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RECONNAISSANCE OF COMMERCIAL HIGH-CALCIUM LIMESTONES IN NEW MEXICO

by Frank E. Kottlowski

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Abstract

New Mexico's rapid growth in population and acquisition of many industries has encouraged consideration of the development of a high-calcium lime industry. Limestones crop out or are near the surface in about one fourth of the State; they range in age from the thin, dolomitic limestone lenses in the Cambrian part of the Bliss Sandstone to the Cenozoic travertine, calcareous tufa, and caliche. Some of the high-calcium limestones of Mississippian, Pennsylvanian, Permian, and Early Cretaceous Ages exceed 100 feet, and locally even 1000 feet, in thickness. Most of the outcrops sampled were those (1) easily mined by open-pit methods, (2) near railroads and accessible by good automobile roads, and (3) within short distances of a gas pipeline.

High-calcium limestones shown by sampling include the Cenozoic travertines of the Mesa del Oro and Ladron Mountains areas; the Tertiary algal limestone of Apache Valley in the southwestern Caballo Mountains; Lower Cretaceous limestones in southwestern New Mexico; upper and lower Permian limestones in the Guadalupe, Sacramento, Robledo, Florida, and Oscura mountains; Pennsylvanian limestones of the Sandia, Sangre de Cristo, Sacramento, Ladron, Magdalena, Oscura, northern Franklin, and northern Hueco Mountains; Cerros de Amado, and near Luna; and Mississippian limestones in the Sacramento, Tres Hermanas, and Peloncillo mountains. Selective quarrying may yield high-calcium lime from the Todilto limestone southeast of Grants, from erratic local deposits of Cenozoic travertine and caliche throughout the State, and from the El Paso Limestone in southwestern and south-central New Mexico.

Any industrial firm wishing to utilize the limestones must do extensive field sampling to gauge the average composition of mineable units, as in places extreme lateral and vertical variation is noticeable.

Introduction

The chief economic uses of high-calcium limestone are as sources of lime, an important basic chemical, as a chemical raw material in the production of paper, glass, alkalies, calcium carbide, and metallurgical flux, and for water purification plants. This pure limestone can be used as crushed stone for concrete aggregate and road metal, to make cement, as fluxstone, and as "aglime" for soil conditioning--all products which can also utilize less pure limestone. Much high-calcium limestone also may meet the requirements of dimension stone.

High-calcium limestone contains at least 95 percent calcium carbonate (about 53.22% CaO) and less than 3 to 5 percent magnesium carbonate (Bowen, 1957; Bates, 1960); limits (Patterson, 1960) for other impurities are alumina, 1 percent; silica, 2 percent; sulfur, 0.05 percent; phosphorous, 0.02 percent; and iron oxide, about 1 percent. The chemical and physical requirements differ slightly depending upon the ultimate use.

Quick and hydrated lime, obtained by calcination of high-calcium limestone, are low cost, flammable, perishable products. Safe transportation is expensive and, with the low price of the bulk material, makes shipping over long distances uneconomical. New Mexico, with only two large metropolitan centers (Albuquerque and El Paso) in or close to the State and a relatively sparse industrial population, at present is unfavorably located for a large usage of chemical- and industrial-grade lime, except for cement plants. In the event of a "nonatomic" war (or even an atomic one), however, the very disadvantages of the State--long distances from either coast and from large populous areas--would become strategic advantages. High-calcium limestone quarries and associated calcination plants could be located in New Mexico along major lines of transportation but away from high-priority targets and out of effective range of firings from submarines. Moreover, the State's rapid growth in population and the addition of many industries, fostered by the warm climate and favorable tax structure, may encourage the development of a high-calcium lime industry.

Much of the cement used in the area has been supplied for many years by the Southwestern Portland Cement Company from quarries in the Cretaceous rocks near El Paso. The growing demand from construction projects led to the recent installation of the Ideal Cement Company quarry and cement plant at Tijeras near Albuquerque; Pennsylvanian limestones are part of the raw materials. Two new gypsum quarries and their related wallboard plants, the Kaiser Gypsum Company operation at Rosario between Albuquerque and Santa Fe and the American Gypsum Company quarry near San Ysidro (Weber and Kottlowski, 1959), are added sources of industrial minerals available for chemical industries. The State also has large deposits of coal, uranium, vanadium, oil, gas, potash, halite, and dolomite, as well as reserves of fluorspar, barite, beryllium, tantalum, and numerous metallic ores.

Limestones crop out or are near the surface in about one fourth of the State; they range in age from the thin dolomitic limestone lenses in the Cambrian part of the Bliss Sandstone to the Cenozoic travertine, calcareous tufa, and caliche. Some of the high-calcium limestones of Mississippian, Pennsylvanian, Permian, and Early Cretaceous Ages exceed 100 feet, and locally even 1000 feet, in thickness. The purity ranges from almost pure calcite to the calcareous tufa and caliche which in places contain as much as 40 percent insoluble residues. Locating outcrops of high-calcium limestone is no problem, but the most economical deposits should fulfill three requirements: (1) be easily mined by open-pit methods; i.e., should cap extensive mesas and underlie thin overburden; (2) be within 20 miles of a railroad and accessible by good automobile roads; and (3) be within short distance of a gas pipeline. The intersections of highways, railroads, and gas pipelines (fig. 1) with limestone outcrop areas determined most of the deposits investigated; numerous other limestones that do not meet these economic requirements were given only cursory examination. Some limestones in relatively inaccessible areas were sampled to obtain a fairly complete stratigraphic coverage of limestones in the State.

Limestones checked and sampled as possible economic high-calcium deposits include Cenozoic travertine of the Lucero Mesa, Mesa del Oro, and Ladron Mountains areas; the caliche "caprock" of the Llano Estacado; the Tertiary algal limestone of Apache Valley; limestone beds in the northern and central New Mexico Upper Cretaceous sequence; the Lower Cretaceous limestones of southwestern New Mexico; the Jurassic Todilto limestone southeast of Grants and east of Santa Rosa; favorable Permian, Pennsylvanian, Mississippian limestones in the Robledo, Guadalupe, Sacramento, Peloncillo, Florida, Tres Hermanas, Oscura, Sandia, Manzano, Sangre de Cristo, Ladron, and Magdalena mountains, Border Hills, Cerros de Amado, and near Luna; and the El Paso Limestone in the Victorio Mountains. The samples collected are merely a partial testing of the limestones in these areas and are meant only as a rough guide to commercial possibilities. Any industrial firm wishing to utilize the limestones must do extensive field sampling to gauge the average composition of mineable units.

LOCAL USES OF LIMESTONE

Small crude lime kilns were built by the Spanish-Americans and Mexicans some centuries ago in the north-central part of the State to obtain minor quantities of whitewash and lime mortars. Local lime kilns were used in many areas until centralization of the lime industry after World War I. In 1910, Burchard (1912) reported that New Mexico ranked 36th among the states in the quarrying of limestone for production of lime; 4445 tons were produced by five operators, at an average value of \$4.03 a ton. There were working quarries in eight counties during 1912 (Burchard, 1913), with the limestone used for

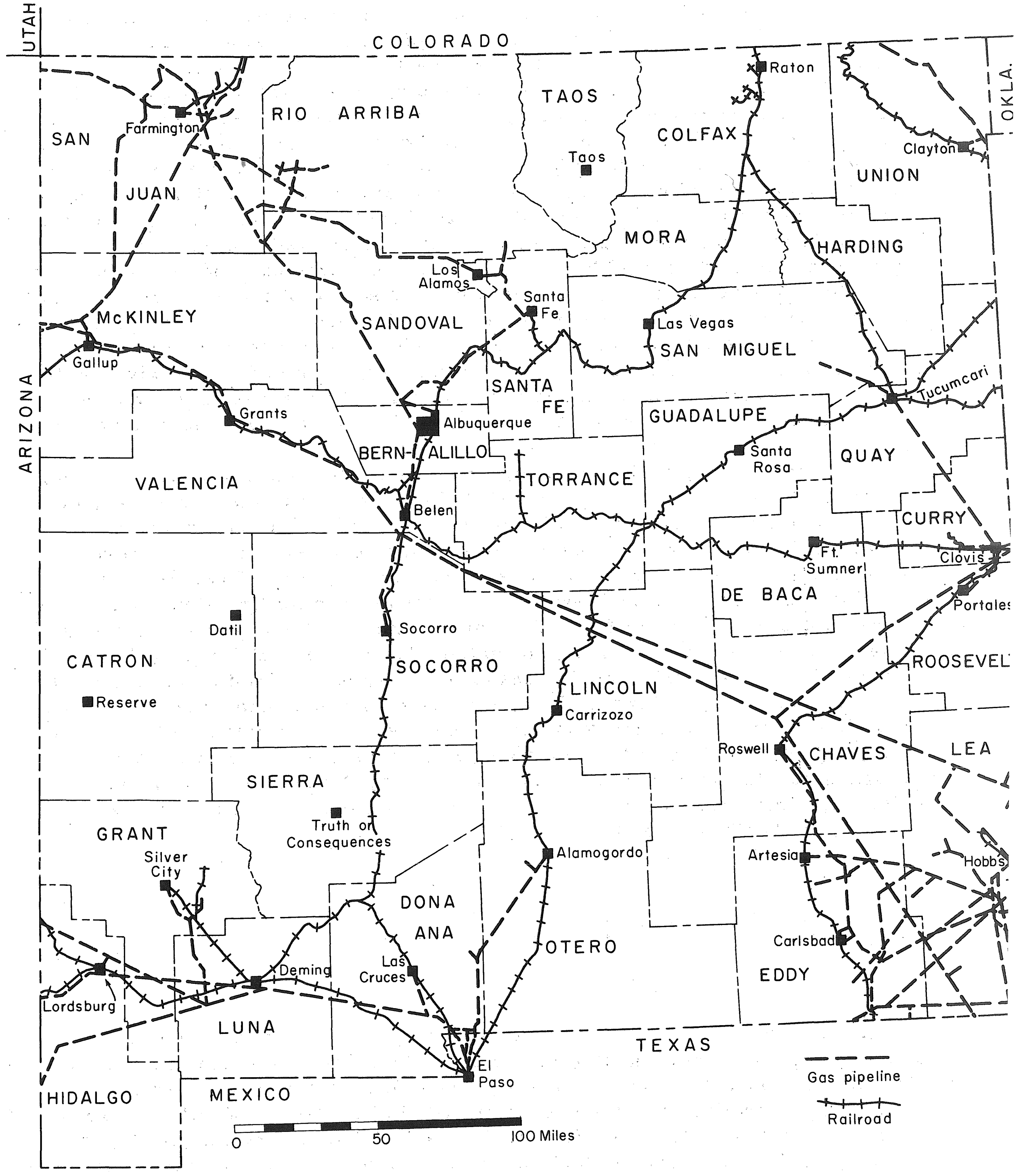

Figure 1
Index map of New Mexico showing railroads, gas pipelines, counties, and larger cities

manufacture of lime, railroad ballast, and cement. Kilns were in operation near Silver City, Watrous in Mora County, Kirtland in San Juan County, Las Vegas, Santa Fe, and near Bluewater in Valencia County. Limestone was also quarried near Vaughn, Tecolote in Lincoln County, Cerrillos in Santa Fe County, on Cerro de Muleros, and near Alamogordo.

During 1920, only 3034 tons of lime were sold in New Mexico (Loughlin and Coons, 1923), and only 660 tons of the lime were produced in the State, the rest being "imported" from Texas and Colorado. That year 1134 tons of limestone building stone were quarried and sold; thereafter, the sale of limestone for building stone and "onyx marble" decreased to a small part of the annual average of building stone produced in the State, which has been about 450 tons a year, priced at slightly more than a dollar a ton. During the height of the boom, prior to the 1930-1932 depression, each year about 15,400 tons of lime were shipped into New Mexico, in contrast to only 700 tons manufactured in the State; the major plant was in East Las Vegas, with small local-use plants in Kirtland and Santa Fe (Coons, 1932). Until the recent installation of the Ideal Cement Company quarry and cement plant at Tijeras near Albuquerque, cement and other lime products were shipped into the State from Colorado, Texas, and Arizona.

Use of limestone as a source of lime, a major basic industrial chemical, depends upon future development and acquisition of industry in the State, as does the use of limestone as a chemical raw material in such varied processes as glass making and acid neutralization. Crushed and ground limestone, caliche, and some travertine is used locally as a soil conditioner. The Chino Mines Division of Kennecott Copper Corporation quarries Pennsylvanian limestone from Lone Mountain; this is calcined in their kiln at Hurley, about 35,000 tons of hydrated lime being produced annually, and used for neutralization of the flotation circuits in their Hurley mill. Some limestone is used as a conditioning agent in various mills in the New Mexico area. Ground limestone is applied as a dust to the walls of many of the coal mines in the northern part of the State to reduce fire hazards. The largest possible use at the present time is as crushed stone for concrete aggregate, road metal, railroad ballast, sewage filter beds, and roofing granules. Being a monomineral rock, pure limestone has more uniform weathering characteristics than other common rocks, such as impure sandstone, granite, basalt, rhyolite, and andesite; most limestone, therefore, is a more resistant rock for road metal or concrete aggregate.

If foreign sources of sugar are curtailed, domestic manufacture of sugar from beets could become a large-scale operation in New Mexico. Milk of lime is used to clarify and purify beet juice to produce sugar. Carbon dioxide is also used in the process, so that most sugar-beet factories produce their own lime and use the carbon dioxide obtained from their kilns for the carbonation process. This industry requires a very pure grade of high-calcium lime (Bowles, 1952), with silica less than 1 percent, magnesia less than 3 percent, and ferric oxide less than 0.5 percent. Some other physical properties are necessary, depending on the details of the process used; for example, many sugar-beet factories in California (Bowen, 1957) require that the limestone must retain its lump form during calcination.

Limestone has been used in small amounts as dimension stone in New Mexico and in larger quantities as flagstone and for similar rough stone utilizations. Dimension stone must be uniform in color and texture, free from iron sulfides which may oxidize to stain the rock, low in chert and quartz, and not too porous (less than 10 percent). A relatively "soft" (but not friable) limestone that can be worked easily but that later hardens during weathering--like the famous Indiana building stone, the Mississippian Salem Limestone--is desirable. Some of the Mississippian and Pennsylvanian crinoidal calcarenites in the State have most of these characteristics, although they tend to be too coarse-grained and too hard. The Mississippian Lake Valley Limestone has been quarried as "marble" in Marble Canyon east of Alamogordo, and some of the travertines, especially those of the northeastern Lucero Mesa area, have been used in small amounts as travertine orthomarble. Many of the thin- to medium-bedded slabby limestones in the State have been used locally as flagstone, to build rough-faced stone houses, and for walls and low dams. Most artificial stone is cheaper than natural limestone, and competition with well-known "name" natural limestones would be a great handicap for any dimension stone quarries worked in New Mexico.

PROCEDURE

Sampling areas were picked after extensive use of geologic maps, geologic reports, and aerial photographs. Key areas were selected a short distance from gas pipelines, not more than 20 miles from a railroad, and where thick limestone beds cap extensive mesas or dip slopes. Favorable units were walked out for some distance in the field and sampled. Massive, cliff-forming limestones were a problem to sample; fresh fragments were obtained by breaking off many chips with a 10-pound sledge hammer, and discarding chips with weathered faces or joint faces. If the limestone appeared uniform, chips approximately one cubic inch were collected from about each six inches of thickness. Where the limestone unit is made up of beds of differing types of limestone (the usual case), chips of each type were obtained, again about one cubic inch per six vertical inches.

Tonnage calculations were based on 160 pounds per cubic foot, as limestone ranges from 150 to 169 pounds per cubic foot. A ton, therefore, consists of about 13 cubic feet; a 13-foot-thick limestone bed, outcropping as a 100-foot-wide ledge and extending for less than 2 miles (10,000 feet), could yield a million tons of limestone.

The chip samples were crushed in a Chipmunk crusher. Vein material and fragments with weathered surfaces were removed during examination under a binocular microscope; then the small chips were ground to about 50 mesh in a Braun pulverizer. Quartered and requartered parts of the sample (200-500 grams) were leached slowly at room temperature in concentrated hydrochloric acid (HCl) to determine the percentage of insoluble material;

parts of the purer limestones were sent to Chapman, Wood, and Griswold for chemical analyses, or to Richard K. Leininger, Elmer M. Craig, and Maynard E. Coller for spectrographic and partial chemical analyses.

Even if the field samples were representative of the vertical variations in the limestone unit, there may be some lateral, chemical variation. Complete mixing in the laboratory is difficult because a thick limestone unit yielded as much as 20 pounds of chips; crushed and ground, the final part analyzed is only several hundred grams at most, or in the instance of the spectrographic analyses, 10 miligrams from a 10-gram split of the sample. Despite attempts at thorough mixing and uniform division of the entire sample into small parts, several determinations of insoluble residues on different parts of samples from an impure limestone (residue 8-11%) gave as much as 3 percent variance in the amount of insoluble residues.

As noted by Grim (1953), part of the various clay minerals may dissolve in HCl, although this occurs chiefly at elevated temperatures. Some minor part of insoluble clay minerals, and perhaps silica of clay size, may be lost during even careful decanting. For some samples, the chemical and spectrographic analyses showed larger amounts of insoluble residue oxides (silica, alumina, etc.) than determinations of residues by leaching 200 to 500 grams in HCl. For a few samples, the leached residue was larger than that determined by the other methods. Any major differences, on the order of one percent, appear to be due to poor mixing and faulty quartering of the samples.

ACKNOWLEDGMENTS

Most of the crushing, grinding, and insoluble-residue determinations were by Donald A. Stephenson, student assistant. He also checked some of the residues under the petrographic microscope and ran several X-ray diffraction powder photographs of residues. Some of the chemical analyses were by D. H. Reynolds of Chapman, Wood, and Griswold; other chemical determinations were by Maynard E. Coller and Elmer M. Craig; and the spectrographic determinations were by Richard K. Leininger and Elmer M. Craig, Geochemistry Section, Indiana Geological Survey. Alvin J. Thompson, Director of the New Mexico Bureau of Mines and Mineral Resources division of New Mexico Institute of Mining and Technology, suggested and encouraged this study; Max E. Willard, Robert H. Weber, George B. Griswold, Roy W. Foster, Frederick J. Kuellmer, Robert A. Bieberman, and Ming-Shan Sun, Bureau staff members, gave technical advice and constructive criticism.

Technical editing was by Roy W. Foster, George B. Griswold, and Alvin J. Thompson of the New Mexico Bureau of Mines staff; Miss Terry Ray, our Publications Editor, supervised editing and proofing of the report. Most of the drafting was done by William E. Arnold, Bureau staff, and the typing of various stages of the manuscript was performed by Shirlee Stahmann, Patricia Johnson, Josie M. Baca, Lois Devlin, and Jeri Roche, also of the Bureau staff. Charles S. Treseder, assisted by Joaquina C. Trujillo, set up and printed this report in the Institute's Photographic Laboratory.

Stratigraphy

Small lenses of carbonate rocks, dolomitic in most places, occur amid rocks of Precambrian Age in widely scattered points of southern New Mexico, such as in the Redrock area (Hewitt, 1959) and near Hembrillo Canyon in the central San Andres Mountains. The thick Precambrian quartzite and schist sequences of the central and northern parts of the State lack appreciable amounts of limestone (Foster and Stipp, 1961).

Most of the high-calcium limestones in New Mexico are of Paleozoic Age, and mainly of late Paleozoic (Mississippian through Permian) Age. Locally the Jurassic Todilto limestone is high in calcium. The Lower Cretaceous strata of southwestern New Mexico include high-calcium limestones, but the thin limestones of the Upper Cretaceous contain at least 10 percent impurities. The Cenozoic caliches and travertines are impure except for local high-purity lenses (table 1, nos. 2, 3); the algal limestone in the Palm Park Formation, however, is high-calcium limestone (table 1, no. 1).

PRE-MISSISSIPPIAN LIMESTONES

Fossiliferous pre-Mississippian post-Precambrian strata crop out only in southwestern and south-central New Mexico, the northeasternmost outcrops being in the northern San Andres and southern Oscura mountains. The oldest unit is the Bliss Sandstone, of Cambrian and Ordovician Ages; locally, there are a few limy beds near the top of the sandstone, sensu stricto. The overlying El Paso and Montoya groups, of Ordovician Age, are chiefly of dolomite and magnesium limestone. The El Paso Group may contain some local high-calcium limestone beds; it thickens, under a pre-Montoya erosion surface, from a knife-edge at the northern sections (in the northern San Andres Mountains) to more than 1400 feet near El Paso, being about 800 feet thick in the latitudes of Las Cruces and Deming. Analyses of the El Paso Group limestones from scattered localities (Kottlowski, 1957) show more than 10 percent magnesium carbonate, and most samples at least 5 to 10 percent insoluble residues, chiefly of quartz silt. Selected limestones from the El Paso Group in the Victorio Mountains, however, contain almost 94 percent calcium carbonate (table 2, no. 28). Purer limestones may occur locally in other areas within the El Paso Group.

Except for a few beds of impure limestone in the upper Cutter Formation, the Montoya Group is entirely of dolomite or dolomitic limestone (except for basal dolomitic sandstones), although locally there are beds of magnesium limestone. Limestones have been reported in the Montoya from the Cooks

TABLE 1. Analyses of High-Calcium Limestones in New Mexico

o.	CaO	MgO	SiO_2	Al_2O_3	Fe_2O_3	P_2O_5	CO_2	S	$CaCO_3$	$MgCO_3$	Rock unit; location
1.	-	-	0.73	0.23	0.16	0.034	44.00	0.042	97.10	1.59	Palm Park Fm.; Apache Valley
2.	-	-	0.11	0.04	0.04	0.007	43.80	0.056	99.00	0.46	travertine; E. of Riley
3.	54.61	0.14	tr	0.23	0.31	-	42.68	-	96.48	0.29	travertine; Mesa del Oro
4.	-	-	2.62	0.56	0.28	0.008	42.40	0.001	95.40	0.70	Lower Cretaceous; Tres Hermanas Mts.
5.	-	-	3.22	0.46	0.05	0.360	42.20	0.020	95.40	0.46	Lower Cretaceous; Tres Hermanas Mts.
6.	-	-	insol;1.42	--0.15--		0.000	-	0.120	96.63	1.17	Castile Fm.; Guadalupe Mts.
7.	-	-	insol;1.94	--0.23--		0.000	-	-	96.02	1.08	Lamar Ls.; Guadalupe Mts.
8.	-	-	insol;1.16	--0.24--		0.000	-	-	97.66	1.78	Rader Ls.; Guadalupe Mts.
9.	-	-	0.10	0.00	0.10	-	-	-	96.00	3.80	Capitan Ls. talus; Guadalupe Mts.
0.	-	-	0.40	-	-	-	-	-	98.20	1.30	Capitan Ls. reef; Guadalupe Mts.
1.	-	-	1.26	0.08	0.06	0.087	43.30	0.008	97.40	0.86	San Andres Ls.; Rio Penasco Canyon
2.	-	-	insol;0.96	--0.20--		0.060	-	-	98.20	0.60	Victorio Peak Memb.; Guadalupe Mts.
3.	-	-	0.40	0.05	0.13	-	-	-	97.30	2.24	patch reef, Bone Spring Ls., Guadalupe Mts.
4.	54.70	0.26	1.47	0.10	0.10	0.020	42.66	0.014	97.60	0.50	Hueco Ls.; Robledo Mts.
5.	-	-	3.10	0.24	0.32	0.004	42.20	0.006	95.40	0.40	Hueco Ls.; Florida Mts.
6.	-	-	-	-	-	-	-	-	97.00	-	Hueco Ls.; Hueco Mts.
7.	-	-	0.54	0.22	0.19	0.016	43.60	0.010	96.80	1.92	reef, Laborcita Fm.; near Tularosa
8.	-	-	0.80	0.14	0.05	0.029	43.30	0.001	98.20	0.30	Bursum Fm.; Oscura Mts.
9.	53.44	0.36	4.06	0.63	0.21	0.016	41.64	0.012	95.40	0.80	Virgilian ls. near Tijeras
0.	55.09	0.02	1.29	0.14	0.11	0.010	43.12	0.011	98.30	0.04	Council Spring Ls.; Cerro de Amado
1.	54.31	0.02	1.87	0.43	0.19	0.022	42.66	0.009	96.90	0.04	Moya Fm; Cerro de Amado
2.	55.47	0.04	0.61	0.02	0.11	0.010	43.62	0.015	99.00	0.08	reef, Holder Fm.; Sacramento Mts.
3.	-	-	2.46	0.34	0.19	0.035	42.10	0.001	96.10	0.44	Story Fm.; Cerro de Amado
4.	-	-	1.66	0.05	0.15	0.055	42.90	0.001	97.20	0.46	Desmoinesian ls. near Luna
5.	-	-	1.50	0.20	0.12	0.012	43.10	0.010	96.80	0.92	Madera Ls.; northern Ladron Mts.
6.	-	-	2.44	0.38	0.28	0.023	42.40	0.001	95.60	0.84	Madera Ls.; Magdalena Mts.
7.	-	-	0.52	0.07	0.04	0.013	43.50	0.003	98.40	0.46	Council Spring Ls.; Oscura Mts.
8.	-	-	insol;0.71	--0.61--		-	-	-	97.99	0.91	Pennsylvanian ls.; Las Vegas
9.	53.52	0.58	-	-	-	-	-	-	95.40	1.21	Pennsylvanian ls.; Franklin Mts.
0.	-	-	-	-	-	-	-	-	99.80	-	Pennsylvanian ls.; Hueco Mts.
1.	55.47	0.04	0.50	0.04	0.12	0.014	43.38	0.006	99.00	0.08	Lake Valley Ls.; Sacramento Mts.
2.	-	-	0.11	0.05	0.11	0.021	43.60	0.006	98.80	0.40	Escabrosa Ls.; Tres Hermanas Mts.
3.	-	-	1.36	0.06	0.07	0.009	43.60	0.003	98.80	0.38	Escabrosa Ls.; Peloncillo Mts.
4.	55.00	0.31	0.30	-	0.30	-	44.00	-	98.20	0.65	Lake Valley Ls.; Sacramento Mts.

amples Nos. 1, 2, 4, 5, 11, 15, 17, 18, 23-27, 32, and 33 analyzed by Richard K. Leininger, Elmer M. Craig, and [aynard E. Coller, Geochemical Section, Indiana Geological Survey; Nos. 14, 19-22, and 31 by D. H. Reynolds of hapman, Wood, and Griswold; No. 3 from Jicha (1958); Nos. 6-8, and 12 from King (1948); Nos. 9, 10, and 13 from ewell et al. (1953); Nos. 16 and 30 from Haigh (1958); Nos. 28 and 34 from Burchard (1912); and No. 29 from ichardson (1908).

TABLE 2. Selected Analyses of Limestones in New Mexico

No.	CaO	MgO	SiO_2	Al_2O_3	Fe_2O_3	P_2O_5	CO_2	S	$CaCO_3$	$MgCO_3$	Rock unit; location
1.	47.66	0.66	10.11	0.91	0.61	0.025	37.66	0.160	85.07	1.38	travertine; near South Garcia
2.	-	-	9.18	2.14	1.29	0.100	37.70	0.035	85.00	1.27	Ft. Hays Ls.; near Springer
3.	-	-	13.10	3.06	2.20	1.120	33.90	0.180	76.80	2.56	Mancos Fm.; near Capitan
4.	-	-	8.40	0.14	0.09	0.012	40.10	0.001	90.00	0.92	Lower Cretaceous ls.; Tres Hermanas Mts.
5.	-	-	8.76	1.92	0.29	0.140	37.70	0.005	85.90	1.50	Lower Cretaceous ls.; East Potrillo Mts.
6.	-	-	3.70	0.66	0.43	0.020	41.70	0.024	93.30	1.32	Lower Cretaceous ls.; Cerro de Muleros
7.	52.36	1.01	3.22	0.78	0.28	-	-	0.050	93.46	2.11	Lower Cretaceous ls.; near El Paso
8.	52.83	0.19	3.64	0.58	0.64	0.021	41.42	0.090	94.30	0.40	Todilto ls.; SW of Mesita
9.	-	-	1.03	0.17	0.14	0.021	43.30	0.070	94.60	3.48	Todilto ls.; E. of Santa Rosa
10.	51.90	0.68	6.55	0.32	0.28	-	-	-	92.64	1.42	Todilto ls.; Chuska Mts.
11.	45.84	0.72	13.04	1.08	-	-	36.03	-	81.82	1.50	Todilto ls.; Chuska Mts.
12.	47.06	0.68	12.15	0.59	-	-	36.97	-	84.00	1.42	Todilto ls.; Chuska Mts.
13.	47.00	0.83	11.63	0.72	-	-	36.90	-	83.90	1.73	Todilto ls.; Chuska Mts.
14.	-	-	0.30	0.00	0.00	-	-	-	93.70	6.00	talus, Capitan Ls.; Guadalupe Mts.
15.	-	-	0.20	0.10	0.10	-	-	-	77.60	22.40	talus, Capitan Ls.; Guadalupe Mts.
16.	-	-	0.60	0.07	0.07	0.005	44.90	0.010	82.90	16.20	reef, Capitan Ls.; Dark Canyon
17.	-	-	0.14	0.06	0.07	0.006	46.20	0.043	65.60	34.00	talus, Capitan Ls.; Jurnigan Draw
18.	-	-	1.70	0.18	0.11	0.040	44.80	0.038	75.20	22.30	San Andres Ls.; Border Hills
19.	-	-	10.64	0.66	0.30	0.007	40.10	0.021	66.20	21.20	Colina Ls.; Peloncillo Mts.
20.	51.21	2.11	2.28	0.32	0.17	0.007	42.54	0.030	91.41	4.41	Hueco Fm.; Robledo Mts.
21.	-	-	7.70	0.20	0.30	0.005	40.20	0.003	91.00	0.28	Hueco Fm.; Tres Hermanas Mts.
22.	52.18	0.69	4.57	0.59	0.52	0.024	41.38	0.015	93.14	1.44	Virgilian ls.; Abo Canyon
23.	-	-	4.78	0.49	0.39	0.049	41.20	0.015	92.50	1.30	Virgilian ls.; Abo Canyon
24.	-	-	7.39	1.08	0.82	0.120	39.50	0.020	88.90	0.75	Derryan ls.; near Bishop's Lodge
25.	-	-	5.78	0.59	0.24	0.074	40.60	0.007	92.30	0.61	Burrego Fm.; Oscura Mts.
26.	-	-	1.52	0.20	0.48	0.016	43.30	0.038	90.80	6.36	Mississippian ls.; near Bishop's Lodge
27.	-	-	5.62	0.43	0.29	0.120	40.80	0.035	91.00	2.11	Mississippian ls.; NE Sandia Mts.
28.	-	-	3.02	0.17	0.20	0.036	42.50	0.004	93.60	2.56	El Paso Ls.; Victorio Mts.

Sample Nos. 1, 8, 20, and 22 analyzed by D. H. Reynolds of Chapman, Wood, and Griswold; Nos. 2-6, 9, 16-19, 21, and 23-28 by Richard K. Leininger, Elmer M. Craig, and Maynard E. Coller, Geochemical Section, Indiana Geological Survey; No. 7 from Richardson; No. 10 from Allen and Balk, (1954); Nos. 11-13 from Allen, (1955); and Nos. 14 and 15 from Newell et al..

Peak and other areas (Flower, 1959; Howe, 1959); several such beds contain more than five percent magnesium carbonate.

The Silurian Fusselman Dolomite is more than 800 feet thick in the triangular area from the Victorio Mountains southeastward to the Franklin Mountains, but it thins rapidly northward and westward as a result of erosion during early Devonian and/or late Silurian time. Some of its carbonate-rock beds are as calcic as dolomitic limestone, but all its units appear to be high in magnesium (Kottlowski, 1957) with dolomite dominating. Devonian rocks typically are calcareous shales and calcareous siltstones; the only limestone beds are impure, thin, and lenticular. Silty dolomites, however, occur in the Onate Formation. Pre-Mississippian limestones are not likely sources of high-calcium lime in New Mexico.

MISSISSIPPIAN LIMESTONES

Mississippian strata in northern and central New Mexico occur as discontinuous remnant outcrops beneath an erosion surface of late Mississippian and early Pennsylvanian Ages (Armstrong, 1955, 1958; Fitzsimmons et al., 1956; Baltz and Read, 1960). Some of the crinoidal calcarenites in the Sandia, Ladron, Magdalena, Nacimiento, and Sangre de Cristo mountains appear to be relatively high-calcium limestone except for sparse to abundant chert lenses and nodules. Locally, these encrinites are thick (20 to 50 feet) and cap low benches below ledges and slopes eroded on the shaly lower Pennsylvanian strata. Samples from cherty Mississippian limestones near Bishop's Lodge (table 2, no. 26) in the southwestern Sangre de Cristo Mountains and along Las Huertas Creek Canyon (table 2, no. 27) in the northeastern Sandia Mountains contained only 91 percent calcium carbonate, 2 to 6 percent magnesium carbonate, and 1.5 to 5.6 percent silica. These samples are representative of the total thickness of the Mississippian limestones at these localities; selected purer samples had insoluble residues (quartz and clay) of 0.3 to 0.7 percent. In the southeastern Sangre de Cristo Mountains along Gallinas Canyon east of Montezuma, as reported by Baltz and Read, the Cowles Member of the Tererro Formation (upper unit of the Mississippian) is as much as 40 feet thick and consists of a crinoidal calcarenite with insoluble residue (grab sample) of about 0.6 percent.

The Mississippian Lake Valley Formation exceeds 100 feet in thickness in the Sacramento Mountains (Pray, 1961), southern San Andres Mountains (Kottlowski et al., 1956), Cooks Peak-Lake Valley area (Jicha, 1954), and Silver City-Santa Rita district (Hernon, Jones, and Moore, 1953). Similar limestones, partly correlative with the Lake Valley Formation, are placed in the Escabrosa Group by Armstrong (1961). This group includes as much as a thousand feet of carbonate rocks in the Big Hatchet and Animas mountains and Klondike Hills, and locally it may exceed 500 feet in the Peloncillo and Tres Hermanas mountains. Analyses of these crinoidal strata (table 1, nos. 31-34) show them to be high-calcium limestone; near Alamogordo millions of tons are available within a short distance of a gas line and railroad.

The Mississippian strata in the Franklin Mountains are mainly siliceous impure limestone of the Rancheria Formation. To the north along the Rio Grande, the Mississippian section is thin or absent in the Robledo and Caballo mountains.

PENNSYLVANIAN LIMESTONES

The sedimentary beds of Pennsylvanian Age are thick, if variable, in New Mexico (Thompson, 1942; Kottlowski, 1960a; Read and Wood, 1947) and crop out in most of the major mountain ranges. The majority of the outcrops include high-calcium limestones, and in many areas these limestones underlie dip-slope mesas where they could be quarried from open pits with removal of only thin overburden. Extensive outcrops of Pennsylvanian limestones occur in the Sangre de Cristo, Nacimiento, Sandia, Manzano, Los Pinos, Ladron, Magdalena, Oscura, San Andres, Sacramento, Franklin, Robledo, Big Hatchet, and Peloncillo mountains, the Cerro de Amado, and the Silver City–Santa Rita area. Smaller outcrop areas are scattered in many other mountain ranges. An average section (if there is one) of the Pennsylvanian strata is 1000 to 3000 feet thick and consists of a basal clastic unit in which most of the limestones are arenaceous, a thick medial unit of cherty to high-calcium limestones, and an upper unit of interbedded marine limestones and shale-sandstone beds (i.e., siliciclastic beds). The medial unit forms ledgy cliffs in many mountain ranges. Dip slopes of the tilted fault-block ranges are, in many places, of massive limestones in the upper unit. Obviously, the best quarry locations (such as that of the Ideal Cement Company east of Albuquerque) are within high-calcium limestones of the upper Pennsylvanian, where the interbedded, shaly, clastic strata have been removed by erosion, leaving thick, pure limestones near the surface covered by only thin overburden. Such possible quarry locations occur in most of the mountain ranges listed; analyses from typical high-calcium Pennsylvanian limestones are listed in Table 1 (nos. 19-30).

PERMIAN LIMESTONES

The basal Permian strata in many parts of south-central New Mexico are the interbedded red beds and marine limestones of the Bursum Formation (Wilpolt and Wanek, 1952; Thompson, 1954). Southward from the Oscura Mountains, this formation and correlative units include some massive high-calcium limestones that are near transportation facilities in the northern

Sacramento Mountains (Otte, 1959) and Robledo Mountains (Kottlowski, 1960b). The upper part of the Horquilla Limestone, hundreds of feet of massive limestone, is of early Permian Age in the Big Hatchet (Zeller, 1958) and Peloncillo (Gillerman, 1958) mountains.

The basal Permian in most of north-central New Mexico is within the Abo Redbeds, the Sangre de Cristo Formation, or the Cutler Redbeds. The Abo Redbeds grade southward into the Hueco Formation which includes thick, high-calcium limestones in the San Andres (Kottlowski et al.), Franklin (Harbour, 1960), Robledo, Dona Ana (Kottlowski, 1960b), Florida, and Tres Hermanas (Kottlowski and Foster, 1962) mountains (table 1, nos. 14-16).

The Yeso Formation, conformable on the Abo Redbeds, consists of interbedded gypsum, brown sandstone, pinkish shale, and thin, impure limestone. The amount of limestone, as well as the thickness of the limestone units, increases southward. In most areas, however, the Yeso limestones appear to be dolomitic and silty. Outcrops of the Yeso Formation are shown only locally where some of the carbonate-rock beds may be high-calcium limestone. In the central part of the State, the Yeso is overlain by the Glorieta Sandstone and it in turn by the San Andres Limestone. In south-central New Mexico, however, the Yeso grades up into the San Andres Limestone with any of several thin, lenticular, arenaceous beds in the upper Yeso or lower San Andres being called the "Glorieta" or Hondo Sandstone.

The San Andres Limestone (and uppermost beds of the Yeso) crops out over extensive areas in the central, south-central, and southeastern parts of the State. The formation is the surface bedrock of Chupadera and Jumanes mesas, the higher mesas east of Socorro and on the southeast back slope of the Los Pinos Mountains; the wide plateau (on the west edge of the High Plains) extending south from near Vaughn onto the east back slopes of the Jicarilla, Capitan, White, and Sacramento mountains; and much of the Otero Mesa–western Guadalupe Mountains area of southeastern Otero County. The San Andres Limestone caps dip-slope cuestas or hogback ridges in or bordering the Zuni, Nacimiento, Sandia, San Andres, Fra Cristobal, and Caballo mountains, Lucero Mesa, Sierra Cuchillo, and the Phillips Hills. The formation crops out on the Glorieta Mesa escarpment and occurs in small outcrop patches along Nogal Canyon in the volcanic San Mateo Mountains and on the south side of Horse Mountain amid the volcanic rocks of the Datil Plateau.

Descriptions of the carbonate-rock beds of the San Andres Limestone show most individual beds to be dolomitic limestone or magnesium limestone (i.e., more than 5 percent magnesium carbonate). Beds quarried near Gallinas in central New Mexico, for example, showed (written communication from Vincent C. Kelley, 1957) 20.02 percent magnesium oxide, 32.20 percent lime, and 3.26 percent silica. In the central Guadalupe Mountains, Boyd (1958, p. 24) reported that samples typical of the San Andres Formation contained 1.1 to 0.5 percent silica, 40.6 to 45.7 percent magnesium carbonate, and 53.1 to 58.8 percent calcium carbonate--nearly pure dolomites! In contrast, however, samples from the type section of the San Andres Limestone, in Rhodes Canyon of the San Andres Mountains, gave (Kottlowski, 1957) analyses high (13.2 percent) in silica (quartz sand and silt) for the basal 95 feet of dolomitic limestones, but an average lime content of 53.5 percent for the overlying 220 feet (insoluble residue 1.3 percent) of relatively pure limestones, whereas the upper 255 feet of the formation contains 20.3 to 28.7 percent magnesium carbonate. On the eastern slopes of the Sacramento Mountains, and in oil tests drilled in that area, the lower part of the San Andres Limestone is reported as chiefly limestone (table 1, no. 11), whereas the upper beds are mainly dolomite (table 2, no. 18). Extensive sampling of the widespread San Andres Limestone outcrops should locate some high-calcium limestones in places where they could be quarried economically.

Northward from the type section (Lee and Girty, 1909; Needham and Bates, 1943; Kottlowski et al.), the San Andres Limestone thins from the 600 to 750 feet in the northern San Andres Mountains to 110 feet in the southeastern Zuni Mountains and 15 feet on northern Glorieta Mesa. Interbeds of gypsum occur in such areas as Mesa del Oro (Jicha, 1958), Lucero Mesa (Kelley and Wood, 1946), and southeastern Chupadera Mesa (Wilpolt and Wanek), suggesting deposition in nearshore lagoonal evaporite basins. Toward the southeast, the San Andres Limestone apparently thickens in the Guadalupe Mountains to about 1200 feet (Hayes, 1959) locally, although there is considerable disagreement as to formation boundaries (Boyd) and as to the carbonate rocks included within the San Andres Limestone. Triassic or younger strata overlie eroded parts of the San Andres Limestone where it is present in the State, except in the eastern part where the Guadalupian Bernal Formation and Artesia or Whitehorse Group (Chalk Bluff) rests upon the San Andres Limestone.

The interbedded red beds, gypsum, and dolomitic rocks of the Artesia–Whitehorse–Chalk Bluff–Bernal Group (Formation) crop out along the Pecos River Valley from Carlsbad northward, and in the Guadalupe Mountains. The carbonate-rock beds are thin, lenticular, impure, and dolomitic. Correlative basinal beds of the Cherry Canyon and Bell Canyon formations crop out in the State only along the New Mexico–Texas stateline in the southern Guadalupe Mountains. The limestone members of these formations locally are as much as 100 feet thick. The carbonate rocks of the Cherry Canyon Formation are impure or dolomitic (King; Newell et al.); the Rader and Lamar Limestone Members of the Bell Canyon Formation, however, include high-calcium limestones (table 1, nos. 7, 8) that crop out on the southeast side of the Guadalupe Mountains. The basinal Yeso equivalent, the Bone Spring Limestone, crops out in the Brokeoff Mountains, the western part of the Guadalupe Mountains, a relatively inaccessible area. Analyses from King of the upper part of the Victorio Peak Member of the Bone Spring Limestone show that it is high-calcium limestone (table 1, no. 12).

The massive Capitan reef limestone crops out along the southeast Guadalupe Mountains escarpment front and is 1500 to 2000 feet thick if measured vertically without regard to the dip of the reef-flank beds. This limestone, according to Newell et al., is mainly of unstratified calcitic limestone, whereas the bordering reef-talus beds contain high percentages of dolomite. Newell et al. listed 11 analyses of the Capitan reef rock; they average (table 1, no. 10) 98.2 percent calcium carbonate, 1.3 percent magnesium carbonate, and 0.4 percent silica. Obviously, this appears to be a huge mass of high-calcium limestone, near gas fields, a railroad, and U.S. highways. Much of the outcrop area is within Carlsbad Caverns National Park, but the outcrop belt extends for about 10 miles northeast of the Park, and from the Park southwestward to the New Mexico–Texas stateline. Cursory sampling of the Capitan Limestone, however, suggests that the limestone and dolomite facies are complexly mingled. Whereas most of the reef-flank beds do appear to be dolomitic, or at least magnesium-rich (table 2, nos. 14, 15, 17), some of the reef-core beds also contain appreciable amounts of magnesium carbonate. A chip-channel sample (table 2, no. 16) of the reef core in Dark Canyon yielded 16 percent magnesium carbonate. Where the reef-core facies is overlain by sandstone tongues of the Yates and Tansill Formations, the core appears to be dolomitic and siliceous, as along North Slaughter Canyon. Also, along parts of McKittrick, Rattlesnake, and West Slaughter canyons, the reef-flank beds, especially the more massive ones, appear to be chiefly limestone, as determined by dilute HCl and by specific gravity tests (in heavy liquids).

The Ochoan Castile and Rustler Formations crop out above the Guadalupian rocks in the Delaware basin, forming low hills between the valleys of Black River and the Pecos River south of Carlsbad. The Rustler Formation is of dolomite, gypsum, and siltstone, whereas the underlying Castile Formation outcrops consist of gypsum, interlaminated gypsum and limestone, and some thin beds of limestone. In the subsurface, both formations include much anhydrite and some halite. Oddly enough, an analysis of a basal limestone from the Castile Formation, as given by King (p. 90), shows a high-calcium limestone containing 96.63 percent calcium carbonate (table 1, no. 6). Most of the Castile limestones are too thin and too intimately interlaminated with gypsum to be of commercial use.

In the southwestern corner of New Mexico, Permian rocks younger than the Hueco Formation crop out in the Big Hatchet, Peloncillo, and Animas mountains. The section, as described in detail by Zeller (1958) and Gillerman, consists of the Horquilla Limestone (of Pennsylvanian and Wolfcampian Ages), Earp Redbeds, Colina Limestone, Epitaph Dolomite, Scherrer Sandstone, and Concha Limestone. Fusulinids date the upper Horquilla as Wolfcampian and the Concha Limestone as Leonardian. Yochelson (1956) identified Wolfcampian gastropods in the Colina Limestone from southeastern Arizona; the upper Horquilla Limestone, Earp Redbeds, and the overlying Colina Limestone appear to be a sequence similar to that in the Robledo Mountains (Kottlowski, 1960b) where the Hueco Limestone includes a tongue of the Abo Redbeds. Both the Horquilla and Colina Limestones probably contain high-calcium limestone beds but crop out in relatively inaccessible areas. A chip-channel sample from the Colina Limestone in the Peloncillo Mountains (table 2, no. 19) showed large amounts of silica and magnesium carbonate, but the sample was collected in a metamorphosed zone near a granite intrusive mass.

The Epitaph Dolomite includes gypsum and siltstone interbeds and may be a southwestern correlative of the Yeso and Bone Spring Formations; no appreciable amount of high-calcium limestone is known from the Epitaph Dolomite. Likewise, the Concha Limestone (correlative to the San Andres Limestone ?) appears, from the scant data available, to be too cherty and too dolomitic to contain high-calcium limestones.

MESOZOIC LIMESTONES

Limestones in Triassic rocks are limited to thin, lenticular, arenaceous to conglomeratic, limy beds in the Chinle and Moenkopi Formations of northwestern New Mexico and the Dockum Group of the eastern part of the State.

Within Jurassic strata, limestones occur in the Todilto Formation of northern New Mexico. Where typically developed, this formation consists of a lower limestone and an upper gypsum; locally, the limestone is as much as 40 feet thick. The limestone is dark, laminated, thin- to massive bedded, fetid, and contains upper laminae of gypsum. Near the western edge of limestone deposition, in Todilto Park close to the New Mexico–Arizona stateline, the limestone grades laterally from a 14-foot limestone bed into limy sandstone and siltstone. A typical analysis of the limestone in this area is listed in Table 2, no. 10 (Allen and Balk). North of Todilto Park near Beautiful Mountain, Allen noted an extensive mesa capped by 7 to 14 feet of Todilto limestone and estimated the reserves at 36 million tons. Analyses of three channel samples from this locality are given in Table 2, nos. 11-13. These samples average 12.27 percent silica. Allen believed the silica is present as arenaceous laminae within the lower foot of the limestone. He suggested that if this lower foot were selectively left in quarrying, the upper beds would be a high-calcium limestone averaging 97.5 percent calcium carbonate.

The Todilto limestone crops out (fig. 2-4) along the north edge of the Zuni Mountains from near Wingate to east of Grants. Smith (1954) reported the limestone to be 7 to 30 feet thick in this area (average thickness of about 14 feet) with numerous laminae of sandstone, siltstone, and gypsum--as well as pods of uranium ore. Farther to the southeast the Todilto limestone crops out along the north valley wall of Rio San Jose from near Mesita to north of Suwanee and in several isolated outcrops on the flanks of Mesa Redonda and Lucero Mesa. Darton (1928) reported the thickness as 5 to 16 feet. Similar thicknesses occur northeast of Acoma.

Along the north wall of the broad valley of Arroyo Colorado, the Todilto limestone is thick and caps extensive benches extending from Mesita southeast to Petoch Butte which is near its southwest wedge-edge. Silver (1948) and Darton reported local thicknesses of 40 feet; a representative sample from this locality is given as no. 8 in Table 2. This sample contains about 94.3 percent calcium carbonate; selective mining may yield a high-calcium limestone.

East of the Rio Grande Valley there are small patches and some, more extensive, outcrops of the Todilto Formation northeast and east of the Sandia Mountains, near Lamy and near Rosario siding, and south of Galisteo (Read et al., 1944). The limestone member is thin (3 to 8 feet thick) and impure. Steeply dipping beds of the Todilto Formation occur along the west side of Sierra Nacimiento south of Cuba southward to White Mesa near San Ysidro; here the limestone member, a thin-bedded shaly unit, is 6 to 12 feet thick and is overlain by interlaminated limestone and gypsum that grade up into the thick, massive gypsum member (Weber and Kottlowski). The Todilto limestone is exposed north of Gallina in a northward structural extension of the hogback ridges near Cuba, as well as to the east along the canyon of Rio Chama and two of its tributaries, Rio Puerco and El Rito. Outcrops of the Todilto Formation encircle Mesa Prieta in this Rio Chama area; Budding, Pitrat, and Smith (1960) reported the limestone member is lenticular, ranging from 1 to 18 feet in thickness, and consists of lower dark shale grading upward from thin-bedded gray limestone into massive gray limestone; this in turn grades up into the gypsum member. Typically, the Todilto caps benches above cliffs of the Entrada Sandstone and below slopes cut in the Morrison Formation.

The Todilto limestone crops out in the hogback ridges along the southeast edge of the Sangre de Cristo Mountains near Las Vegas but is thin. On the south edge of Louisiana Mesa near the west border of Quay County east of Ima (sec. 18, T. 8 N., R. 27 E.), the eastern pinchout of the Todilto limestone borders the valley of Alamogordo Creek (Dobrovolny, Summerson, and Bates, 1946). The limestone is 2 to 10 feet thick and is a thinly laminated, platy to fissile bed containing paper-thin laminae of siltstone and gypsum. Amazingly, however, a channel sample shows almost 95 percent calcium carbonate with only slightly more than one percent silica (table 2, no. 9). The Todilto limestone crops out as a ledge, capping the soft, brown to light-gray Wingate Sandstone, and is overlain by the slope-forming shales and sandstones of the Morrison Formation.

Cretaceous strata in New Mexico change abruptly from the sandstone-shale-coal of northern and central New Mexico, which is chiefly of Late Cretaceous Age, southward to the marine limestones, cobble conglomerates, and reddish clastic rocks of southwestern New Mexico, which are mainly of Early Cretaceous Age. Limy beds above the Dakota Sandstone occur within the Mancos Shale, Mesaverde Group, and Lewis Shale in northwestern New Mexico, Mancos Shale in central New Mexico, and Graneros Shale, Greenhorn Limestone, Carlile Shale, Niobrara Formation, and Pierre Shale of the northeastern part of the State. These formations tend to contain more limestones, and thicker limestones, as one goes from the west to the northeast.

Along the west edge of the San Juan Basin, limy beds in the Cretaceous are thin, argillaceous limestone lenses or concretionary strata in the lower part of the Mancos Shale or in the Lewis Shale (Hayes and Zapp, 1955; Beaumont, 1954, 1955; Zieglar, 1955; Allen and Balk). In the Gallup-Zuni Basin, Sears (1925) noted a 10-foot-thick bed of fossiliferous impure limestone near the base of the Mancos. Eastward into the Mount Taylor region and to the southeast edge of the San Juan Basin, the limy beds are only calcareous, fossiliferous sandstone and zones of limestone concretions (Sears, 1934; Hunt, 1936; Dane, 1936). Along the northeast edge of the San Juan Basin, and in the eastward adjoining Chama basin, equivalents of the Graneros, Greenhorn, Carlile, and Niobrara are recognized (Dane, 1948). The Greenhorn Limestone member of the Mancos Shale consists of interbedded, gray, dense limestone and dark-gray calcareous shale; the limestone beds (units) are as much as 2-1/2 feet thick (Dane, 1960; Budding, Pitrat, and Smith) and are described as a limonitic *Globigerina* biomicrite by Muehlberger et al. (1960). Dane (1960) also noted some thin, gray, shaly limestones in the Niobrara calcareous shale member. Obviously, none of the Cretaceous limestones of northwestern New Mexico is high-calcium limestone and is not plotted on Figure 2. Burchard (1913) reported a lime kiln active near Kirtland; limy lenses in the Lewis Shale were quarried for this operation.

In northeastern New Mexico, limestones occur as thin, impure beds in the Graneros, Carlile, and Pierre Shales, and in the Greenhorn Limestone and Fort Hays Limestone (a member of the Niobrara Formation; the Timpas Limestone of Darton). In northwest Union County, Baldwin and Muehlberger (1959) noted that the Greenhorn Limestone is 20 to 30 feet thick, consisting of tan limestone in 1- to 2-foot-thick beds separated by shale laminae and thin beds, whereas the Fort Hays Limestone, 40 to 50 feet thick, contains much less shale. In Colfax County and farther to the southwest near Las Vegas, the Greenhorn is of thin (3 to 14 inches thick), argillaceous, fossiliferous, ferruginous limestones interbedded with calcareous shale (Griggs, 1948). To the southwest, the interbeds of shale increase in thickness to form more than half of the Greenhorn unit (Northrop et al., 1946); thus, the outcrop of the Greenhorn is shown only in Union County on Figure 4. The Fort Hays Limestone Member of the Niobrara Formation is 15 to 60 feet thick in Colfax County and northern Mora County and consists of 1- to 2-foot-thick beds of gray, finely crystalline limestone with interbedded dark-gray shale. Near Springer the limestone (table 2, no. 2) has been quarried for road metal. To the south, outcrops of the Fort Hays Limestone occur northwest of Las Vegas where they cap low hills.

An isolated patch of the Greenhorn(?) Limestone occurs near the east border of the State in south-central Quay County (sec. 33, T. 8 N., R. 32 E.) below and north of the north-facing bluffs of the Llano Estacado where Dobrovolny, Summerson, and Bates reported 30 feet of light-gray, shaly, argillaceous limestone.

Scattered areas of Cretaceous rocks crop out in southern Santa Fe County and the adjoining eastern parts of Sandoval and Bernalillo counties; however, the Greenhorn Limestone is merely interbedded limestone (in beds 6 to 12 inches thick) and shale, and the Niobrara Formation appears to be comprised entirely of clastic rocks (Stearns, 1953). Similarly, only thin, impure limestones occur in the Cretaceous of the Carthage coal field (Wilpolt and Wanek), Caballo Mountains (Kelley and Silver, 1952), southern San Andres Mountains (Kottlowski et al.), Cooks Range (Jicha, 1954), and Silver City area (Paige, 1916). Near the Capitan coal field in south-central Lincoln County on the east side of the Sierra Blanca volcanic complex, Allen and Jones (1951) reported a 60-foot-thick sequence of dark-gray limestone in the lower part of the Mancos Shale. Shale interbeds make up much of the sequence, and the limestone beds are impure (table 2, no. 3).

Cretaceous strata near the Mexican border include thick fossiliferous limestones, chiefly of Early Cretaceous Age. These Cretaceous limestones, and interbedded clastic units such as limestone-cobble conglomerate, sandstone, and tuff-breccia, range from hundreds to thousands of feet in thickness in the East Potrillo (Bowers, 1960), Tres Hermanas (Kottlowski and Foster), Big Hatchet (Zeller, 1953), Little Hatchet (Lasky, 1947), Animas, Peloncillo (Gillerman), and Victorio mountains, and form small areas of outcrop on Cerro de Muleros, on the west edge of the West Potrillo Mountains, and in faulted areas of Sierra Rica and the Apache Hills. Large masses of relatively high-calcium Cretaceous limestone are in remote localities, except the somewhat marly beds that encircle Cerro de Muleros near El Paso. Richardson gave an analysis (table 2, no. 7) of the limestone used by the Southwestern Portland Cement Company from quarries near Cerro de Muleros; it is almost high-calcium limestone, being barely too high in silica (3.2 percent) and with considerable magnesium carbonate (2.1 percent). This analysis is probably of the Edwards Limestone (Finlay Limestone, Goodland Formation). Higher, thick-bedded limestone from the Buda Formation, collected on the outskirts of Sunland Park Village, is similar in composition (table 2, no. 6), containing several percent too much silica (3.7 percent) and clay (alumina 0.7 percent).

The thick, Early Cretaceous limestone section in the East Potrillo Mountains (Bowers) probably contains some high-calcium limestone; it is 25 miles west of El Paso, reached by good ranch roads. A sample of the marbleized Early Cretaceous limestones along the fault zone at the base of section (table 2, no. 5) shows much silica and alumina, about 10 percent combined. These lower limestones are overlain by 400 to 600 feet of intercalated limestone-cobble conglomerate, arenaceous limestone, and limy sandstone; above is 200 to 500 feet of massive fossiliferous reefoidal limestone similar to high-calcium limestones in the Early Cretaceous of the Tres Hermanas Mountains. These massive limestones, however, cap the range and may be costly to quarry.

The Early Cretaceous beds that crop out (fig. 8) on the west side of the Tres Hermanas Mountains (Kottlowski and Foster) are more than 1530 feet thick and include massive beds of high-calcium limestone. Four lithic units, bounded above and below by faults, make up the section (fig. 9): (a) lower 375 feet of chert conglomerate, sandstone, pale-red siltstone, and silty limestone; (b) 395 feet of massive limestone; (c) 425 feet of limestone conglomerate and reddish sandstone; and (d) upper 340 feet of sparsely fossiliferous limestone. Many of the massive limestones (lower part of unit 10 and unit 16, fig. 9) contain more than 95 percent calcium carbonate (table 1, nos. 5 and 4, respectively) but 2.6 to 3.2 percent silica, whereas some of the limestones with scattered chert nodules (upper part of unit 10) include more than 8 percent silica exclusive of the chert nodules. These high-calcium limestones crop out on low dip-slope cuesta ridges but are reached only by sandy ranch roads from State Highway 11, the Deming to Columbus highway.

The section of Early Cretaceous rocks near the Cornudas Mountains, along the center of the southern border of Otero County (fig. 11), is chiefly of clastic beds with only a minor amount of sandy and shaly limestone.

CENOZOIC LIMESTONES

Most of the Cenozoic sedimentary strata of New Mexico are of clastic rocks which are highly calcareous because of their derivation, in part, from pre-Cenozoic limestones. The distinct "limestones" in the Cenozoic are classified as follows: (1) fresh-water lacustrine limestones, (2) spring deposits, calcareous tufa, and travertine, and (3) caliche blankets. With but few exceptions, these nonmarine calcium carbonate deposits do not qualify as high-calcium limestone because of their high content of clay and noncarbonate-rock sand and silt. Impure limestones occur in many of the Tertiary sedimentary units—for example, there are thin beds (several inches thick) and laminae of tuffaceous limestone and limy tuff within the basal Tertiary of the Robledo Mountains, a unit of interbedded red siltstones, gypsum, and tuff. Travertine and calcareous tufa spring deposits are extensive in the State; some of the larger deposits are those around Lucero Mesa and Mesa del Oro. The banded porous travertine of the northeastern Lucero Mesa area has been quarried as travertine "marble" and makes an attractive ornamental stone. Jicha (1956) described similar spring deposits from the Mesa del Oro area and gave an analysis (table 1, no. 3) showing the calcium carbonate content as 96.5 percent. The three samples that he combined for the analyses yielded insoluble residues of 0.3, 1.3, and 3.0 percent.

The travertine deposits on the northeast end of Lucero Mesa near South Garcia station were sampled extensively; only a few samples gave less than 10 percent insoluble residues, and these higher grade travertines were from thin lenticular beds. A representative chip-channel sample of a 17-foot-thick "bed" (table 2, no. 1) shows about 85 percent calcium carbonate, 11 percent silica and alumina, and almost 1 percent combined iron oxide and sulfur. Some of these spring deposits form thick extensive beds capping benches but they tend to be erratic in composition and thickness. Others are almost vertical veins along joints or faults. Some of the latter type are coarsely crystalline calcite. These travertine deposits are in most places near outcrops of older limestones, and only in a few areas do they appear to be of higher grade than the older calcium-carbonate strata.

West of the Ladron Mountains, and overlooking Rio Salado to the south, massive-bedded and laminated travertine caps the Santa Fe Formation and older beds, occurring along a north-south belt about 3 miles wide and about 9 miles long, underlying about 20 square miles of upland plains. The section exposed in the NE corner of sec. 22, T. 2 N., R. 3 W. is, above the canyon floor, more than 55 feet of conglomerate and sedimentary breccia, strongly cemented by calcite; clasts are of Precambrian rock types and of various Paleozoic rocks; then is light-brown to light-gray, laminated, algal limestone, beds 1 to 2 feet thick, unit up to 20 feet thick; and uppermost is loosely consolidated, calichified gravel and sand. Near the Rio Salado, the conglomerate overlies sands and sandstones typical of the Santa Fe Formation. A chip-channel sample of the laminated limestone (table 1, no. 2) shows 99 percent calcium carbonate. Grab samples from other localities contain scattered grains of quartz silt.

To the southeast, south of Rio Salado and west of the Lemitar Mountains and between the canyons of La Jencia and Silver Creeks, is similar laminated travertine capping the plains that overlook Rio Salado from the south. Here, approximately 2 square miles are underlain by travertine, in what is apparently a southeastward extension of the high-purity travertine west of the Ladron Mountains. Lower, impure travertines are interbedded with laminated tan clays that apparently are of lacustrine origin. Southward, the massive, relatively pure, travertine beds (individual beds are 3 to 5 feet thick) appear to grade laterally into limy sandstones. East of the Gray and Ligon Ranch, the travertine beds appear to grade westward into limy conglomeratic sandstones that dip westward underneath typical Santa Fe Formation sands and sandstones.

These travertines differ from spring deposits of the Lucero Mesa country which occur only along fault zones, in most places cover a belt only one-fourth to one-half mile wide, and include nearly vertical "veins" along fissures. The travertines west of the Ladron and Lemitar mountains, and east of Riley, in contrast, occupy a north-northwest-trending belt at least 3 miles wide, appear to thin both to the north and south, seem to grade westward and southward into Santa Fe Formation clastic strata, and eastward are covered by alluvial fans from the mountains. The western edges of the Ladron and Lemitar mountains do not appear to be fault controlled, except locally, being chiefly dip slopes of Paleozoic and Tertiary beds. Present-day springs occur on the east side, not the west side, of the ranges. Furthermore, the southern outcrops of the "Riley" travertine, those south of Rio Salado, are west of volcanic rocks in the northern part of the Lemitar Mountains; if ancient springs existed west of the northern Lemitars, one would not expect a high content of calcium carbonate in the spring waters.

The Riley travertine, therefore, is believed to have been deposited chiefly as lacustrine limestone in a late Tertiary playa. The fresh-water lake, or series of partly coalesced ponds, appears to have been about 16 miles long and 3 to 5 miles wide, with the calcium carbonate derived from solution of the Pennsylvanian limestones of the Ladron Mountains to the east and from limestones of the San Andres and Yeso Formations to the northwest. Rejuvenated uplift of the ranges tilted the southern part of the deposits so that they dip to the southwest, whereas the travertine north of Rio Salado appears to dip gently to the southeast. An alternative hypothesis (Denny, 1941) is that the Riley travertine is a pure, thick caliche, capping an erosion surface of intra-Santa Fe time, or even of post-Santa Fe time. The distribution of the travertine is related to outcrops of the Pennsylvanian limestones in the Ladron Mountains; they are believed to have provided a high lime content to ground water that was pulled into the subsoil by capillary action and there evaporated to form the unusually thick layers of massive-bedded caliche.

The banded travertine deposits described by Jicha (1956) at the northern tip of Mesa del Oro also occur in a rather anomalous situation for spring deposits. They cap the easily eroded Triassic red beds high above valleys carved in the red beds, and locally are overlain by Quaternary basalt flows. Apparently they are not related to any faults. Being erosional remnants, their original extent is not known, but they form a continuous north-south belt about 5 miles long and 2 miles wide. About 7 to 10 miles to the northeast of Mesa del Oro, and 1 to 5 miles west of Lucero Mesa, high, isolated buttes are capped by areally small remnants of similar travertine. If these travertine deposits were a single continuous sheet during the late Tertiary, they covered an area of at least 35 square miles and may be similar in origin to the Riley travertine, i.e., playa lake deposits, or relatively pure caliche capping an old erosion surface.

Several lenticular (reefoid ?) algal limestones, locally in lenses as much as 40 feet thick, occur in the Tertiary Palm Park Formation of the southwestern Caballo Mountains. In the valleys of Apache and Green Creeks (fig. 10), the Palm Park Formation, about 900 feet thick, is unconformable on Paleozoic rocks and consists of three units: (1) a basal one third of interbedded red siltstones and pebble to boulder conglomerates with clasts of Precambrian and Paleozoic rocks as well as of andesitic lavas, (2) a middle one third of light blue-gray to purple porphyritic latite tuff, and (3) an upper one third of pinkish tuffaceous sandstones and lenticular algal limestones. The mound-like masses of algal limestone appear to be high in calcium (table 1, no. 1) with one chip-channel sample of a 40-foot-thick mass yielding 97 percent calcium carbonate.

Caliche is widely used for road metal in the intermontane plateaus and the High Plains parts of the State, being in those areas the only monolithologic calcium-carbonate rock inexpensively available. Finely banded (algal-like) and pisolitic travertine lenses occur in many localities in the caliche, especially in the "caprock" of the High Plains in eastern New Mexico. As described by Bretz and Horberg (1949), the typical caliche profile (developed on limestone-pebble gravels), in descending order consists of (1) dense, banded to structureless caprock, (2) less dense, brecciated caprock, (3) chalky caliche with concretionary nodules, (4) impure caliche with cupped pebbles, and (5) slightly leached and coated precaliche limestone gravels. In most areas the relatively pure "limestone" is thin, 1 to 2 feet, and lenticular. Bretz and Horberg reported an average of only 3 percent insoluble residues from 12 samples of the "caprock" caliche. Sampling of the top 2-1/2 zones (banded caprock, brecciated caprock, and upper chalky concretionary caliche) from 3 widely separated localities in southeastern New Mexico gave an average insoluble residue of more than 31 percent. Selected fragments of the upper caprock may contain only 3 to 10 percent insoluble residues, but any appreciable thickness or lateral mass of the caprock appears to be high in siliceous impurities.

Thick (thicker than 2 feet), extensive, and relatively high-calcium caliche appears confined, except for localized deposits, to surfaces bordering the the valley of the Rio Grande and its tributaries and to the Llano Estacado of eastern New Mexico and its isolated western remnants. The parent material in southeastern New Mexico, the Ogallala Formation, contains a high percentage of limestone pebbles and cobbles when compared to the Santa Fe Formation of the Rio Grande area. The caliche developed in southeastern New Mexico (or under surfaces of comparable age), therefore, is thicker and contains more lime than most of the caliche "caprocks" of central and western New Mexico. The caliche of eastern New Mexico is more important economically as it provides road metal and aggregate for that part of the State.

The northern edge of the Llano Estacado was checked in southern and west-central Quay County. Outcrops north of Ragland along State Highway 18, the Clovis to Tucumcari road, are typical. The Triassic red beds (Redonda Member of the Chinle Formation; Dobrovolny, Summerson, and Bates) are unconformably overlain by partly cemented Ogallala sands and gravels. The upper 15 to 30 feet of the Ogallala varies irregularly from limy sandstone and siltstone to lenses of caliche; the upper 5 to 15 feet is of banded, dense, and brecciated caliche with scattered pebbles, cobbles, and grains of siliceous rocks. The underlying Ogallala Formation is rich in clasts of volcanic rocks and Precambrian(?) metamorphic and igneous rocks. Farther east, near Ima, larger percentages of limestone clasts occur in the Ogallala Formation and the caliche appears to be thicker. A chip-channel sample from 15 feet of caliche caprock near Ragland yielded 36.4 percent insoluble residues, chiefly of rounded to subangular quartz grains, clear, pink, and smoky, 0.1-0.4 mm in diameter, and with frosted surfaces.

To the southwest near Taiban, the caliche is developed mainly on limy sands and silts; the upper caprock and lower porous caliche is 5 to 10 feet thick with relatively high-calcium travertine insignificant. Near Kenna, along the Chaves-Roosevelt county line, the caliche is in very irregular lenses and is cut by many vertical solution-and-collapse features. Pods and blocks, highly brecciated, average about 5 feet in thickness, although locally they are 10 to 20 feet thick. A chip-channel sample from an 18-foot-thick pod had 39.7 percent insoluble residues.

Near Caprock (east of Roswell) and southward, the caliche caprock appears to be thicker and higher in lime, compared with the outcrops to the north. There is a gradual change from the parent Ogallala limy sands and silts upward into the upper localized massive caprock. The upper massive brecciated laminated travertine is 2 to 20 feet in thickness, averaging 5 to 10 feet, with variable amounts of impurities. Beneath this caprock is porous impure nodular caliche which grades down into the Ogallala. The "cupped" pebble zone occurs only above local limestone-pebble gravel lenses. As reported by Bretz and Horberg, the caprock reaches a thickness of 30 feet south of Caprock, with the underlying chalky caliche 10 to 15 feet thick. Insoluble residues make up 18.9 percent of a chip-channel sample from the caprock and are mainly rounded to subangular quartz grains, 0.1 to 0.4 mm in diameter.

Local pods of the caprock caliche, as reported by Bretz and Horberg, may be high-calcium "limestone," but these high-purity masses are erratic and discontinuous and do not appear to be of economic significance other than for use as road metal.

High-Calcium Limestone Deposits

Six regional maps (figs. 2-5, 7, 11) show the outcrops of limestones throughout New Mexico. Some small parts of the State not covered by these maps are (1) extreme northwestern and extreme north-central New Mexico where the only limy beds are thin, highly argillaceous limestones and limy siltstones in the Upper Cretaceous sequence; (2) part of west-central New Mexico, chiefly Catron County and westernmost Socorro County, where the only limestones are limy tuffs and small, isolated fault blocks or float blocks of pre-Tertiary strata; (3) part of southeastern New Mexico in eastern Chaves County, eastern Eddy County, and DeBaca, Curry, Roosevelt, and Lea counties where the only limy beds are the caliche capping the Ogallala Formation, dolomitic limestones within the Upper Permian sequence, and a few isolated remnants of Cretaceous limestone.

Catron County is underlain chiefly by Cenozoic volcanic rocks; no limestones have been reported from this thick extrusive sequence. Several fault blocks of pre-Tertiary limestones occur in the county. On the south side of Horse Mountain, bordering the Plains of San Agustin, the upper part of the Yeso Formation, the Glorieta Sandstone, and the San Andres Limestone crop out along a small cuesta amid alluvial gravels and volcanic rocks. The San Andres Limestone appears to be relatively pure but has not been sampled for analysis. Near the New Mexico–Arizona stateline, northwest of Luna along Trout Creek, in sec. 3, T. 5 S., R. 21 W., a partial section of Pennsylvanian limestones crops out (Kottlowski, 1960a) and includes high-calcium limestones (table 1, no. 24). These limestones are too far from any large market to be of economic use except as road metal.

NORTHWESTERN NEW MEXICO

Limestones in northwestern New Mexico (fig. 2) occur within the Mississippian and Pennsylvanian Systems, the Yeso Formation, San Andres Limestone, Todilto Formation, and Upper Cretaceous sequence, and as Cenozoic travertine and calcareous tufa. Mississippian limestones in the area have been left as pre-Pennsylvanian erosional remnants only in the southern Ladron Mountains, and appear to be similar to the Mississippian limestones of the Magdalena Mountains. Carbonate-rock beds in the Yeso Formation of northwestern New Mexico are mostly dolomitic and silty, and thus are not shown on the limestone outcrop map although they could be used as crushed stone. Some of the limestones in the San Andres Limestone of the Zuni Mountains and Lucero Mesa areas may be high in calcium, as judged by HCl tests in the field, but cherty limestones, arenaceous limestones, and dolomitic limestones dominate the unit in this region. Limestones in the Upper Cretaceous sequence are within the marine black shales, such as the Mancos Shale, are highly argillaceous, and are not shown on the map. Black argillaceous limestones in the Mancos Shale are the only limy beds in the Quemado area, cropping out north of Salt Lake in Carrizo Creek valley along State Road 32, the Quemado-Fence Lake-Gallup highway. Combined, selected samples of these Mancos limestones contained 26.4 percent insoluble residues but the "limestone" could be used for road metal.

Arroyo Colorado Valley

Along the northwest wall of Arroyo Colorado valley, the Todilto limestone is thick and caps extensive benches extending from Petoch Butte northwestward to Mesita. The outcrops can be reached along 1 to 10 miles of sandy ranch roads from U.S. Interstate Highway 40 (U.S. 66) and are within the Laguna Indian Reservation. One of the thicker sections of the limestone occurs several miles southwest of Mesita where Silver measured the following section (in sec. 22, T. 9 N., R. 5 W.):

Dakota Sandstone; more than 75 feet thick with many shale interbeds; caps high mesa, unconformable on underlying rocks.

Morrison Formation consisting in descending order of variegated shale member, white cross-bedded sandstone member, brown-buff sandstone member (75 feet thick), and basal buff shale member (125 feet thick).

Todilto limestone; 40 feet thick; caps prominent bench.

Entrada Sandstone; cliff-forming cross-bedded sandstone 130 feet thick with upper one third light gray and lower two thirds reddish brown.

Wingate Sandstone; upper 85 feet of reddish shaly siltstone; lower 30 feet of cliff-forming reddish-brown cross-bedded sandstone.

Chinle Formation; several hundred feet of slope-forming red shales.

The limestone ranges from 15 to 40 feet in thickness along the cliffs southwest of Mesita, in general thinning both to the southwest (to a feather pinch-out edge near Petoch Butte) and to the northeast. The upper part of the limestone is gypsiferous, and the lower few inches are arenaceous. Some of the beds are laminated calcarenites, and most are carbonaceous with silt partings. An analysis (table 2, no. 8) of a chip-channel sample collected along the south line of the SW1/4 sec. 34, T. 9 N., R. 5 W. shows 94.3 percent calcium carbonate, 3.6 percent silica, 0.09 percent sulfur, and 0.02 percent phosphorus pentoxide. Selective mining of all the limestone except the lower few inches and upper one-half foot should yield a high-calcium limestone.

North of the mouth of Arroyo Colorado where it joins Rio San Jose, the Todilto limestone crops out on south-facing cliffs, being 5 to 16 feet thick (Darton), and overlain by 50 to 80 feet of the Todilto gypsum. To the southeast, several isolated outcrops of the limestone member occur near Mesa Redonda and near the north tip of Lucero Mesa; in these localities the limestone is thin, with only a few lenses reaching 15 feet in thickness. Similar thicknesses and small areas of outcrop occur northeast of Acoma.

From Wingate to five miles east of Grants, the Todilto limestone crops out on the north flanks of the Zuni anticline and has an average thickness of about 14 feet, but it includes many laminae of gypsum, siltstone, and sandstone, as well as dolomitic interbeds (Smith, 1954). Near the type locality at Todilto Park, in northwestern McKinley and southwestern San Juan counties, the limestone grades laterally, and erratically, from a 5- to 14-foot-thick limestone into limy sandstone and siltstone (Allen and Balk). Locally in the Todilto Park region, the limestone caps extensive mesas but contains about 12 percent silica (table 2, nos. 11-13) and crops out in relatively inaccessible areas.

Lucero Mesa Area

The San Andres Limestone crops out on the west, and least accessible, flank of northern Lucero Mesa and on the east sides of its southern extension, Gallina and Pato mesas (sometimes called Sierra Lucero). Interbeds of shale, sandstone, and gypsum occur in the San Andres of this area, and many of its limestone beds are impure. Capping Mesa Aparejo and Mesa Sarca, southeast of northern Lucero Mesa, are thick sequences of Pennsylvanian limestones with some interbedded clastic strata. Many of the thick limestone beds appear to be high-calcium limestone similar to those sampled in the northern Ladron Mountains (table 1, no. 25) but are long distances from paved roads.

Travertine and calcareous tufa spring deposits are extensive along the fault zone bounding Lucero Mesa, Mesa Aparejo, and Mesa Sarca on the east. These are the banded travertines that have been quarried as travertine "marble" near South Garcia. Whereas selected grab samples may be of high-calcium limestone, a chip-channel sample of an average spring deposit (table 2, no. 1) showed only 85 percent calcium carbonate and more than 10 percent silica. As noted above, at the northern end of Mesa del Oro, west of Lucero Mesa, Jicha described a large, high-level, blanket-like travertine deposit that contains high-calcium limestone (table 1, no. 3); this Mesa del Oro deposit may have been derived from springs or may be a remnant lacustrine limestone.

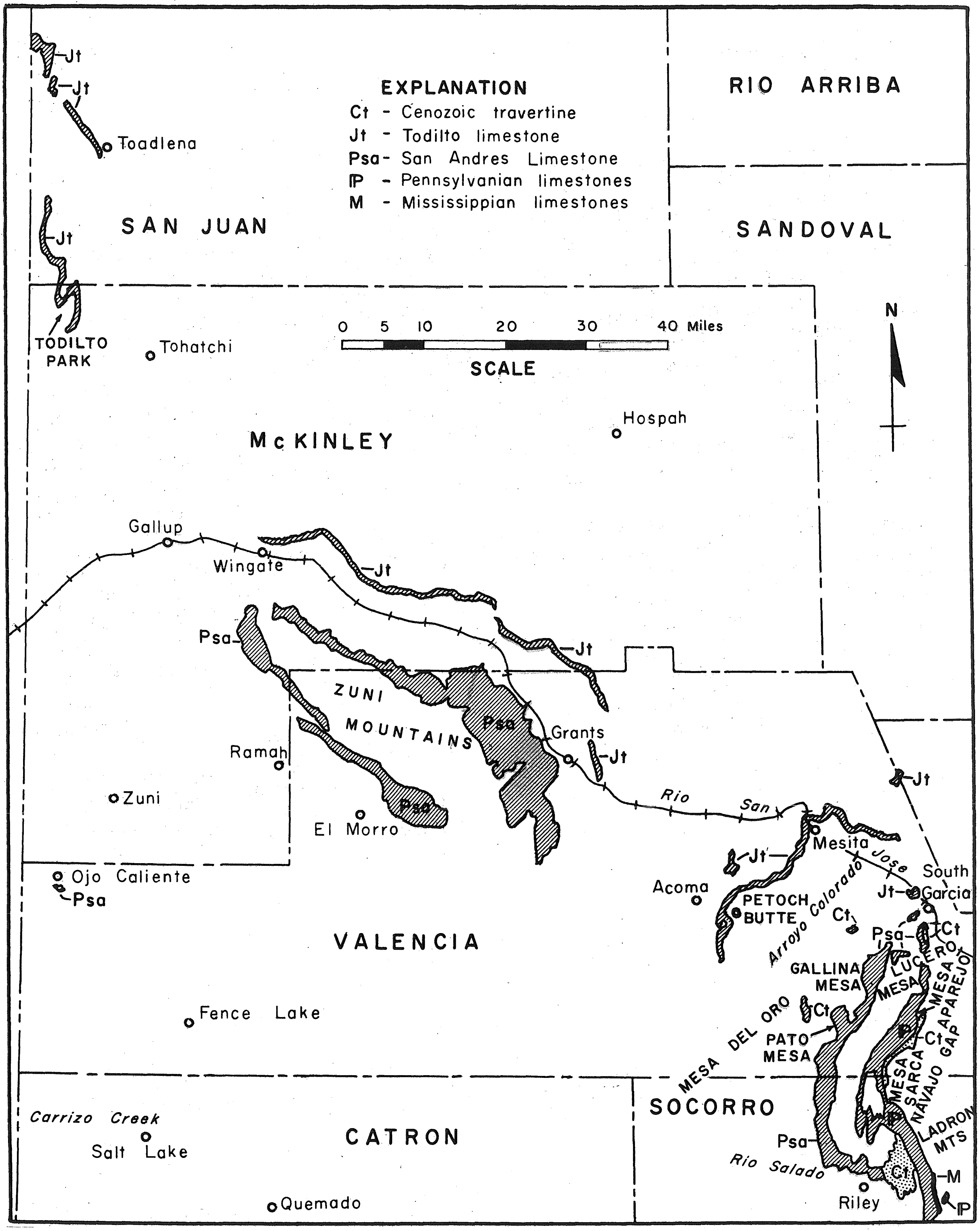

Figure 2
Map of northwestern New Mexico showing limestone outcrops

Ladron Mountains Area

Mississippian limestones crop out in the southwestern Ladron Mountains, capping a dip-slope ledge above Precambrian rocks and below slope-forming lower Pennsylvanian clastic strata. Amid the Mississippian sequence (Armstrong, 1958) are crinoidal calcarenites of apparent high-calcium content, but interbeds are of cherty limestone and arenaceous limestone. To the north in the central Ladron Mountains, the Mississippian beds have been removed by erosion during late Mississippian and early Pennsylvanian time. These Mississippian limestones and the overlying thick Pennsylvanian limestone sequence of the southern and central Ladron Mountains can be reached only over poor ranch roads. At the northern tip of the Ladrons, however, thick high-calcium limestones (table 1, no. 25) of middle Pennsylvanian Age crop out on dip-slope cuestas, bordering Navajo Gap, and can be reached from Bernardo on U.S. Interstate Highway 25 (U.S. 85) over 17 miles of good ranch road.

South and southwest of Navajo Gap, stretching westward from the west dip-slope of the Ladron Mountains, is an extensive plain underlain by the "Riley" travertine. South of Rio Salado and west of the Lemitar Mountains, a southern extension of this travertine underlies about 8 square miles of the northern part of Snake Ranch Flats. As described in the section on Cenozoic limestones, this Riley travertine includes much high-calcium limestone, averaging 99 percent calcium carbonate (table 1, no. 2), and could be a source of easily stripped limestone. The southern deposits are about 15 miles by good ranch road from Magdalena on U.S. Highway 60, but these southern travertines appear to be less pure and thinner than those north of Rio Salado. The northern high-calcium beds are relatively inaccessible, being reached by 18 miles of good ranch road to Riley from Magdalena, but then by 3 to 5 miles of poor sandy "track" down the stream bed of Rio Salado.

NORTH-CENTRAL NEW MEXICO

Limestones of north-central New Mexico (fig. 3) occur within the Mississippian sequence of the Sangre de Cristo, Sandia, and Nacimiento mountains, the Pennsylvanian System in those ranges and in the Manzano and Manzanita mountains, locally in the Bursum and Yeso Formations, in the San Andres and Todilto Formations, and amid the marine beds of the Upper Cretaceous sequence.

The Mississippian Arroyo Penasco Formation of the Nacimiento Mountains (Armstrong, 1955) consists of basal sandstones and shales that grade upward and laterally into arenaceous calcarenites, and upper limestones as much as 120 feet thick. Some of the limestones appear to be relatively pure, but dense limestones with scattered to abundant chert dominate. Similarly, arenaceous and cherty limestones characterize the thin Pennsylvanian section (Northrop and Wood, 1946), whereas limestones in the Yeso Formation (in the upper San Ysidro Member) are thin and silty. The San Andres Limestone is thin and arenaceous or absent (northward) in the Nacimiento Mountains area. The Todilto limestone is only 1 to 12 feet thick, with local lenses up to 18 feet in thickness, in the entire region stretching from San Ysidro northward to the Rio Chama valley; interbeds of dark shale and silty sandstone occur in many localities. In central Rio Arriba County, some of the limestone beds in the Greenhorn Limestone Member of the Mancos Shale are as much as 2-1/2 feet thick but are highly argillaceous.

Sandia Mountains

Mississippian limestones crop out in the northeastern Sandia Mountains, being easily accessible along Las Huertas Canyon and at the base of the Crest of Montezuma about a mile east of Placitas (Armstrong, 1955). Basal beds are conglomerates and sandstones that grade upward into arenaceous shales and limestones. As much as 75 feet of limestone forms the upper part of the Mississippian sequence and varies from dense cherty beds to coarsely crystalline crinoidal calcarenites. The latter have been quarried locally as "marble", and apparently include high-calcium limestone, especially east of Placitas. A chip-channel sample of the 40-foot-thick crinoidal Mississippian limestone along Las Huertas Canyon, however (table 2, no. 27), showed 5.6 percent silica and 2.1 percent magnesium carbonate with only 91 percent calcium carbonate.

Thick limestone units make up the bulk of the Pennsylvanian System and form extensive dip-slope outcrops in the Sandia, Manzanita, and Manzano mountains. Near Tijeras, these limestones are quarried for use by the Ideal Cement Company. Many of the lower Pennsylvanian limestones are arenaceous, and the middle limestones, chiefly of Desmoinesian Age, are cherty. Extensive sampling of these middle beds, the gray limestone member of the Madera Limestone, showed that most of the limestones contain 4 to 10 percent silica as quartz silt and as finely disseminated replacement silica. A typical sample of relatively noncherty Desmoinesian limestone capping dip slopes southwest of Placitas contained 5.96 percent insoluble residue of silt-size silica. Upper limestone beds, in contrast, appear to be purer and include less than 5 percent insoluble residues. A thick, fossiliferous calcarenite representative of the upper Pennsylvanian, cropping out along Cedro Canyon just south of Tijeras (table 1, no. 19), showed 95.4 percent calcium carbonate and 4.1 percent silica.

The Yeso Formation is 400 to 450 feet thick at the east foot of the Sandia Mountains. Near San Antonio, the Yeso is chiefly massive cross-bedded orange sandstone with upper siltstone and shale beds, whereas east of Placitas orange siltstone dominates and several thin (less than 5 feet thick) silty limestones occur near the top of the formation. The San Andres Limestone in these areas

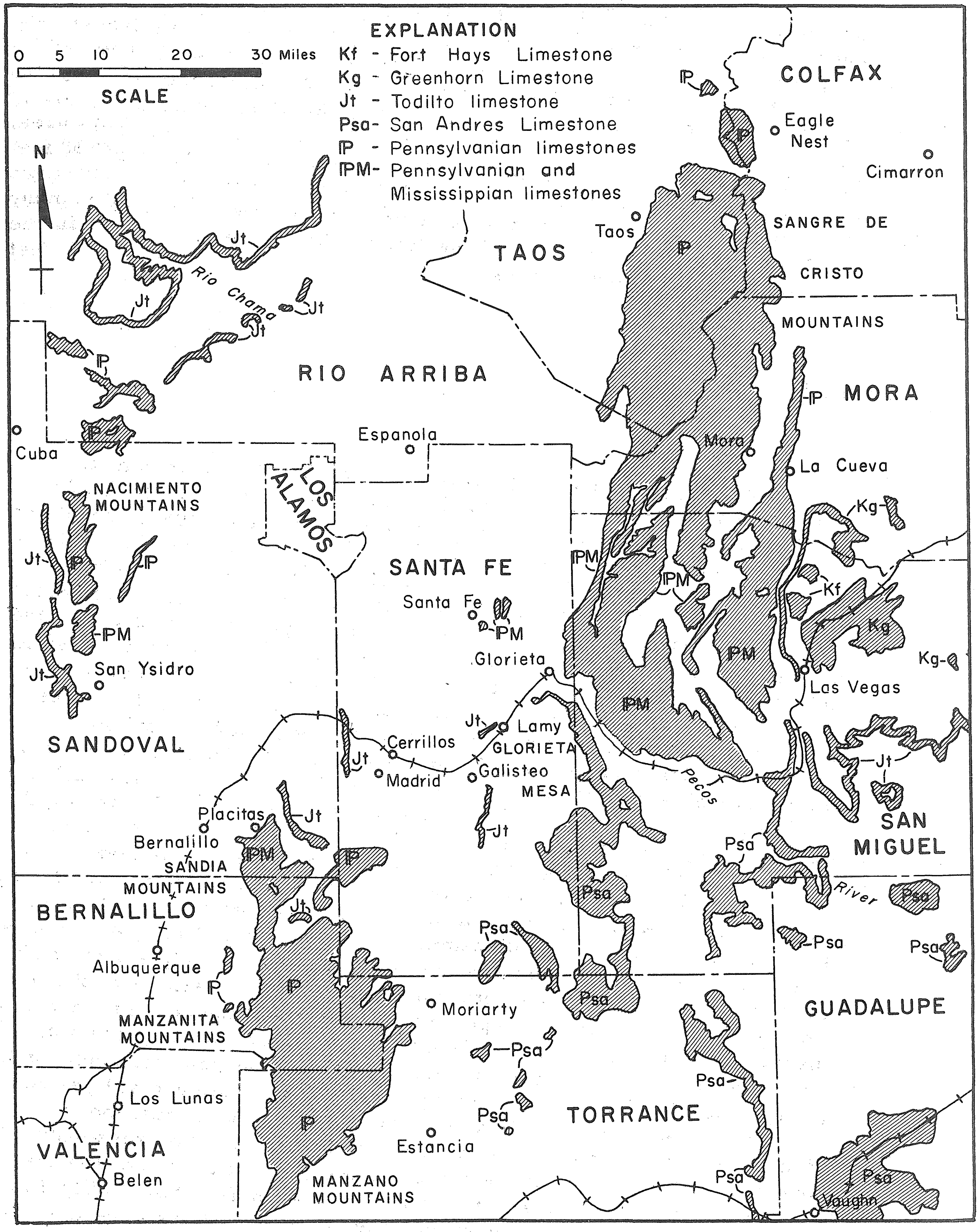

Figure 3
Map of north-central New Mexico showing limestone outcrops

consists of interbedded arenaceous limestone and gray limy sandstone sandwiched between the Glorieta Sandstone and Bernal Formation (Read et al.); some of the sandy limestones are more than 10 feet thick but, as with the thin limestones in the Yeso, they are too impure to be used except as crushed rock. The Todilto Formation is mainly of gypsum in the Tijeras to Placitas area; the lower limestone member is 3 to 10 feet thick, consisting of dark, thinly laminated limestone containing many partings and laminae of limy silt and gypsum.

Sangre de Cristo Mountains

Mississippian limestones crop out in much of the southern Sangre de Cristo Mountains above an unfossiliferous sandstone that rests on the Precambrian rocks, and beneath early Pennsylvanian clastic beds. These limestones have been referred to the Arroyo Penasco Formation by Armstrong (1955), based in part on Meramec Age microfossils collected from middle and upper beds, and to various members of the Tererro Formation by Baltz and Read. Some of the crinoidal calcarenites of the Mississippian are thick (20 to 50 feet) and appear to be high-calcium limestone. A chip-channel sample (table 2, no. 26) of the upper 26 feet of the Mississippian near Bishop's Lodge, several miles north of Santa Fe, showed only 90.9 percent calcium carbonate, 6.4 percent magnesium carbonate, and 1.5 percent silica. These magnesium limestones near Santa Fe appear to be similar to some of the cherty limestones placed by Baltz and Read in their Espiritu Santo Formation. This formation includes the basal unfossiliferous post-Precambrian strata considered as a basal unit of the Arroyo Penasco Formation by Armstrong (1955), but is believed to be of Devonian Age by Baltz and Read. The unit sampled near Bishop's Lodge contains sparse, poorly preserved, silicified brachiopods and corals of Mississippian aspect.

Along Pecos River canyon and in the southeastern Sangre de Cristo Mountains west of Las Vegas, crinoidal calcarenites in the Cowles Member of the Tererro Formation, or uppermost beds of the Arroyo Penasco Formation, are as much as 40 feet thick, do not appear to be dolomitic, and contain (grab samples) less than one percent insoluble residues.

The Pennsylvanian System of the Sangre de Cristo Mountains includes many siliciclastic beds and appears to grade upward and laterally into the unfossiliferous red beds of the Sangre de Cristo Formation. Limestones in the clastic member of the Sandia Formation, the Sandia Formation as restricted by Baltz and Read, include much quartz sand and silt. As in the Sandia Mountains, the limestones of the overlying gray limestone member of the Madera Limestone are predominantly cherty, but some thick limestone units in this member are relatively noncherty. Grab samples of noncherty limestones in the gray limestone member of the Madera along Pecos River canyon and west of Las Vegas gave 2 to 6 percent insoluble residues. The upper arkosic limestone member of the Madera Limestone is characterized by many interbeds of arkose and by arkosic limestones—bioclastic calcarenites containing abundant angular grains of feldspar. Some of the massive limestones in the arkosic sequence, however, appear to be relatively pure, yielding less than one percent insoluble residues from grab samples, and one of these limestones is probably the bed quarried west of Las Vegas which is high in calcium (Burchard, 1912; table 1, no. 28). Similar beds near Taos (which may be in the gray limestone member, depending on individual interpretations) contain less than two percent insoluble residues.

Pennsylvanian beds near Santa Fe unconformably overlie either Precambrian rocks or erosional remnants of the Mississippian sequence. Locally the basal beds are carbonaceous black shales and bone coal, but in most places sandstone and shale make up the lowest sediments. Thin representatives of the three post-Mississippian Magdalena Group units appear to be present—the basal clastic member of the Sandia Formation, the gray limestone member of the Madera, and the arkosic limestone member of the Madera Limestone. Prof. Patrick K. Sutherland, University of Oklahoma (oral communication, 1961) found, however, that fossils from the entire thin section are all of early Pennsylvanian Age, and believes the isolated Pennsylvanian outcrops near the State Capitol correlate with the lower Sandia Formation (clastic member) of the Pecos River valley. A generalized description of the lower part of the section as measured near Bishop's Lodge is as follows:

Santa Fe Group: sandstones and conglomerates

Unconformity

Gray limestone member, Madera Limestone: 88 feet thick

*Fossiliferous bioclastic gray-brown limestone, 15 feet
Pinkish-yellow laminated lenticular shale, 2-1/2 feet
Finely crystalline fossiliferous brown limestone, 5 feet
Gray-brown massive medium-grained sandstone, 5 feet
Gray sandy platy shale, 3 feet
*Aphanitic gray-brown massive limestone, 16 feet
Red and green banded shale, 5 feet
*Gray-brown fossiliferous limestone, 4 feet
Red and green banded shale, 8 feet
Coarsely crystalline bioclastic limestone, 2 feet
Green and red banded shale, 2-1/2 feet
*Coarsely crystalline bioclastic limestone, 20 feet

Clastic member, Sandia Formation: 79 feet thick

Red, black, and green banded clay, 11 feet
*Gray-brown fossiliferous limestone, 20 feet

*Sampled for analysis; see Table 2, no. 24 (Pennsylvanian limestones) and no. 26 (Mississippian limestone).

Pink laminated soft shale, 16 feet
Black carbonaceous coaly shale, 7 feet
Brown, limy, pebbly sandstone, 4-1/2 feet
Interbedded green shale and sandstone, 10-1/2 feet
Black carbonaceous shale, 3 feet
Fine-grained green sandstone, 7 feet

Unconformity

Mississippian strata: 51-1/2 feet thick

*Gray medium-crystalline massive limestone with chert lenses in lower part, 26 feet
Interbedded brown calcareous sandstone and gray platy limestone, 9-1/2 feet
Yellowish-buff sandy shale, 3 feet
Light-gray argillaceous thin-bedded limestone, 7 feet
Light-gray calcareous coarse-grained sandstone, 6 feet

Unconformity

Precambrian granites, schists, and amphibolites

Several thin dolomitic limestones occur in the upper part of the Yeso Formation south and east of the Sangre de Cristo Mountains on the northward-facing scarp of Glorieta Mesa and in the foothills near Las Vegas. Northward, near the Mora River Gap at La Cueva, the Yeso Formation intertongues with and is indistinguishable from the Sangre de Cristo Formation red beds. The San Andres Limestone consists of interbedded silty arenaceous limestones and siliciclastic beds that grade northward into the Sangre de Cristo Formation north of Las Vegas (Baltz and Bachman, 1956). The individual limestone beds are impure on Glorieta Mesa and only local lenses exceed 8 feet in thickness.

The Todilto limestone crops out near Lamy and to the east along the southeast flank of the Sangre de Cristo Mountains from Sapello southward to where the Canadian Escarpment swings eastward. The limestone crops out along the Canadian Escarpment farther eastward to and beyond the mouth of the Canadian River Canyon, capping a cliff of massive cross-bedded Entrada (Ocate) Sandstone and beneath slopes carved in the Morrison Formation. The limestone is only 5 to 15 feet thick in most of this area, pinching out northward and eastward, and contains partings and laminae of silt and quartz sand. The outcrop is shown on Figures 3 and 4 because it is the only limestone available as crushed stone in most of central and eastern San Miguel County, even though the Todilto limestone in this area is thin, impure, and, in many places, difficult to reach.

South of the Sangre de Cristo Mountains on Glorieta Mesa and its southern extension into northern Torrance County, other than thin, silty limestones in the upper part of the Yeso Formation, the impure San Andres Limestone is the main possible source of limestone, discounting caliche cappings of high-level gravels. Near Clines Corners, Smith (1957) reported about 100 feet of the San Andres Limestone with interbeds of gypsum and reddish clastic strata; the unit appears to thicken southward toward Vaughn, but the thickness is highly irregular because of solution features.

Highly argillaceous, dark limestones and hard limy shales occur within the Late Cretaceous Mancos Shale in several synclinal areas between the Sangre de Cristo and Sandia mountains south of Lamy near Galisteo, and near Cerrillos and Madrid. East and northeast of Las Vegas, thin argillaceous beds of the Greenhorn Limestone crop out and have been used locally for crushed stone. Somewhat thicker limestone beds occur in the Fort Hays Limestone which caps a few high ridges northeast of Las Vegas, but these Late Cretaceous limestones (table 2, no. 2) are too impure for high-calcium uses.

NORTHEASTERN NEW MEXICO

Limestones and limy rocks of note in northeastern New Mexico (fig. 4) occur only in the Todilto Formation, Greenhorn Limestone, Fort Hays Limestone, and as the "caprock" caliche of the Ogallala Formation. As noted above, a thin, impure limestone of the Todilto extends eastward along the Canadian Escarpment to its pinchout in northeastern San Miguel County. The southeastern pinchout of the Todilto limestone occurs near the Quay–Guadalupe county line east of Santa Rosa. Here, on the south edge of Louisiana Mesa, the limestone is lenticular, 2 to 10 feet thick, and is a thinly laminated, platy to fissile bed containing partings and thin laminae of siltstone and gypsum. A chip-channel sample (table 2, no. 9) showed 94.6 percent calcium carbonate, 3.5 percent magnesium carbonate, 1.0 percent silica, and 0.07 percent sulfur; this analysis indicates much purer limestone than is suggested by the appearance of the weathered outcrops.

The northeast-trending belt of Late Cretaceous outcrops in northeastern New Mexico includes reasonably thick limestones only in the Fort Hays Limestone of eastern Colfax County and northwesternmost Union County, and the Greenhorn Limestone of northwesternmost Union County. Limestones of the Greenhorn southwest of Union County are too thin and too impure to be of use except as a low-grade crushed stone. A similar impure Greenhorn Limestone remnant crops out in southeastern Quay County, below and north of the north-facing bluffs of the Llano Estacado southeast of Tucumcari, where Dobrovolny, Summerson, and Bates reported 30 feet of argillaceous limestone; in an area where caliche is the only limy rock available, this Greenhorn Limestone may be of some future use.

The Greenhorn Limestone of northwestern Union County is 20 to 30 feet thick and consists of tan limestone in 1- to 2-foot-thick beds separated by shale beds of similar thickness (Baldwin and Muehlberger). The Fort Hays Limestone in that area is thicker (40 to 50 feet) and contains much less shale. To the

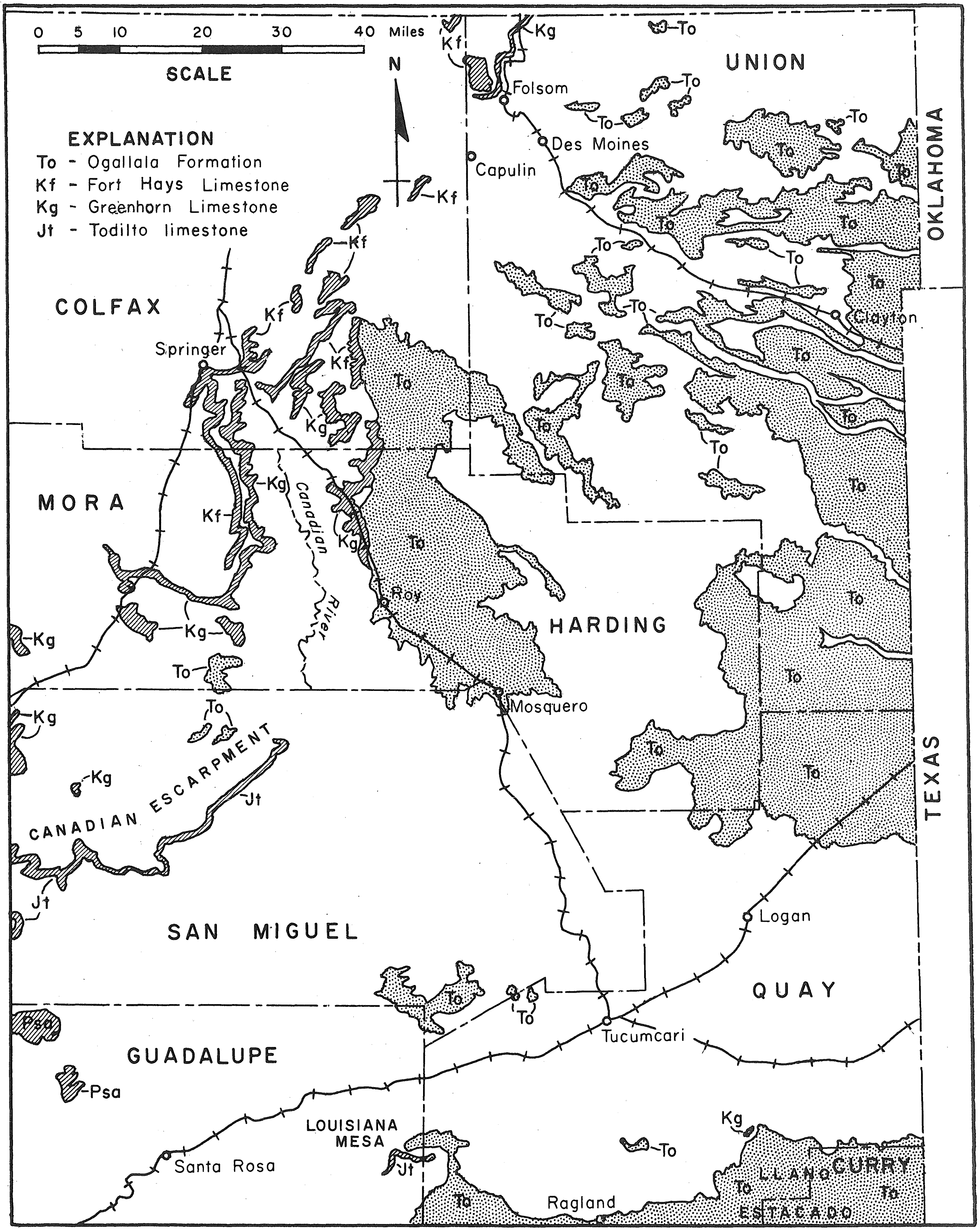

Figure 4
Map of northeastern New Mexico showing limestone outcrops

southwest in eastern Colfax County, the Fort Hays Limestone ranges from 15 to 60 feet in thickness and consists of 1- to 2-foot-thick interbeds of gray, finely crystalline limestone and dark-gray shale. A chip-channel sample of the limestone beds from the quarries south of Springer along the Cimarron River, limestone used for road metal, showed (table 2, no. 2) 85.0 percent calcium carbonate, 1.3 percent magnesium carbonate, 9.2 percent silica, 2.1 percent alumina, and 0.035 percent sulfur.

Much caliche is used in eastern New Mexico as road metal, since it caps high surfaces cut on the Ogallala gravels and underlies much of the High Plains area. Individual irregular masses within the caliche may be of high-calcium limestone, occurring chiefly as pisolitic and finely banded (algal-like) travertine, but most of the caliche is impure. The caprock near Ragland, south of Tucumcari, was sampled and yielded 36.4 percent insoluble residues, mainly quartz sand and silt. The sampled section is 15 feet thick, consisting of banded, dense, brecciated caliche with scattered clasts of siliceous rocks, and rests irregularly on sands and gravels of the Ogallala Formation.

In Union County, Baldwin and Muehlberger reported lenticular masses of caliche capping uplands above the Ogallala Formation but also locally overlying the Dakota Sandstone and in some places Cenozoic basalt flows. Algal-like caliche, composed of bunlike masses of light-orange, concentrically banded calcium carbonate, is a prominent feature of the caliche caprock. Areas underlain by the Ogallala Formation, which in most places is capped by caliche, are shown in northeastern New Mexico (fig. 4) to illustrate localities where this impure but relatively monolithographic rock may be available for crushed stone.

CENTRAL NEW MEXICO

In central New Mexico (fig. 5), limestones occur within the Mississippian beds, Pennsylvanian sequence, Bursum Formation, Hueco Limestone, Yeso Formation, San Andres Limestone, and Mancos Shale. Cenozoic limestones or limy beds are relatively sparse in this part of the State except for the travertines west of the Lemitar Mountains, which were described above.

Mississippian limestones crop out in the Lemitar, Magdalena, and San Andres mountains and the Coyote Hills. The Mississippian thickens southward in the San Andres range, underneath an erosion surface cut in late Mississippian and early Pennsylvanian time, from a knife edge in the northern part of the range (Bachman, 1961) to more than 400 feet near Ash Canyon (Kottlowski et al.). Thick sections of limestone mark the Pennsylvanian and Permian sequences in the San Andres Mountains, but as the mountains are entirely within White Sands Missile Range, they are off-limits and the limestones were not sampled for chemical analysis.

The Mississippian in the Lemitar Mountains occurs in small fault slivers and has been silicified locally. In the Coyote Hills, the Mississippian

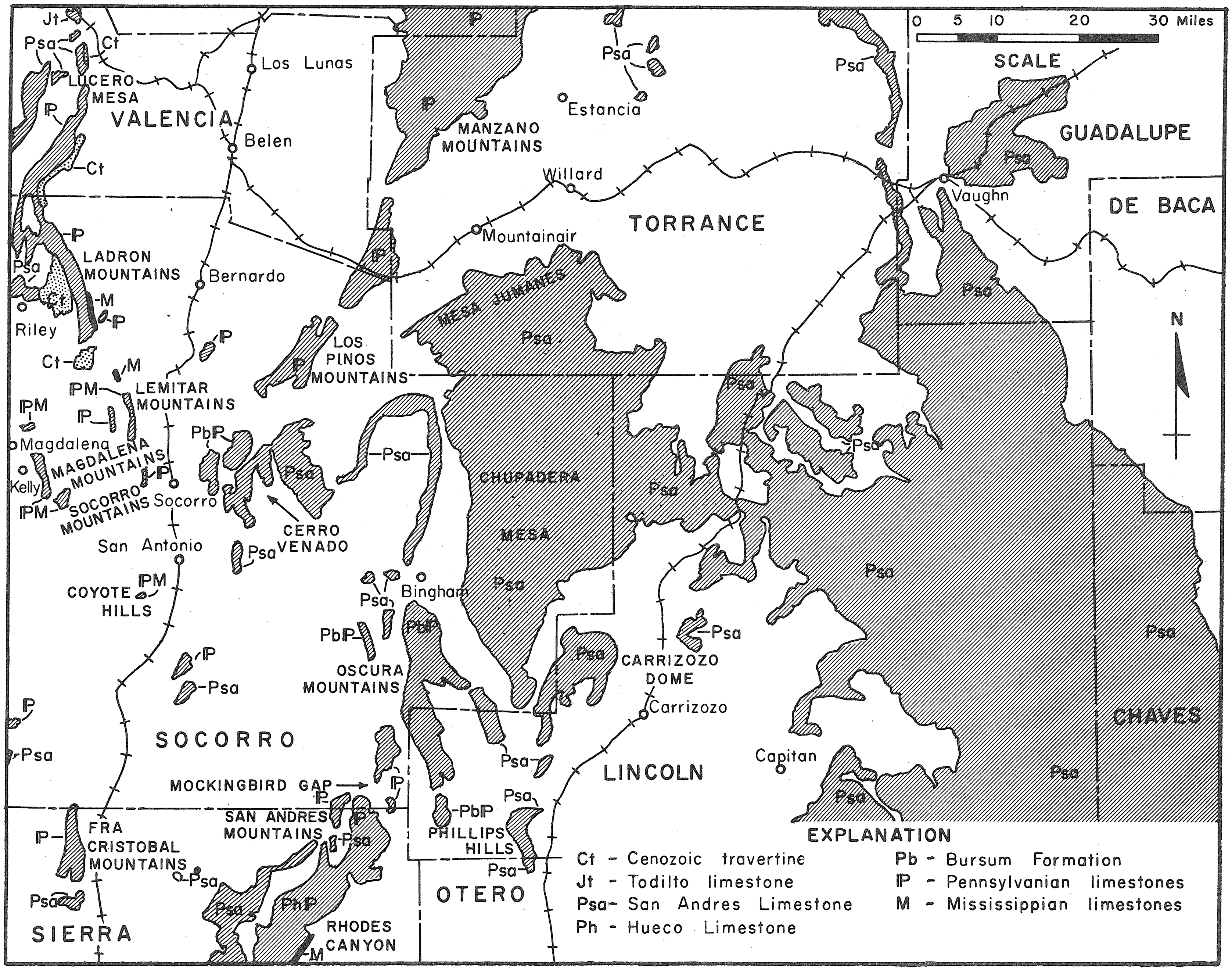

Figure 5

Map of central New Mexico showing limestone outcrops is an erosional remnant of small extent. The Mississippian Caloso and Kelly Formations total more than 100 feet in thickness in the Magdalena Mountains but are cherty and in many places highly mineralized; a grab sample of noncherty limestone near the top of the Caloso Formation, collected on the northeast cliffs of Tip Top Mountain, showed 8.3 percent insoluble residues, mainly of silt-size silica.

The Yeso Formation underlies broad areas in northeastern Socorro County and crops out on the slopes at the base of Chupadera Mesa and Mesa Jumanes (Weber and Kottlowski). The type section near Mesa del Yeso, northeast of Socorro, is about 595 feet thick and includes only 67 feet of limestone in units 1 to 15 feet thick separated by the gypsum and orange siliciclastic beds that dominate the formation (Needham and Bates). The limestones are thin and impure, with the thicker units being chiefly of dolomitic silty limestone. Southward, limestone makes up a larger proportion of the formation, but the beds do not appear to be high-calcium limestone. The limestones of the Yeso Formation may be used as crushed rock, but their outcrop areas are not shown on Figure 5 because higher quality limestone is available within the San Andres Limestone or the Pennsylvanian System.

The San Andres Limestone is 200 to 750 feet thick in central New Mexico and outcrops over large areas since it caps Chupadera Mesa, Mesa Jumanes, the western flank of the High Plains west of the Pecos River, eastern dip slopes of Sierra Blanca and the Sacramento Mountains, western cuestas of the San Andres Mountains, the high ridges east of Socorro (especially the mesa northwest of Cerro Venado), Phillips Hills, and the Carrizozo dome. In northeastern Sierra County and southeastern Lincoln County, the San Andres unit is mainly of carbonate rocks, but to the north and northwest interbeds of gypsum and some pinkish siliciclastic strata form increasingly larger parts of the formation. Many of the limestone beds of the formation in central New Mexico include variable amounts of dolomite. Possible high-calcium limestone appears available from the San Andres only to the south. Grab samples collected southwest of Vaughn, on the north-facing rim of Mesa Jumanes south of Willard, at the south end of Chupadera Mesa east of Bingham, northwest of Cerro Venado, along the canyon of Rio Bonito east of Capitan, and in the Phillips Hills appeared to be dolomitic and contained 3.4 to 7.8 percent insoluble residues, chiefly quartz silt. The San Andres Limestone of the western High Plains is reported to consist of a lower, dominantly limestone part, and an upper dolomite unit. Upper beds of the San Andres Limestone were sampled in the Border Hills anticline where about 20 feet of the formation is exposed in a crushed-rock quarry on U.S. Highway 70, almost 4 miles west of the Lincoln-Chaves county line (sec. 16, T. 11 S., R. 19 E.). The medium-bedded to massive, dark-gray, fossiliferous limestone appears to be dolomitic and is contaminated by thin laminae of fossiliferous marl and gypsum veinlets. Spectrographic analysis (table 2, no. 18) showed 22.3 percent magnesium carbonate and 1.7 percent silica. Farther to the south along Rio Penasco canyon east of Elk, the lower part of the San Andres Limestone is high in calcium (table 1, no. 11), containing 97.4 percent calcium carbonate and only 0.9 percent magnesium carbonate.

Limy beds in the Mancos Shale north of Capitan were sampled because

Allen and Jones reported a 60-foot-thick sequence of limestone interbedded in the lower part of the Mancos. These limestone beds are lenticular, impure black limestone that weathers light tan, and occur in lenses up to a foot thick, interbedded with black shale. They have been used for crushed rock. A sample collected 1.2 miles north of Capitan at the southwest corner of sec. 34, T. 8 S., R. 14 E. (table 2, no. 3) showed 76.8 percent calcium carbonate, 2.6 percent magnesium carbonate, 13.1 percent silica, 3.1 percent alumina, 2.2 percent iron oxide, and 0.18 percent sulfur.

Abo Pass Area

Pennsylvanian limestones on the eastern dip slopes of the southern Manzano and northern Los Pinos mountains east of Abo Pass have been prospected by the Permanente Cement Company. Some of the Virgilian limestones near the top of the Pennsylvanian sequence reportedly are of high-calcium grade. Large areas of the mesas at the east foot of the two mountain ranges are capped by a thick limestone sequence just below the top of the arkosic limestone member of the Madera Limestone (Wilpolt et al., 1946; see their columnar section 11). This unit was sampled along the eastern part of Abo Canyon (center NL, NE1/4 sec. 6, T. 2 N., R. 5 E.). The upper 10 to 20 feet is of thin- to medium-bedded gray limestone containing scattered chert nodules and cropping out as slabby patches on the higher parts of the mesas. A prominent bench caps the cliffs of the middle part of the sequence which consists of massive, finely crystalline, fossiliferous limestone, 30 to 50 feet thick. The center part of this middle unit is cherty, but the upper 15 feet contains only widely scattered, although large (6 or more inches in diameter), chert nodules. Thick-bedded cherty limestones crop out below this middle massive limestone. A chip-channel sample was collected from the upper and middle units, excluding any chert nodules, and showed a cherty limestone (table 2, nos. 22, 23) with about 93 percent calcium carbonate, 1.4 percent magnesium carbonate, and 4.7 percent silica. Insoluble residues are of spongy chert, tiny euhedral quartz crystals, and angular milky quartz silt. Selective quarrying of the noncherty beds may yield high-calcium limestone.

Remnant lenses of crinoidal Mississippian limestone occur locally in the central Manzano Mountains (Armstrong, 1955) but are relatively inaccessible. Limestones in the lower Pennsylvanian of the Manzano and Los Pinos mountains tend to be arenaceous, whereas those of the middle Pennsylvanian are dominantly cherty, although locally some of the Desmoinesian limestones (gray limestone member of the Madera Limestone) appear to be of high-calcium grade in the Los Pinos Mountains. Limestones in the Bursum Formation cap broad north-south-trending mesas east of the mountain ranges but are only 1 to 4 feet thick, except for local lenticular masses of small horizontal extent. These Wolfcampian limestones are relatively pure calcarenites, interbedded with soft red shales, but include lenses and laminae of arenaceous calcarenite and scattered silicified fossils.

U. S. Highway 60 passes through Abo Pass between Mountainair and Bernardo and is paralleled by the Clovis to Belen line of the Santa Fe Railway. Gas pipelines also go through the pass. The large area underlain by limestone, the many shales in the upper Pennsylvanian and lower Permian, and the gypsum available from the Yeso Formation make the Abo Pass region a favorable one for the location of a cement plant and similar users of calcium-rich rocks.

Oscura Mountains

U. S. Highway 380 crosses the northern end of the Oscura Mountains, but they are about 30 miles from the nearest railhead at San Antonio, and the southern part of the mountains is in White Sands Missile Range. Thin, dominantly clastic beds of the Early Pennsylvanian rest unconformably upon Precambrian rocks in the range, except at the southern tip near Mockingbird Gap where early Paleozoic strata come in beneath the Pennsylvanian. Middle Pennsylvanian limestones are mainly cherty and crop out only on the west-facing scarp of the fault-block mountain range. Late Pennsylvanian, Missourian, and Virgilian limestones cap extensive dip-slope mesas atop the mountains and on the eastern dip slopes. These upper Pennsylvanian limestones are in thick units separated by sequences of interbedded shale, minor sandstone, and marly calcarenitic limestone. Here occur the type sections of Thompson's (1942) Missourian and Virgilian formations, classified as follows:

Virgil Series	
	Bruton Formation, 75-80 feet of interbedded red shale and nodular, dense gray limestone
Keller Group	Moya Formation, 50-75 feet of massive to nodular, fossiliferous, cliff-forming limestone
	Del Cuerto Formation, 80-100 feet of interbedded limestone, arkose, limestone conglomerate, and gray and red shale
Missouri Series	
Hansonburg Group	Story Formation, 55-100 feet of upper massive, light-gray fossiliferous limestone and lower red to light-gray shale interbedded with sandstone and minor limestone

	Burrego Formation, 50 to 100 feet of thick-bedded to nodular limestone with lenses of dark-gray shale and brown sandstone in lower part, as well as beds of green to purple calcarenite near the base
Veredas Group	Council Spring Limestone, 15 to 20 feet of coarsely crystalline to aphanitic, massive, light-gray, cliff-forming limestone
	Adobe Formation, 45 to 70 feet of interbedded nodular argillaceous limestone, gray cherty limestone, gray and red shale, and limy feldspathic sandstone
	Coane Formation, 55 to 70 feet of limestone ranging from cherty massive beds to thin, nodular, argillaceous units

The limestones of the Moya Formation and the upper limestones of the Story Formation cap many dip-slope surfaces in the range. Chip-channel samples of the upper 18 feet of the Moya Formation, collected from the canyon wall north of Julian Arroyo about a mile west-northwest of Burrego Spring, appear to be high-calcium limestone containing only 0.8 percent insoluble residues. The upper 32 feet of the Story Formation capping the mountain front one-half mile south of the mouth of Julian Arroyo (near Julian Tank) also appears to be high-calcium limestone containing 1.4 percent insoluble residues.

The massive, cliff-forming Council Spring Limestone underlies extensive benches cut back in the shales of the lower Burrego Formation and is high-calcium limestone where not mineralized by the barite-galena-fluorite ores of the Hansonburg mining district. A chip-channel sample of the 18-foot-high cliff southeast of Julian Tank (table 1, no. 27) showed 98.4 percent calcium carbonate, 0.5 percent magnesium carbonate, and 0.5 percent silica. The calcarenites in the lower part of the overlying Burrego Formation, in contrast (table 2, no. 25), contain 5.8 percent silica, 0.6 percent magnesium carbonate, and only 92.3 percent calcium carbonate. As the Council Spring Limestone could be quarried over a width of at least 100 feet for miles along the front of the range, it is probably the best source of high-calcium limestone in the Oscura Mountains. The Moya and Story Formations are in higher, less accessible, parts of the mountains and their upper surfaces are weathered and locally contaminated by remnants of shales from overlying units.

The overlying, basal Wolfcampian, Bursum Formation consists of interbedded purple and gray shale, lenticular arkose, and nodular to massive limestone. Near the top of the formation is a massive fossiliferous limestone, 15 to 20 feet thick, locally including small algal bioherms, that appears to thicken southward to where it may be correlative with the massive 60-foot-thick biostromal limestone in the basal Wolfcampian beds near Rhodes Canyon.

A chip-channel sample collected one-half mile east-northeast of Julian Tank (table 1, no. 18) showed 98.2 percent calcium carbonate, 0.3 percent magnesium carbonate, and 0.8 percent silica, being a high-calcium limestone. Locally, this Bursum limestone caps small mesas and could be extensively quarried without removal of much, if any, overburden, but in many areas the limestone forms a cliff or ledge below steep slopes cut on the Abo Redbeds. Similar limestones occur in the Bursum (?) and Hueco Formations of the San Andres Mountains to the south but are within White Sands Missile Range.

Cerros de Amado

Pennsylvanian limestones crop out on extensive mesas east of the Rio Grande east of Socorro in Cerros de Amado and surrounding areas (fig. 6). The Pennsylvanian sequence is about 2100 feet thick, including many sandstones in the lower part and much shale in upper beds. Upper Pennsylvanian limestones crop out amid less resistant interbeds of shale and minor sandstone and include many high-calcium beds. Thompson's (1942) Oscura Mountain units can be recognized within the Missourian and Virgilian strata, with the massive pure limestones cropping out southeast of Ojo de Amado where they can be quarried without removal of much overburden. This area is accessible by 4-1/2 miles of good to poor (sandy) ranch road from the Escondida bridge over the Rio Grande, which is near the Socorro railroad facilities of the Santa Fe Railway and connects with U. S. Interstate Highway 25.

Limestones of the Moya Formation cap many mesas east of Ojo de Amado. Just southeast of the spring, the upper 20 to 25 feet of the Moya was sampled and showed (table 1, no. 21) 96.9 percent calcium carbonate, less than 0.1 percent magnesium carbonate, and 1.9 percent silica. The upper limestones of the Story Formation are lenticular, ranging from 15 to 27 feet in thickness, separated by shale partings that locally thicken to 4-foot-thick lenses of limy shale and argillaceous limestone. The limestones are medium-bedded to nodular, very fossiliferous, and contain widely scattered silicified fossils. A chip-channel sample southeast of Ojo de Amado showed (table 1, no. 23) 96.1 percent calcium carbonate, 0.4 percent magnesium carbonate, and 2.5 percent silica. The Council Spring Limestone at this locality is very lenticular, ranging from 5 to 18 feet in thickness, the thickness variation being due chiefly to lenses of algal bioherms. Locally the light-gray limestone is cherty but a 15-foot-thick noncherty sequence that caps a north-dipping cuesta southeast of Ojo de Amado (table 1, no. 20) showed 98.3 percent calcium carbonate, less than 0.1 percent magnesium carbonate, and 1.3 percent silica. Selective mining of the noncherty zones would yield high-calcium limestone. The chert appears to be related, at least in part, to fault zones that cut this Cerros de Amado belt of outcrops.

Farther to the east, in relatively inaccessible rugged canyon-and-mesa country, there are other extensive outcrops of high-purity Pennsylvanian

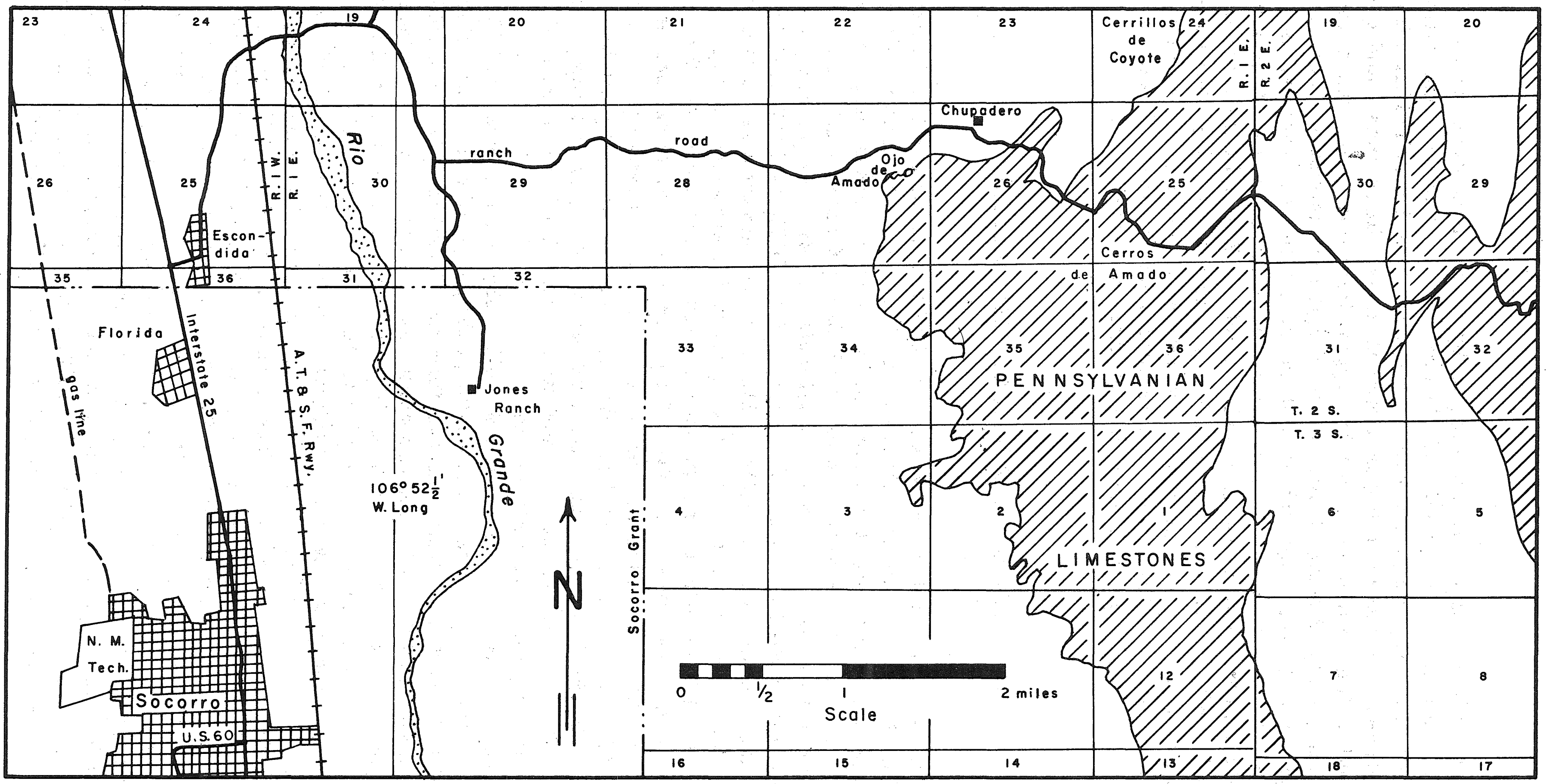

Figure 6
Geologic map of Cerros de Amado area near Socorro

limestones as well as high mesas capped by thick limestone units of the San Andres Limestone. Just west of Socorro in the Socorro and Lemitar mountains, the Tertiary volcanic rocks are underlain by crinoidal Mississippian limestones, arenaceous lower Pennsylvanian limestones, and cherty middle Pennsylvanian limestones, but the upper Pennsylvanian was removed by erosion during early Tertiary time. In the Magdalena Mountains near Kelly, upper Pennsylvanian limestones and part of the Abo Redbeds were left beneath the Tertiary erosion surface; also near Kelly, Mississippian limestones occur between the Precambrian and Pennsylvanian rocks. Thick-bedded limestone at the base of the Madera Limestone near Kelly (table 1, no. 26) showed 95.6 percent calcium carbonate, 0.8 percent magnesium carbonate, and 2.4 percent silica. These limestones are fossiliferous calcarenites, the silica occurring as detrital quartz grains and as minor replacement of fossils.

SOUTHWESTERN CORNER OF NEW MEXICO

Limestones in southwestern New Mexico (fig. 7) occur within the Cambrian and Ordovician Bliss Sandstone, Ordovician El Paso and Montoya Groups, Silurian Fusselman Dolomite, Devonian shaly units, Mississippian beds, Pennsylvanian sequence, Permian units, and Early Cretaceous strata, and amid Tertiary volcanic rocks. Pre-Pennsylvanian sedimentary rocks thicken southward to about 4000 feet near El Paso and to 3000 to 3700 feet in the southwesternmost corner of the State. Most of the limestones in the pre-Mississippian sequence, however, contain appreciable amounts of magnesium carbonate and fall chiefly into the magnesium limestone and dolomitic limestone classes, with gradations into dolomite. Silty and/or arenaceous limestones occur in many of the pre-Mississippian units. Selected relatively pure limestones of the El Paso Group in the Victorio Mountains were sampled (table 2, no. 28) and showed 93.6 percent calcium carbonate, 2.1 percent magnesium carbonate, and 3.0 percent silica. Concentrated search of the El Paso Group may uncover some high-calcium limestone.

The Mississippian Lake Valley and Kelly Limestones exceed 100 feet in combined thickness in Cooks Peak–Lake Valley, southern Black Range, and Silver City–Santa Rita areas but are thin or absent in Sierra Cuchillo, Caballo Mountains, and Fra Cristobal Mountains. Outcrops are in relatively inaccessible places and locally are near highly altered zones of mining districts. These limestones grade southward into the lower part of the Escabrosa Group (Armstrong, 1962) which is as much as a thousand feet thick in the Big Hatchet (Zeller, 1958) and Animas mountains and the Klondike Hills, and locally more than 500 feet thick in the Tres Hermanas and Peloncillo mountains. As shown by selected samples (table 1, nos. 31-34), the Lake Valley and Escabrosa limestones include many beds that are of high-calcium grade.

The Pennsylvanian sequence is 800 to 2400 feet thick in the region and except locally is mainly of limestone. Many of the mountain ranges are capped by these Pennsylvanian limestones which form extensive outcrops in the Fra Cristobal, Mud Springs, Caballo, Big Hatchet, and Peloncillo mountains, Sierra Cuchillo, Black Range, and Silver City–Santa Rita areas. Most of the outcrops, however, are in relatively inaccessible places at considerable distances from either or both railroads and gaslines. Grab samples from the Pennsylvanian limestones throughout southwestern New Mexico appear to show high-calcium limestone in most of the large outcrop areas.

Limestones in the Yeso Formation and San Andres Limestone of western and central Sierra County appear to be mainly magnesium-rich or impure, thus were not sampled for chemical analysis. These formations were removed by erosion during early Mesozoic time from the Grant and Luna counties area. Faunal equivalents crop out, to the southwest in Hidalgo County as parts of the Epitaph Dolomite, Scherrer Sandstone, and Concha Limestone--units which appear to contain little if any high-calcium limestone.

The Wolfcampian Hueco Formation crops out in the Florida and Tres Hermanas mountains and grades northward into the Abo Redbeds. Correlative units occur in the upper part of the Horquilla Limestone, Earp Formation, and Colina Limestone of the Big Hatchet, Animas, and Peloncillo mountains. Some of the limestones of these Wolfcampian formations are of high-calcium grade (table 1, no. 14-16).

Lenticular black limestones crop out amid the Mancos Shale of the Caballo and Fra Cristobal mountains area and within the Colorado Formation near Cooks Peak and in the Silver City-Santa Rita area but are impure argillaceous limestones typical of the Mancos. The thick Early Cretaceous sequence that crops out in southern Dona Ana, southern Luna, southern Grant, and southern and central Hidalgo counties includes thick fossiliferous limestones, many of which are of high-calcium grade (table 1, nos. 4-5), although being chiefly bioclastic calcarenites they may contain much detrital silica (table 2, nos. 4-6). The thickest known Early Cretaceous section in the State crops out in the Little Hatchet Mountains where Lasky measured 15,300 to 21,000 feet of Early Cretaceous beds. Thick, high-calcium limestones may occur in the Broken Jug Limestone, Howells Ridge Formation, and Playas Peak Formation, all of which contain many thick reefoid limestones. Similar limestones crop out to the south in and near the Big Hatchet Mountains (Zeller, 1958).

Cenozoic sedimentary beds are almost entirely sandstone, siltstone, and conglomerate, principally derived from Tertiary volcanic rocks and from older pre-Tertiary sedimentary strata. Many of the clastic beds are limy but Cenozoic limestones are rare. Impure caliche caps many of the extensive surfaces, such as that of the Jornada del Muerto east of Hatch, but all grab samples collected showed at least 29 percent insoluble residues. High-calcium algal limestone does occur within the Tertiary Palm Park Formation of the southwestern Caballo Mountains but is only of local extent and is far from transportation facilities.

Tres Hermanas Mountains

Paleozoic strata crop out on the northeastern flank of the Tres Hermanas Mountains (fig. 8), and Early Cretaceous beds form a fault-block ridge along the west side of the mountains. Near the Tertiary monzonite stock that makes up the core of the mountain mass, the pre-Tertiary strata are contact meta-

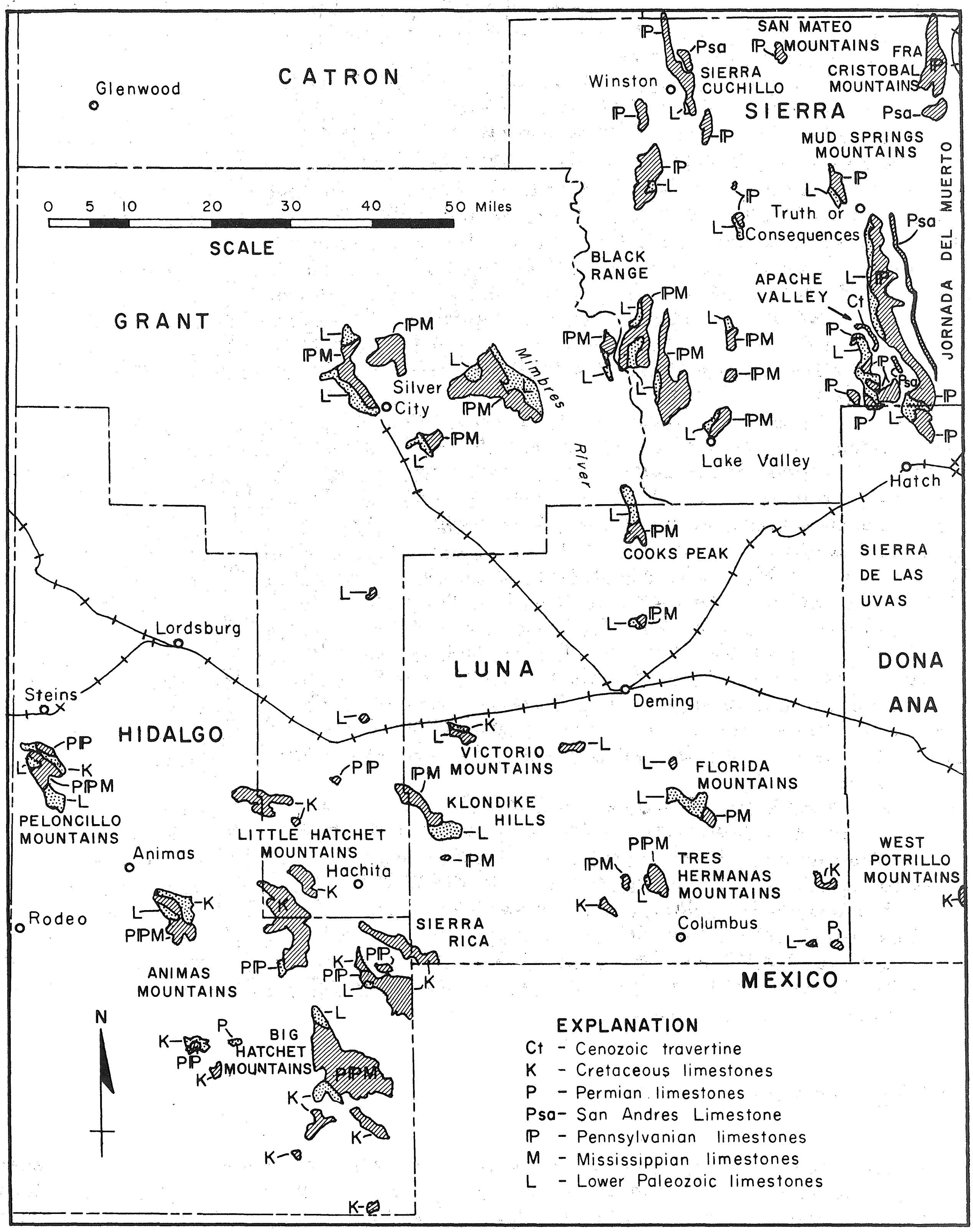

Figure 7
Map of southwestern New Mexico showing limestone outcrops

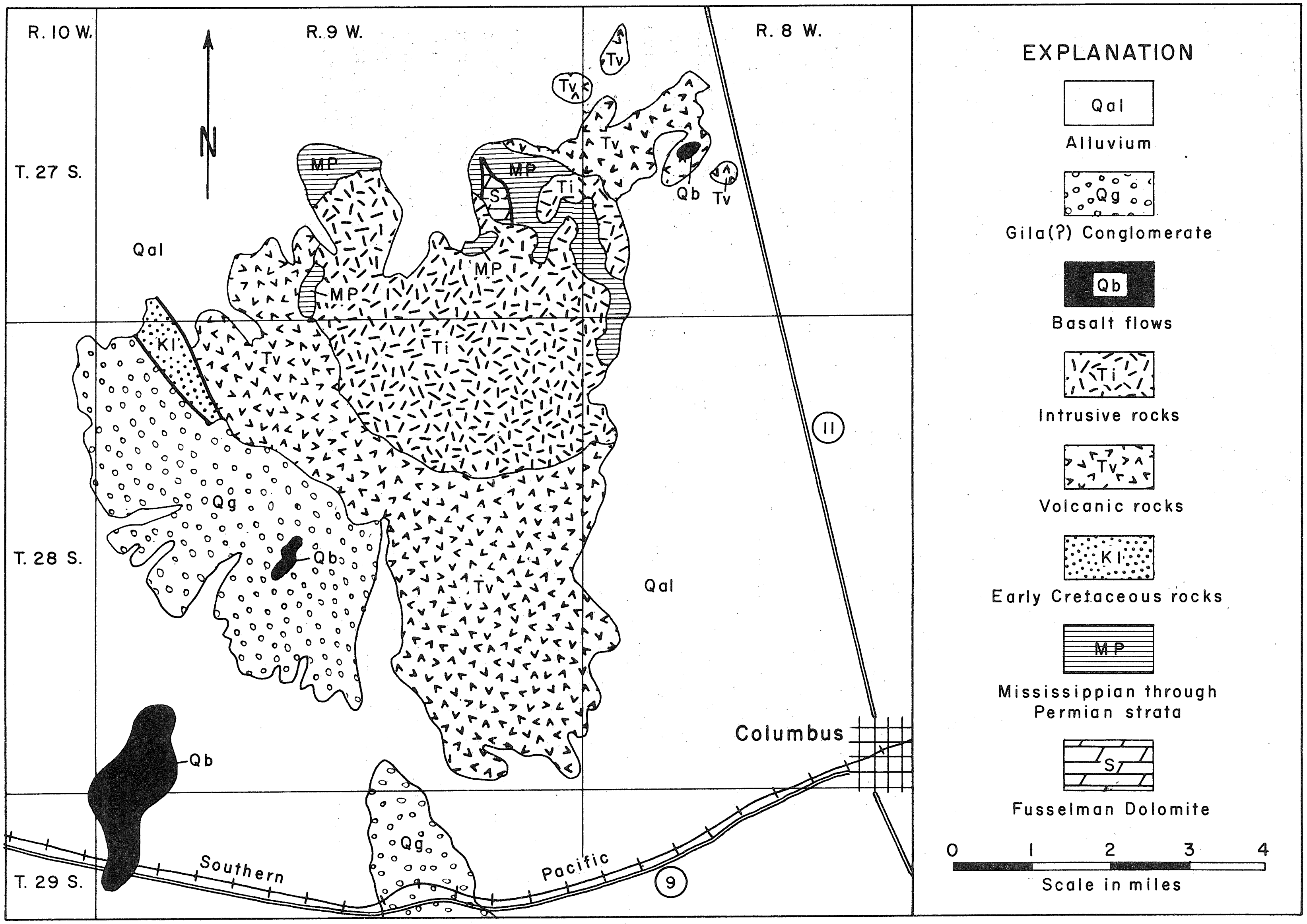

Figure 8
Geologic sketch map of the Tres Hermanas Mountains

morphosed, the chief effect on the limestone units being some addition (or redistribution ?) of silica and a recrystallization to coarsely crystalline marble. The oldest beds exposed are part of the Silurian Fusselman Dolomite which consists of dolomitic limestone and dolomite. Only the upper part of the Escabrosa limestone is exposed, but it is more than 360 feet thick, consisting of light-gray cherty marble on the northeast tip of the mountains but relatively noncherty, white, massive crinoidal limestone and marble on the north-central flank. A chip-channel sample of the upper 100 feet of the Escabrosa limestone at the latter locality (table 1, no. 32) showed 98.8 percent calcium carbonate, 0.4 percent magnesium carbonate, and only 0.1 percent silica. The limestone on the northeast flank of the range, however, contains 5 to 30 percent megascopic silica in large chert nodules that consist of an inner core of original (?) chert surrounded by a thick rim of added silica which cuts poorly preserved bedding planes.

To the northeast in the Florida Mountains, the carbonate rocks of the pre-Mississippian early Paleozoic sedimentary sequence consist almost entirely of dolomite and dolomitic limestone, although individual beds in the El Paso Group may be of high-calcium grade. Only the lower 200 feet of the Mississippian remains beneath Permian clastic rocks and consists of dark-gray, cherty, thin- to medium-bedded limestone. Pennsylvanian rocks are absent. In the Tres Hermanas Mountains, the Pennsylvanian is thin, only 560 feet thick, and consists almost completely of limestone except for lenses and partings of shale and a 60-foot-thick sandstone unit. However, all the limestones are clastic, being chiefly bioclastic calcarenites and calcilutites containing much detrital quartz.

The Hueco Formation is at least 525 feet thick in the Tres Hermanas Mountains with the upper contact a fault zone. Basal units are of chert-and-limestone pebble-and-cobble conglomerates and algal siliceous microcrystalline limestone. The middle and upper parts of the exposed Hueco Formation consist of dark-gray, thin-bedded to massive limestones, oolitic in part, containing many gastropods and much crinoidal debris. A representative sample from a typical thick limestone near the top of the Hueco (table 2, no. 21) showed 91.0 percent calcium carbonate, 0.3 percent magnesium carbonate, and 7.7 percent silica. Similar limestone beds from the Hueco of the southeastern Florida Mountains, however (table 1, no. 15), yielded 95.4 percent calcium carbonate, 0.4 percent magnesium carbonate, and only 3.1 percent silica. The Hueco Formation in the Florida Mountains consists of about 350 feet of dark-gray limestone, with a thin, basal clastic unit, and is overlain unconformably by limy Cretaceous(?) conglomerates.

The Early Cretaceous sequence (Kottlowski and Foster) that forms the fault-block ridge on the west side of the Tres Hermanas Mountains is more than 1530 feet thick and includes massive beds of high-calcium limestone. The section contains 4 lithic units (fig. 9): (1) lower 375 feet of interbedded chert conglomerate, sandstone, pale-red siltstone, and silty limestone; (2) 395 feet of massive limestone; (3) 425 feet of limestone conglomerate and reddish sandstone; and (4) upper 340 feet of sparsely fossiliferous limestone. Many of the massive limestones below the center of the section are high in calcium (table 1, no. 5) as shown by beds in the lower part of unit 10, Figure 9, with 95.4

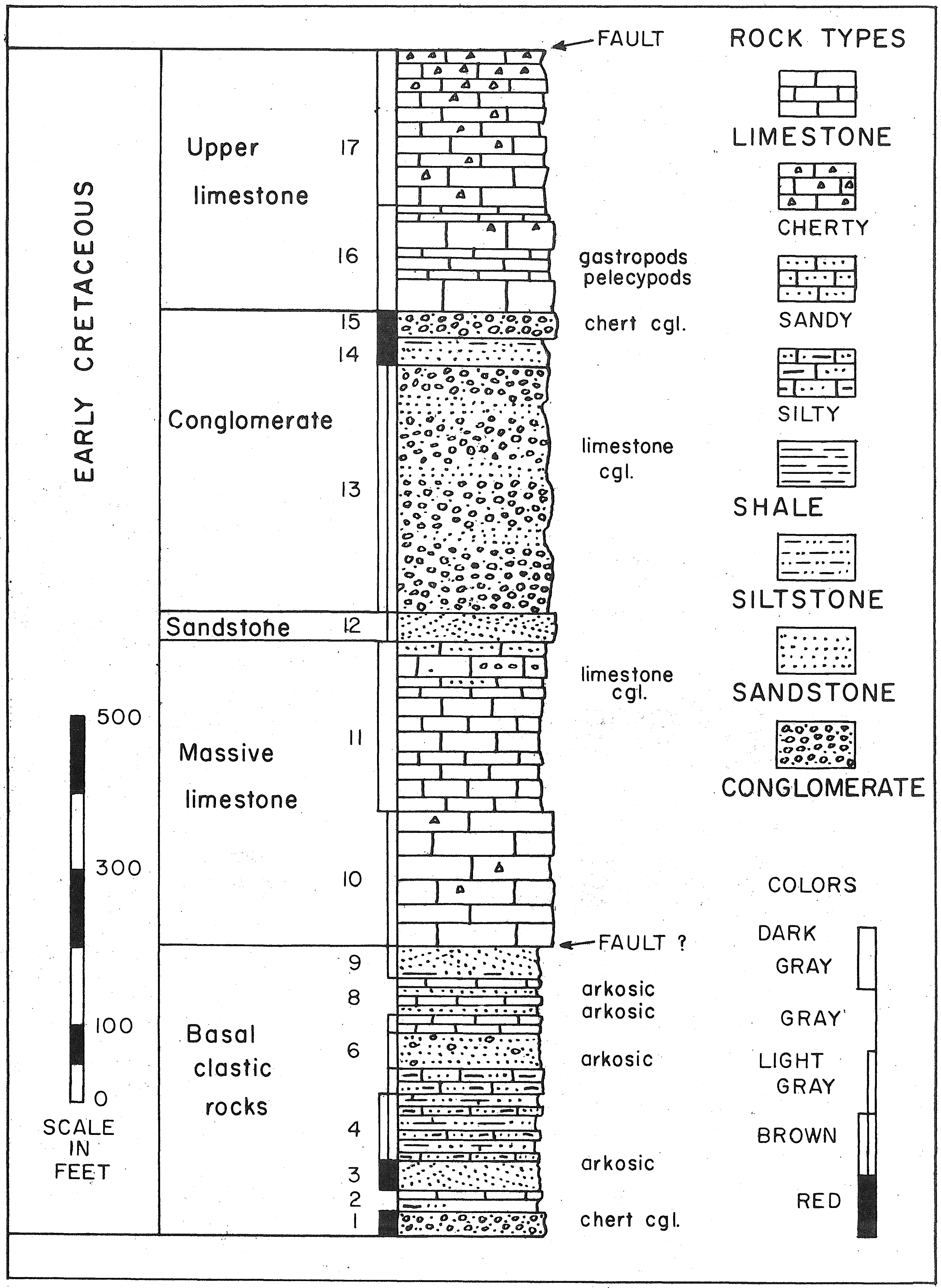

Figure 9
Columnar section of Early Cretaceous strata in Tres Hermanas Mountains

percent calcium carbonate and 3.2 percent silica. Upper beds in the same unit are more siliceous and contain 8.4 percent silica (table 2, no. 4). Massive limestones in the lower part of the upper limestone sequence, unit 16, Figure 9, also are somewhat siliceous but are high in calcium (table 1, no. 4), showing 95.4 percent calcium carbonate and 2.6 percent silica. Some of these relatively pure Cretaceous limestones cap low dip-slope cuesta ridges and could be quarried over large areas; however, they are reachable only over sandy ranch roads from State Highway 11, the Deming to Columbus highway.

Peloncillo Mountains

Volcanic rocks make up most of the bedrock in the Peloncillo Mountains but a large area south of Steins Pass to two miles south of Granite Gap is underlain chiefly by Paleozoic and Mesozoic sedimentary beds. The strata are cut by many faults and intruded by numerous dikes and small stocks of granite, quartz monzonite, latite, and rhyolite. Silicification is widespread near faults and near intrusive masses. Pre-Tertiary and post-Precambrian strata include the Bliss or Bolsa Sandstone, El Paso Limestone, Montoya Dolomite, Percha Shale, Escabrosa Limestone, Paradise Formation, Horquilla Limestone, Earp Formation, Colina Limestone, Scherrer Formation, and Concha Limestone of Paleozoic Age and several units of Early Cretaceous Age (Gillerman). High-calcium limestones probably occur only in the Escabrosa Limestone, Horquilla Formation, and Colina Limestone. The upper crinoidal calcarenite of the Escabrosa, more than 100 feet thick and in thick to massive, relatively noncherty limestone beds, was sampled on the southeast cliffs of Blue Mountain (<u>see</u> Gillerman, pl. 1) (table 1, no. 33) and showed 98.8 percent calcium carbonate, 0.3 percent silica, and 0.4 percent magnesium carbonate. The widely scattered chert nodules that appear to make up less than 1 percent of the unit were not included in the sample.

Grab samples of selected limestones in the Horquilla Limestone on Blue Mountain appear to be high in calcium as they contain only 0.6 to 1.2 percent insoluble residues. The Horquilla, however, is marked by sparse to abundant chert and much secondary silica in veinlets, irregular laminae, and scattered patches. Outcrops of the Colina Limestone are in relatively inaccessible places, so a sample was collected on the northeast slope of Cienega Peak—unfortunately not far from a small stock of the Cienega Peak granite. The upper 120 feet of the formation, consisting of alternating light-gray and black calcarenite, appears to be relatively pure although partly marbleized, and near fractures contains tiny needles of tremolite. Other metamorphic minerals occur in the Colina near the contact with the Cienega Peak granite. A chip-channel sample of this upper part of the Colina (table 2, no. 19) showed 66.2 percent calcium carbonate, 21.2 percent magnesium carbonate, 10.6 percent silica, and 0.7 percent alumina. Only a few of the outcrop beds appeared to be dolomitic but insoluble residues totaled 11.7 percent of the sample and contained several calcium silicate minerals. Unmetamorphosed limestones of the Colina on the west side of the range appear to be relatively pure limestone.

Most of the limestones in the thick sequence of Early Cretaceous rocks south of Steins Pass are interbedded with conglomerates and sandstones and in large part are also arenaceous and conglomeratic. These Cretaceous strata crop out around and south of the Carbonate Hill Mine chiefly in altered, faulted, and mineralized areas. The fossiliferous dark-gray, medium-grained, arenaceous calcarenites of the Carbonate Hill Limestone seem most promising for high-calcium limestone; grab samples collected from a small fault block just west of U.S. Highway 80 in the easternmost tip of the range (sec. 18, T. 25 S., R. 20 W.) and south of the Carbonate Hill Mine, however, yielded insoluble residues 4.6 to 11.2 percent. The residues are mainly of angular to subrounded quartz grains.

Big Hatchet Mountains Area

High-calcium limestone probably occurs in the Big Hatchet Mountains (Zeller, 1958) within the Escabrosa Group, Horquilla Limestone, Colina Limestone, and in the thick sequence of Early Cretaceous strata. In particular, some of the massive, thick, reefoid limestones in Zeller's (1958) U-Bar Formation and some of the massive encrinites of the Escabrosa appear to be of high-calcium grade. Some of the thick stromatolitic limestones in the upper part of the El Paso Group are reported by Dr. Rousseau H. Flower (oral communication, 1962) to be relatively pure and probably are of high-calcium grade. Similar limestones also crop out in the Little Hatchet and Animas mountains, and in Sierra Rica, but share with the outcrops of the Big Hatchet Mountains the disadvantages of difficult access, especially since the southern branch of the Southern Pacific Railway from El Paso to Douglas via Columbus, Hachita, Animas, and Rodeo is scheduled to be abandoned.

Silver City–Santa Rita Area

High-calcium limestones are probably limited to the Mississippian and Pennsylvanian sequences near Silver City and Santa Rita, but because of the extensive mineralization and regional alteration no samples were collected in this area. East of Santa Rita and extending to the Mimbres River valley, the pre-Tertiary rocks are relatively unaltered with some of the Mississippian and Pennsylvanian limestones seeming to be of high-calcium grade, as judged from reaction with HCl and their appearance in the outcrop.

Apache Valley and Caballo Mountains

The Caballo Mountains are on the east side of the Rio Grande; U.S. Highway 85 runs along the west side of the river, so only a few poor ranch roads lead into the western side of the range. The mountains are a complex fault block (Kelley and Silver) uplifted along the west side, with beds generally dipping eastward under the Jornada del Muerto. Possible high-calcium limestones appear limited to the Pennsylvanian sequence which caps the higher parts of the range, crops out as benches along the west-facing scarp, and is in most places difficult to reach. Limestones in the San Andres Limestone crop out as dip-slope cuesta ridges along the east foot of the range but appear to be partly dolomitic, somewhat cherty and impure, and are interbedded with clastic strata. Mississippian beds, other than small erosional remnants, are absent except near the southern tip of the mountains. The Pennsylvanian limestones in the small block-faulted Mud Springs Mountains northwest of Truth or Consequences are closer to paved roads than most of the Caballo Mountains Paleozoic outcrops.

Along the southwest edge of the range, a broken chain of small fault-slices forms foothills southwest of the main bulk of the Caballos; between (to the northeast) these outcrops of Precambrian and Paleozoic rocks and the high peaks of the Caballo Mountains, a broad northwest-trending valley has been cut in the relatively less resistant Tertiary rocks that unconformably overlie the Pennsylvanian and Permian strata. This valley, labeled Apache Valley by Kelley and Silver, is drained mainly by Green Creek, but the southern part is tributary to McCleed Creek and the northern tip has been carved by Apache Creek. Numerous faults, chiefly of longitudinal trend, and extensive alluvial fan gravels obscure the geologic relationships in the Valley. The Tertiary Palm Park Formation is unconformable on various Paleozoic units, is about 900 feet thick, and consists of (1) a basal one third of interbedded red siltstones and pebble-to-boulder conglomerates (clasts of Precambrian and Paleozoic rocks and Tertiary andesitic lavas); (2) a middle one third of light blue-gray to purple porphyritic latite tuff; and (3) an upper one third of pinkish tuffaceous sandstones and lenticular algal limestones. The Palm Park Formation is conformably overlain by the Thurman Formation whose basal unit in most places is thick, tan, cliff-forming rhyolite tuff-breccia, but locally either light-gray rhyolitic tuff or pinkish sandy claystone and tuffaceous sandstone mark the base of the Thurman.

The uppermost part of the Palm Park Formation is exposed in only five places, as far as is known from reconnaissance mapping by William D. Tipton and the writer (fig. 10): along the upper reaches of Apache Creek, near the head of McCleed Creek, northeast of Tipton Ranch, in and near Palmer (Palm) Park, and in the Rincon Hills. The algal limestone beds appear to be present only as far south as the Tipton Ranch where a remnant caps Tepee Butte. Around the headwater arroyos of Apache Creek, and cut by the creek, the algal limestones are thick but lenticular. A lower thin-bedded to massive, grayish-brown algal limestone weathers light-gray, and is 40 to 100 feet thick including intercalated lenses of limy reddish-brown mudstone. Above is a 30- to 75-foot-thick unit that is covered in most places but shows scattered ledges of limy reddish-brown mudstone, pumice, pink marl, and cobble conglomerates with

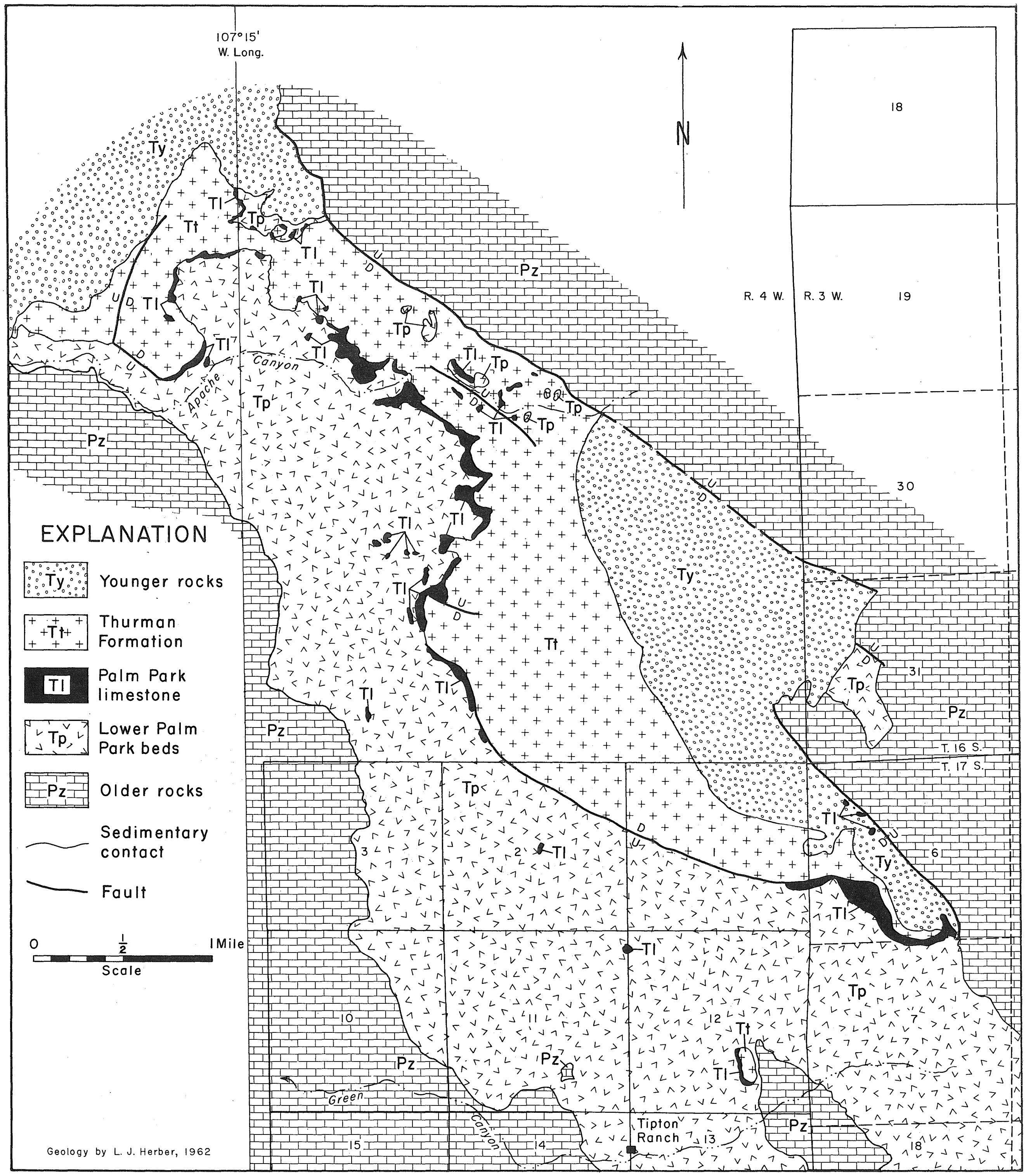

Figure 10
Reconnaissance geologic map of Apache Valley area

clasts of Paleozoic limestones and dolomites and of andesite and latite. The upper limestone is very lenticular and consists of light-gray algal limestone marked by gray calcite laminae and some paper-thin partings of gypsum. In one place this upper limestone swells into a 40-foot-thick mound-like mass of high-calcium limestone (table 1, no. 1) containing 97.1 percent calcium carbonate, 1.6 percent magnesium carbonate, and 0.7 percent silica. Grab samples from the lower limestone--which is the more persistent of the two limestone units--yielded 0.9 to 2.1 percent insoluble residues consisting of silt-sized quartz, orthoclase, biotite, and glass shards. Both limestones cap benches overlain by less resistant clastic strata and could be quarried for several miles along the outcrop. Where the upper algal limestone is thick, it is almost directly overlain by the massive, cliff-forming, rhyolite tuff-breccia of the Thurman Formation, but where the upper limestone is thin, it is overlain by nonresistant, pink to light-gray pumice, crystal tuff, tuffaceous sandstone, and mudstone.

In part, these Tertiary limestones of the Apache Valley area resemble the algal limestones of Tertiary Flagstaff Limestone of Utah and like the Flagstaff are probably lake deposits with some of the mound-like masses being algal bioherms. Known outcrops of the Palm Park limestone occur in a small area and outline a relatively small lake that was overwhelmed by eruptions of rhyolitic pyroclastic rocks.

SOUTH-CENTRAL NEW MEXICO

South-central New Mexico as used in this report (fig. 11) covers a diverse country ranging eastward from the typical basin-and-range topography of the Robledo and East Potrillo mountains, into the Sacramento section of tilted fault-block plateaus like the Sacramento and Guadalupe Mountains, and onto the western edge of the Pecos River section of the High Plains. The structure is relatively simple and becomes even less complex eastward; likewise, the amounts and number of occurrences of igneous rocks and attendant alteration die out eastward.

West of the Sacramento Mountains' crest, most of the limestone outcrops are of pre-Permian Age; to the east, the outcropping limestones are only of Permian Age in New Mexico, unless the caliche capping of the Llano Estacado is classed as limestone. Pre-Mississippian strata thicken southward along the San Andres–Organ–Franklin chain of ranges, from a knife edge near Mockingbird Gap to about 3600 feet in the northern Franklin Mountains near the New Mexico–Texas stateline. None of the pre-Mississippian units (Bliss Sandstone, El Paso Group, Montoya Group, Fusselman Dolomite, or various Devonian formations) appears to contain high-calcium limestone in this part of the State, as even the El Paso Group limestones are too impure and contain too much magnesium. The Caballero Formation, of Early Mississippian Age, crops out only along an east-west belt from the central Sacramento Mountains

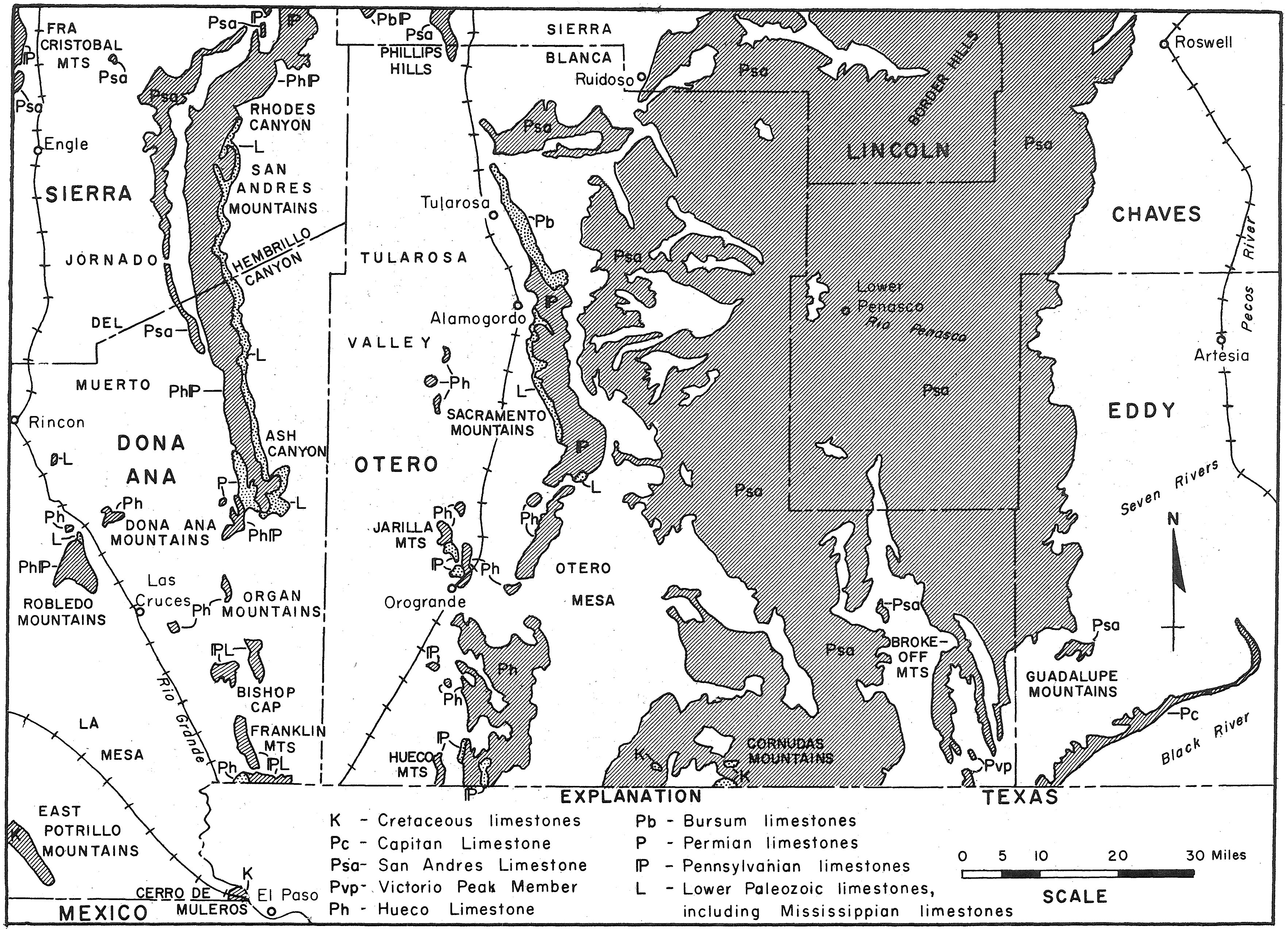

Figure 11
Map of south-central New Mexico showing limestone outcrops

westward through the central and southern San Andres Mountains to the Robledo Mountains and beyond to the Lake Valley area. This unit, of Kinderhook Age, is of interbedded argillaceous limestones and limy shales that are too impure to include high-calcium beds.

The overlying Lake Valley Limestone thickens southward in the San Andres range from about 60 feet in Rhodes Canyon to 390 feet near Ash Canyon and southeastward to almost 400 feet in the central Sacramento Mountains. Farther southward, the Lake Valley Limestone thins to 75 feet at Bishop Cap and then pinches out to the south where the Rancheria Formation, of dark siliceous limestones, is the basal Mississippian unit. The Rancheria Formation thickens abruptly in the southern San Andres and southern Sacramento mountains from a knife edge to 200 feet within a few miles, in about the same area where the Lake Valley thins proportionately. The Rancheria Formation is overlain by the Chester Age Helms Formation, which consists of interbedded yellowish fossiliferous sandstone, arenaceous limestone, and shale. Neither the Rancheria nor the Helms Formation contains any appreciable amount of high-calcium limestone but many of the fossiliferous encrinites of the Lake Valley Limestone are high in calcium (table 1, nos. 31, 34).

The Pennsylvanian sequence varies greatly in thickness and lithology throughout this region but most of the western ranges contain high-calcium limestone (table 1, nos. 22, 27, 29, 30). In contrast to the basal Pennsylvanian of central and northern New Mexico, the lower Pennsylvanian strata in southern New Mexico include many thick, relatively pure limestones, although siliciclastics and arenaceous calciclastic beds occur near the base. Desmoinesian Age limestones, in the middle of the sequence, include many that are cherty. The upper Pennsylvanian strata are dominantly impure calciclastic beds, along with much dark shale and sandstone in the San Andres, Franklin, and Sacramento mountains, but thick beds of high-calcium limestone occur amid this siliciclastic sequence throughout south-central New Mexico except in the southern San Andres, Organ, and Franklin mountains.

High-calcium limestone occurs within the Wolfcampian Bursum Formation of the Robledo and northern San Andres Mountains, the Laborcita Formation of the northern Sacramento Mountains, and the Hueco Formation of the Robledo, Dona Ana, San Andres, Franklin, Sacramento, and Hueco mountains. The Yeso Formation becomes dominantly limestone in the southern Sacramento Mountains and on Otero Mesa where some of the limestones may be of high-calcium grade. High-calcium limestones are present in the San Andres Limestone in the San Andres and Sacramento mountains. In the latter range, lower carbonate rocks of the San Andres Limestone appear to be chiefly limestone whereas upper beds are dolomitic. The entire San Andres unit seems to be dolomitic or dolomite in the Guadalupe Mountains (Boyd; Hayes).

Above the San Andres Limestone, along the Pecos River valley and in parts of the Guadalupe Mountains, are the interbedded red beds, gypsum, and dolomitic rocks of the Artesia–Whitehorse–Chalk Bluff–Bernal Group (Formation). Carbonate-rock beds in this unit are thin, lenticular, impure, and dolomitic. Correlative beds deposited in the Permian Age Delaware basin, the Cherry Canyon and Bell Canyon Formations, crop out only along the New Mexico–Texas stateline in the southern Guadalupe Mountains. These formations are dominantly of siliciclastic rocks but include some high-calcium limestones (table 1, nos. 7, 8) as well as impure or dolomitic limestone members. The basinal Yeso equivalent, the Bone Spring Limestone, crops out in New Mexico only in the Brokeoff Mountains, a relatively inaccessible area, but its Victorio Peak Member locally includes high-calcium limestone (table 1, no. 12). The reef equivalents of these middle Permian basinal and backreef strata are chiefly carbonate rocks but vary from the dolomite of the Goat Seep reef to high-calcium masses (table 1, no. 10) in the core of the Capitan reef. Dolomitization of the Capitan Limestone is complex as discussed below.

The Castile and Rustler Formations of Latest Permian, Ochoan Age, crop out above the previously mentioned Guadalupian rocks in the Delaware basin, forming low hills between the valleys of Black River and the Pecos River south of Carlsbad. These Ochoan units are mainly of dolomite, gypsum, siltstone, and some thin limestones; most of the limestone beds are too thin and too intermixed with gypsum to be of commercial use, although the Castile Formation contains some high-calcium limestone (table 1, no. 6).

The numerous springs on the eastern dip slope of the Sacramento Mountains, and in the Guadalupe Mountains and Otero Mesa area, issue mainly from limestone bedrock and are characterized by large local deposits of calcareous tufa and travertine. Most of these spring deposits appear to be contaminated by much detrital and precipitated silica and by gypsum. Caliche caps many of the older gravels of the Pecos River valley area and is especially thick as the "caprock" of the Llano Estacado to the east of the Pecos River. Local lenses may contain high-calcium limestone as reported by Bretz and Horberg, but samples collected from scattered points along the west-facing edge of the caprock in Lea, Chaves, Roosevelt, DeBaca, Quay, and Guadalupe counties showed 19 to 40 percent insoluble residues for complete sections of the caliche cap. This caliche has been and is being used for road metal throughout the High Plains areas, but it does not seem to contain high-calcium limestone.

East Potrillo Mountains and Cerro de Muleros

The East Potrillo Mountains lie on La Mesa 25 miles west of El Paso and are accessible by good ranch roads. The section exposed in the range appears (to the writer) to be entirely of Early Cretaceous strata consisting of four lithic units (Bowers): (1) basal light-gray to dark-gray marbleized limestone, about 250 feet thick, and locally brecciated along the frontal fault zone of the range; (2) intercalated limestone-cobble conglomerate, arenaceous calcarenite, and limy sandstone, 400 to 600 feet thick; (3) massive, fossiliferous limestone grading up into intercalated arenaceous calcarenite and limy sandstone, 400 to 600 feet thick; and (4) upper medium-bedded limestone with lower beds very fossiliferous and upper beds silty and argillaceous, about 500 feet thick.

A sample of the lower marbleized limestones (table 2, no. 5) showed only 85.9 percent calcium carbonate, 8.8 percent silica, and 1.9 percent alumina.

The massive limestones of the third unit include some lenticular reefoid masses that contain (grab sample) less than 1 percent insoluble residues as well as other thick, fossiliferous limestone beds that seem to be of high-calcium grade. However, these upper massive limestones cap the East Potrillo Mountains and may be costly to quarry.

A thick Early and Late Cretaceous sequence crops out on Cerro de Muleros across the Rio Grande from El Paso, as well as in the northwestern part of the city. The core of the circular hill is a laccolith(?) of diorite porphyry which has not appreciably altered the intruded Cretaceous strata. The section exposed around Cerro de Muleros and in low hills to the south across the New Mexico-Mexico boundary is as follows, using the classifications of Bose (1906), Adkins (1932), and Imlay (1944):

Late Cretaceous		Eagle Ford Formation, as much as 750 feet of interbedded dark-gray to reddish limy shales, limestones, and limy sandstones
		Woodbine Sandstone, 200 to 800(?) feet of light-gray quartzitic cross-bedded sandstone
Early Cretaceous	Washita Group	Buda Formation, 90 feet of limestone with yellowish shale lenses
		Del Rio Formation, 75 feet of yellowish limy shale with lenses of limestone
		Main Street Formation, 75 to 330 feet of reddish hard sandstone with upper marly shales and arenaceous calcarenites
		Pawpaw and Weno Formations, 35 to 75 feet of interbedded dark shale and brown marly sandstone
		Denton and Fort Worth Formations, 100 to 165 feet of marl and nodular dark limestone
		Duck Creek Formation, 100 to 165 feet of marly shale with basal shaly limestone

Fredericksburg Group	Kiamichi Formation, 80 feet of arenaceous limestone, gray limy sandstone, and dark shale
	Edwards Limestone (Finlay or Goodland), 85 feet of limy clay and marly limestone with basal white limestone
Trinity(?) Group	Unfossiliferous sandstone, at least 200 feet thick

Limestone used by the Southwestern Portland Cement Company from the Edwards Limestone in quarries near Cerro de Muleros showed (table 2, no. 7) 93.5 percent calcium carbonate, 2.1 percent magnesium carbonate, 3.2 percent silica, and 0.8 percent alumina; this is almost a high-calcium limestone, but it is interbedded with much limy shale. Thick-bedded, light-gray fossiliferous limestone from the Buda Formation, higher in the section, collected on the southern edge of Sunland Park village, is similar in composition (table 2, no. 6), showing 93.3 percent calcium carbonate, 1.3 percent magnesium carbonate, 3.7 percent silica, and 0.7 percent alumina. The limestones in the Cretaceous rocks on and near Cerro de Muleros appear to be too intimately intermixed with quartz sand and clays to yield high-calcium limestone. Thicker sections of Early Cretaceous limestones are reported to the south in the Juarez Mountains of Mexico, probably stratigraphically lower than the Edwards Limestone, and may contain high-calcium limestone that would be accessible by sandy roads built on La Mesa to the west side of the mountains.

Robledo and Dona Ana Mountains

Pre-Pennsylvanian strata in the Robledo Mountains crop out only at the north end of the range on the cliffs bordering Lookout Peak and are relatively inaccessible. Pennsylvanian rocks form a southward-facing U-shaped outcrop belt on the northern, upper, slopes of Robledo Mountain and are also difficult to reach. The Early Pennsylvanian series is thin, the middle part of the sequence is chiefly of highly cherty limestone, but the Missourian and Virgilian strata include some thick, cliff-forming high-calcium limestone. Unfortunately most of the outcrops of these Late Pennsylvanian limestones surmount cliffs 1000 to 2000 feet above the foot of the mountain and would be expensive to quarry.

Most of the central and southern parts of the Robledo Mountains, which are a southward-tilted wedge-shaped fault block, are underlain by outcrops of the Hueco Formation. The lower northwestern hills of the Dona Ana Mountains are also chiefly outcrops of the Hueco strata. Numerous thick, massive limestones within the Hueco Formation crop out as cliffs rimming extensive mesas and could be quarried by removing thin overburden. Sampling showed considerable variation in the types and purity of the limestones within the formation. Massive limestones in the lower part of the formation, and comprising most of the underlying Bursum Formation, appear to be high-calcium beds and contain (from grab samples) less than 1.5 percent insoluble residues; however, these cliff-forming lower limestones crop out on Robledo Mountain and in the central part of the range where access is difficult. Several massive limestones near the middle of the formation, and below the Abo red-bed tongue that occupies the lower part of the upper half of the formation, cap extensive dip-slope mesas near the Rio Grande and are of high-calcium grade. A chip-channel sample from one such mesa-capping limestone (table 1, no. 14) showed 97.6 percent calcium carbonate, 0.5 percent magnesium carbonate, and 0.3 percent silica. This sample was collected from the northwest corner of sec. 18, T. 22 S., R. 1 E., where 21 feet of light-gray, fossiliferous, medium-bedded to massive limestone caps mesas both north and south of "Middle" Canyon. These outcrops are 1.6 miles from the good gravel road that leads northward, along the west side of the Rio Grande, from the paved Picacho farm road near Shalem bridge. A good quarry road could be easily and inexpensively built on top of the gravel-covered Picacho terrace that extends from the edge of the mountains eastward to the Rio Grande.

Thick limestone beds in the upper part of the Hueco Formation, above the Abo red-bed tongue, cap large mesas north of Apache Canyon in the southern Robledo Mountains. In part, the surfaces cut on these beds may be an exhumed erosion surface of early Tertiary time, because along Apache Canyon the upper resistant limestones of the Hueco are unconformably overlain by Tertiary (Tertiary ? Cretaceous ?) conglomerates, red beds, and gypsum. One to five feet of the top limestones on the mesa caps are irregularly silicified. On "Limestone Mesa" just south of "Shalem" Arroyo (NW1/4 SE1/4 sec. 30, T. 22 S., R. 1 E.), the capping 35 feet of limestone was sampled (table 2, no. 20) and yielded 91.4 percent calcium carbonate, 4.4 percent magnesium carbonate, and 2.3 percent silica, exclusive of megascopic chert masses. Other than the top 1 to 5 feet of limestone with variable silica (locally much silica), there are only scattered small chert nodules and local shale partings.

Grab samples from the Bursum and Hueco Formation in the northwestern Dona Ana Mountains show possible high-calcium limestones with low amounts of insoluble residues. The limestone beds dip steeply, locally being vertical, and in places are metamorphosed (chiefly only marbleized) near the intrusive syenite dikes and sills of the Dona Ana Mountains. At present, only jeep tracks lead into this area.

The red siltstones, gypsum, and andesitic breccia that unconformably overlie the Hueco Formation in the southern Robledo Mountains appear to be of Tertiary Age, although they may be of Early Cretaceous Age. These lacustrine deposits may be equivalent to the Palm Park Formation of the southwestern Caballo Mountains; interlaminated with the red siltstones and gypsum are laminae and thin beds of impure gypsiferous limestone (maximum of 6 inches thick), but no algal limestones, such as occur in Apache Valley of the Caballos, have been observed.

San Andres Mountains

Pennsylvanian, and locally Mississippian limestones cap the east-facing escarpment of the San Andres Mountains; many of the higher peaks and high dip-slope ridges of the range are underlain by massive resistant Pennsylvanian limestones. Ridges and mesas in the central and western parts of the mountains are held up by thick limestones within the Hueco, Yeso, and San Andres Formations. Most of the calcium-carbonate beds in the pre-Mississippian units are dolomitic and/or high in silica (Kottlowski, 1957). In the southern part of the range, but not at the south end, the Lake Valley Limestone is thick (100 to 400 feet) and appears to be of high-calcium grade, being lithologically similar to the pure Lake Valley limestones of the central Sacramento Mountains (table 1, nos. 31, 34).

Pennsylvanian beds are lithologically variable in the San Andres Mountains (Kottlowski et al.). Basal beds of the Derry Series are 105 to 345 feet thick in the range. They include silty arenaceous limestones near Rhodes Canyon, black, fossiliferous, carbonaceous limestones in Hembrillo Canyon, and siliceous, fossiliferous limestones near Ash Canyon. The Des Moines Series is about 600 feet thick in the central and northern parts of the range, but less than 200 feet near Ash Canyon. Cherty limestone dominates this series, along with some arenaceous calcarenites near the base, but some relatively pure limestones occur amid the cherty beds. Missourian strata are 140 to 300 feet thick in the San Andres Mountains and include some apparent high-calcium limestones, although many of the carbonate beds are impure. The thick Virgilian sequence, which forms most of (if not all) the Panther Seep Formation, thickens southward from 800 feet near Mockingbird Gap to almost 2400 feet near Ash Canyon. It is characterized by thick units of siliciclastic rocks and arenaceous calciclastic units. Thick, noncherty limestones do occur within this sequence, especially in the northern and central parts of the range, and appear to be of high-calcium grade. Similar massive, locally reefoid, limestones are present in the overlying Bursum Formation of the Rhodes Canyon area, and in the Hueco Formation throughout the mountains.

Limestones make up an aggregate thickness of 265 feet in the Yeso Formation near Rhodes Canyon, but pinch out southward. Most of these limestones are calciclastic and contain much quartz silt, some clay, and some carbonaceous matter. The San Andres Limestone is 600 to 750 feet thick in the northern part of the range and thins southward because of erosion during Mesozoic time. At the type section near Rhodes Pass, the "limestone" consists of four lithic units: (1) basal 95 feet of light-gray limestones, dolomitic limestones, arenaceous calcarenites, and limy sandstones; (2) 220 feet of massive, dark-gray limestone having some argillaceous and carbonaceous beds; (3) 115 feet of light-gray dolomitic limestones and calcic dolomites; and (4) upper 140 feet of light-gray dolomitic limestones having basal argillaceous beds. Chip-channel samples from the lower unit (Kottlowski, 1957) were high (13.2 percent) in insoluble residues and were dolomitic, but the second unit averaged 95.5 percent calcium carbonate, only 2.5 percent magnesium carbonate, and 1.3 percent insoluble residues. The upper two units contain 20.3 to 28.7 percent magnesium carbonate. Some of these high-calcium limestones of the San Andres Limestone crop out just west of White Sands Missile Range west of Rhodes Pass, but the rest of the mountains are within the missile range; thus, they are off-limits for private business operations.

Bishop Cap and Northern Franklin Mountains

Pre-Tertiary strata in the Organ Mountains were intruded by the Organ Mountains monzonite batholith and have been altered, silicified, and locally mineralized. Bishop Cap is an isolated series of fault blocks, south of the Organ Mountains, which are made up of early Paleozoic strata and lower Pennsylvanian beds. On Bishop Cap, the Lake Valley Limestone is thin and cherty, whereas the overlying middle and upper Mississippian is represented by the siliceous Rancheria Formation, and the arenaceous beds of the Helms Formation. Lower Pennsylvanian rocks include some thick, noncherty limestones that may be of high-calcium grade.

In the northern Franklin Mountains, north of the New Mexico–Texas stateline, the pre-Pennsylvanian strata include few, if any, high-calcium limestones. The Pennsylvanian sequence is about 2700 feet thick (Harbour) and similar lithologically to the sequence near Ash Canyon in the southern San Andres Mountains. Thick limestones in the lower and middle Pennsylvanian appear to be of high-calcium grade. Richardson sampled Carboniferous limestones in the northern Franklin Mountains (table 1, no. 29) that showed 95.4 percent calcium carbonate and 1.2 percent magnesium carbonate. His samples were probably from either the Pennsylvanian beds or from limestones in the Hueco Formation.

The Hueco Formation is about 2200 feet thick in the northern Franklin Mountains (Harbour), and includes more limestone than the thinner sequences of the Hueco in the Hueco Mountains to the east and in the Robledo Mountains to the northwest. Only a few pinkish siliciclastic beds remain of the Abo redbed tongues that thicken northward. Grab samples from massive Hueco limestones collected southwest of Anthony Gap show a range of 1.4 to 11.3 percent insoluble residues, but otherwise appear to be high-calcium limestone.

Faulted slices of Early and Late Cretaceous rocks crop out in the southwestern foothills of the Franklin Mountains in Texas and contain limestones similar to those exposed on Cerro de Muleros as described above.

Sacramento Mountains

Pre-Mississippian strata crop out along the lower part of the west-facing Sacramento Mountains escarpment from Alamogordo southward for about 20 miles but do not seem to contain high-calcium limestone. The thick Lake Valley Limestone southeast of Alamogordo caps wide benches and contains much high-calcium limestone. As this area is serviced by a gas pipeline from El Paso, lies near the mainline tracks of the Southern Pacific Railway, and is only a few miles from U.S. Highways 54 and 70, power and transportation facilities are ideal for utilization of high-calcium limestones. The Lake Valley Limestone is 150 to 400 feet thick southeast of Alamogordo, including some of the larger biohermal buildups, but southward thins to where it is replaced by the siliceous limestones of the Rancheria Formation. The lower members of the Lake Valley, the Andrecito, and the Alamogordo Members, locally contain (grab samples) more than 2 percent insoluble residues, as do the intrabiohermal facies of the Nunn and Arcente Members. The bioherms and the Tierra Blanca and Dona Ana Members appear to be mainly high-calcium limestone. The quarries in Marble Canyon, east of Alamogordo, are cut primarily in the Tierra Blanca Member (table 1, nos. 31, 34) and show more than 98 percent calcium carbonate and less than 0.5 percent silica. Millions of tons of high-calcium limestone appear to be present in the Lake Valley Limestone of the west-central Sacramento Mountains.

The Pennsylvanian sequence of this mountain range is as much as 3000 feet thick. The lower Pennsylvanian rocks include many siliciclastic beds, and some of the middle Pennsylvanian limestones are highly cherty, but high-calcium beds do occur within the middle Pennsylvanian. However, these massive, middle Pennsylvanian limestones crop out as ledgy cliffs high on the westward-facing escarpment of the range and are difficult to reach. The upper Pennsylvanian consists of interbedded shale, sandstone, some conglomerate, and calciclastic limestones; most of the limestones appear to be arenaceous. Near the base of the Virgilian strata in the Holder Formation (Pray), however, algal bioherms and algal biostromal limestones crop out as cliffs capping narrow benches. A chip-channel sample (NW corner, sec. 3, T. 16 S., R. 10 E.) from the famous Dry Canyon bioherm (Plumley and Graves, 1953; Wray, 1959), taken (with considerable effort required) from a vertical interval of 65 feet (table 1, no. 22), showed 99.0 percent calcium carbonate, 0.1 percent magnesium carbonate, and 0.6 percent silica. This biohermal unit could be quarried near Dry Canyon and State Highway 83 for several miles along its sinuous outcrop.

The Pennsylvanian rocks are unconformably overlain by the Abo Redbeds in the central and southern Sacramento Mountains (Pray) but northward near Tularosa, the Pennsylvanian appears essentially to grade up into the Early Permian. The boundary between the systems is within the lower part of the Laborcita Formation (Otte), a unit of early Wolfcampian Age that pinches out southward between the Holder and Abo Formations. In part, the Laborcita is correlative with the Bursum Formation of the Oscura Mountains area. Extreme lateral and vertical variation in rock types characterizes the Laborcita Formation with a range from red beds to massive marine limestone. East of Tularosa, thick algal bioherms in the upper part of the formation form caps on the low mesas bordering the Tularosa Valley. A chip-channel sample from the 60-foot-thick bioherm in the SW1/4SW1/4 sec. 16, T. 14 S., R. 10 E., one-half mile north of U.S. Highway 70 (table 1, no. 17), showed 96.8 percent calcium carbonate, 1.9 percent magnesium carbonate, 0.5 percent silica, and 0.2 percent alumina. These moundlike masses thin laterally into similar but thinner algal limestones that contain (grab sample) less than 1 percent insoluble residues and also appear to be of high-calcium grade.

In the southern part of the Sacramento Mountains, a southward-thickening tongue of the Hueco Limestone appears in the middle of the Abo Redbeds, and grab samples suggest that some of the limestone beds are of high-calcium grade (insoluble residues of 1.2 percent). The Yeso Formation is 1300 to 1800 feet in thickness in the range and crops out chiefly on the timbered slopes below the crest of the mountains and along canyon bottoms of the eastern dip-slopes. Pray reported that the percentage of limestone in the Yeso increases southward from about 25 percent east of Tularosa to 45 percent at the southern tip of the range. He noted that dark-gray, thin-bedded, argillaceous limestone is a common type in the Yeso and that many of the carbonate-rock beds in the unit are impure.

The San Andres Limestone forms the resistant uppermost strata of nearly all the crest and much of the eastern slope of the Sacramento Mountains, ranging from 100 to 700 feet in thickness beneath the present erosion surface. Pray found that some of the limestones are dolomitic but except for basal dolomitic limestone interbedded with limy sandstone in the basal Hondo Member, dolomite is uncommon. Reconnaissance sampling suggests that most of the lower (excluding the Hondo Member) San Andres Limestone is relatively high in calcium, whereas upper beds, 500 and more feet above the Hondo Member, are dolomitic. In southwestern Chaves County, far out on the eastern slope of the Sacramento Mountains (perhaps too far east to be considered part of the mountains but rather the western edge of the High Plains), the lower part of the San Andres Limestone is of high-calcium grade. A chip-channel sample (table 1, no. 11) from the lower 40 feet of the formation, above the Hondo Member, collected along Rio Penasco Canyon (and along State Highway 83) 1.9 miles west of the junction of State Highways 83 and 24, showed 97.4 percent calcium carbonate, 0.9 percent magnesium carbonate, and 1.3 percent silica. These lower limestones of the San Andres could be quarried over extensive areas on this eastern slope of the Sacramento Mountains.

Otero Mesa and Northern Hueco Mountains

Southward from the southern end of the Sacramento Mountains, a low west-facing escarpment borders Otero Mesa on the west, extending southward to join with the northern Hueco Mountains. Impure limestones of the Yeso Formation, interbedded with pinkish siliciclastic rocks and minor gypsum, cap the escarpment and dip gently eastward to pass under the San Andres Limestone near the Cornudas Mountains. Locally, the Hueco Formation and interbedded tongues of Abo Redbeds crop out at the base of the escarpment, and in many places form low foothills extending westward to the Southern Pacific Railway.

The Hueco includes high-calcium limestone in this area, limestones similar to those that have been quarried farther south near Powwow Canyon in the Hueco Mountains of Texas where Haigh (table 1, no. 16) reported 97 percent calcium carbonate from massive limestones in the lower part of the Hueco Formation. Below the Hueco Formation in the northern extension of the Hueco Mountains, upper Pennsylvanian limestones crop out (Hardie, 1958) and include thick limestones similar to those quarried farther south (Haigh) (table 1, no. 30) which contain 99.8 percent calcium carbonate.

Pennsylvanian and Permian rocks crop out in the Jarilla Mountains near and north of Orogrande (Reynold and Craddock, 1959; Seager, 1961); in many parts of the range they are intruded and metamorphosed by masses of granodiorite and monzonite porphyry. The sequence is similar to that in the southern San Andres and southern Sacramento Mountains. The oldest sedimentary rocks exposed are of Desmoinesian and Missourian Age, are referred to the Bug Scuffle Limestone Member of the Gobbler Formation (Seager; Pray), and consist of cherty limestone with some interbedded sandstone and shale, totaling about 900 feet thick. Above is about 2900 feet of the Panther Seep Formation, perhaps chiefly of Virgilian Age, consisting of calcilutite, silty limestone, tan siltstone, calcareous sandstone, and brown to black shale with minor amounts of limestone-pebble conglomerate and coarse-grained arkose. Lenticular masses in the Panther Seep Formation appear to be coral-algae bioherms.

The Hueco Formation gradationally overlies these basinal Pennsylvanian strata and is at least 1075 feet thick with an additional estimated 300 feet not exposed. Gray to black limestone makes up about 75 percent of the formation with interbeds of chert-and-limestone pebble conglomerate, sandstone, graywacke, and shale. Near the top of the exposures, a single five-foot-thick bed of red cross-bedded sandstone is believed (Seager) to represent a tongue of the Abo Redbeds. Moundlike, possible bioherms are reported within the Hueco Formation.

Outcrop ridges of these upper Paleozoic strata are crossed by the Southern Pacific Railway near Orogrande; some of the limestones in both the Pennsylvanian and Hueco sequences appear to be of high-calcium grade.

The Cornudas Mountains on the New Mexico–Texas stateline have cores of sodic intrusives, flanked by quaquaversal outward-dipping beds of the Yeso and San Andres Formations which locally are unconformably overlain by Early Cretaceous strata. These Mesozoic beds are chiefly siliciclastic and contain only a minor amount of sandy and shaly limestone. As this range, along with much of the Otero Mesa area, is within or isolated by the McGregor Missile Range, the limestones were not sampled.

Guadalupe Mountains

The Guadalupe Mountains are essentially a broad plateau shaped like a crooked Y. The leg of the Y extends into Texas to a culmination at Guadalupe Peak; the longer northwest arm reaches into southwestern Chaves County, bounded on the southwest by a steep escarpment, and dipping northeastward into the Seven Rivers embayment; and the short northeast arm extends toward Carlsbad, bounded on the southeast by an abrupt escarpment, and sloping gently northwestward into the Seven Rivers embayment. The northwestern part of the range is bounded on the southwest by a fault zone and is capped chiefly by the San Andres Limestone; where the San Andres dips northeastward under the Artesia Group, these less resistant beds, in the evaporate facies of the Artesia Group, have been deeply eroded by the Seven Rivers. Massive limestones of the Capitan Limestone cap Guadalupe Peak and the southeastern scarp edge of the eastern arm of the Guadalupe Mountains, but resistant dolomites and sandstones in the carbonate-rock facies of the Artesia Group cap the back slopes of the central and eastern Guadalupes. Carbonate rocks in the San Andres Limestone and the Artesia Group appear to be dolomitic or dolomites (Hayes), as shown by Boyd who reported that samples typical of the San Andres "Limestone" in the western Guadalupe Mountains and Brokeoff Mountains contained 40.6 to 45.7 percent magnesium carbonate and only 53.1 to 58.8 percent calcium carbonate.

Basinal equivalents of the Yeso, San Andres, and Artesia units crop out in New Mexico only along the New Mexico–Texas stateline in the southern Guadalupe Mountains and in the Brokeoff Mountains to the west of the Guadalupe range. The Bone Spring Limestone, which is roughly the Yeso correlative, contains mostly siliciclastic beds and dark impure limestones, but high-calcium limestone does occur in the Victorio Peak Member (table 1, no. 12) which shows 98.2 percent calcium carbonate, 0.6 percent magnesium carbonate, and 1.0 percent residues (King). Patch reefs in the Bone Spring also are of high-calcium limestone (Newell et al.) (table 1, no. 13) showing 97.3 percent calcium carbonate and 0.4 percent silica, but 2.2 percent magnesium carbonate. Most of the carbonate rocks of the overlying, highly siliciclastic Cherry Canyon and Bell Canyon Formations are impure or/and dolomitic, but parts of the Rader and Lamar Limestone Members of the Bell Canyon Formation are high-calcium limestone (table 1, nos. 7, 8).

The Ochoan Castile and Rustler Formations crop out above the Artesia Group in the Delaware basin, forming low hills between the valleys of Black River and the Pecos River south of Carlsbad, as well as discontinuous flanking foothills east of the Guadalupe Mountains near Dark Canyon (fig. 12). Outcrops of the Castile Formation consist of gypsum, interlaminated gypsum and limestone, and some thin beds of limestone. The overlying Rustler Formation outcrops are of dolomite, gypsum, and siltstone; both formations in the subsurface include much anhydrite and some halite. Most of the Castile limestones are too thin and too intimately interlaminated with gypsum to be of commercial use, but locally the basal limestones are of high-calcium grade (table 1, no. 6) containing 96.6 percent calcium carbonate, 1.2 percent magnesium carbonate, and 1.4 percent insoluble residues.

The massive Capitan reef limestone crops out along the southeastern edge of the eastern Guadalupe Mountains escarpment, extending from Guadalupe Peak in Texas northeastward to near Dark Canyon (fig. 12) where the reef goes underground. Locally this reef limestone is 1500 to 2000 feet thick if measured vertically without regard to the dip of the reef-flank beds. Newell et al.

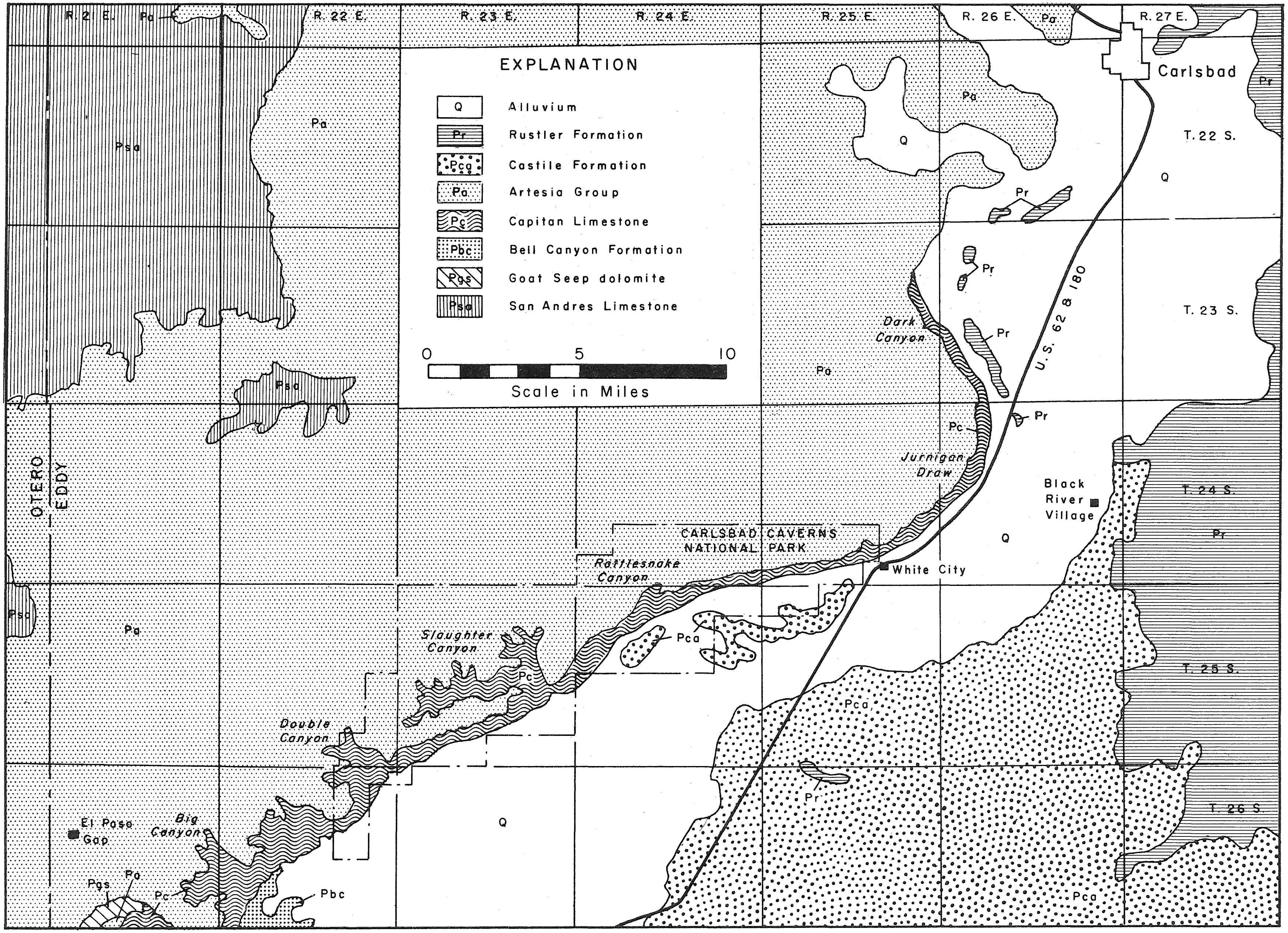

Figure 12
Geologic map of Capitan Reef Limestone in the Guadalupe Mountains of New Mexico

suggested that the reef core is of unstratified calcitic limestone, whereas the bordering reef-talus beds contain high percentages of dolomite. They listed 11 analyses of the Capitan reef core (table 1, no. 10) which average 98.2 percent calcium carbonate, 1.3 percent magnesium carbonate, and 0.4 percent silica. Some of the reef-flank or reef-talus beds are dolomitic or magnesium rich; Newell et al. showed a range (table 2, nos. 14, 15) of 77.6 to 93.7 percent calcium carbonate, 6.0 to 22.4 percent magnesium carbonate, and about 0.3 percent silica for samples of reef talus, whereas the reef-flank beds along Jurnigan Draw (table 2, no. 17) contain only 65.6 percent calcium carbonate, 34.0 percent magnesium carbonate, and 0.2 percent silica. However, reef talus from the mouth of Double Canyon (table 1, no. 9) showed 96.0 percent calcium carbonate, 3.8 percent magnesium carbonate, and 0.1 percent silica. Cursory sampling of the Capitan Limestone from Guadalupe Peak to Dark Canyon suggests that the limestone and dolomite facies are complexly mingled. Whereas most of the reef-flank beds do appear to be magnesium rich, some of these flanking beds are high-calcium limestone, and parts of the reef core contain appreciable amounts of magnesium. For example, a chip-channel sample (table 2, no. 16) of the reef core in Dark Canyon showed 16.2 percent magnesium carbonate, only 82.9 percent calcium carbonate, and 0.6 percent silica. Where the reef-core facies is overlain by sandstone tongues of the Yates and Tansill Formations of the Artesia Group, the core appears to be dolomitic and siliceous, as along North Slaughter Canyon. Also, along parts of McKittrick, Rattlesnake, and West Slaughter canyons, the reef-flank beds, especially the more massive ones, appear to be chiefly limestone, as determined by dilute HCl and by specific gravity tests (in heavy liquids).

If most of the reef core, and some large part of the reef flanks, is of high-calcium limestone in the southeastern Guadalupe Mountains, this is a huge deposit near gas fields, a railroad, and U.S. highways. Much of the outcrop belt (fig. 12) is within Carlsbad Caverns National Park, but the outcrop area extends about 10 miles northeast of the Park and from the Park southwestward to and beyond the New Mexico–Texas stateline. Careful, detailed sampling is needed to determine the amount of high-calcium limestone and to be able to make any suggestion as to the relationships of and reasons for dolomitization.

The underlying Goat Seep Limestone is reported to be chiefly dolomite and dolomitic limestone; its outcrops are in the relatively inaccessible south-central part of the Guadalupe Mountains, mainly in Texas, and were not sampled by the writer. Newell et al. sampled the Goat Seep reef in North McKittrick Canyon where it showed 55.4 percent calcium carbonate and 44.3 percent magnesium carbonate.

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