostly mosaic of fine- to coarse-grained calcite, some dolomite replaced by goethite and calcite, some radial calcite around intraclasts, and scarce trilobite debris. Goethite impregnated pelmatozoan debris is in part secondarily enlarged, phosphatic brachiopod debris common.

Sandstone (HP17)—coarse grained, grains well rounded down to fine-grained size, a few small angular grains; mostly quartz, extinction mostly straight to slightly undulatory, a few composite grains, bubble trains abundant, numerous tiny impact fractures invaded by goethite; microcline common; ooids of goethite containing a few hematite layers abundant, quartz nuclei common, a few compound ooids. Matrix very coarse-grained poikilitic calcite. Large fragments and finer debris of phosphatic brachiopods common.

Sandstone (HP13) (Pl. V, B, C)—coarse grained, a very few coarse grains, grains well rounded down to fine and very fine-grained sizes, a few small angular grains; mostly quartz, extinction mostly straight to slightly undulatory, composite grains common, bubble trains abundant, numerous tiny impact fractures invaded by goethite; some microcline and cloudy feldspar rhombs; goethite ooids in part hematitic, quartz nuclei common. Matrix coarse-grained poikilitic calcite and some dolomite replaced by goethite and calcite. Some phosphatic brachipod debris.

Sandstone (HP10)—coarse grained, grains well rounded down to fine-grained size, below this angular grains common; mostly quartz, extinction mostly straight to slightly undulatory, composite grains common, bubble trains common; microcline scarce; geothite ooids common, quartz nuclei common. Matrix hematite. Some well-rounded phosphatic brachiopod debris.

Sandstone (HP9)—fine grained, some very fine grains, a few well-rounded medium grains, rest angular; mostly quartz; feldspar rhombs in part cloudy abundant, microcline common; a few black opaque grains. Matrix goethite and hematitic goethite.

Sandstone (HP6)—coarse to very coarse grained, grains well rounded down to fine-grained size, below this angular grains common; mostly quartz, extinction mostly straight to slightly undulatory, composite grains scarce, bubble trains abundant, numerous tiny impact fractures invaded by goethite; microcline scarce; ooids common composed of alternating goethite and considerable hematite, quartz nuclei abundant. Matrix in part fine-grained calcite, in part dolomite mostly replaced by goethite and calcite, in part hematite, in part radial calcite around scarce trilobite debris. Phosphatic brachiopod shells and debris abundant.

Sandstone (HP4)—very coarse grained, grains well rounded ranging down to very fine grained size, below this angular grains abundant; mostly quartz, extinction mostly straight to slightly undulatory, composite grains very scarce in larger sizes, common in smaller sizes, grain boundaries invaded by goethite, bubble trains abundant, numerous tiny impact fractures invaded by goethite; goethite ooids fairly common. Matrix mostly goethitic hematite and dolomite replaced by goethite and calcite, calcite scarce. Phosphatic brachiopod debris scarce.

Sandstone (HP1) (Pl. V, A)—very coarse grained, grains well rounded down to very fine-grained size, below this mostly angular; mostly quartz, extinction mostly straight to slightly undulatory, composite grains scarce, boundaries invaded by goethite, bubble trains abundant, numerous tiny impact fractures invaded by goethite; microcline scarce; ooids of goethite and an occasional layer of hematite common. Matrix mostly hematite and dolomite replaced by goethite and calcite. Phosphatic brachiopod debris common.

Description of Lion Mountain and Welge Sandstones in Cut along Ranch Road 501, San Saba County, Texas

Description	*Thickness in Feet* *Interval*	*Cumulative*	*Feet above base*
Wilberns Formation:			
Welge Sandstone Member: 12 feet measured			
Sandstone—coarse grained, light brown, thin bedded, some cross-bedding and burrows.	2	2	13 – 15
Shale (16 inches thick)—light greenish gray, in part slightly sandy, fragments of thin phosphatic brachiopod shells common.	1	3	12 – 13
Sandstone—coarse grained, massive, cross-bedded, near top cross-beds dip northeast, top 6 inches burrowed, a few burrows elsewhere.	5	8	7 – 12
Sandstone and shale—lower foot coarse-grained sandstone, burrowed, nonglauconitic; upper 3 feet interbedded sandy shale and shaly sandstone, reddish brown to greenish gray.	4	12	3 – 7
Riley Formation:			
Lion Mountain Sandstone Member: 3 feet measured			
Greensand—mostly glauconite and quartz sand, some bedded greensand sparkles from secondarily enlarged quartz grains, mostly burrowed, burrows somewhat hematitic red.	3	15	0 – 3

Plates III–VI

PLATE III

Photomicrographs of thin sections of red Hickory sandstone, Llano and Mason counties, Texas
(A–D, ×30; E, F, ×40)

Section in highway material pit at foot of Lone Oak Mountain, Llano County—

A. Hematitic sandstone from 1 foot above base of section.

Hematite matrix was infilled after breakage of goethite ooid and growth of dolomite rhombs. Dolomite was later replaced by calcite and goethite, and the broken ooid was in part replaced by hematite.

B, C. Calcitic sandstone from 13 feet above base of section.

B. Broken goethite ooids with patchy hematite replacement and goethite-coated quartz grains in poikilitic calcite matrix.

C. Broken goethite ooids with patchy hematite replacement and goethite-coated quartz grains in coarse-grained poikilitic calcite which has replaced dolomite rhomb.

D. Calcitic sandstone from 23 feet above base of section.

Pelmatozoan fragment replaced by goethite, goethite ooids, goethite-coated quartz grains, and goethite penetration along percussion fractures in quartz grains and along grain boundaries of a mosaic quartz grain.

Section in highway material pit on H. Sell property near Camp Air, Mason County—

E, F. Hematitic sandstone from 1 foot above base of section.

E. Isolated goethite ooid in slightly silty hematite matrix and goethite penetration along percussion fractures in quartz grain.

F. Goethite ooids in part replaced by hematite, and quartz grains in light-colored hematite matrix.

c = calcite matrix — g = goethite
d = dolomite replaced by calcite — h = hematite
F = fossil fragment — Q = quartz
p = goethite-filled percussion fracture in quartz grain

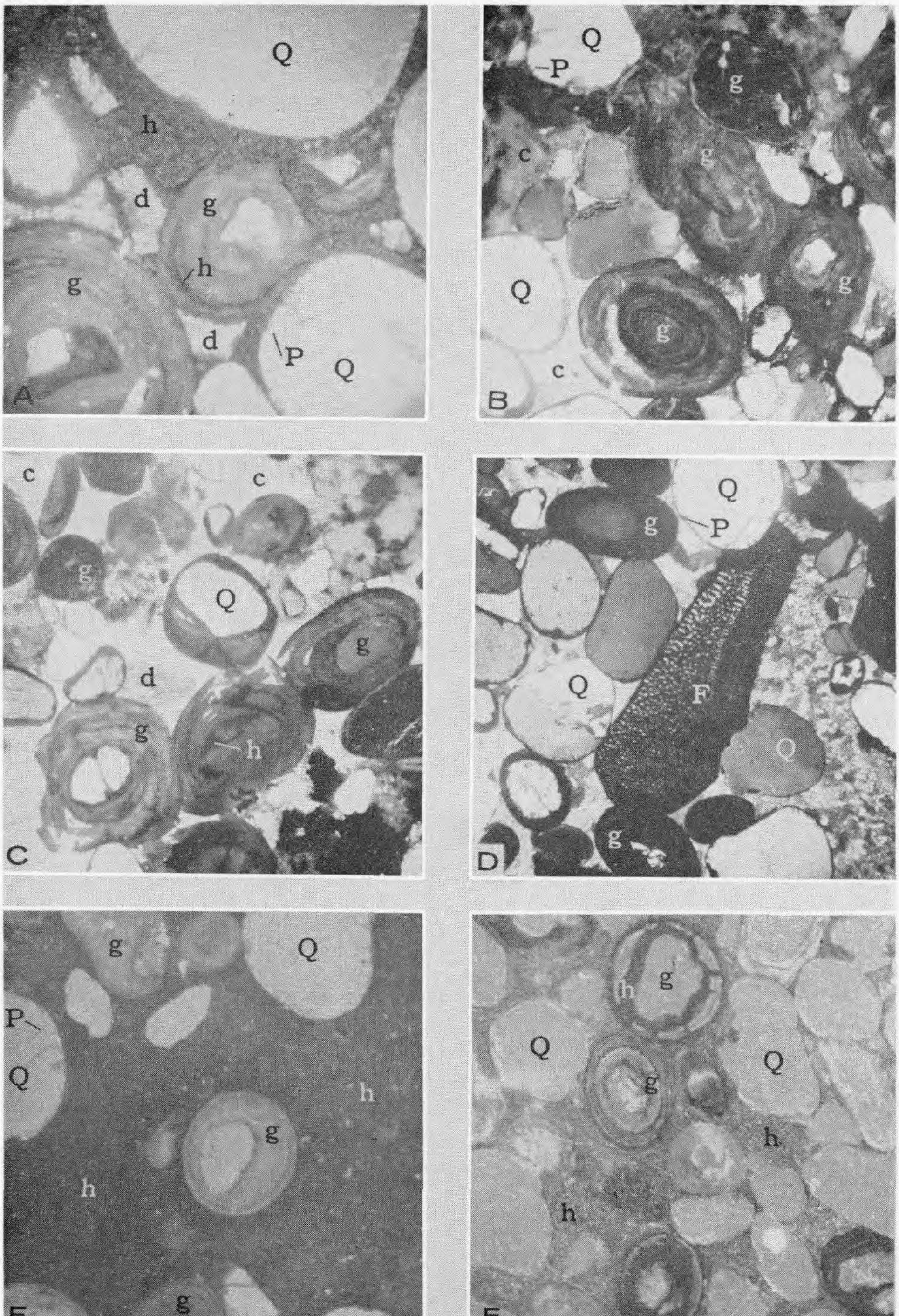
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PLATE IV

Photomicrographs of thin sections of red Hickory Sandstone, Mason County, Texas
(A, B, ×40; C–F, ×30)

Section in highway material pit on H. Sell property near Camp Air—

A. Hematitic sandstone from 4 feet above base of section.

Goethite penetration along grain boundaries of a mosaic quartz grain, and goethite ooids in hematite and calcite matrix.

B. Calcitic sandstone from 15 feet above base of section.

Hematite replacement of goethite ooids and compound ooids in coarse-grained calcite matrix.

C. Calcitic sandstone from 18 feet above base of section.

Goethite-coated quartz and feldspar grains, goethite replacement of feldspar, and goethite films outlining fossil fragment in coarse-grained poikilitic calcite matrix.

D–F. Calcitic sandstone from 22 feet above base of section.

D. Intraclast composed of quartz grains and goethite ooid in a matrix of goethite, and goethite-coated quartz grains and goethite ooids in coarse-grained poikilitic calcite matrix.

E. Intraclasts composed of quartz grains and phosphatic brachiopod fragments in a goethite matrix, and goethite-coated quartz grains and goethite ooids in coarse-grained poikilitic calcite matrix.

F. Intraclast composed of goethite ooid and quartz grains in calcite matrix which served as a nucleus for a calcite ooid which continued to grow and incorporated goethite ooids and quartz grains in its outer part after deposition.

c = calcite matrix	g = goethite
co = calcite ooid	h = hematite
f = feldspar	i = intraclast
F = fossil fragment or cast	q = quartz

p = goethite-filled percussion fracture in quartz grain

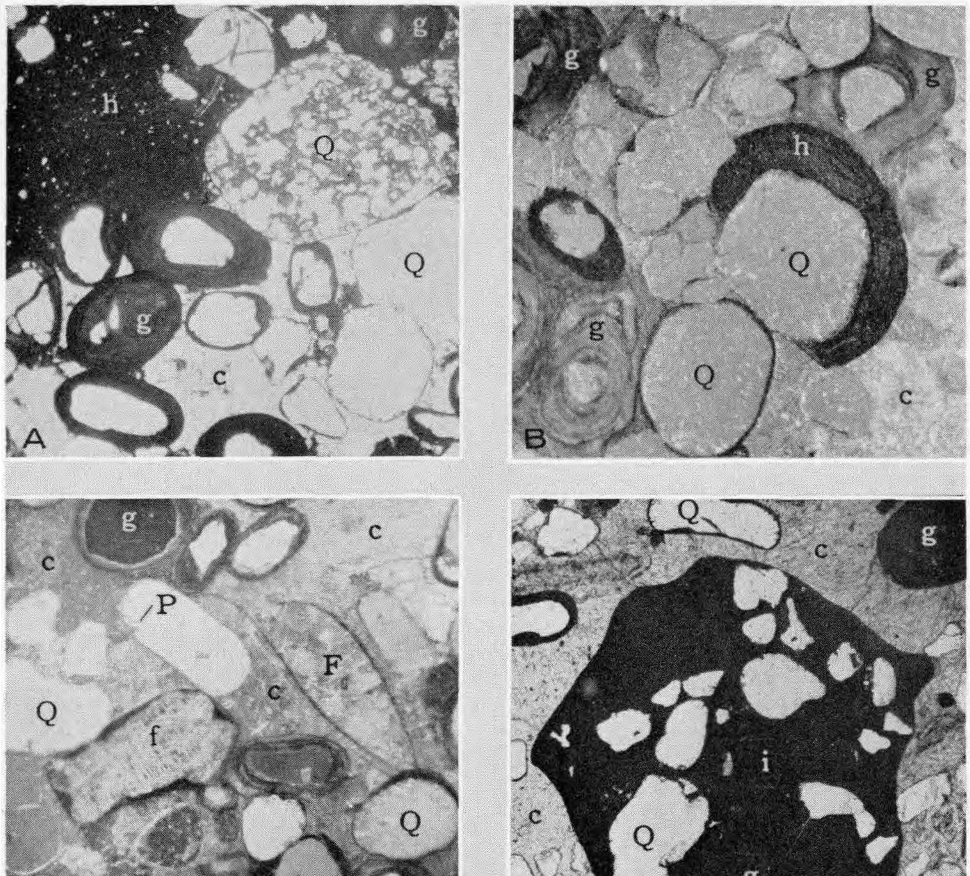
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PLATE V

Pennsylvania Glass Sand Corporation hydraulic-fracturing sand operation,
McCulloch County, Texas

A. Quarry and processing plant near Voca.

B. Loading facilities at Brady.


A


B

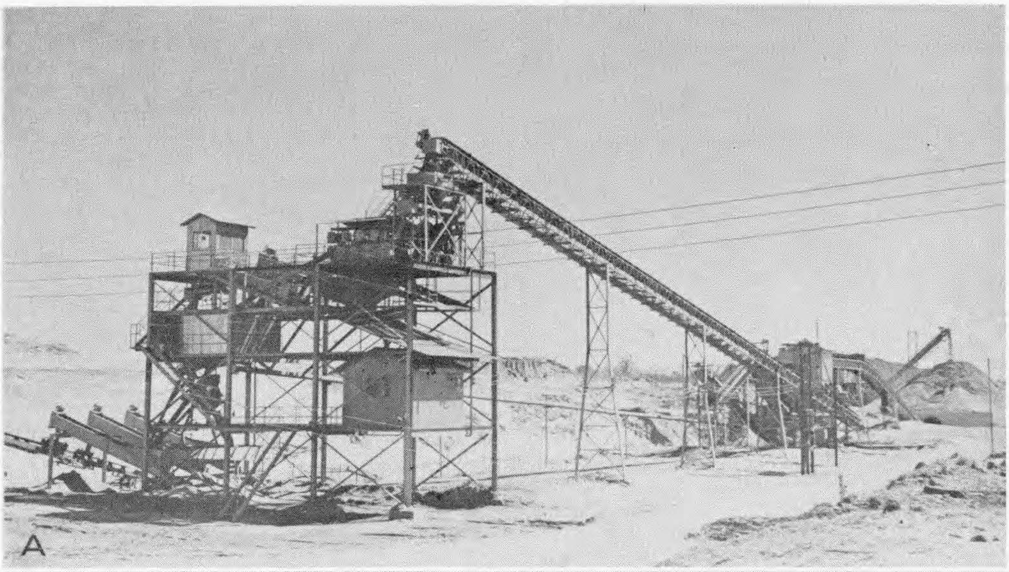
PLATE VI

Heart of Texas Mining Corporation hydraulic-fracturing sand operation, McCulloch County, Texas

A. Processing plant near Voca.

B. Quarry near Voca.

C. Drying plant and loading facilities at Brady.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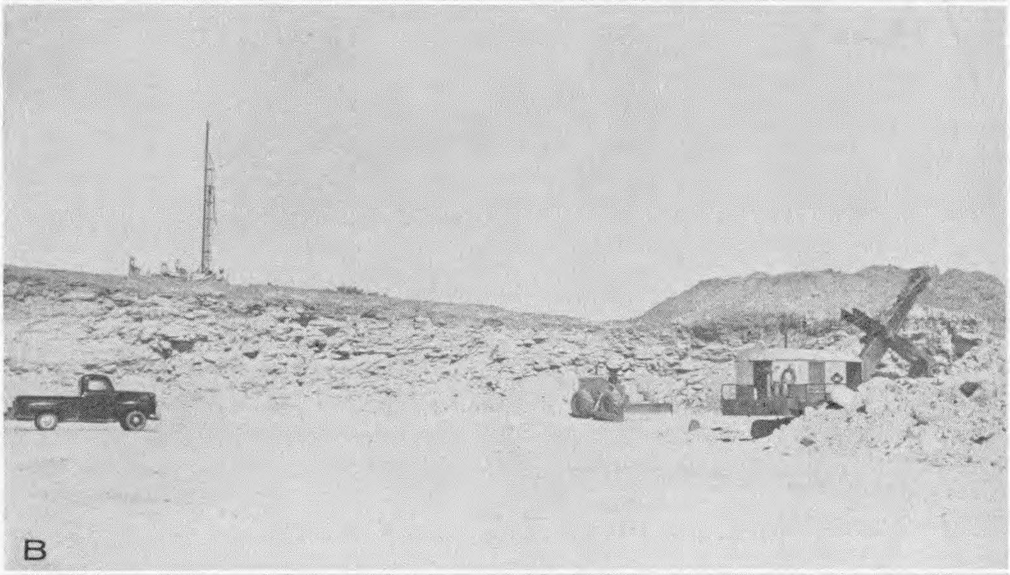
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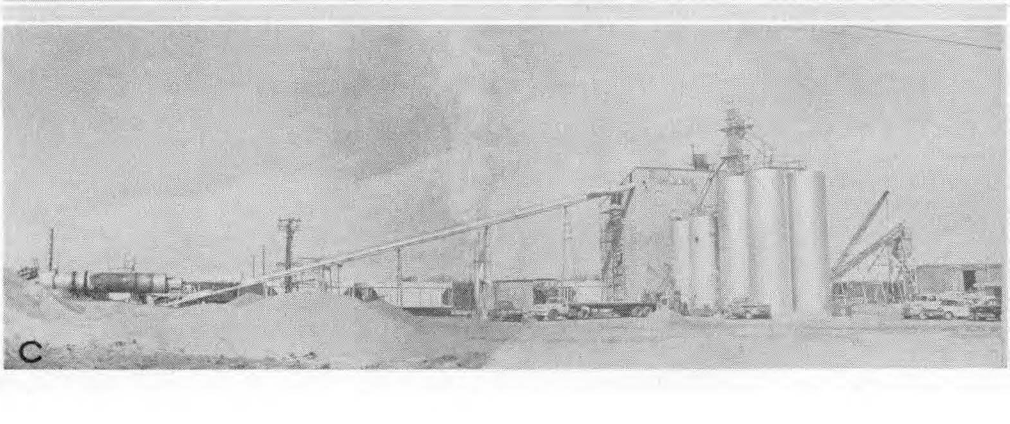
C

Index