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Sources for Lightweight Shale Aggregate in New Mexico

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Abstract

This report is the result of studies on the shales of New Mexico for their possible use as a lightweight aggregate in concrete. Of the 42 shales sampled and tested, four are considered suitable for this purpose and six others may be suitable but require additional testing. Shales that might be used are restricted to the Devonian, Pennsylvanian, Triassic, Cretaceous, and Tertiary Systems.

Limited testing of Devonian shales in central New Mexico indicates that the carbonate content of these rocks is too high for proper expansion. In most sections examined, Pennsylvanian shales are intimately interbedded with other rock types and low-cost surface mining methods cannot be used. In addition, most of the Pennsylvanian shales tested have very short expansion ranges and would be difficult to fire in a rotary kiln. However, two possibly useful deposits were discovered in rocks of this age, one near Abo Pass, the other in the Mud Springs Mountains. Red shales of Triassic age were not investigated.

The Cretaceous System contains numerous thick shales that crop out in many parts of the state. Large deposits with good expansion properties occur in the Pierre Shale of northeastern New Mexico. Other thick intervals of shale present in the northeast melt at relatively low temperatures and either have short expansion ranges or are too refractory. Possible sources in the Mancos Shale of northwestern and central New Mexico include the Mount Powell and Carthage areas. Additional Cretaceous shales that look promising occur in the Fruitland Formation at the Navajo Coal Mine, in the Menefee Formation near Chaco Canyon National Monument, and in the Lewis Shale near Dulce. Considerable sampling would have to be done to evaluate fully the potential of the Cretaceous section. Tertiary shales possibly suitable for expanded aggregate are restricted for the most part to the San Juan and Raton basins. Limited sampling in the Raton area failed to reveal any suitable deposits.

All samples were tested initially by flash firing at 2100° F for 15 minutes. After examination to determine the degree of expansion, favorable shales were tested further by firing at temperatures between 1800° and 2200° F at increments of 100° F and retention times of 5, 10, and 15 minutes. Each locality sampled is described in the report, and bulk specific gravity, weight in pounds per cubic foot, absorption per cent, and internal structure are discussed for the more favorable deposits.

Introduction

Localities in New Mexico where a lightweight shale aggregate plant might be commercially feasible are Albuquerque, Roswell, Farmington, Santa Fe, Los Alamos, and the vicinity of Las Cruces and El Paso. All these areas are served by highways, natural-gas pipelines, and railroads. There is a possibility, of course, of an increase in heavy construction in other parts of the state. Raton, Gallup, Grants, Silver City, Hobbs, and other areas of more or less concentrated population must be considered. For this reason, some sampling was done in the vicinity of several of these population centers.

This report does not represent a complete study of possible raw-material sources for expanded shale. Instead, areas where there are shales that appear to have the necessary properties to make a good lightweight aggregate are indicated. Further research into these fine-grained rocks and their fired properties, as well as market analyses, would have to be made prior to establishing a plant in any of the favorable source areas noted. In some instances, samples were collected considerable distances from possible markets. Where this is true, formations of the same age, if present, could be tested nearer the potential market. It does not necessarily follow, however, that the lithology and the ceramic properties will be uniform from one locality to the next. For example, a sequence of Pennsylvanian shales near Abo Pass in the southern Manzano Mountains makes an excellent lightweight aggregate, but careful sampling and testing of correlative units in the Sandia Mountains east of Albuquerque failed to reveal any raw material suitable for expanded shale. In contrast, the Pierre Shale of northeastern New Mexico, and possibly correlative units in northwestern New Mexico as well, appear to be fairly uniform in their properties over a large outcrop area and, when fired, make a good lightweight aggregate.

Only a few raw-material sources for expanded shale were discovered. These include part of the Pennsylvanian section at Abo Pass (66-1) , shales in the Cretaceous Fruitland Formation at the Navajo Coal Mine (2-2), and the Cretaceous Pierre Shale between Raton and Cimarron (8-4 and 9-7). Other intervals that appear to be suitable but need additional sampling and testing are Pennsylvanian shales at Bishops Cap (113-1) and in Mud Springs Mountains (88-2) , Cretaceous Menefee shales near Chaco Canyon National Monument (27-1), Cretaceous Mancos Shale at Mount Powell (38-1) and Carthage (77-1), and the Cretaceous Lewis Shale near Dulce (4-4). Several of these deposits contain, for all practical purposes, unlimited reserves. This study also disclosed that in some parts of the state it will be difficult or impossible to find suitable raw material. In the Las Cruces area, many of the possible shale sources are within White Sands Proving Grounds, and in southeastern New Mexico there are very few outcrops of shale, particularly in the vicinity of the population centers.

ACKNOWLEDGMENTS

The author has been fortunate during the preparation of this, as well as other reports, to have as assistants graduate and undergraduate students attending the New Mexico Institute of Mining and Technology. For this report, students not only did the bulk of the laboratory work, but also, during many discussions, formulated ideas for additional meaningful tests and improvements for established test procedures. The students directly involved in this study, both in the field and in the laboratory, were Lewis Culver, Ken Grace, Philip Luce, Doris Mallard, Bur Maras, Clifford Owens, and James Tyree.

Immeasurable benefit was derived from discussions with William L. Hawks, Frank E. Kottlowski, and Alvin J. Thompson of the New Mexico Bureau of Mines and Mineral Resources. The report was edited, very ably, by Miss Teri Ray, William L. Hawks, and Frank E. Kottlowski, all of the Bureau, and by Robert L. Bates, Department of Geology, The Ohio State University. Special gratitude is extended to F. B. Pyle and Melvin Chandler of the Shoenail Cattle Company for granting access to the Abo Pass area and to Al Geiger and James Olson, Utah Mining and Construction Company, for permission to enter the pit area of the Navajo Coal Mine.

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USES OF EXPANDED SHALE AGGREGATE

Lightweight aggregate includes a wide variety of materials. Naturally occurring aggregates that require only crushing and screening are pumice and scoria. Processed aggregates include perlite, vermiculite, expanded clay, shale, and slate, and such by-products as blast-furnace slag and coal cinders. New Mexico leads in the production of crude perlite in the United States with about 80 per cent of the national total, and ranks third behind Arizona and California in the combined production of pumice and scoria. Considerable bottom and fly ash are produced but at present there is no market for this by-product. New Mexico has no production of the other lightweight aggregates.

Lightweight shale aggregate has a variety of applications in concrete products. Cement block has been the principal product for a number of years, but this is rapidly being overtaken by uses in tilt-up wall panels, precast floor and roof slabs, bridge superstructure and decks, airplane runways and aprons, load-bearing and nonload-bearing concrete castings and forms, highway construction, piers, overpasses, large-diameter pipes, cable conduits, utility poles, and monolithic concrete structural material. In almost all of these uses, expanded shale is a superior aggregate to natural and manufactured lightweight aggregates because of its high strength-to-weight ratio. Concrete made with expanded shale has about two thirds the strength and weight of concrete in which heavy aggregates such as crushed stone or sand and gravel are used, thus allowing considerable reduction in reinforcing steel and foundations. The compressive strength of a concrete made with lightweight shale may even exceed that of a concrete in which a heavy aggregate i's used. Apparently the reason is that in addition to the fairly high strength of the particle, the greater absorption of expanded shale, normally from 5 to 10 per cent, forms a stronger bond with the cement and the concrete breaks through instead of around the particle. The average weight in pounds per cubic foot (based on bulk specific gravity) of ten specimens of each of various aggregates studied during this investigation is as follows: bottom ash, 45; pumice, 55; expanded shale, 60; scoria, 70; and granite, 155. The weight of expanded shale, which is dependent on physical properties and the fired temperature, ranges from about 40 to 100 pounds per cubic foot. With a decrease in weight there is also a decrease in strength.

Other advantages of expanded shale are excellent thermal and acoustical insulating properties and, for "coated" aggregates, lower water absorption compared with the open-pore structure of other types of lightweight aggregates, a corresponding reduction in cement, and better workability. The main disadvantages compared with natural and by-product lightweight aggregates are the added costs of firing at relatively high temperatures and the greater investment in plant facilities.

Possible uses of lightweight shale aggregate in New Mexico include housing, office buildings, and factories, most of which probably would be centered in the Albuquerque and El Paso areas. Extensive use is possible in many State and Federal projects. Some of these are highway construction (particularly bridges and overpasses), State offices in Santa Fe and elsewhere, large concrete structures at Los Alamos and White Sands Proving Grounds, and possibly in the San Juan—Chama diversion projects in places where weight is not a factor, such as in the lining of tunnels and waterways.

PRODUCTION

There were 7.6 million tons of expanded shale produced in the United States in 1964 from approximately 70 plants. Most of these plants are in the eastern, midwestern, and west coast parts of the country. At present, no plants produce this aggregate in New Mexico, the nearest ones being in the Denver, Dallas, Salt Lake City, and southern California areas. Small tonnages have been shipped into the state for use in Albuquerque.

At most plants, expanded shale is produced by firing in a rotary kiln. In this method, the crushed and sized shale is heated while passing through a gently inclined revolving cylinder, with flash heating to temperatures of 2000° to 2200° F at the lower (discharge) end. The fired shale is then screened and the various sizes are separately stockpiled. By this method, a "coated" or "glazed" aggregate is produced. In the other method commonly used, the shale passes through a stationary furnace on a sintering grate and then is crushed and sized. In the latter process, the resulting product has an open-pore structure and is similar to scoria and slag.

Geology

Shales and clays are the most common sedimentary rocks exposed on the surface of the earth, but deposits suitable for use in making any of the numerous clay products are limited in some areas. Thus a knowledge of the compositional variations and the lateral extent of possibly useful clay deposits, involving the application of geologic methods, is just as essential to the utilization of these deposits as is the knowledge of their fired properties. Shales and clays are widely exposed in New Mexico and in some areas are many thousands of feet thick. Elsewhere they are thin and are intimately interlayered with other sedimentary rocks, such as limestone and sandstone. In the latter areas, mining costs are prohibitive where low-value uses are contemplated.

Several terms are used in defining the fine-grained sedimentary rocks composed principally of clay minerals and quartz, the most common being *clay* and *shale*. Geologists, engineers, agronomists, and ceramists have different connotations for these terms, and often within each discipline the terms are used interchangeably. From the geologic standpoint, shale is considered to be a fine-grained sedimentary rock that has a platy or fissile structure along which it normally breaks. It therefore is not restricted to rocks made up of clay-size particles (less than 1/256 mm) but may include siltstones or even impure sandstones. The reason for this seemingly inaccurate and loose definition is that greater precision is restricted by the grain size of the material. Modifiers may be applied if variations in grain size are readily apparent. For example, some shales may contain enough coarse silt or very fine-grained sand so that its presence is obvious with a hand lens or binocular microscope or from the gritty feel that the coarser material imparts. The rock could then be called a silty or sandy shale. More sophisticated techniques are necessary, however, to determine if the rock is a clay shale, for the presence and amount of fine sand and silt cannot be determined by routine methods. The same problems exist in the definition of clays. In general, clay is considered to be a plastic material made up of particles of clay minerals (kaolinite, illite, montmorillonite, chlorite) less than 1/256 millimeter in diameter. Some clays, however, are nonplastic, and almost all so-called clays contain at least some quartz in the silt range and actually may have a low percentage of clay minerals. Basically, the only difference between a clay and a shale is that clays lack fissility. Except for descriptions of specific outcrops, the term *shale* as used in this report includes both shales and clays. This is done for purposes of simplicity and to avoid needless repetition.

Rocks representative of every major subdivision of geologic time from Precambrian to Recent are present in New Mexico. Shales, though areally abundant, are restricted to certain parts of the geologic section, and an awareness of where they occur facilitates exploration. The following discussion gives the gross lithologic character of the rocks of each of the major geologic systems within the state, with emphasis on those parts of the section that contain shales possibly suitable for lightweight aggregate.

PRECAMBRIAN

The Precambrian sequence consists primarily of igneous and metamorphic rocks. This sequence is widely exposed in numerous mountain ranges in central and southwestern New Mexico. Possible sources for expanded aggregate are limited for the most part to slates and phyllites, the metamorphosed equivalents of shales. There are no known occurrences of slate within the state, but an outcrop of phyllite in the Picuris Mountains south of Taos has been mapped in some detail by Montgomery (1953) and was sampled and tested for this report (19-5).

CAMBRIAN—ORDOVICIAN—SILURIAN

Rocks representing these geologic periods are exposed only in the ranges of south-central and southwestern New Mexico. They consist almost entirely of carbonate rocks and sandstones. The minor shale beds present are considered too thin for commercial purposes.

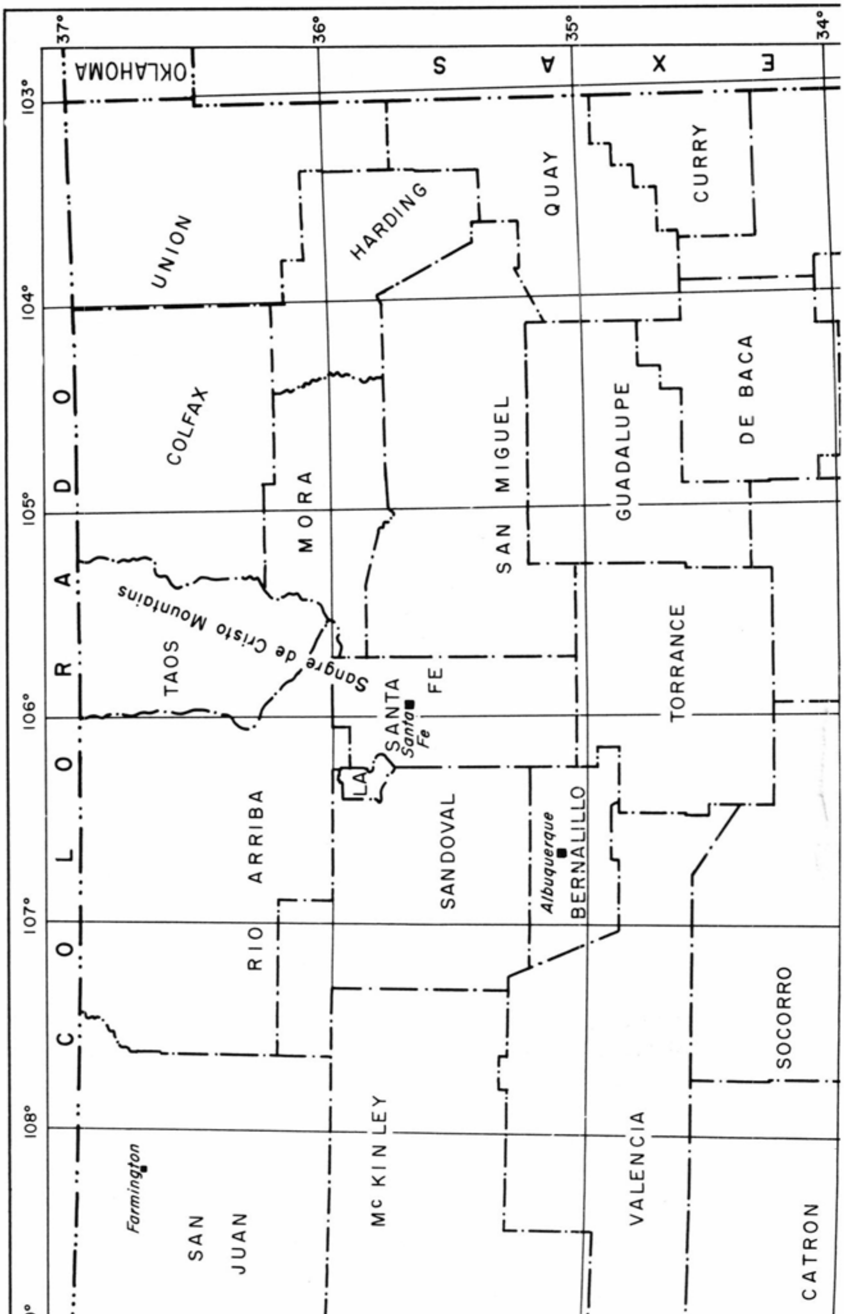
DEVON IAN

The distribution of Devonian rocks is shown in Figure 1. As far as is known, outcrops occur only in the ranges of south-central and southwestern New Mexico, although possible Devonian rocks have been reported in the Sangre de Cristo Mountains north and east of Santa Fe by Baltz and Read (1960). Principal exposures are in the San Andres, Sacramento, Big Hatchet, and Peloncillo mountains, in the Black Range, and near Silver City. The sequence consists of calcareous and dolomitic shales interbedded with minor siltstones, nodular limestones, and dolomites. Commonly, Devonian beds weather to a steep slope overlain by massive, cliff-forming limestones of Mississippian age. In most areas it would be difficult to strip shale from this interval, and interbedded limestones and siltstones would make mining selective and costly.

Devonian shales were sampled at two localities, 88-1 in the Mud Springs Mountains west of Truth or Consequences and 99-1 in the Black Range near Kingston.

MISSISSIPPIAN

Rocks of this age were deposited in a shallow sea that covered much, if not all, of New Mexico. Deposits consist almost entirely of limestone.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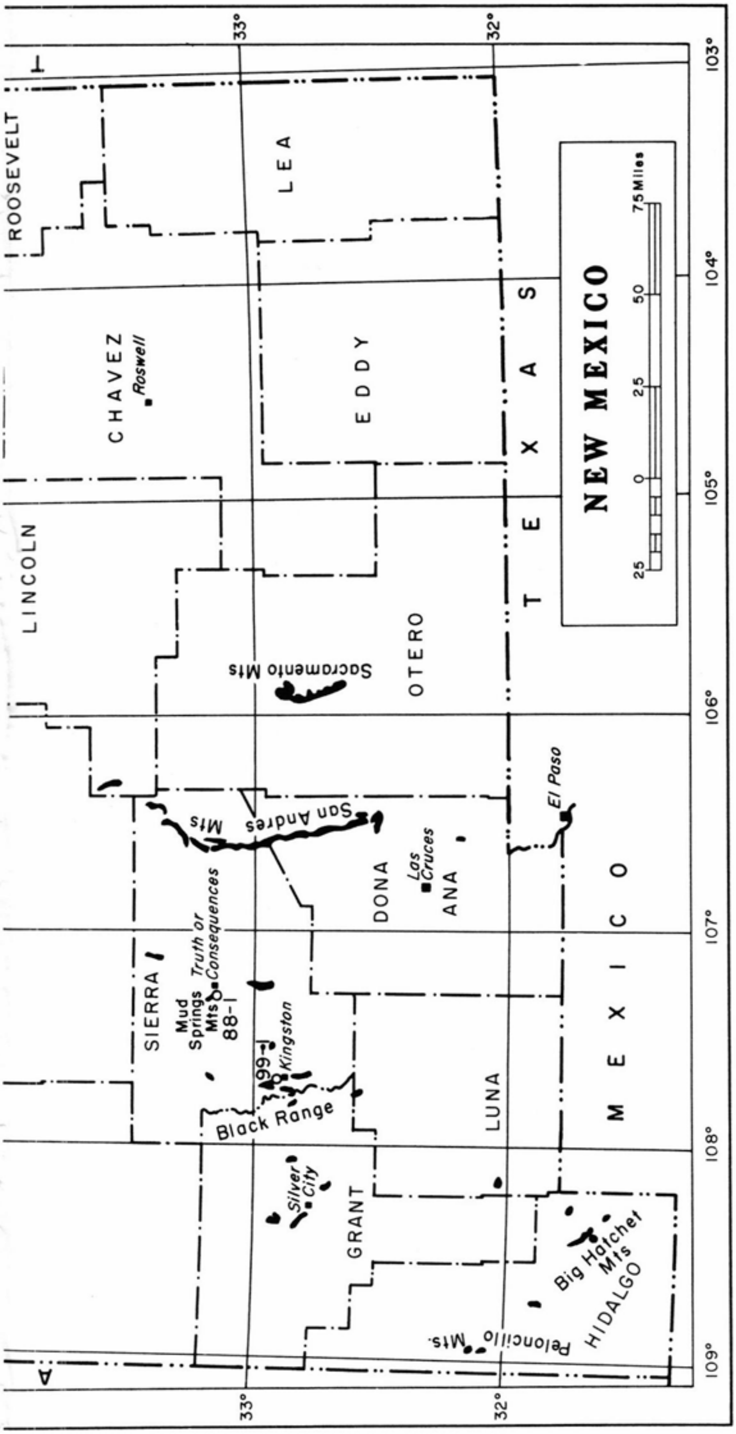


Figure 1

Outcrop distribution of Devonian rocks and sample locations (width of outcrop exaggerated)
Circle, sample location of shales not suitable for lightweight aggregate.

The thin shales present contain numerous nodules and thin beds of limestone.

PENNSYLVANIAN

Pennsylvanian strata are widely exposed in New Mexico (fig. 2). They consist of interbedded limestone, sandstone, arkose, and shale, and locally attain thicknesses in excess of 3000 feet. At most outcrops examined during this investigation, shale beds are thin and intimately interbedded with other rock types to form a cliff-slope topography. Locally, the basal unit of the Pennsylvanian consists primarily of sh de, but it is commonly thin and is overlain by massive limestones. Ratter special topographic and/or structural conditions would be required Pennsylvanian shales to be suitable for large-scale strip mining in most areas.

Shales were sampled at a few localities, particularly where there appeared to be some possibility for low-cost mining. Samples were collected in the Sangre de Cristo Mountains (20-4 and 31-2), Sandia Mountains (42-7), Manzanita Mountains (42-6), Manzano Mountains (54-1, 65-1, and 66-1), Mud Springs Mountains (88-2), and at Bishops Cap (113-1 and 113-2). Each section sampled represents only a part of the total Pennsylvanian sequence present. The most complete section tested was 65-1 and 66-1, at Abo Pass in the southern Manzano Mountains, where all but the lowermost shales were sampled. In general, results were poor. The exceptions are a part of section 66-1 and a thin interval in the Mud Springs Mountains.

Thick sequences of Pennsylvanian strata also crop out in the Sacramento, San Andres, and Caballo mountains in the south-central part of the state, and in numerous ranges in southwestern New Mexico. Suitable raw material probably occurs in some of these areas, but distance from markets and lack of adequate roads leave doubt as to the economical suitability of these deposits for lightweight aggregate.

PERMIAN

Red shales are fairly common in the lower part of the Permian interval, and in some areas they form thick sequences. These shales have been sampled at only one locality (42-10), in the Sandia Mountains. Other studies in this part of the Permian section indicate that the shales normally contain a high percentage of silt and sand-size quartz and probably are not suitable for expanded aggregate. Younger Permian rocks include thick sandstones, limestones, and evaporites deposited in a shallow sea that covered a large part of New Mexico.

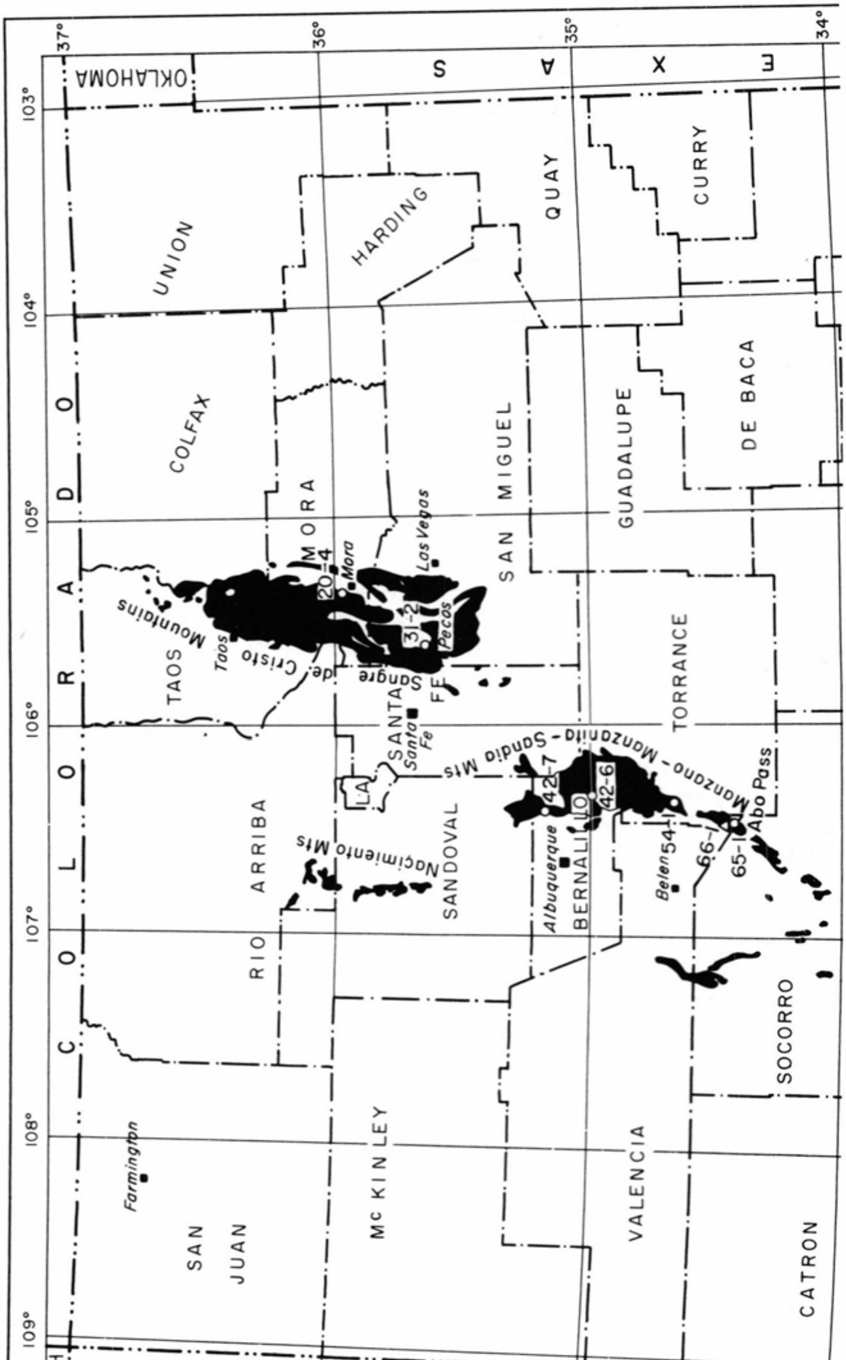
TRIASSIC—JURASSIC

Rocks of these ages consist of fluviatile and eolian sediments comprised mostly of sandstone. They are well exposed in the Zuni Mountains area, in the northeastern part of the state, and locally in other parts of New Mexico. Shales in the Jurassic are not considered favorable as a raw material for lightweight aggregate because they are intimately interbedded with and grade abruptly into sandstones, and are themselves commonly sandy. As yet, no tests have been conducted on Triassic shales; these rocks may prove to be a good source for lightweight aggregate. The dominant clay mineral throughout the Triassic section is montmorillonite. Montmorillonite- and illite-base shales may be favorable for expansion because they contain some of the necessary fluxes and gas-forming constituents. Many of the Triassic shales are thick, are fairly uniform in composition, and do not appear to contain excessive amounts of quartz sand. Locally, however, many of the shales contain abundant small carbonate pellets that would affect both the expansion and melting range of the material.

CRETACEOUS

Cretaceous strata are composed of a complex sequence of marine and nonmarine deposits of sandstone, shale, limestone, coal, and conglomerate. These rocks are widely exposed, particularly in the northern half of the state. On the accompanying map (fig. 3), the Cretaceous rocks have been subdivided into Lower and Upper Cretaceous intervals. Extensive exposures of Upper Cretaceous sandstones and shales occur in the San Juan Basin, in the area south of the Zuni Mountains, and in northeastern New Mexico. Other important outcrops are present south of Santa Fe, in the Capitan and Carthage areas, on the east side of the Caballo Mountains, and between Silver City and Deming. Thick sequences of Lower Cretaceous sandstones, shales, and limestones crop out in numerous ranges in extreme southwestern New Mexico, particularly in the Big and Little Hatchet mountains, in the East Potrillo Mountains, and near El Paso, Texas.

In the San Juan Basin, the Cretaceous includes the following formations in ascending order: Dakota Sandstone (minor shale and coal); Mancos Shale (shales, sandstones, and minor limestones); Mesaverde Group, subdivided into the Gallup Sandstone (minor shale and local coal beds), Crevasse Canyon Formation (sandstone, shale, and coal), Point Lookout Sandstone, Menefee Formation (sandstone, shale, and coal), and Cliff House Sandstone; Lewis Shale (minor sandstone); Pictured Cliffs Sandstone; Fruitland Formation (shale, sandstone, and coal); Kirtland Shale (including Farmington Sandstone Member); and the Ojo Alamo Sandstone. In northeastern New Mexico, subdivisions of the Cretaceous rocks are Dakota Sandstone (locally containing sandstones and shales of Lower Cretaceous age), Graneros Shale, Greenhorn Limestone (interbedded limestone and shale), Carlile Shale, Niobrara Formation (calcareous shale and minor limestone), Pierre



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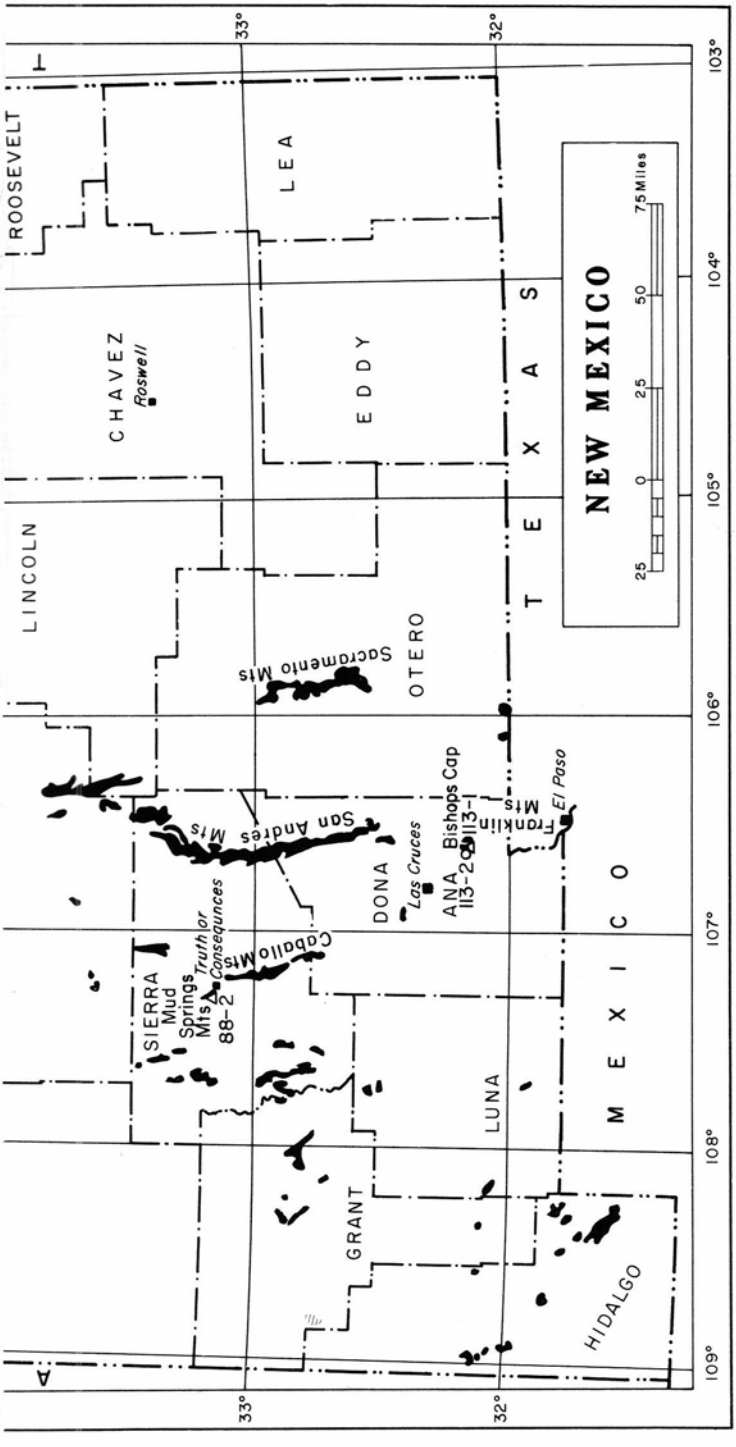
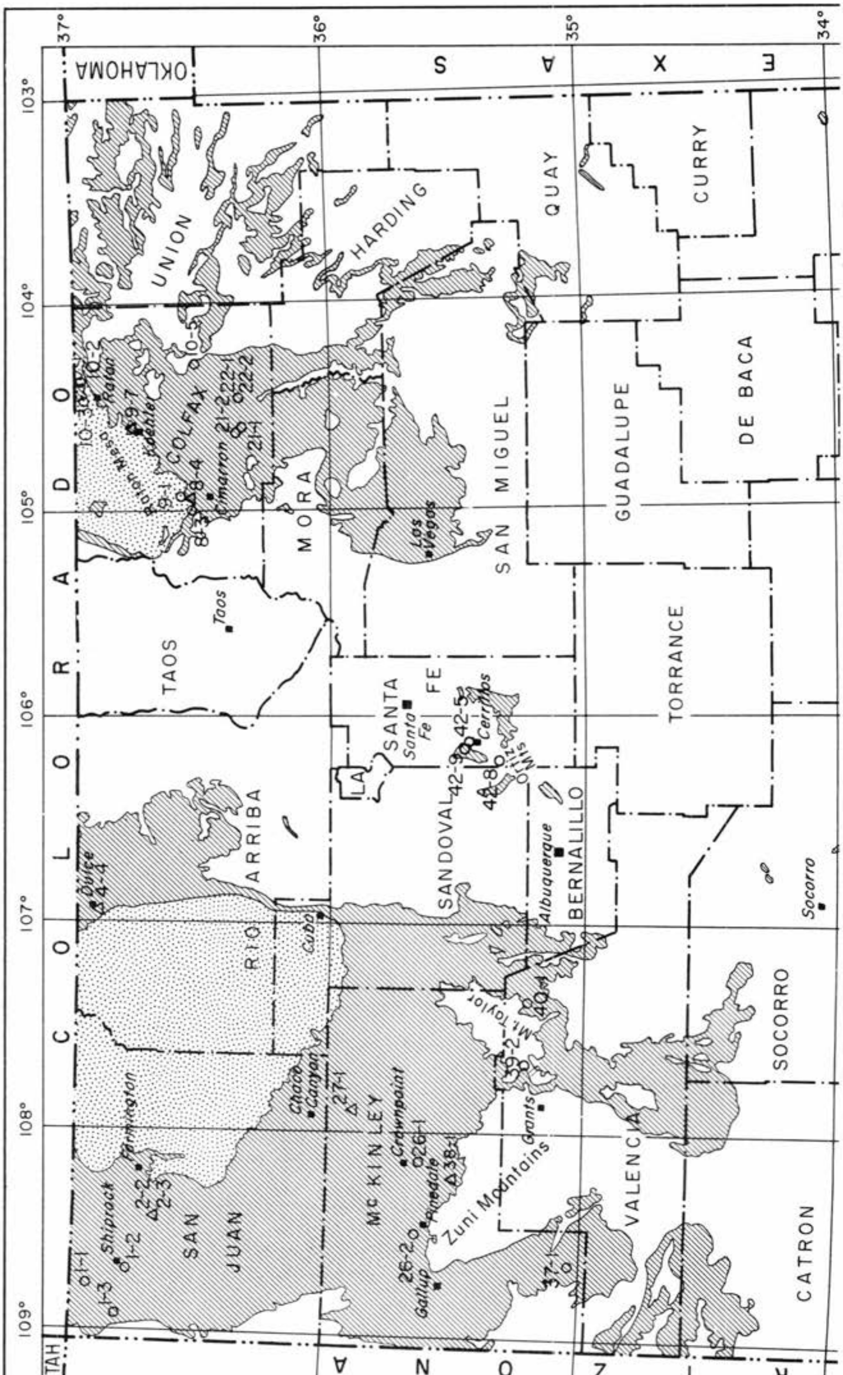


Figure 2

Outcrop distribution of Pennsylvanian rocks and sample locations

Triangle, location of shales suitable for lightweight aggregate; circle, location of unsuitable shales.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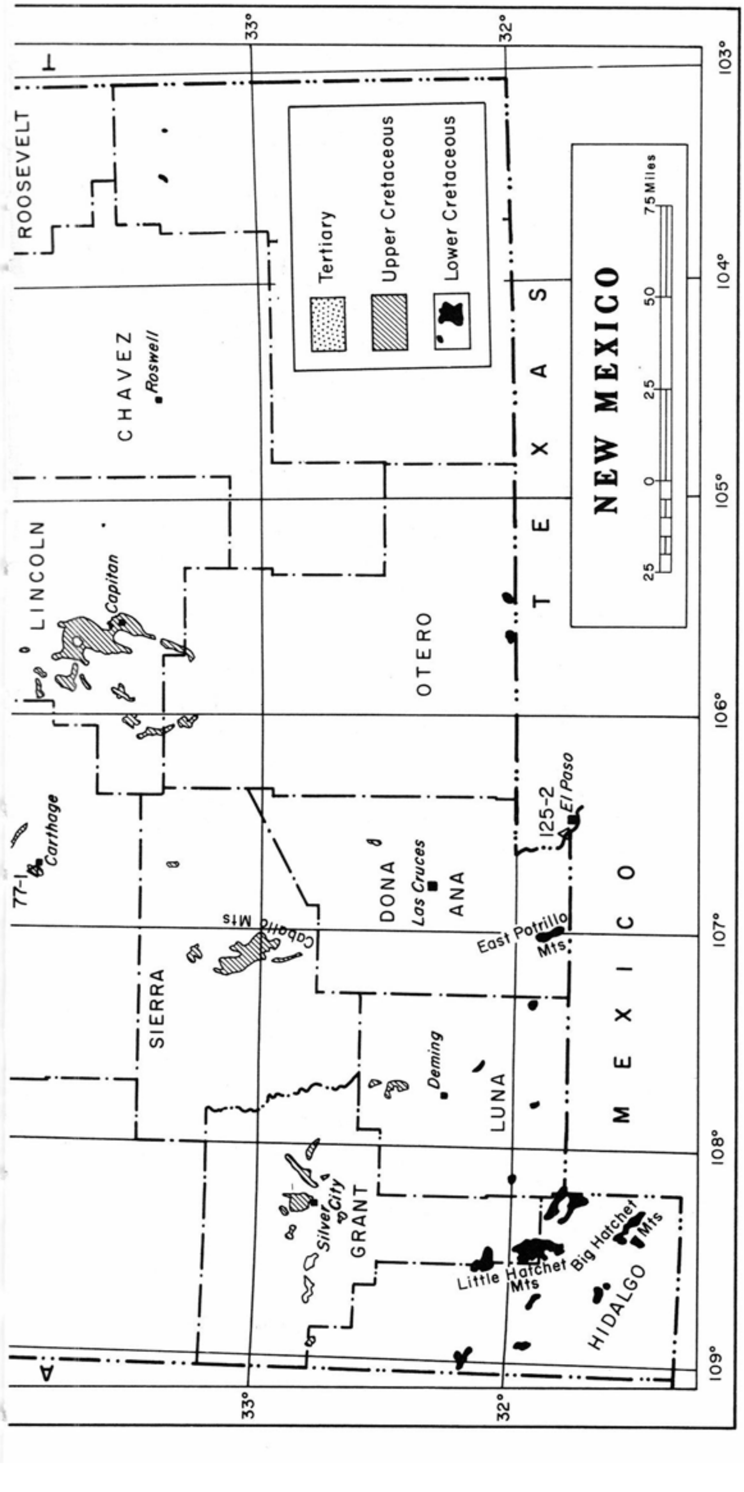

Figure 3

OUTCROP DISTRIBUTION OF TERTIARY (RESTRICTED) AND CRETACEOUS ROCKS AND SAMPLE LOCATIONS

Triangle, location of shales suitable for lightweight aggregate; circle, location of unsuitable shales.

Shale, Trinidad Sandstone, and Vermejo Formation (shale, sandstone, and coal). Part of the overlying Raton Formation is considered to be of Cretaceous age. In most of the remaining outcrop areas of Upper Cretaceous rocks, strata younger than the Mesaverde Group are not present, and the rock sequence has been subdivided into the Dakota Sandstone, Mancos Shale, and Mesaverde Formation.

The Lower Cretaceous rocks of southwestern New Mexico have been subdivided only locally, and formation names are not used in this report.

Because the Cretaceous represents the largest possible source for expanded shale aggregate, most of the sampling done for this report was concentrated in this sequence of rocks. Upper Cretaceous shales tested in the northern part of the state include material from ten localities in the Mancos Shale (west of Shiprock, 1-2 and 1-3; north of Shiprock, 1-1; near Pinedale, 26-2; southeast of Zuni Pueblo, 37-1; on Mount Powell, 38-1; east of Cebolleta, 40-1; near Cerrillos, 42-5 and 42-9; and in the Ortiz Mountains, 42-8), two localities in the Pierre Shale (8-4 near Cimarron and 9-7 near Koehler), two localities in the Vermejo Formation near Cimarron (8-3 and 9-1), two from the Niobrara Shale south (21-1), and west (21-2) of Springer, and one each from the Graneros Shale east of Springer (22-1), Greenhorn Limestone in the same area (22-2), Carlile Shale near Chico (10-5), Menefee Formation near Chaco Canyon National Monument (27-1), Crevasse Canyon Formation south of Crownpoint (26-1), undifferentiated Mesaverde beds on Mount Taylor (39-2), Fruitland Formation at the Navajo Coal Mine (2-2), and the Lewis Shale near Dulce (4-4). In the southern part of the state, tests were limited to shales in the Mancos and Mesaverde in the Carthage area southeast of Socorro (77-1) and shales of Lower Cretaceous age at Brickland across the Rio Grande from El Paso, Texas (125-2).

TERTIARY—RECENT

The outcrop distribution of Tertiary rocks shown in Figure 3 is limited to areas that contain shales that might be suitable as raw material for lightweight aggregate. The large area in west-central New Mexico underlain by Tertiary volcanic rocks is excluded for obvious reasons. The even larger area where sedimentary rocks of the Tertiary Gila—Santa Fe—Ogallala Formations and Recent alluvial deposits are exposed is excluded because these rocks consist primarily of sands and gravels. Clay and shale intervals present in these sediments are almost all too friable or contain too much silt and sand-size quartz.

Tertiary rocks that may contain suitable raw material appear to be limited to the San Juan and Raton basins, although small areas in the Caballo Mountains and Capitan region might also be included. The only sampling conducted thus far has been from two localities in the

Raton Formation. These were at Maloya Dam east of Raton (10-2) and along the old Raton Pass road (10-3) west of that city. The sections consist of interbedded sandstones, conglomerates, shales, and coals; many of the shales are too thin and carbonaceous for use as raw material for lightweight aggregate. Some of the thicker shales tested showed good expansion properties but are too intimately mixed with more refractory shales.

Field and Laboratory Procedures

On weathered slopes, samples were collected by digging a channel, perpendicular to the strike of the beds, to a depth of approximately one foot and collecting about ten pounds of relatively unweathered shale from each ten feet or less of the section. At fresh exposures, or where the shales were particularly hard, the channeling amounted to only a few inches, and the material from the channel was used for test purposes. In previous investigations of this type, it has been the normal practice to collect a single sample from one part of the section regardless of the total thickness involved. By sampling at intervals of ten feet or less over the entire exposure, there is little likelihood of overlooking possibly useful deposits. As an example, the shale at locality 66-1 could have been missed by taking a single sample from the base of the shale section.

In some places, because of the vagaries of natural exposures, it is not always possible to sample in detail by the method described above. Where this is true, different parts of the section could be sampled if additional outcrops are available elsewhere, and the general expansion properties for the entire section could be evaluated. Naturally, some lateral sampling is necessary to determine the extent of the deposit, especially where the deposit is relatively thin. Detailed sampling also gives valuable information regarding variations in the expansion properties of the entire section of shale that might be mined. Minimum melting points that could cause numerous problems in a rotary kiln are determined and an average weight for the aggregate is obtained. Single samples from a thick deposit may result in either unfavorable or overly optimistic reports of the potential of the shale at that locality.

Samples collected in the field were tested initially by firing selected pieces at 2100° F for 15 minutes or longer. The specimens were then examined to determine whether expansion appeared to warrant further testing. If the sample melted at this temperature, the temperature range during which expansion would take place probably is too short. This is based on observations that indicate that temperatures of at least 1900° F and for the most part in excess of 2000° F are required before uniform pore development takes place. Samples that lack or have very little pore development at 2100° F would probably require temperatures much higher than is considered commercially feasible. This is a rapid, simple method for determining whether or not a shale should be tested further. Some samples eliminated by this test may make adequate expanded shales either by firing at a higher temperature or by closely controlled furnace conditions to avoid melting.

Samples that indicated good pore development at 2100° F were prepared for complete firing tests. The raw shale was first crushed and sieved to obtain a size range between minus 0.375 inch and plus 4 mesh (0.185 inch). This size range approximates coarse to medium grades of commercial aggregates. About 200 grams of the sized material from each sample were preserved for testing purposes. The 200 grams were then subdivided into fifteen 10-gram samples for firing tests, the remainder being saved for descriptive purposes and X-ray identification of the clay minerals.

Descriptions of the raw shales were made with the aid of a binocular microscope. Lithologic features noted were color (Munsell system), compactness, and, where possible, presence or absence of silt, sand, carbonate, sulphates, micas, carbonaceous material, and fossils. X-ray diffraction patterns were prepared for each of the shales by pulverizing the sample in a mortar and packing it firmly in an aluminum holder. The packing tends to increase the preferred orientation of the clay minerals and generally results in diffraction patterns adequate for qualitative determinations. The clay-mineral content of some shales proved to be too low for determination by this method. Selected samples were then disaggregated in water, mixed thoroughly in a beaker, and the minus 4-micron fraction collected on a glass slide following appropriate settling times. A preferred orientation is accomplished, and for almost all of these samples, it was possible to determine the clay minerals present.

The fifteen 10-gram specimens from each sample collected were dried at 100° to 110° C for at least 24 hours, placed in scorifier dishes, and fired in a stationary electric furnace of the silicon carbide resistor type. Each sample was fired at retention times of 5, 10, and 15 minutes at increments of 100° F from 1800° to 2200° F unless melting occurred at 2200°F or lower. After firing, three weighings of each sample were made. These were the oven-dry weight in air (A), the saturated (immersion in water for 24 hours) surface-dry weight in air (B), and the saturated weight in water (C). From these data, the bulk specific gravity,* weight in pounds per cubic foot, and the absorption per cent were calculated. *(See also* Hamlin and Templin, 1962.) Absorption per cent was determined by the formula

$$\frac{B-A}{A} \times 100.$$

The bulk specific gravity, if greater than one, is equal to

$$\frac{A}{B-C},$$

and if less than one, to

$$\frac{A}{B+C}.$$

* A.S.T.M. Designation C127-42.

The weight in pounds per cubic foot is obtained by multiplying 62.5, the weight of one cubic foot of water, by the bulk specific gravity. For commercial purposes, the container method is used to determine the weight in pounds per cubic foot. This involves a container of known weight and volume, normally one cubic foot. The container is filled with the aggregate and the difference between this weight and the weight of the container empty is given as the weight of the aggregate. This weight includes considerable air space and does not take into account water absorption. For example, a commercial aggregate that weighed 47 pounds per cubic foot by the container method had a weight of 85 pounds per cubic foot based on bulk specific gravity. A part of sample 66-1-15 from the Abo Pass area, fired at 2100° F, 15 minutes' retention time, had a weight of 61 pounds per cubic foot by the bulk-specific-gravity method and 38 pounds per cubic foot by the container method.

Fired shales were also examined for color, size, shape and uniformity of pores, thickness of pore walls, particle shape, relative strength, degree of surface vitrification, and tendency to melt and agglomerate.

Material fired and tested in the laboratory by the methods outlined varies in some important aspects from the same material fired in a rotary kiln. In the latter method, the shale reaches expansion temperatures at a slower rate than in a preset stationary furnace. This tends to oxidize and vitrify the shale throughout, imparting a somewhat higher strength than that obtained during the short retention times involved in a stationary furnace. In addition, at 5 or 10 minutes' retention time, particles in the lower part of the scorifier dish are not heated at the same rate as exposed particles. This is particularly evident at temperatures below 2000° F and causes difficulty in obtaining a representative sample for analysis. Although upper temperature limits can be controlled satisfactorily in a stationary electric furnace, the recovery rate to the desired temperature after opening the door to insert a sample is very slow. The maximum temperature reached, particularly for short retention times at high temperatures, may be 20° to 40° F below the desired temperature when the sample is removed. This can be corrected to some extent by staggering retention times.

CAUSES OF EXPANSION

For a shale to expand, it must contain gas-forming material and the exterior of the particles must be in a semiviscous or pyroplastic state while the gases are being evolved. In most of the shales tested that exhibited expansion, pores began to form between 1900° and 2000° F. Pores were not observed in some shales until the temperature reached 2100° F, and in others small pores had developed as low as 1800° F. At these temperatures, many of the gas-forming constituents would normally dissociate, but the exterior of the particle reaches a pyroplastic condition while gas is still being evolved from the interior. At longer retention times in the furnace, the interior of the particle will eventually reach a semiviscous state, and some gas bubbles will migrate outward, coalesce with other gas bubbles, and form larger pores near the surface.

The compounds that are of importance in producing expansion include alkalies, alkaline earths, iron compounds, water, and possibly organic carbon. The alkalies, sodium and potassium, occur in micas, feldspars, and the clay minerals. Sodium is also present as sodium chloride dissolved in connate water. The alkaline earths, calcium and magnesium, are found in calcite, dolomite, gypsum, anhydrite, feldspar, mica, and some of the clay minerals. The principal iron compounds are hematite, limonite, siderite, and pyrite. Water occurs in many of the minerals listed above, but the most important occurrence as far as expansion is concerned appears to be as chemically combined water in the clay minerals.

Fluxing agents present in the shale determine the range and character of the viscous state. The fluxes include calcium, magnesium, potassium, sodium, and iron. Calcium is the most common flux and, if present in appreciable amounts, usually results in premature melting. Melting at low temperatures also may occur in the vicinity of discrete particles of flux, such as fossil fragments consisting of calcium carbonate. The gases that cause expansion probably differ from one shale to the next, but certain gases very likely are more important than others. Gases that may be evolved during the heating of shales include water, carbon dioxide, sulfur dioxide, oxygen, hydrogen, hydrogen sulfide, and chlorine. Carbon dioxide, which may be the most important gas in the expansion process, can be formed from the dissociation of carbonates or from the reduction of ferric iron and the combination of liberated oxygen with organic carbon.

Most of the samples collected during this investigation were examined for carbonates with dilute hydrochloric acid and by X-ray diffractometer. Of the 312 shales studied, 199 contained some carbonates. In the majority of samples, calcite was the dominant carbonate mineral, with dolomite occurring by itself in only 27 of the shales tested. Of the shales containing a carbonate, 67 per cent exhibited some expansion when fired, but in only 10 per cent was the expansion considered suitable for use as a lightweight aggregate. In the others that indicated some expansion, bloating was too low or the range of expansion too short, with melting occurring at fairly low temperatures and shortly after expansion began. The remaining 33 per cent of the carbonate-containing shales showed no evidence of expansion. Most shales that contained very high percentages of calcium carbonate had a tendency to melt at about 2100° F. Lesser amounts of carbonates do not seem to be critical as far as melting is concerned, and in some samples appear to aid the expansion process. In those shales that apparently contained no carbonates (calcite and dolomite), 49 per cent showed some expansion, and 16 per cent of the total number of samples tested were considered suitable for lightweight aggregate. The remaining 51 per cent of the noncarbonate shales gave no indication of expansion. Only 3 of the 113 noncarbonate samples melted at 2100° F.

A study to determine whether there was any correlation between clay mineralogy and expansion was inconclusive. Most of the shales tested contain more than one clay mineral, and thus it could not be determined whether a particular clay mineral was more or less favorable for expansion. Approximately 60 per cent of the shales having montmorillonite, illite, or chlorite as the principal clay mineral exhibited some degree of expansion. Where kaolinite was the principal clay mineral, about 50 per cent of the tested shales expanded. Additional studies based on percentages of the various clay minerals indicated that montmorillonite-illite clays are more favorable for expansion than kaolinite (Fisher and Garner, 1965).

Results of Investigations

The discussion that follows is divided into six parts, five of which deal with areas within an arbitrary 50-mile radius of the following population centers: Farmington, Grants—Gallup, Raton—Las Vegas, Santa Fe—Albuquerque—Belen, and Las Cruces—El Paso. The sixth part covers all samples collected elsewhere. For each of the sections, favorable deposits are discussed first and then those deposits for which results were negative.

FARMINGTON AREA

Major highways in this area include U.S. 666 and U.S. 550. Paved subsidiary highways connect Farmington with Flagstaff, Arizona, on the west (N. Mex. 504) and Albuquerque to the southeast (N. Mex. 44). Numerous natural-gas pipelines cross the area, and a narrow-gauge line of the Denver and Rio Grande Western Railroad terminates at Farmington.

Natural lightweight aggregates such as pumice and scoria do not occur in sufficient amounts in the Farmington area to support a lightweight-aggregate industry. Heavy aggregate is abundant in the various older terrace deposits and present floodplains of the San Juan River and its tributaries. Considerable amounts of bottom and fly ash are produced at the power plant of the Arizona Public Service Company. In October 1965, ash production at this plant amounted to 1400 tons a day, of which 25 per cent consisted of bottom ash. The fly ash produced is reported to have good pozzuolanic properties. It could be used as a cement extender and possibly, in conjunction with bottom ash, as an aggregate for concrete block.

Shales were sampled at five localities in the Farmington area (fig. 3). Three of these are in the Mancos Shale (1-1, 1-2, and 1-3) north and west of Shiprock, and the others in the Fruitland Formation at the Navajo Coal Mine about four miles south of Fruitland (2-2 and 2-3).

SAMPLE LOCALITIES 2-2 AND 2-3

The section examined at the Navajo Coal Mine is part of the Fruitland Formation of Late Cretaceous age. The interval consists of interbedded sandstone, shale, and coal, for the most part of nonmarine origin. Fruitland beds are overlain by the Kirtland Shale and underlain by the Pictured Cliffs Sandstone. Total thickness of the Fruitland Formation in this area varies from 300 to 500 feet.

At the Navajo Mine, the main coal bed is between 8 and 12 feet thick and throughout most of the pit is directly overlain by 20 feet or less of sediments consisting of shale with varying amounts of coal and impure sandstone. Above this is a massive persistent sandstone bed that caps the dip slope to the east. The thickest section of shale observed during field investigations in February 1965 was about 200 yards north of the south end of the pit. A stratigraphic section of the rocks exposed in this area is given in Figure 4. Coal is absent in the shale interval, and only two thin (6-inch) impure sandstone beds, approximately 5 and 8 feet above the main coal bed, are present. A short distance to the south, the shale interval thins beneath the massive sandstone to about 3 to 4 feet in thickness, and at least at one point this sandstone directly overlies the coal in a deep channel. To the north, the shale interval thins rapidly and includes considerable sandstone and some coal. In places, the upper sandstone again cuts down as far as the top of the main coal bed. As the stripping operation continues down dip in the Fruitland Formation, it is doubtful that the shale interval shown in the measured section will maintain its thickness. There is, however, a good possibility that similar thicknesses of shale will occur elsewhere along the strike. Suitable sections could be stockpiled readily as stripping continues.

Ten samples (2-2), each representing between 1 and 2 feet of the shale section, were collected near the south end of the pit. The section can be divided into lower (samples 1 to 7) and upper (samples 8 to 10) parts. The lower interval consists of medium gray (N6), slightly silty, carbonaceous, calcareous shale. The upper part is similar but differs in two respects: it is darker gray (N4.5 to N5.5) and is noncalcareous. A single sample (2-3) was collected from 4 feet of shale above the main coal bed about half a mile north of locality 2-2. This shale is medium gray (N5.5), slightly silty, carbonaceous, and noncalcareous. It is similar to the upper samples of locality 2-2.

X-ray diffraction patterns were run on each sample, primarily to determine the clay mineralogy. The spacing values obtained indicate that the clay minerals are kaolinite and montmorillonite, with minor illite present in samples 2-2-7, -9, -10, and 2-3-1. The higher intensities of the montmorillonite peaks suggest that this is the dominant clay mineral. Based on intensities of the quartz peaks, the content of this mineral appears to be about the same throughout the section. Calcite per cent is fairly uniform through sample 7 of locality 2-2.

Fired Data

The unfired shale has an average specific gravity of 2.36, an average weight of 147.7 pounds per cubic foot, and an average moisture content of 2.35 per cent. Most surface samples give a higher moisture content, but the samples from the Navajo Mine have been exposed only recently and more accurate data in this and other tests can be expected.

From Table 1 and Figure 5, a general bloating range and maximum desired kiln temperatures to obtain the best product can be determined.

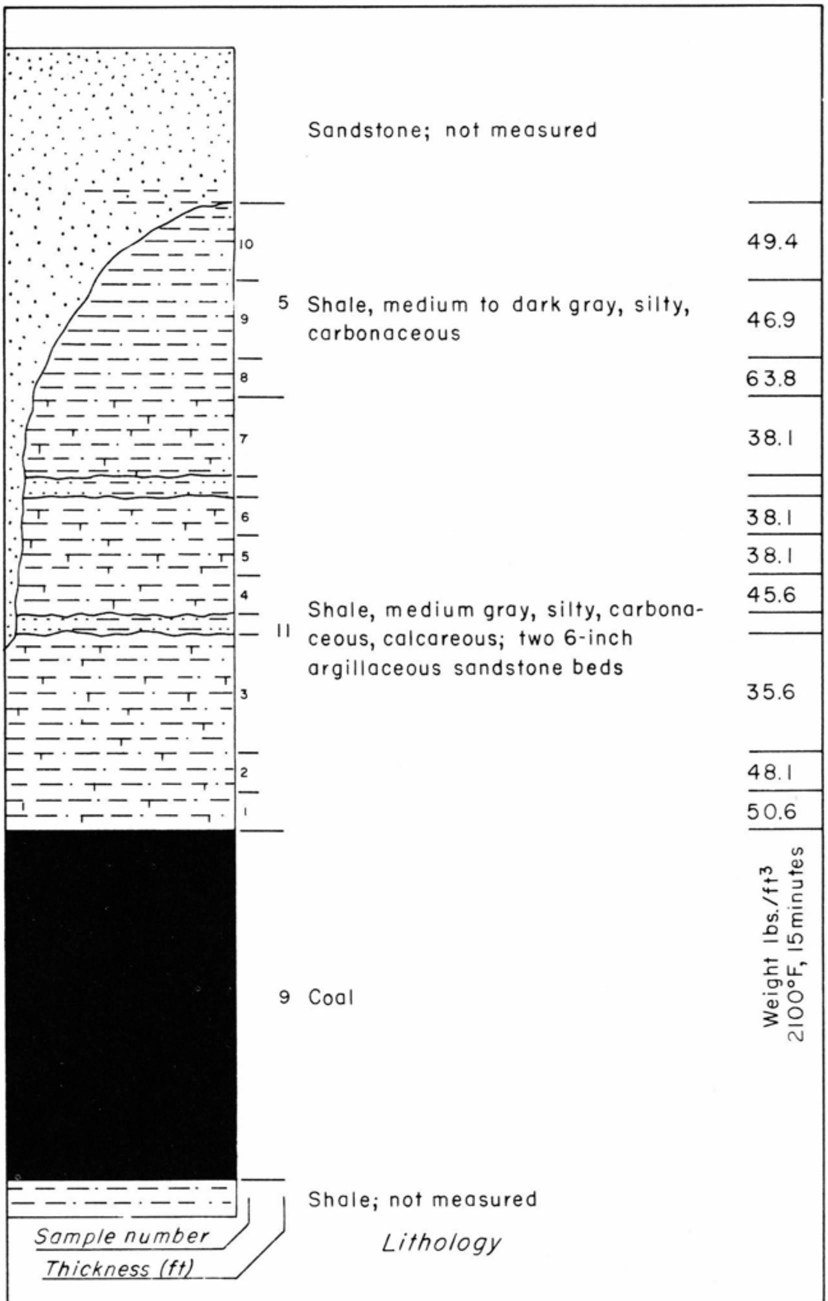

Figure 4

PARTIAL STRATIGRAPHIC SECTION OF FRUITLAND FORMATION; SAMPLE LOCALITY 2-2

Slight agglomeration occurs in all the samples at 2100° F, 15 minutes' retention time. However, the temperature range for expansion to an agregate with weights between 55 and 85 pounds per cubic foot is long enough so that temperatures of this magnitude would not be necessary. From the composite expansion curve, it can be calculated that, with a maximum temperature of 2050° F, an aggregate with a bulk specific gravity of about 1.0 (62.5 pounds per cubic foot) can be produced. The weights measured at this temperature for the ten samples tested range from 54 to 70 pounds per cubic foot. Sample 2-3-1 closely approximates the minimum weight given above. Expansion results for 2-2 are compared in Figure 5 with two grab samples of commercial shales presently being used for expanded aggregate. At 2050° F, 15 minutes' retention time, commercial aggregate 1 has a weight of approximately 90 pounds per cubic foot and commercial aggregate 2, 50 pounds per cubic foot. Comparable weights for the Fruitland shales can be obtained at a temperature range of 1950° to 2075° F, at 15 minutes' retention time. By decreasing the retention time, the temperature at which agglomeration takes place is raised, but the temperature range at which a product of less than 85 pounds per cubic foot can be produced is shortened.

Some typical features of these shales are shown in Figure 6. Most of the particles are equant in shape, a characteristic of the crushing properties of the shale. The sharp edges evident at 1800° F are rounded off as the expansion temperature increases. The higher expansion of sample 2-2-9, at low temperatures, than sample 2-2-2 is evident by a comparison of the degree of rounding of the two samples at 1900° and 2000° F. It is clear that at 2200° F both the calcareous shale of sample 2-2-2 and the noncalcareous shale of sample 2-2-9 exhibit heavy agglomeration. The greater degree of melting of the calcareous shales is evident from the higher luster and almost complete loss of identification of individual particles.

Photomicrographs of sample 2-2-2 (fig. 7) show only a few very small pores developed at 1900° F. At 2000° F, pores are fairly uniform with the size ranging from 0.05 to 0.1 millimeter; a few larger flat pores are developed, mostly near the outer edges of the particle. At 2100° F, the number of pores and their size increases greatly. Several of the pores are 1.0 millimeter or more in diameter, almost all the pores are spherical, and again the larger pores occur near the outer surface. Cell walls are fairly thick, lending good support to the structure. At 2200° F, the particle consists mostly of large pores separated by very delicate walls of glass containing numerous small gas bubbles. The strength of the particles is fairly high through 2100° F. Rapid quenching, a practice at some plants, greatly reduces the strength of this material.

The average water absorption of the aggregate ranges from 7 to 11 per cent, increasing slightly with higher expansion temperatures.

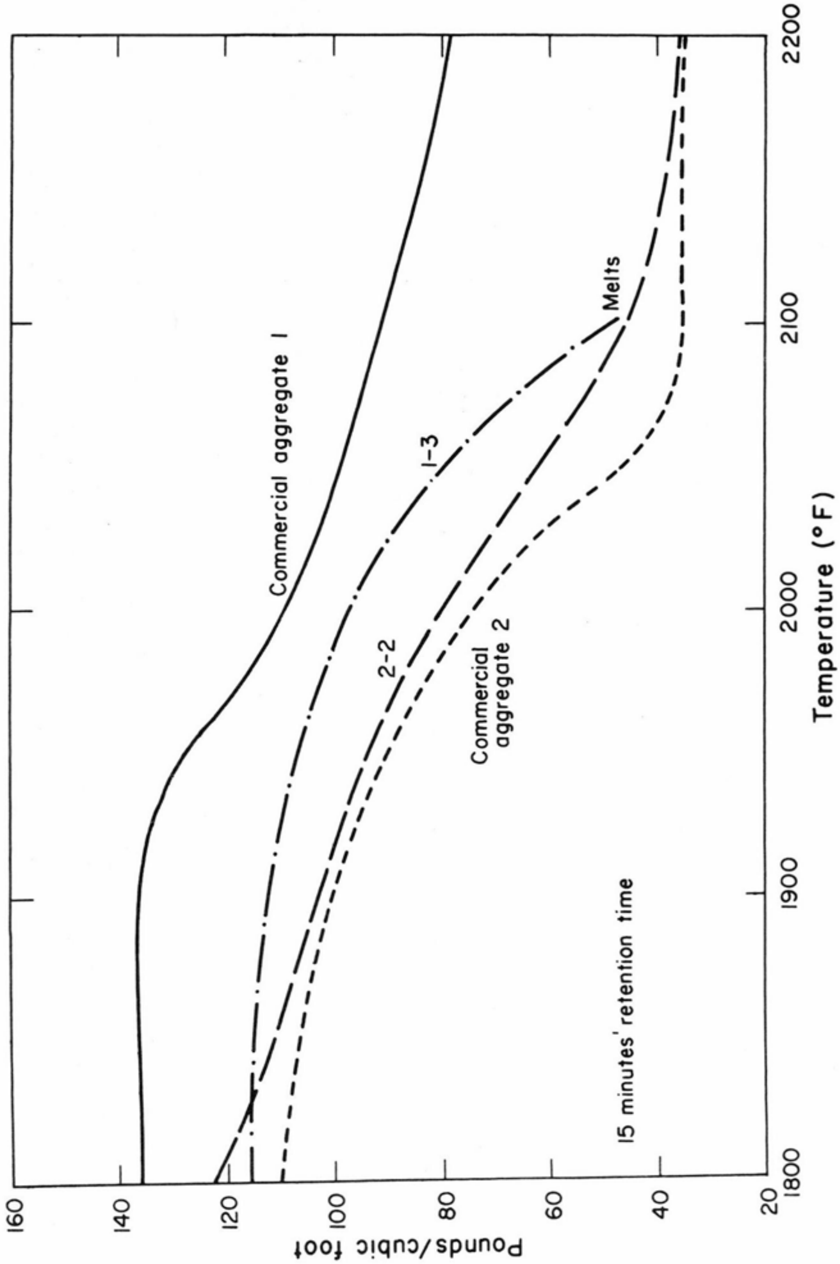

Figure 5

EXPANSION CURVES OF FRUITLAND (2-2), MANCOS (1-3), AND COMMERCIAL SHALES

TABLE 1. EXPANSION TEST DATA

TEMP.	BULK SPECIFIC GRAVITY			WEIGHT LBS/FT^3			AGGLOMERATION		
(°F)	5 min	10 min	15 min	5 min	10 min	15 min	5 min	10 min	15 min
COMMERCIAL AGGREGATE 1									
1800	2.27	2.22	2.18	141.9	138.8	136.3	—	—	—
1900	2.10	1.94	2.19	131.3	121.3	136.9	—	—	—
2000	1.94	1.76	1.72	121.3	110.0	107.5	—	—	—
2100	1.69	1.33	1.46	105.6	83.1	91.3	—	—	—
2200	1.35	1.03	1.26	84.4	64.4	78.8	—	—	—
COMMERCIAL AGGREGATE 2									
1800	1.90	1.74	1.75	118.8	108.8	109.4	—	—	—
1900	1.65	1.59	1.61	103.1	99.4	100.6	—	—	—
2000	1.35	1.34	1.16	84.4	83.8	72.5	—	—	—
2100	0.92	0.71	0.56	57.5	44.4	35.0	L*	L	M*
2200	0.68	0.48	0.54	42.5	30.0	33.8	L	M-H	H*
SAMPLE NUMBER 2-2-1									
1800	2.02	1.94	1.97	126.3	121.3	123.1	—	—	—
1900	1.90	1.82	1.71	118.8	113.8	106.9	—	—	—
2000	1.80	1.43	1.12	112.5	89.4	70.0	—	—	—
2100	1.57	0.92	0.81	98.1	57.5	50.6	—	L	L
2200	1.09	0.76	0.65	68.1	47.5	40.6	L	M	H
SAMPLE NUMBER 2-2-2									
1800	2.03	1.99	1.94	126.9	124.4	121.3	—	—	—
1900	1.96	1.79	1.66	122.5	111.9	103.8	—	—	—
2000	1.87	1.61	1.31	116.9	100.6	81.9	—	—	—
2100	1.65	1.07	0.77	103.1	66.9	48.1	—	L	L
2200	0.93	0.59	0.46	58.1	36.9	28.8	L	M-H	H
SAMPLE NUMBER 2-2-3									
1800	1.97	1.94	1.95	123.1	121.3	121.9	—	—	—
1900	1.92	1.86	1.84	120.0	116.3	115.0	—	—	—
2000	1.88	1.32	1.51	117.5	82.5	94.4	—	—	—
2100	1.62	0.98	0.57	101.3	61.3	35.6	—	L	M
2200	0.77	0.54	0.80	48.1	33.8	50.0	L	H	H
SAMPLE NUMBER 2-2-4									
1800	2.00	1.96	1.99	125.0	122.5	124.4	—	—	—
1900	1.93	1.82	1.81	120.6	113.8	113.1	—	—	—
2000	1.83	1.64	1.50	114.4	102.5	93.8	—	—	—
2100	1.69	0.82	0.73	105.6	51.3	45.6	—	—	L
2200	0.89	0.54	0.45	55.6	33.8	28.1	—	H	H

* L, Light; M, Moderate; H, Heavy.

TABLE 1. EXPANSION TEST DATA (cont)

TEMP. (°F)	BULK SPECIFIC GRAVITY 5 min	10 min	15 min	WEIGHT LBS/FT³ 5 min	10 min	15 min	AGGLOMERATION 5 min	10 min	15 min
				SAMPLE NUMBER 2-2-5					
1800	1.97	1.94	1.94	123.1	121.3	121.3	—	—	—
1900	1.90	1.90	1.69	118.8	118.8	105.6	—	—	—
2000	1.94	1.68	1.20	121.3	105.0	75.0	—	—	—
2100	1.22	0.99	0.61	76.3	61.9	38.1	—	—	L-M
2200	0.69	0.50	0.54	43.1	31.3	33.8	H	H	H
				SAMPLE NUMBER 2-2-6					
1800	1.96	1.93	1.94	122.5	120.6	121.3	—	—	—
1900	1.93	1.88	1.83	120.6	117.5	114.4	—	—	—
2000	1.88	1.71	1.62	117.5	106.9	101.3	—	—	—
2100	1.62	1.16	0.61	101.3	72.5	38.1	—	—	M
2200	1.14	0.48	0.59	71.3	30.0	36.9	—	H	H
				SAMPLE NUMBER 2-2-7					
1800	2.00	1.96	1.97	125.0	122.5	123.1	—	—	—
1900	1.95	1.82	1.74	121.9	113.8	108.8	—	—	—
2000	1.73	1.53	1.35	108.1	95.6	84.4	—	—	—
2100	1.43	0.79	0.61	89.4	49.4	38.1	—	L	L
2200	0.78	0.39	0.60	48.8	24.4	37.5	L	H	H
				SAMPLE NUMBER 2-2-8					
1800	1.99	2.02	1.93	124.4	126.3	120.6	—	—	—
1900	1.93	1.63	1.35	120.6	101.9	84.4	—	—	—
2000	1.83	1.43	1.21	114.4	89.4	75.6	—	—	L
2100	1.37	1.11	1.02	85.6	69.4	63.8	—	L	L-M
2200	1.01	0.74	0.63	63.1	46.3	39.4	L	M	H
				SAMPLE NUMBER 2-2-9					
1800	2.06	1.94	1.98	128.8	121.2	123.8	—	—	—
1900	1.65	1.36	1.33	103.1	85.0	83.1	—	—	—
2000	1.46	1.14	1.03	91.3	71.3	64.4	—	—	—
2100	1.06	0.83	0.75	66.3	51.9	46.9	—	L	M
2200	0.98	0.71	0.49	61.3	44.4	30.6	—	H	H
				SAMPLE NUMBER 2-2-10					
1800	2.10	1.94	1.83	131.1	121.2	114.4	—	—	—
1900	1.70	1.41	1.44	106.3	88.1	90.0	—	—	—
2000	1.44	1.27	1.04	90.0	79.4	65.0	—	—	L
2100	1.31	1.04	0.79	81.9	65.0	49.4	—	L	L
2200	0.82	0.55	0.47	51.3	34.4	29.4	L	M	M-H

TABLE 1. EXPANSION TEST DATA (cont)

TEMP.	BULK SPECIFIC GRAVITY			WEIGHT LBS/FT^3			AGGLOMERATION		
(°F)	5 min	10 min	15 min	5 min	10 min	15 min	5 min	10 min	15 min
				SAMPLE NUMBER 2-3-1					
1800	2.11	1.90	1.94	131.9	118.8	121.3	—	—	—
1900	1.80	1.43	1.78	112.5	89.4	111.3	—	—	—
2000	1.52	1.10	1.05	95.0	68.8	65.6	—	—	—
2100	1.10	0.91	0.73	68.8	56.9	45.6	—	L	L
2200	0.88	0.54	0.43	55.0	33.8	26.9	L	M	H
				SAMPLE NUMBER 4-4-1					
1800	—	2.12	1.98	—	132.5	123.8	—	—	—
1900	1.89	1.97	1.89	118.1	123.1	118.1	—	—	—
2000	—	1.42	1.97	—	88.8	123.1	—	—	—
2100	1.95	1.34	0.92	121.9	83.8	57.5	—	—	—
2200	1.31	0.83	0.83	81.9	51.9	51.9	—	L	M-H
				SAMPLE NUMBER 4-4-2					
1800	2.26	2.12	2.17	141.3	132.5	135.6	—	—	—
1900	1.99	1.89	2.02	124.4	118.1	126.3	—	—	—
2000	2.00	1.91	1.79	125.0	119.4	111.9	—	—	—
2100	1.83	1.40	0.90	114.4	87.5	56.3	—	—	—
2200	1.44	0.97	1.02	90.0	60.6	63.8	—	L	M
				SAMPLE NUMBER 4-4-3					
1800	2.22	2.12	2.11	138.8	132.5	131.9	—	—	—
1900	1.89	2.06	1.99	118.1	128.8	124.4	—	—	—
2000	1.95	1.71	1.59	121.9	106.9	99.4	—	—	—
2100	1.51	1.48	1.01	94.4	92.5	63.1	—	—	—
2200	1.76	1.19	1.03	110.0	74.4	64.6	—	—	M
				SAMPLE NUMBER 8-4-1					
1800	2.21	1.93	2.26	138.1	120.6	141.3	—	—	—
1900	2.00	1.86	1.83	125.0	116.3	114.4	—	—	—
2000	1.88	1.74	1.66	117.5	108.8	103.8	—	—	—
2100	1.59	1.28	1.34	99.4	80.0	83.8	—	—	—
2200	1.31	0.99	0.90	81.8	61.9	56.3	—	L	H
				SAMPLE NUMBER 8-4-2					
1800	2.26	2.11	2.05	141.3	131.9	128.1	—	—	—
1900	2.21	2.15	1.92	138.1	134.4	120.0	—	—	—
2000	1.93	1.86	1.75	120.6	116.3	109.4	—	—	—
2100	1.71	1.51	1.21	106.9	94.4	75.6	—	—	L
2200	1.41	1.07	1.00	88.1	66.9	62.5	—	M	M

TABLE 1. EXPANSION TEST DATA (cont)

TEMP. (°F)	BULK SPECIFIC GRAVITY 5 min	10 min	15 min	WEIGHT LBS/FT^3 5 min	10 min	15 min	AGGLOMERATION 5 min	10 min	15 min
				SAMPLE NUMBER 8-4-3					
1800	2.21	2.08	2.10	138.1	130.0	131.3	—	—	—
1900	1.74	1.93	1.90	108.8	120.6	118.8	—	—	—
2000	2.04	1.77	1.68	127.5	110.6	105.0	—	—	—
2100	1.66	1.34	1.23	103.8	83.8	76.9	—	—	—
2200	1.13	0.93	0.92	70.6	58.1	57.5	—	M	M
				SAMPLE NUMBER 8-4-4					
1800	2.16	1.84	1.85	135.0	115.0	115.6	—	—	—
1900	1.94	1.78	1.73	121.3	111.3	108.1	—	—	—
2000	1.91	1.56	1.54	119.4	97.5	96.3	—	—	—
2100	1.45	1.40	1.16	90.6	87.5	72.5	—	—	L
2200	1.19	0.74	0.86	74.4	46.3	53.8	—	L	M
				SAMPLE NUMBER 8-4-5					
1800	2.12	1.84	1.81	132.5	115.0	113.1	—	—	—
1900	2.03	1.63	1.70	126.9	101.9	106.3	—	—	—
2000	1.66	1.47	1.35	103.8	91.9	84.4	—	—	—
2100	1.48	0.93	0.95	92.5	58.1	59.4	—	—	L
2200	1.06	0.71	0.76	66.3	44.4	47.5	—	L	L
				SAMPLE NUMBER 8-4-6					
1800	2.11	1.85	2.01	131.9	115.6	125.6	—	—	—
1900	1.96	1.70	1.77	122.5	106.1	110.6	—	—	—
2000	1.87	1.46	1.32	116.9	91.3	82.5	—	—	—
2100	1.43	0.88	0.84	89.4	55.0	52.5	—	—	—
2200	0.84	0.59	0.59	52.5	36.9	36.9	—	L	L
				SAMPLE NUMBER 9-7-2					
1800	1.99	1.62	1.72	124.4	101.3	107.5	—	—	—
1900	1.68	1.29	1.27	105.0	80.6	79.4	—	—	—
2000	1.42	1.10	0.97	88.8	68.8	60.6	—	—	—
2100	1.27	0.90	0.73	79.4	56.3	45.6	—	—	—
2200	0.90	0.55	0.55	56.3	34.4	34.4	—	M	H
				SAMPLE NUMBER 9-7-3					
1800	1.79	1.69	1.74	111.9	105.6	108.8	—	—	—
1900	1.61	1.51	1.46	100.6	94.4	91.3	—	—	—
2000	1.50	0.86	0.96	93.8	53.8	60.0	—	—	—
2100	1.37	0.98	0.87	85.6	61.3	54.4	—	—	—
2200	0.88	0.48	0.45	55.0	30.0	28.1	L	M-H	H

TABLE 1. EXPANSION TEST DATA (cont)

TEMP.	BULK SPECIFIC GRAVITY			WEIGHT LBS/FT³			AGGLOMERATION		
(°F)	5 min	10 min	15 min	5 min	10 min	15 min	5 min	10 min	15 min
				SAMPLE NUMBER 9-7-4					
1800	1.93	1.74	1.82	120.6	108.8	113.8	—	—	—
1900	1.66	1.36	1.47	103.8	85.8	91.9	—	—	—
2000	1.32	1.15	1.11	82.5	71.9	69.4	—	—	—
2100	—	0.94	0.79	—	58.8	49.4	—	—	—
2200	0.85	0.56	0.48	53.1	35.0	30.0	—	M	H
				SAMPLE NUMBER 27-1-1					
1800	—	1.82	1.88	—	113.8	117.5	—	—	—
1900	1.63	1.53	1.36	101.9	95.6	85.0	—	—	—
2000	1.19	1.20	1.20	74.4	75.0	75.0	—	—	—
2100	1.08	0.80	0.75	67.5	50.0	46.9	—	L	L
2200	1.36	0.85	0.58	85.0	53.1	36.3	—	L	L
				SAMPLE NUMBER 27-1-3					
1800	2.06	1.82	1.96	128.8	113.8	122.5	—	—	—
1900	1.78	1.46	1.44	111.3	91.3	90.0	—	—	—
2000	1.62	1.31	1.23	101.3	81.9	76.9	—	—	—
2100	1.06	0.94	0.88	66.3	58.8	55.0	—	—	L
2200	1.02	0.81	0.80	63.8	50.6	50.0	—	L	L
				SAMPLE NUMBER 38-1-1					
1800	1.87	1.66	1.84	116.9	103.8	115.0	—	—	—
1900	1.75	1.83	1.68	109.4	114.4	105.0	—	—	—
2000	1.96	1.69	1.80	122.5	105.6	112.5	—	—	—
2100	1.21	0.99	1.05	75.6	61.9	65.6	—	—	L
2200	1.08	0.98	0.96	67.5	61.3	60.0	—	L	L
				SAMPLE NUMBER 9-7-4					
1800	1.93	1.74	1.82	120.6	108.8	113.8	—	—	—
1900	1.66	1.36	1.47	103.8	85.8	91.9	—	—	—
2000	1.32	1.15	1.11	82.5	71.9	69.4	—	—	—
2100	—	0.94	0.79	—	58.8	49.4	—	—	—
2200	0.85	0.56	0.48	53.1	35.0	30.0	—	M	H
				SAMPLE NUMBER 27-1-1					
1800	—	1.82	1.88	—	113.8	117.5	—	—	—
1900	1.63	1.53	1.36	101.9	95.6	85.0	—	—	—
2000	1.19	1.20	1.20	74.4	75.0	75.0	—	—	—
2100	1.08	0.80	0.75	67.5	50.0	46.9	—	L	L
2200	1.36	0.85	0.58	85.0	53.1	36.3	—	L	L

TABLE 1. EXPANSION TEST DATA (cont)

TEMP. (°F)	BULK SPECIFIC GRAVITY 5 min	10 min	15 min	WEIGHT LBS/FT^3 5 min	10 min	15 min	AGGLOMERATION 5 min	10 min	15 min
				SAMPLE NUMBER 27-1-3					
1800	2.06	1.82	1.96	128.8	113.8	122.5	—	—	—
1900	1.78	1.46	1.44	111.3	91.3	90.0	—	—	—
2000	1.62	1.31	1.23	101.3	81.9	76.9	—	—	—
2100	1.06	0.94	0.88	66.3	58.8	55.0	—	—	L
2200	1.02	0.81	0.80	63.8	50.6	50.0	—	L	L
				SAMPLE NUMBER 38-1-1					
1800	1.87	1.66	1.84	116.9	103.8	115.0	—	—	—
1900	1.75	1.83	1.68	109.4	114.4	105.0	—	—	—
2000	1.96	1.69	1.80	122.5	105.6	112.5	—	—	—
2100	1.21	0.99	1.05	75.6	61.9	65.6	—	—	L
2200	1.08	0.98	0.96	67.5	61.3	60.0	—	L	L
				SAMPLE NUMBER 66-1-10					
1800	2.18	2.19	2.18	136.3	136.9	136.3	—	—	—
1900	2.19	2.12	2.08	136.9	132.5	130.0	—	—	—
2000	2.25	2.09	2.11	140.6	130.6	131.9	—	—	—
2100	1.92	1.46	1.32	120.0	91.3	82.5	—	—	—
2200	1.46	1.01	1.14	91.3	63.1	71.5	—	M-H	M-H
				SAMPLE NUMBER 66-1-11					
1800	2.09	1.56	1.97	130.6	97.5	123.1	—	—	—
1900	1.85	1.46	1.40	115.6	91.3	87.5	—	—	—
2000	1.58	1.44	0.95	98.8	90.0	59.4	—	—	—
2100	1.01	0.65	0.60	63.1	40.6	37.5	—	L	L
2200	0.56	0.53	0.47	35.0	33.1	29.4	L	L-M	L-M
				SAMPLE NUMBER 66-1-12					
1800	2.24	2.20	2.21	140.0	137.5	138.1	—	—	—
1900	1.92	1.66	1.97	120.0	103.8	123.1	—	—	—
2000	1.71	1.44	1.11	106.9	90.0	69.4	—	—	—
2100	1.35	0.96	0.73	84.4	60.0	45.6	—	—	—
2200	0.79	0.60	0.61	49.4	37.5	38.1	—	—	L
				SAMPLE NUMBER 66-1-13					
1800	1.92	1.83	1.65	120.0	114.4	103.1	—	—	—
1900	1.68	1.47	1.47	105.0	91.9	91.9	—	—	—
2000	1.33	1.19	1.06	83.1	74.4	66.3	—	—	—
2100	1.02	0.62	0.61	63.8	38.8	38.1	—	—	—
2200	0.61	0.40	0.45	38.1	25.0	28.1	—	L	L

TABLE 1. EXPANSION TEST DATA (cont)

TEMP.	BULK SPECIFIC GRAVITY			WEIGHT LBS/FT^3			AGGLOMERATION		
(°F)	5 min	10 min	15 min	5 min	10 min	15 min	5 min	10 min	15 min
				SAMPLE NUMBER 66-1-14					
1800	2.20	2.17	2.16	137.5	135.6	135.0	—	—	—
1900	1.90	1.77	1.88	118.8	110.6	117.5	—	—	—
2000	2.02	1.39	0.91	126.3	86.9	56.9	—	—	—
2100	1.52	1.01	0.67	95.0	63.1	41.9	—	—	L
2200	0.83	0.66	0.48	51.9	41.3	30.0	—	L	L
				SAMPLE NUMBER 66-1-15					
1800	2.23	2.15	2.17	139.4	134.4	135.6	—	—	—
1900	2.06	1.99	1.93	128.8	124.4	120.6	—	—	—
2000	2.07	1.48	1.41	129.4	92.5	88.1	—	—	—
2100	1.37	0.96	0.77	85.6	60.0	48.1	—	—	—
2200	0.88	0.48	0.60	55.0	30.0	37.5	—	L-M	L-M
				SAMPLE NUMBER 66-1-16					
1800	2.21	2.22	2.13	138.1	138.8	133.1	—	—	—
1900	2.31	2.06	2.00	144.4	128.8	125.0	—	—	—
2000	2.06	1.79	1.75	128.8	111.9	109.4	—	—	—
2100	1.46	0.92	0.79	91.3	57.5	49.4	—	—	—
2200	0.87	0.80	0.75	54.4	50.0	46.9	—	M	M
				SAMPLE NUMBER 66-1-17					
1800	2.34	2.26	2.24	146.3	141.3	140.0	—	—	—
1900	2.21	2.12	1.99	138.1	132.5	124.4	—	—	—
2000	2.14	1.65	1.77	133.8	103.1	110.6	—	—	—
2100	1.65	1.09	1.01	103.1	68.1	63.1	—	—	—
2200	0.98	0.80	0.65	61.3	50.0	40.6	—	—	L
				SAMPLE NUMBER 66-1-18					
1800	2.30	2.30	2.33	143.8	143.8	145.6	—	—	—
1900	2.17	2.12	2.04	135.6	132.5	127.5	—	—	—
2000	2.00	1.67	1.79	125.0	104.4	111.9	—	—	—
2100	1.38	0.91	0.98	86.3	56.9	61.3	—	—	—
2200	0.87	0.68	0.63	54.4	42.5	39.4	—	L	L
				SAMPLE NUMBER 66-1-19					
1800	2.35	2.32	2.34	146.9	145.0	146.3	—	—	—
1900	2.23	2.16	2.25	139.4	135.0	140.6	—	—	—
2000	2.26	2.19	1.81	141.3	136.9	113.1	—	—	—
2100	1.75	1.49	1.44	109.4	93.1	90.0	—	—	—
2200	1.19	1.04	0.87	74.4	65.0	54.4	—	—	—
				SAMPLE NUMBER 66-1-20					
1800	2.35	2.34	2.24	146.9	146.3	140.0	—	—	—
1900	2.23	2.18	2.06	139.4	136.3	128.8	—	—	—
2000	2.09	1.71	1.70	130.6	106.9	106.3	—	—	—
2100	1.73	0.91	1.18	108.1	56.9	73.8	—	—	—
2200	0.99	1.20	0.71	61.9	75.0	44.4	—	—	L

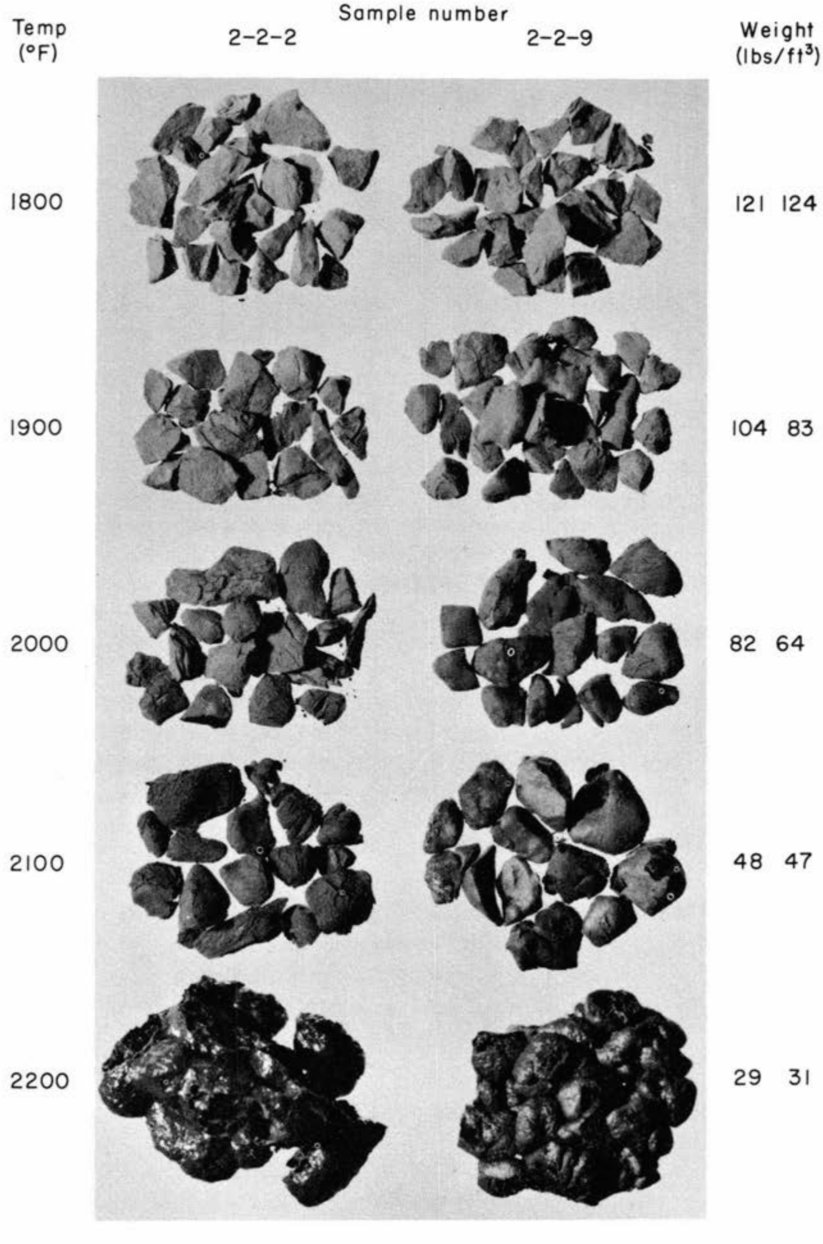

Figure 6
EXPANSION CHARACTERISTICS OF FRUITLAND SHALES
(15 minutes' retention time)

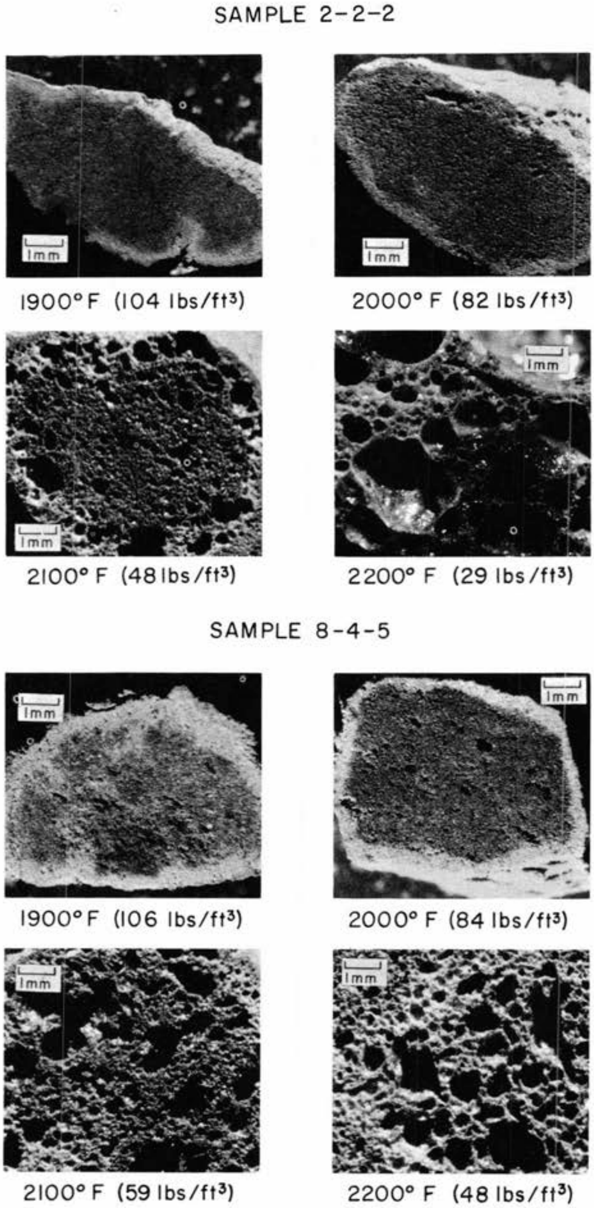

Figure 7

Pore development of Fruitland (2-2-2) and Pierre (8-4-5) shales

(15 minutes' retention time)

Above 2100° F, the absorption increases rapidly to about 13 per cent as the result of fusion and exposure of the pores during removal of the sample from the scorifier dish.

SAMPLE LOCALITY 1-1

Several grab samples from the upper part of the Mancos Shale were collected from exposures on the east side of U.S. 666 at a point 11.5 miles north of Shiprock. No expansion was observed when this material was test-fired at 2100° F, 15 minutes' retention time, and further tests were not conducted.

SAMPLE LOCALITY 1-2

Four channel samples were collected from the Mancos Shale at the first roadcut west of Shiprock on N. Mex. 504. The shales are medium dark to medium gray (N4 to N5), silty, micaceous (muscovite), and calcareous and contain veinlets of gypsum. The principal clay mineral is montmorillonite. Preliminary expansion tests, as above, resulted in weights of 88, 100, 89, and 100 pounds per cubic foot. Because of the relatively high weights and incipient melting, a full series of tests was not considered necessary to eliminate this material as a possible source for lightweight shale aggregate.

SAMPLE LOCALITY 1-3

Two channel samples were taken from the lower part of the Mancos Shale about 15 miles west of Shiprock on the south side of N. Mex. 504. This material and the shale at locality 1-2 had been previously collected by Allen (1955), who concluded after preliminary testing that it was possibly suitable for lightweight shale aggregate. The shale is dark to medium gray (N3 to N5), silty, and slightly to strongly calcareous. As in other Mancos shales, the principal clay mineral is montmorillonite. The shale has a very short expansion range, with bloating beginning at about 2000° F (fig. 5). Most of the pores, developed between 2000° and 2100° F, 15 minutes' retention time, are elongate; spherical pores form only near the outer edges of the particles. At 2100° F, 15 minutes' retention time, and at 2200° F, 10 and 15 minutes' retention times, almost complete melting takes place. Because of the short expansion range and agglomeration, this material is not considered suitable for rotary kiln production of lightweight aggregate. Sintering followed by crushing and sizing of the expanded shale may result in a usable aggregate of the haydite type.

SUMMARY

Limited testing of samples from this area showed the presence of favorable shales for expanded aggregate in the Fruitland Formation. The Mancos Shale does not appear to be suitable, but the sequence of shales in this interval is exceptionally thick and favorable zones might be disclosed by more detailed sampling. Other shale intervals in the Fruitland Formation, as well as additional Cretaceous units, may contain thick, extensive deposits useful for the production of lightweight aggregate.

RATON—LAS VEGAS AREA

Almost 200 channel samples from twelve localities were collected in the area between Las Vegas and the Colorado state line just north of Raton. With one notable exception, results of testing were negative.

Most of the shales tested are of Cretaceous age, but an extensive exposure of Pennsylvanian shales were sampled at one locality, and shales of probable Tertiary age were collected in two areas.

The largest discovered source of shale suitable for expanded lightweight aggregate in New Mexico occurs in the Pierre Shale. This interval and the underlying Niobrara Formation, also consisting almost entirely of shale, crop out over a large area from Raton on the north to as far south as Wagon Mound. In most areas it is difficult, if not impossible, to separate these two formations readily in the field, because of cover and lack of any topographic break. The only recognizable lithologic difference is that the Niobrara is commonly more calcareous than the Pierre. The Niobrara Formation was tested at two localities and does not appear to be suitable for expanded shale because of low melting point and short expansion range. However, even with the exclusion of the Niobrara, the strippable reserves from a thickness of Pierre Shale of more than 1500 feet far exceed any foreseeable production if the expansion properties are as uniform as present testing suggests. The Pierre has been sampled at only two localities in New Mexico, but it is used for expanded shale in Colorado and is known to have similar expansion properties as far north as South Dakota.

The only present potential market where large tonnages of expanded shale from this area might be used appears to be Albuquerque. Other possible markets exist in Raton and in parts of Colorado, Oklahoma, and Texas. This section of northeastern New Mexico is served by U.S. 85 and partly completed Interstate 25 connecting the area with Denver, Santa Fe, Albuquerque, and El Paso. Major east-west highways include U.S. 56, 64, and 87, and at Trinidad, Colorado, U.S. 160. The main line of the Santa Fe Railway parallels U.S. 85—Interstate 25 between Raton and Albuquerque. The nearest large-diameter natural gas pipeline is the Colorado Interstate Gas Company's 24-inch line northeast of Trinidad.

Large deposits of scoria may be found at numerous localities in northeastern New Mexico. Any local construction, particularly of concrete block, has a ready source of lightweight aggregate from these deposits.

SAMPLE LOCALITY 8-4

Six channel samples were collected from the upper fifty feet of the Pierre Shale in a cutbank on the north side of the Cimarron River. The location is 6.5 miles west of the town of Cimarron and immediately west of the easternmost bridge over the Cimarron River on U.S. 64. Outcrops of the Pierre continue from this point east to Cimarron and then north as far as Raton beneath the younger Cretaceous and Tertiary rocks that form the higher cliffs of Raton Mesa. East of Cimarron, the Pierre underlies much of the plains area almost to Springer but is mostly obscured by a thin soil cover. From Cimarron, it is about 20 miles by paved highway (N. Mex. 58) to the nearest railroad siding at French and about 24 miles to the town of Springer, also on the Santa Fe Railway.

Samples collected consisted of dark gray (N3.5), silty, micaceous (muscovite) shale with minor carbonaceous material, some pyrite, and a few grains of calcite, probably from fragmented fossils. Kaolinite appears to be the dominant clay mineral in most of the samples, but there also is minor montmorillonite and illite. Moisture content of the raw shale amounted to less than 2 per cent, but it probably averages somewhat higher during the year on more gentle slopes than where collected. The average specific gravity was 2.46 for a weight of 154 pounds per cubic foot.

Fired Data

A composite curve derived from data on the six samples tested is given in Figure 8. From this curve (8-4), an aggregate of less than 85 pounds per cubic foot could be obtained at a temperature of about 2050° F with a retention time of 15 minutes. Studies of each sample indicate that the temperature necessary for an aggregate of this weight ranges from slightly less than 2000° to 2100° F. Samples from just below the Trinidad Sandstone require the lowest temperatures to produce an aggregate of less than 85 pounds per cubic foot (table 1). In addition, weights decrease more abruptly for samples from the upper part of the section. At 2100° F, 15 minutes' retention time, samples 1 to 6 had weights of 83.8, 75.6, 76.8, 72.5, 59.4, and 52.5 pounds per cubic foot. Weights of 47.5 and 36.9 pounds per cubic foot were measured for the two upper samples when fired at 2200° F, 15 minutes' retention time.

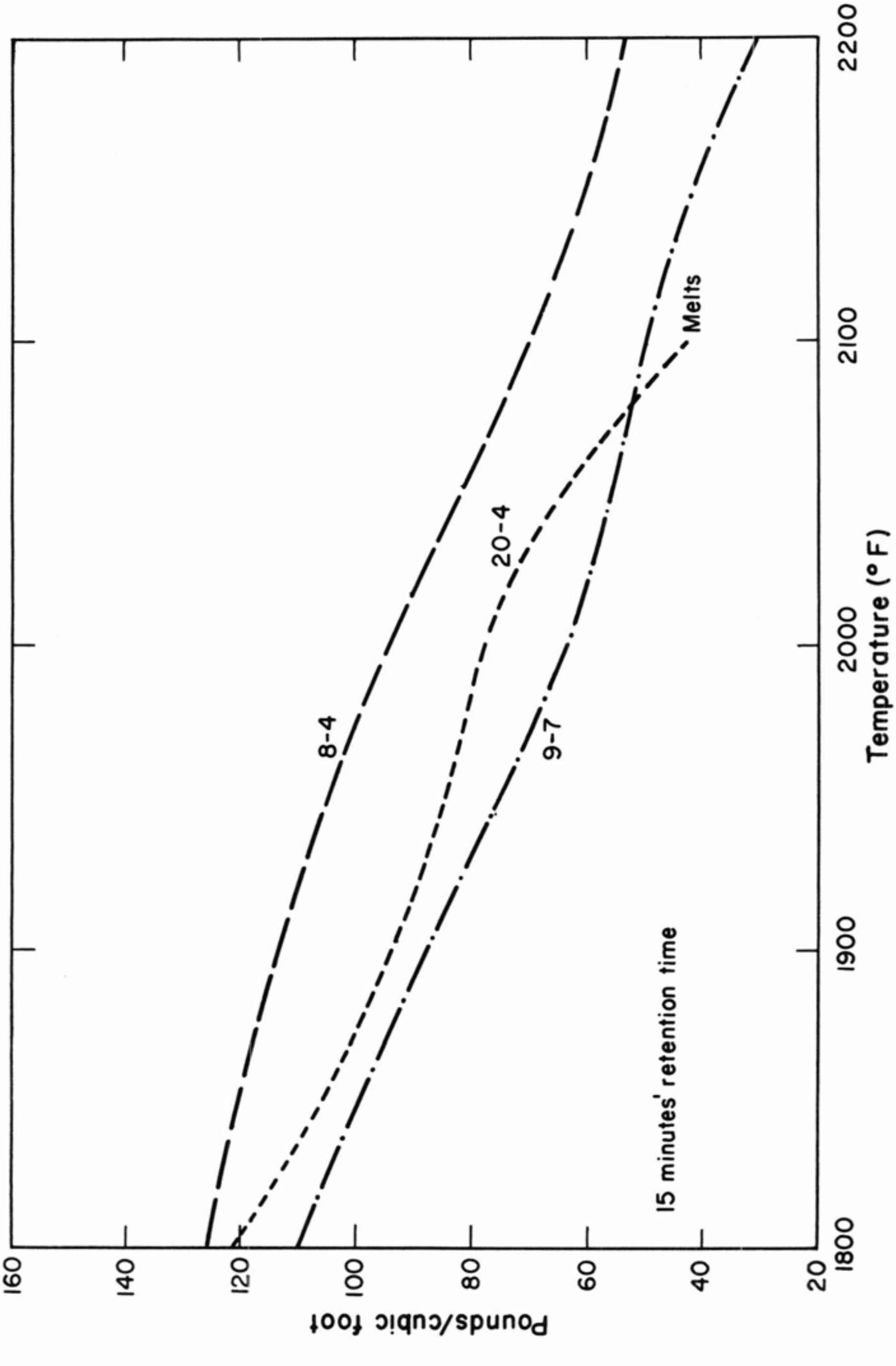

Figure 8

EXPANSION CURVES OF PIERRE (8-4; 9-7) AND PENNSYLVANIAN (20-4) SHALES

Agglomeration poses no serious problem until temperatures above 2100° F are reached. Very slight sticking was noted in three of the samples when fired at 2100° F, 15 minutes' retention time, but there was no agglomeration evident at this temperature with 10 minutes' retention time. Weight increase at this shorter firing period amounted to an average of only 6 pounds per cubic foot. Moderate to heavy agglomeration occurred in the lower four samples at 2200° F, 15 minutes' retention time, but, as can be seen in Figure 9, there was only slight agglomeration in sample 8-4-5 at this temperature.

Development of pores begins at about 1900° F, 15 minutes' retention time, in most samples but started as low as 1800° F, 5 minutes' retention time, in sample 8-4-5. In the photomicrographs of 8-4-5, shown in Figure 7, pore development is fairly extensive at 1900° F, but most pores are elongate with maximum long dimensions of about 0.5 millimeter. Spherical pores form at 2000° F, and there is a marked increase in pore size between 2000° and 2100° F with pores more than 1.0 millimeter in diameter common at 2100° F. Most of the particles are rounded at this temperature (fig. 9) and the relative strength is moderate to high. At 2200° F, pore size increases further and there is a marked reduction in strength as the exterior rim becomes thinner. The strength is somewhat higher, however, than that of sample 2-2-2, as can be inferred by comparing the photomicrographs in Figure 7.

Water absorption remains at about 12 per cent through 2000° F, increasing to almost 17 per cent at 2100° F. The higher absorption at this latter temperature is caused by the formation of surface pores.

SAMPLE LOCALITY 9-7

The Pierre Shale was also sampled 20 miles northeast of locality 8-4 in a cutbank on the north side of Ox Canyon near Koehler. A paved road and railroad spur parallel Crow Creek to the town of Koehler where coal mining was active at the time of sampling in the summer of 1965. The Pierre Shale at this locality is similar in some respects to that in the section at 8-4. The shales are medium dark gray (N4), olive gray (5Y4/1), and silty; lower beds contain small amounts of mica (biotite) and minor carbonaceous fragments. One sample was slightly calcareous and most beds contain small discrete grains of calcium carbonate. Numerous large calcareous concretions occur in this part of the section, which is stratigraphically below that tested to the south. The concretions appear to be restricted to a definite zone in the Pierre Shale and should present little difficulty in mining.

Fired Data

A composite curve (9-7) of the three upper samples collected is given in Figure 8. The lower sample was from the concretion zone and

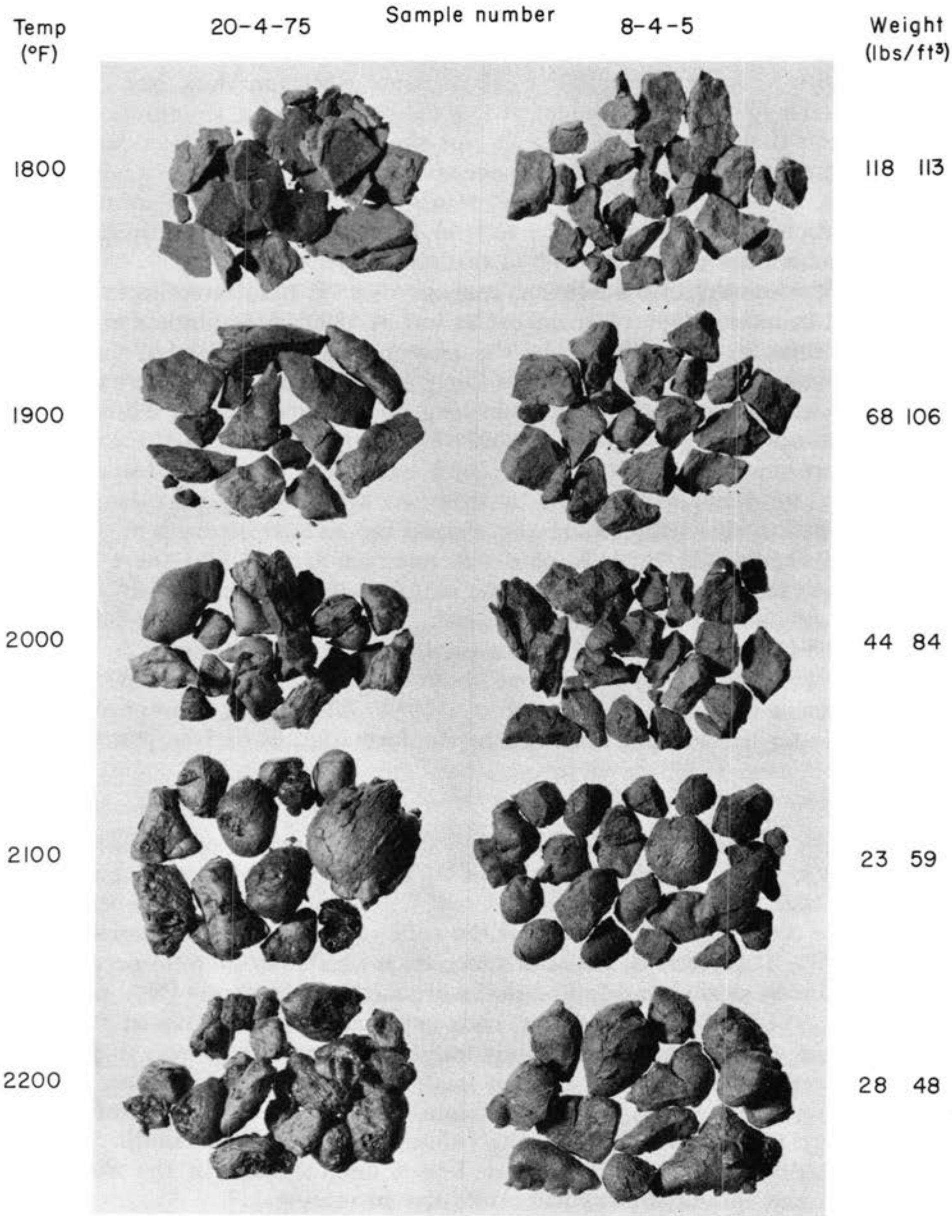

Figure 9
EXPANSION CHARACTERISTICS OF PENNSYLVANIAN (20-4-75) AND PIERRE (8-4-5) SHALES
(15 minutes' retention time)

gave abnormally high weights at all temperatures. The upper samples are fairly uniform in their firing characteristics and have much lower weights than were obtained with samples from locality 8-4 (table 1 and fig. 8). At 2100° F, 15 minutes' retention time, measured weights were 45.6, 54.4, and 49.4 pounds per cubic foot. A bulk specific gravity of slightly more than 1.0 was obtained for all samples at 2000° F. Pores began to form between 1800° and 1900° F and were fairly uniform in size and distribution at 2000° and 2100° F. Agglomeration occurs in all the samples at 2200° F, 10 minutes' retention time, and is very heavy at 15 minutes' retention time. There was no evidence of sticking at 2100° F, 15 minutes' retention time. Water absorption was very high for the upper two samples, increasing from 10 to 30 per cent between 1800° and 2100° F.

SAMPLE LOCALITY 20-4

Northwest of Mora, N. Mex. Highway 3 recently has been reconstructed high on the slopes above Vigil Creek. In the numerous new roadcuts, a thick sequence of Pennsylvanian sandstones, shales, and limestones has been exposed. Seventy-five samples were collected from these roadcuts between the village of Holman and the divide that separates Mora and Taos counties. Just below the divide, there are exposures of a thick limestone that contains abundant fusulinids determined to be from the lower part of the Pennsylvanian sequence. The thousands of feet of rock exposed below this limestone are also of Early Pennsylvanian age and show a marked lithologic change between this area and outcrops in other parts of the Sangre de Cristo Mountains. Particularly noteworthy is the great thickness of shales present here, compared with Lower Pennsylvanian rocks elsewhere in northern New Mexico.

Preliminary tests were made on all the samples collected, and several shale beds appear to have good expansion properties. However, with the exception of the uppermost part of the section, a sequence thick enough to be stripped does not appear to be present, and only the data for samples 71 to 75 are given in this report. These samples were collected from roadcuts just within the eastern boundary of Carson National Forest. The shales are medium dark gray (N4), silty, micaceous (muscovite), and, with the exception of sample 75, calcareous. The clay-mineral content is varied, with illite apparently the most abundant mineral, except in sample 74 where kaolinite appears to exceed illite. The dominance of kaolinite over illite is true, in general, of the clay mineralogy of the entire Lower Pennsylvanian section at this locality.

Fired Data

A composite curve (20-4) for samples 71 to 75 is given in Figure 8. From this curve, the shales in the upper part of section 20-4 appear to make a very good lightweight aggregate. Weights as low as 23 pounds per cubic foot were obtained, but expansion ranges were fairly short with slight to moderate agglomeration occurring as low as 2000° F, 15 minutes' retention time. Most of the samples melted completely at 2200° F, 10 minutes' retention time. The temperature necessary to obtain weights below 85 pounds per cubic foot and to avoid agglomeration ranges from 15° to 215° F. Sample 20-4-75, which had the best expansion properties, is shown in Figure 9. The high degree of expansion is evident, as is the degree of agglomeration. The agglomeration, although not so serious in this sample as in the others, is shown by the exposed pores caused by the separation of the particles fired at 2100° and 2200° F. At temperatures between 1950° and 2000° F, an aggregate with an average weight of 70 pounds per cubic foot can be produced, but the variation in weight is extreme, ranging from 44 to 110 pounds per cubic foot. In addition, pore development for the most part is not uniform and the numerous large pores (greater than 2.0 millimeters in diameter) result in a low-strength aggregate. At 2100° F, pores more than 8.0 millimeters in size are formed and the strength decreases still further. Here again, although the average weight is 40 pounds per cubic foot, the range is from 23 to 79 pounds per cubic foot. Water absorption is not excessive through 2100° F, ranging from 11 to 12 per cent.

SAMPLE LOCALITY 8-3

Shales from the Vermejo Formation were collected from roadcuts on the north side of U.S. 64 in Cimarron Canyon about 8 miles west of Cimarron. The shales are dark to medium gray (N3 to N5) and silty, and they contain considerable carbonaceous and coaly material. Montmorillonite is the most common clay mineral, but lesser amounts of kaolinite and/or illite are present in all the samples. When fired at 2100° F, 15 minutes' retention time, a few of the eight samples tested showed a little expansion.

SAMPLE LOCALITY 9-1

The Vermejo Formation also was sampled along Ponil Creek from cuts on N. Mex. 204, 5 miles west of the junction with U.S. 64. As at locality 8-3, the section consists of interbedded sandstone, shale, and minor thin coal beds. Expansion properties were similar to that of samples from locality 8-3 with slight pore development observed in a few of the specimens.

SAMPLE LOCALITY 10-2

The Raton Formation is a thick sequence of sandstones, conglomerates, shales, and coals that underlies a large part of Raton Mesa, as well as other mesas east of Raton. Twenty-two shale samples were collected from this unit at excellent exposures on the east side of Maloya Dam in sec. 27, T. 32 N., R. 24 E. The shales are medium dark to light gray (N4 to N7) and yellowish gray (5Y7/2), silty, and carbonaceous. Preliminary firing tests indicated only minor expansion from a few thin intervals.

SAMPLE LOCALITY 10-3

Eleven additional samples of Raton shales were collected along the Old Raton Pass Road, now a scenic drive, northwest of Raton. As at locality 10-2, shale intervals are thin and expansion is limited. Thicker beds of Raton shales probably occur locally, but the refractory nature of most of the samples tested indicates that further examination of this part of the section is not warranted.

SAMPLE LOCALITY 10-5

Sixteen channel samples were collected from roadcuts in the upper part of the Carlile Shale between Maxwell and Chico Post Office. Location is in the NE1/4 NE1/4 sec. 5, T. 26 N., R. 25 E. The Carlile Formation consists of a little more than 200 feet of shale with minor thin beds of limestone (Griggs, 1948). Large calcareous septarian concretions are common in the upper part of the section. The shales are dark to light gray (N3 to N7) and yellowish gray (5Y7/2), slightly silty to silty, and micaceous (muscovite) in part. The lower five samples are noncalcareous; most of the remaining shales are calcareous. Upper shale beds contain abundant complete fossil casts and small fossil fragments. The dominant clay mineral is montmorillonite.

Preliminary tests at 2100° F, 15 minutes' retention time, indicated some pore development in all the specimens and fair expansion in a few. Specific gravities were greater than 1.0 for all noncalcareous shales fired at this temperature and less than 1.0 for calcareous shales, except for those containing appreciable amounts of silt and/or laminae of small grains of calcite. Only slight agglomeration was observed, but flaking caused by popping of the shales was severe in most of the samples. No further tests were run, although controlled firing may produce a good aggregate from parts of the Carlile section. Reserves in the area are very large.

SAMPLE LOCALITY 21-1

Thin shales interbedded with thin limestones comprise the Fort Hays Limestone Member of the Niobrara Formation. Preliminary firing tests gave no evidence of expansion, so additional tests were not conducted. Samples were collected from stream cuts just south of the rodeo grounds at Springer.

SAMPLE LOCALITY 21-2

Shales from the Niobrara Formation were sampled in roadcuts and exposed slopes along the south side of N. Mex. 199 west of Springer. The lowest samples collected were from just above the Fort Hays Limestone, and only a part of the total Niobrara section was sampled. Outcrops are poor and very limited in vertical extent. The shales are dark to medium light gray (N3.5 to N6.5), silty, and highly calcareous. Like most of the other Cretaceous shales tested, the most common clay mineral is montmorillonite; a little kaolinite and/or illite may be present. The quartz content in the silt and possibly clay-size range appears to be somewhat lower than in other Cretaceous shales. Tests for calcium carbonate with dilute hydrochloric acid indicates a high percentage of this mineral in the samples. This was substantiated by extremely strong X-ray peaks for calcite.

Test-fired at 2100° F, 15 minutes' retention time, all nine samples overexpanded and fused. Tests at lower temperatures were not conducted, but it is suspected that the expansion range is very short. Inasmuch as the entire section of 900-plus feet was not tested, it is possible that higher beds may give results similar to the overlying Pierre Shale, thus making a suitable aggregate.

SAMPLE LOCALITY 22-1

Ten samples were collected from a fairly complete section of the Graneros Shale about a quarter of a mile north of U.S. 56 along a tributary to the Canadian River. The approximate location is sec. 4, T. 24 N., R. 23 E. Shales are dark gray (N3), silty, and calcareous and contain numerous fossil fragments. Two thin bentonite beds occur near the base of the section and thin laminae of finely crystalline limestone are present in the upper few feet. Montmorillonite is the principal clay mineral and there are subordinate amounts of kaolinite. Illite was identified in only one sample. A short expansion range is indicated for almost all the samples, and nearly complete melting takes place at 2100° F, 15 minutes' retention time.

SAMPLE LOCALITY 22-2

Directly overlying the Graneros Shale is a sequence of thin interbedded limestones and shales, assigned to the Greenhorn Limestone. Excellent exposures of this interval occur immediately east of locality 22-1. The shales are very similar to those of the Graneros, and fired results were the same.

SUMMARY

Almost all formations of the Cretaceous section of northeastern New Mexico were at least partly sampled and tested for this report. The only part of the Cretaceous that indicated good expansion properties was the Pierre Shale. All other intervals either had too short an expansion range or were too refractory. Inasmuch as the lithology of these units appears to be fairly uniform in most of the area, further sampling does not appear to be warranted. The two sections of Pierre Shale tested for this report give indications of considerable variation in fired properties from different parts of the stratigraphic sequence. These variations may occur within correlative intervals along the strike as well. Even though the entire Pierre interval may be suitable for expanded shale, considerable testing would be advisable before selecting a site for stripping operations. The Pennsylvanian shales tested at section 20-4 probably could be used as a source for lightweight shale aggregate, but closely controlled kiln temperatures would be necessary to avoid serious agglomeration, and aggregate strength would be low.

GRANTS—GALLUP AREA

Very little testing was done in this area. Natural lightweight aggregates (pumice and perlite) are abundant on Mount Taylor north of Grants, and scoria is available south of the Zuni Mountains. U.S. 66—Interstate 40, the Santa Fe Railway, and two 30-inch natural-gas pipelines cross the area in an east-west direction. Numerous dirt roads extend north from the main highway. N. Mex. 53 and 32 skirt the east, south, and west sides of the Zuni Mountains.

Sampling was restricted to the Cretaceous interval, the outcrop distribution of which is shown in Figure 3. Gray to black shales interbedded with sandstone, siltstone, conglomerate, and coal comprise the Cretaceous section in the outcrop belt north of U.S. 66 and southwest of Gallup. Shales are by far the most common lithic type, but good exposures are sparse in many areas. Samples collected from seven localities within a 50-mile radius of Grants and Gallup include material from the Mancos, Mesaverde, and Menefee intervals. Three of the seven shales tested gave some promise as raw material for lightweight aggregate.

SAMPLE LOCALITY 27-1

Four channel samples were collected from meager outcrops of the Menefee Formation along N. Mex. 56 about 8 miles north of Seven Lakes in SW% sec. 6, T. 19 N., R. 10 W. Samples 2 and 4 consisted of highly carbonaceous shale with thin coal seams and were not tested. The Menefee forms a broad outcrop belt between Chaco Canyon National Monument and Crownpoint. The interval has been mapped west of Gallup, in the southeastern part of the San Juan Basin, and north from Gallup, paralleling U.S. 666 to the Colorado line. The outcrop narrows markedly where the beds are exposed along the Hogback Monocline. Total thickness of the unit ranges from 400 to 800 feet. The Menefee Formation is overlain by the Cliff House Sandstone and underlain by the Point Lookout Sandstone throughout most of the San Juan Basin. Outcrops are poor, being for the most part covered by slope wash, soil, and dunes.

The shales are medium gray (N6) and contain minor silt and carbonaceous material. The dominant clay mineral is montmorillonite; little illite and kaolinite are present. The quartz content appears to be about the same in the two samples tested.

Fired Data

Small pores began to develop as low as 1800° F, becoming larger at 2000° F, and uniform in size at 2100° F. At 2100° F, almost all the pores were between 0.2 and 0.5 millimeter in diameter. Melting of the particle surface appears to begin at 2000° F, 15 minutes' retention time. The lag between appreciable gas development and surface melting apparently is the cause of severe surface cracking of the particles that begins at 1900° F. At higher temperatures, this may produce an accordionlike expansion of the shale, although this structure also may be caused by expansion perpendicular to the shale partings or to alternating laminae of shale and silty shale. An example of this not uncommon feature can be seen in Figure 10 in the specimens fired at 2200° F. The surface cracking at low temperatures also causes a reversal of the absorption curve from that obtained with most other samples, the lower water absorptions occurring at higher temperatures. The absorption per cent, however, is fairly low, reaching a maximum of 11 at 2000° F, 10 minutes' retention time.

The early pore development is evident from the light weights obtained at relatively low temperatures (table 1 and curve 27-1 on fig. 11) . Weights of about 90 pounds per cubic foot were measured with material fired at 1900° F, 10 and 15 minutes' retention times, and weights of

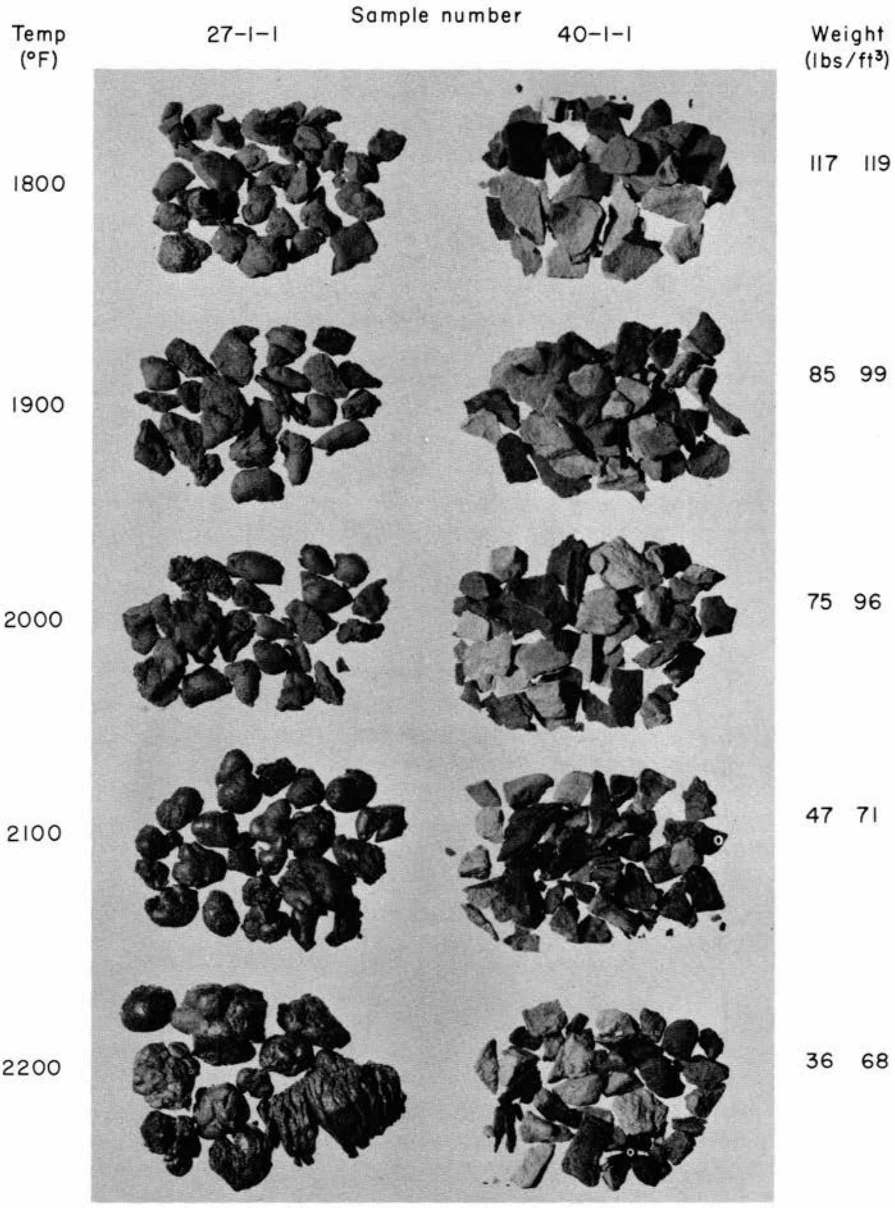

Figure 10
EXPANSION CHARACTERISTICS OF MENEFEE (27-1-1) AND MANCOS (40-1-1) SHALES
(15 minutes' retention time)

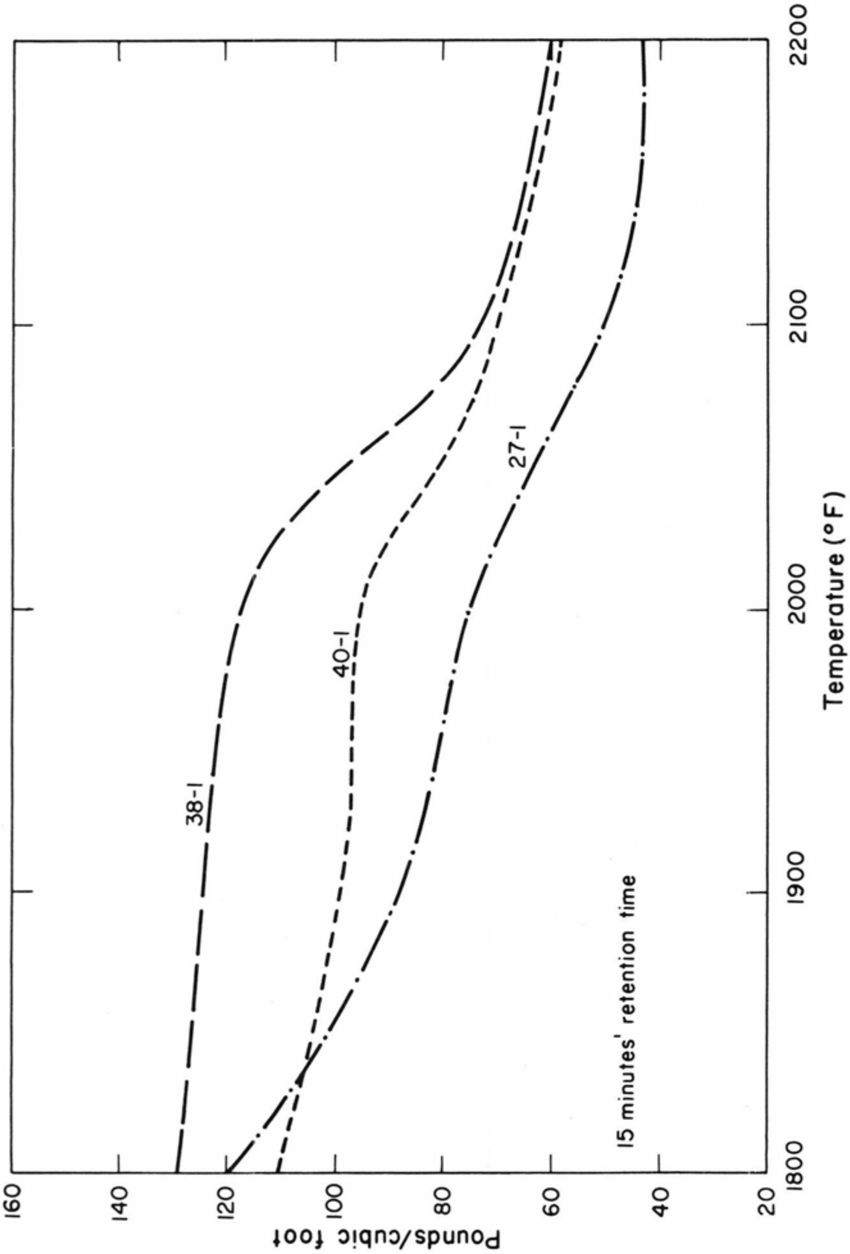

Figure 11

Expansion curves of Menefee (27-1) and Mancos (38-1; 40-1) shales about 60 pounds per cubic foot at temperatures between 2050° and 2100° F. Very slight sticking occurred at 2100° F, 15 minutes' retention time, and slight sticking at 2200° F, 10 and 15 minutes' retention times. The expansion curve shown in Figure 11 is a composite of the two channel samples tested. Individual curves are quite similar, with the lower interval having slightly lower weights at given temperatures and retention times. Particles are rounded at 2000° F and above and fairly strong through 2100° F, 5 minutes' retention time. A good lightweight aggregate could be made from this shale at a fairly long expansion range from about 1950° to above 2050° F without serious agglomeration.

SAMPLE LOCALITY 38-1

A single channel sample of Mancos Shale was collected from a road-cut just east of the Mount Powell fire lookout in NW1/4 sec. 4, T. 14 N., **R.** 13 W. The shale is light olive gray (5Y6/2), silty, and montmorillonitic. Most of the Mancos in this area is covered by soil, making it difficult to collect enough samples to test a thick vertical sequence. Because of its considerable thickness, wide outcrop belt, and predominance of shale, the Mancos appears to be the most promising interval for testing in the northwestern part of New Mexico. For these reasons, it was sampled more than any other unit for this report. Thus far, however, results have not been encouraging.

Fired Data

Sample 38-1-1 has a rather short expansion range. Even though pores begin to develop as low as 1800° F, 10 minutes' retention time, weights remain above 100 pounds per cubic foot until temperatures higher than 2000° F are reached (table 1 and curve 38-1 on fig. 11). Weights then decrease rapidly to about 70 pounds per cubic foot at 2100° F and 60 pounds per cubic foot at 2200° F, both at 15 minutes' retention time. Very slight agglomeration occurs at 2100° F, 15 minutes' retention time, and slight agglomeration at 2200° F, 10 and 15 minutes' retention times. Thus, to obtain an aggregate with weights less than 85 pounds per cubic foot, the expansion range would probably be less than 50° F.

Although pores were noted at 1800° F, they are few until temperatures of 2000° F and higher are reached. The size distribution is fairly uniform at 2100° and 2200° F, with most pores between 0.05 and 0.3 millimeter in diameter. Some very large pores form near the outer surface of the particle at high temperatures and long retention times, indicating that the viscosity of the interior of the particle is low, allowing gas bubbles to migrate outward. Escape of gas was also evidenced by numerous surface pores formed at 2200° F. Particle strength is somewhat low compared to that of most other shales tested.

SAMPLE LOCALITY 40-1

Three channel samples were collected from good exposures of the Mancos Shale, 1.6 miles east of Cebolleta on the north side of N. Mex. 334. The samples were from the lower to middle part of the Mancos interval in this area. The shales are medium gray (N5.5), slightly silty, and noncalcareous and contain a few pelecypod fragments, abundant calcareous concretions, and gypsum veinlets. The dominant clay mineral is montmorillonite; kaolinite and illite are present in trace amounts.

Fired Data

Difficulty was encountered in firing these samples because of extreme popping at temperatures of 1800° F and higher. This is caused by too rapid expansion of gases, believed to be caused by chemically combined water. The average moisture content of the raw shale was only 3.9 per cent, and the sample was oven-dried prior to firing. Popping causes loss of much of the sample and the development of a large number of thin flakes (fig. 10).

Weights below 85 pounds per cubic foot were obtained at temperatures in excess of 2050° F (curve 40-1, fig. 11). The lowest weights measured were between 50 and 70 pounds per cubic foot at 2200° F, 15 minutes' retention time. Very slight agglomeration occurred in one of the samples at this temperature. The expansion range, therefore, is fairly long and the upper limit—that is, below agglomeration—was not established.

A few flat pores formed as low as 1800° F, but spherical pores of uniform density were not observed until the shales had been fired at 2100° F, 10 minutes' retention time. Fired strength is low and particles are angular. Water absorption is fairly high, ranging between 14 and 16 per cent.

SAMPLE LOCALITY 26-1

Ten samples were collected from exposures of the Crevasse Canyon Formation a few hundred yards west of N. Mex. 56 and 4.6 miles south of Crownpoint. The section consists of interbedded sandstone, shale, and coal and is overlain by massive sandstone. Individual lithologic units are thin and grade rapidly into other rock types within short distances. The shales could not be mined economically at this locality, but it was hoped to obtain some idea of the expansible properties of this part of the Cretaceous section and possibly to use this information for studies in other areas where shale beds are thicker. The shales vary considerably in color from medium dark to light gray (N4.5 to N7.5), pale brown (5YR5/2), and yellowish gray (5Y7/2). All are silty and carbonaceous and some contain fairly abundant mica (muscovite). Montmorillonite and kaolinite are present in all samples with the per cent of montmorillonite higher, except in samples 1 and 3. The amount of quartz, mostly in the silt to very fine sand fraction, appears to be fairly uniform in all the shales tested.

When fired at 2100° F, 15 minutes' retention time, four of the samples showed only a few very small pores. There was no evidence of fusion, suggesting that the shales were too highly refractory, although the actual melting point was not determined. It is not known whether the shales would expand at temperatures in excess of 2100° F.

SAMPLE LOCALITY 26-2

Nine samples from the lower part of the Mancos Shale were collected 1.7 miles northwest of Pinedale in SW1/4 sec. 13, T. 16 N., R. 16 W. The shales are medium gray (N6), silty, becoming sandy in the upper part, micaceous (muscovite), and contain minor carbonaceous material. Almost all the shales contain more montmorillonite than kaolinite, but two samples (6 and 7) appear to have a mixed-layer, montmorillonite-illite clay. Very little pore development was observed at 2100° F, 15 minutes' retention time, and the shale was underfired at this temperature. Further testing was not conducted, but if these samples are like many other Mancos shales, melting probably takes place at slightly higher temperatures.

SAMPLE LOCALITY 37-1

The lower part of the Mancos Shale also was sampled a short distance northeast of the junction of the Horsehead Canyon road and N. Mex. 32. The approximate location is in NEV$_I$ sec. 31, T. 10 N., R. 17 W. Preliminary tests indicated a short firing range with rather strong agglomeration evident at 2100° F. No further tests were conducted on this material, although if the fusion temperature could be raised somewhat by adding refractory materials, it might be possible to obtain an adequate lightweight aggregate.

SAMPLE LOCALITY 39-2

A single channel sample of shale underlying a coal bed was collected on the west side of Mount Taylor in NE1/4 sec. 33, T. 12 N., R. 8 W. The shale is part of an interbedded sequence that includes sandstone and coal and is typical of the Mesaverde Group in this area. The material sampled consisted of medium gray (N6), silty to sandy (very fine-grained), carbonaceous shale. An X-ray diffraction pattern indicated that the dominant clay mineral is kaolinite. Preliminary tests gave no indication of expansion or melting.

SUMMARY

Shales in the Menefee Formation appear to be the best source for lightweight aggregate in this area. More complete sampling must be done before the potential of the Menefee can be estimated. One problem, possibly serious, concerns the crushing properties of the shale. The material is soft and a large amount of fines was produced during preparation of the samples.

The Mancos Shale was tested at several localities, and results, for the most part, were similar to those observed elsewhere from this formation. The severe popping of the samples from locality 40-1 is not characteristic of the Mancos shales, and the samples tested have a higher melting point than is normal for the Mancos. Popping may not be serious in a rotary kiln where heating is at a slower rate than in a preset stationary furnace. Experiments to eliminate this problem and the effect of preheating at slow rates are discussed under sample localities 66-1 and 113-1.

SANTA FE—ALBUQUERQUE—BELEN

Considerable sampling was done in this area in the hope of finding a suitable aggregate close to Albuquerque. It was found that shales potentially suitable for lightweight aggregate are limited to rocks of Pennsylvanian, Triassic, and Cretaceous ages. Pennsylvanian strata crop out in the Manzano, Manzanita, and Sandia mountins, east and south of Albuquerque, in the Sangre de Cristo Mountains north and east of Santa Fe, and in the Nacimiento Mountains northwest of Bernalillo (fig. 2). The Pennsylvanian section consists of 500 to 2000 feet of interbedded limestone, shale, sandstone, conglomerate, and arkose. Shale is restricted to thin beds, or it underlies steep slopes beneath massive limestone cliffs. Except for a very few areas, utilization of strip-mining methods would be impossible without removal of considerable overburden. The only locality sampled during this investigation that had shale with good expansion qualities combined with the necessary structural and topographic conditions for relatively easy mining was in the southern Manzano Mountains (66-1). Pennsylvanian shales were tested at three localities in the Manzano Mountains (54-1, 66-1, 65-1) and at one each in the Sangre de Cristo (31-2), Manzanita (42-6), and Sandia mountains (42-7). Limited good exposures of Triassic rocks are found on the north and east sides of the Sandia Mountains, in the area south of Lamy, and at the southern end of the Nacimiento Mountains. The outcrop distribution of Cretaceous rocks is shown in Figure 3. Cretaceous intervals in this area are restricted to the Dakota Sandstone, Mancos Shale, and Mesaverde Formation. Sampling of the Cretaceous was restricted to two localities in the Mancos Shale near Cerrillos (42-5 and 42-9) and one in the Ortiz Mountains (42-8).

SAMPLE LOCALITY 66-1

Twenty-seven channel samples were collected from Pennsylvanian shales near Abo Pass in the southern Manzano Mountains. The samples were taken from outcrops north of Abo Canyon in the NW1/4 sec. 24, T. 3 N., R. 4 E. The area is served by U.S. 60 which connects with Interstate 25 at Bernardo 20 miles to the west. N. Mex. 6 leads from Abo Pass northwest 22 miles to a junction with U.S. 85 at Belen. This all-paved, heavy-duty route to Albuquerque involves a distance of a little more than 50 miles. The southern line of the Santa Fe Railway passes within a mile of section 66-1 and a siding is present at the mouth of Abo Canyon. Two 30-inch natural gas pipelines operated by Transwestern Pipeline Company and El Paso Natural Gas Company cross the area a short distance south of Abo Canyon.

A stratigraphic section of 66-1 is given in Figure 12. Sample intervals 1 through 3, below the lower massive limestone, are not shown. The partial Pennsylvanian section measured at this locality consists of limestone, shale, impure sandstone, and massive arkose and sandstone. An interval primarily of shale occurs between units 8 and 22, a thickness of a little more than 85 feet. Preliminary firing tests indicated good expansion over a continuous thickness of 56 feet (samples 10 through 20). In addition to shale, the expansible interval contains several thin beds of argillaceous, silty, very fine-grained sandstone. There are also small calcareous concretions, 2.5 inches in diameter, in a thin zone in sample interval 10 and a few large ironstone concretions, one foot or more in diameter, in intervals 14 through 17.

Shales from the expansible interval are light olive gray (5Y4/2) and medium dark gray (N4), micaceous (muscovite), and silty and contain minor plant fragments. Most of the shales are compact and should crush well with a minimum production of fines. The content of calcium carbonate varies considerably; samples 10, 11, and 14 are calcareous, 13 and 16 slightly calcareous, and the remainder noncalcareous. Illite is the dominant clay mineral except for the upper beds where kaolinite appears to be more abundant. The remaining samples collected at this locality, 1 through 9 and 21 through 27, are similar to the expansible interval at the level of observation used in the preparation of this report. Why these samples showed little or no expansion is not known.

The massive limestone at the base of the section in Figure 12 dips gently to the east at the southern limit of the exposures in Abo Canyon. At sample locality 66-1, half a mile to the north of Abo Canyon, beds through unit 20 dip 42° to 45° E but decrease in dip rapidly away from the Montosa thrust fault to about 25° E in the massive cross-bedded sandstone at the top of the measured section. Dips are about the same a quarter of a mile up the canyon. At the head of the canyon, the beds are overturned and dip 60° to 65° W. This appears to be a

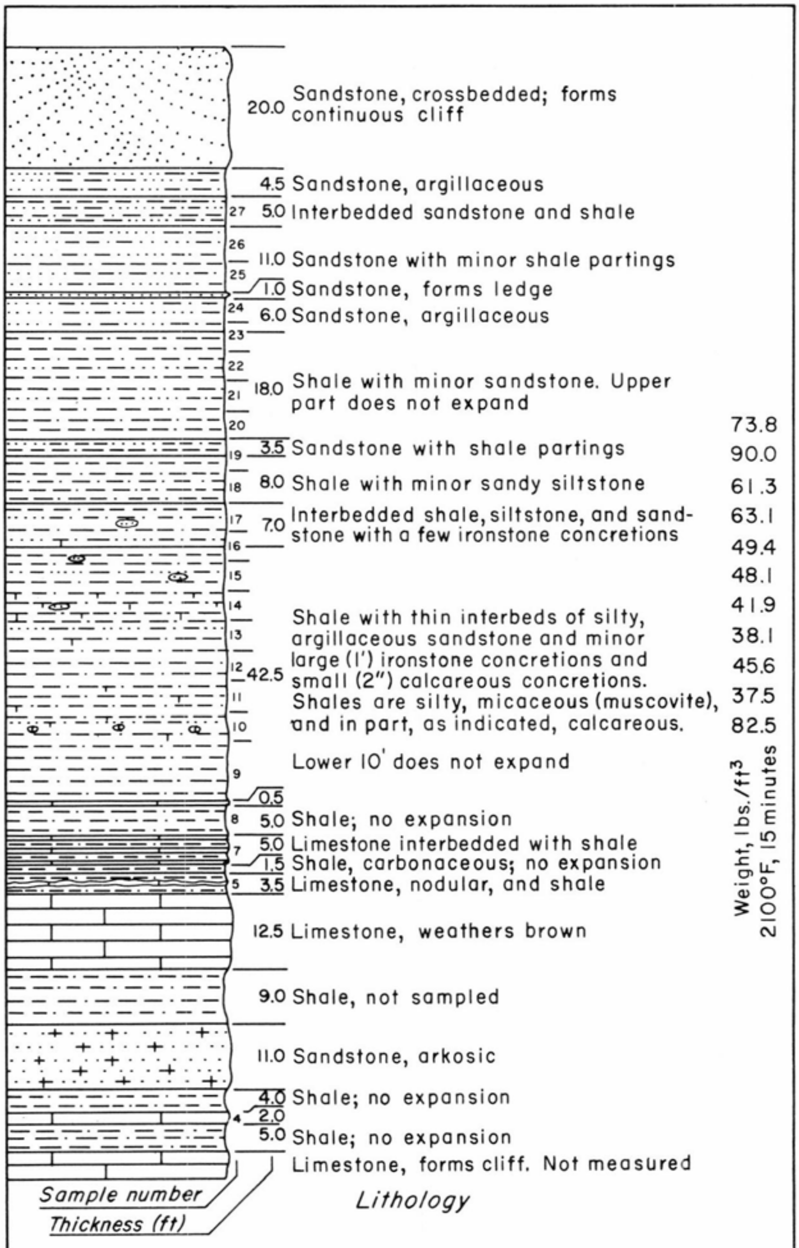

Figure 12

Partial stratigraphic section of Pennsylvanian rocks north of Abo Pass; sample locality 66-1 simple roll of the beds approaching the northeast-striking Montosa fault. Small faults with displacements less than one foot were noted at section 66-1 and larger scale faulting may be present but concealed by the alluvial cover. The thickness along the strike between the massive arkose and the upper cross-bedded sandstone is fairly uniform. At locality 66-1, this interval measures 155 feet and a quarter of a mile to the north, 132 feet.

The area north of Abo Canyon underlain by shales included in the stratigraphic section is 2 miles in length. The section ends on the north in a structurally complex area where the strata abut against the Montosa fault. This part of the Pennsylvanian section should be present again east of the fault farther north in the Manzano Mountains. The critical part of the section is not exposed south of Abo Canyon but should underlie alluvial deposits for three quarters of a mile before again terminating at the Montosa fault.

Because of limited exposures, only two additional samples could be collected from beds equivalent to units 10 through 20. These are a quarter of a mile north of sample locality 66-1 and half a mile farther north at the head of the canyon. The basal limestone and massive arkose can be walked out to the divide, and thus the position of the interval of expansible shales can be determined by measuring from either of these lower beds using the dip at that point and the thicknesses given in Figure 12. The alluvial and soil cover does not appear to exceed 10 feet and is much less in most places.

Even though the thickness of expansible shales is not great and the shales form a steep slope, considerable tonnages could be stripped because of the length of outcrop available. Somewhere between locality 66-1 and the divide, the strata must dip vertically and therefore could be trenched. At one point the arroyo cuts into the shale to form a near-vertical slope beneath the upper cross-bedded, cliff-forming sandstone. Very little shale could be stripped here, but this is the only place where this situation was observed.

Fired Data

Pore formation takes place in one sample as early as 1800° F, 5 minutes' retention time. Some pores are developed in all samples except interval 10 by 2000° F, 10 minutes' retention time. At this test setting, uniformity of pore size is good, the pores averaging about 0.1 millimeter in diameter (fig. 13). At 2100° F, 15 minutes' retention time, the average pore size increased to 0.5 millimeter. The size increases further but remains uniform through 2200° F, 15 minutes' retention time, the upper test level. Cell walls are substantial up to about 2100° F, 15 minutes' retention time; above this, the structure becomes fairly fragile. As in the other samples tested, the cell walls at higher temperatures consist of glass containing numerous minute gas bubbles. Particle strength is very

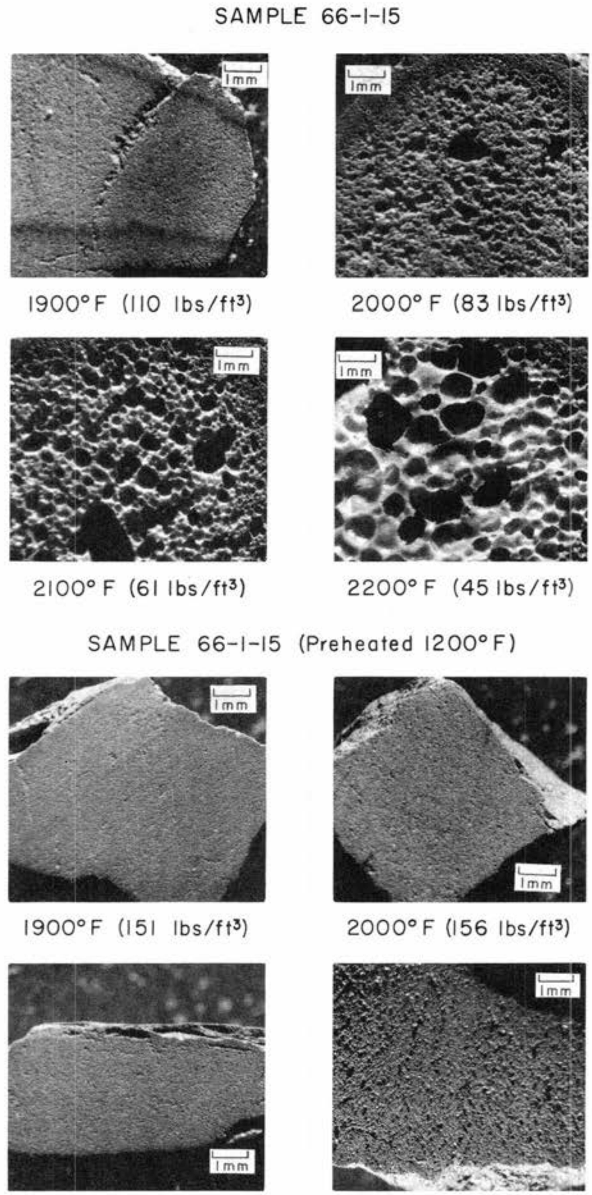

Figure 13

Pore development of Pennsylvanian shales, Abo Pass
(15 minutes' retention time)

high when fired at temperatures up to 2100° F. Much of this strength results from the thick exterior rim of the particles where only very small pores are formed. The photograph of the internal structure of 66-1-15 (fig. 13) at 2000° F shows an excellent example of this exterior rim. Slight sticking was noted in only two of the samples (11 and 14) when fired at 2100° F, 15 minutes' retention time. At 2200° F, some agglomeration was observed in all but one (19) of the samples, but moderate to heavy agglomeration occurred in only four (10, 11, 15 and 16).

From the composite curve of samples 10 through 20 (curve 66-1, fig. 14), it can be determined that an average weight of 85 pounds per cubic foot can be obtained at a temperature of 2025° F and of slightly less than 60 pounds per cubic foot at 2100° F, both at retention times of 15 minutes. At higher temperatures there is less variation in the weight range of the final product. For example, the weight range in pounds per cubic foot for samples 10 through 20 at 2000°, 2100°, and 2200° F, 15 minutes' retention time, was respectively 77.5, 52.5, and 43.2. The lowest weights measured were from samples 11 through 15 (table 1). Weights from overlying samples averaged 21 pounds per cubic foot higher at 1900° F, 42 pounds per cubic foot at 2000° F, 26 pounds per cubic foot at 2100° F, and 13 pounds per cubic foot at 2200° F. This clearly shows the rapid expansion that takes place in samples 11 through 15 between 1900° and 2000° F and the major expansion in the upper samples that takes place between 2000° and 2100° F. Interval 10 grades imperceptibly into underlying nonexpansible shales and, in general, had the highest weights measured.

The shape of most of the shale fragments after firing above 2000° F is equant to prolate, with rounded edges (fig. 15). Color of the fired particles ranges from light brown (5YR6/8) at lower temperatures to a grayish brown (5YR3/2) at 2200° F. The average per cent of water absorption increases gradually with increase in fired temperature. Absorption is about 6 per cent at 1800° F and about 10 per cent at 2100° and 2200° F.

No definite correlation could be established between calcium carbonate content and bloating properties. Weights measured at various temperatures were generally more uniform in the noncalcareous shales; lower weights were obtained at lower temperatures in the calcareous shales. Two of the calcareous shales exhibited some agglomeration at 2100° F, 15 minutes' retention time, while no agglomeration was noted at this test position in any of the noncalcareous shales.

Preliminary firing tests at 2100° F, 15 minutes' retention time, were made on the two samples collected to the north of section 66-1. The sample collected one quarter of a mile to the north had a fired bulk specific gravity of 0.94, a weight of 58.6 pounds per cubic foot, and an absorption per cent of 8.1. This is comparable to some of the aggregate produced from the upper samples of locality 66-1. The sample from

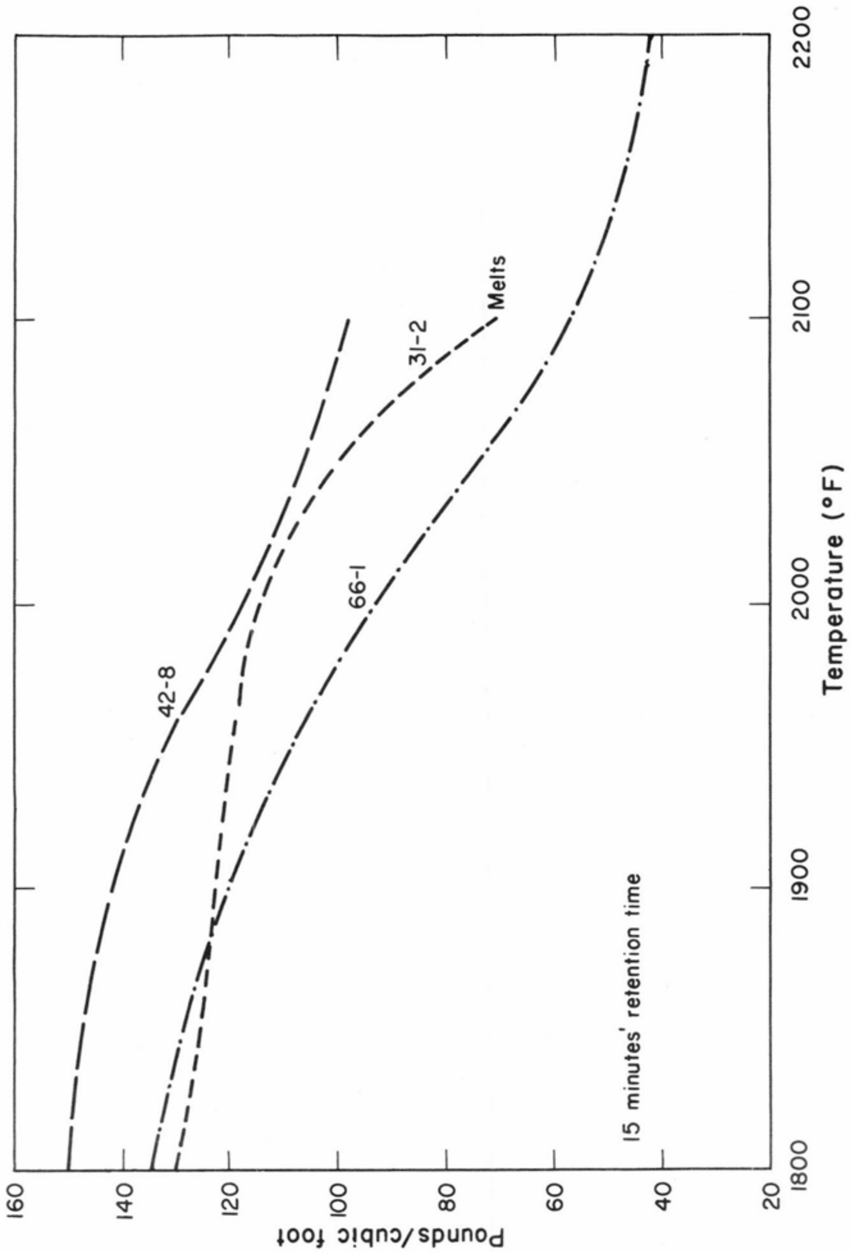

Figure 14

EXPANSION CURVES OF PENNSYLVANIAN (31-2; 66-1) AND MANCOS (42-8) SHALES

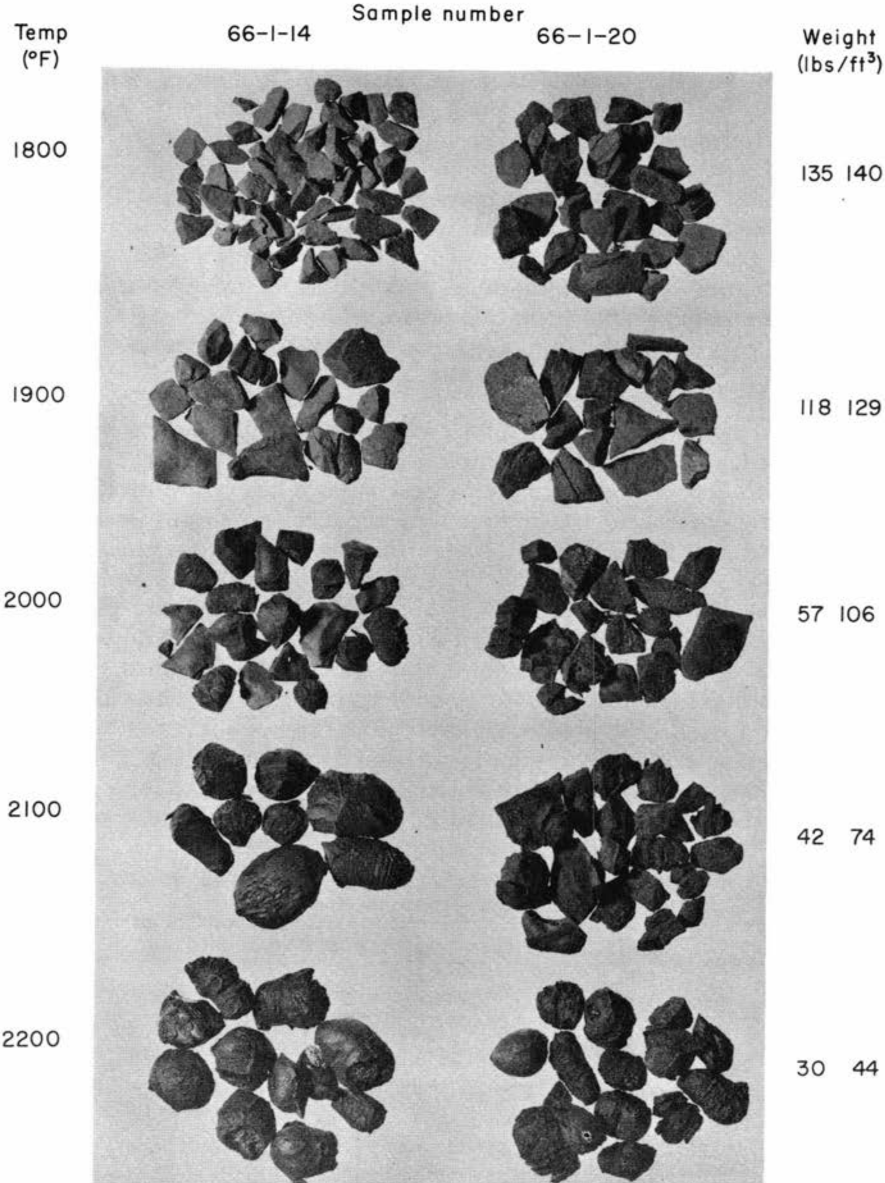

Figure 15
EXPANSION CHARACTERISTICS OF PENNSYLVANIAN SHALES
(15 minutes' retention time)

the divide was slightly heavier with a bulk specific gravity of 1.03, a weight of 64.5 pounds per cubic foot, and an absorption per cent of 7.5. Both samples indicate that the expansible properties can be expected to be fairly uniform along the strike. The impure sandstone beds included in the shale section might not have to be separated from the shales prior to firing. Apparently there is enough fine-grained material present for adequate expansion. Preliminary tests at 2100° F, 15 minutes' retention time, on one of the sandstones resulted in a bulk specific gravity of 1.25 and a weight of 78.1 pounds per cubic foot. These figures are less than those obtained from some of the shale samples at comparable firing temperatures.

PREHEAT TESTS

Eight samples from interval 15 were placed in the electric furnace at room temperature and a sample was removed every 200° F, beginning with 400° F and ending at a maximum temperature of 1800° F. Following preheating, the samples were retained in a drying oven until flash-fired for 15 minutes at preset furnace temperatures of 1800°, 1900°, 2000°, 2100°, and 2200° F. Expansion curves for samples preheated at 400° to 800° F, 1000° F, and 1200° to 1800° F are given in Figure 16, along with a sample of 66-1-15 not preheated. Samples preheated at 1200° F and above show very little expansion until fired at temperatures higher than 2100° F (table 2 and fig. 17). Even at 2200° F, the lowest weights obtained were more than 100 pounds per cubic foot. Photomicrographs of the sample preheated to 1200° F (fig. 13) show only minor pore development through 2100° F, and although evenly distributed, pores are very small at 2200° F. Samples preheated at 800°

TABLE 2. PREHEAT TESTS; SAMPLE 66-1-15*
(15 minutes' retention time)

FLASH TEMP. (°F)	PREHEAT TEMPERATURE (°F)							
	400	600	800	1000	1200	1400	1600	1800
1800	2.16 135.0	2.17 135.6	2.27 141.9	2.29 143.1	2.38 148.8	2.34 146.3	2.37 148.1	2.32 145.0
1900	1.94 121.3	2.05 128.1	2.17 135.6	2.30 143.8	2.41 150.6	2.30 143.8	2.43 151.9	2.38 148.8
2000	1.23 76.9	1.51 94.4	1.82 113.8	1.89 118.1	2.50 156.3	2.48 155.0	2.47 154.4	2.42 151.3
2100	1.12 70.0	0.83 51.9	1.09 68.2	1.73 108.1	2.27 141.9	2.36 147.5	2.58 161.3	2.46 153.8
2200	0.63 39.4	0.73 45.6	0.94 58.8	1.35 84.4	1.66 103.8	1.82 113.8	2.10 131.3	1.73 108.1

* First number listed is bulk specific gravity; second number, weight in pounds per cubic foot.

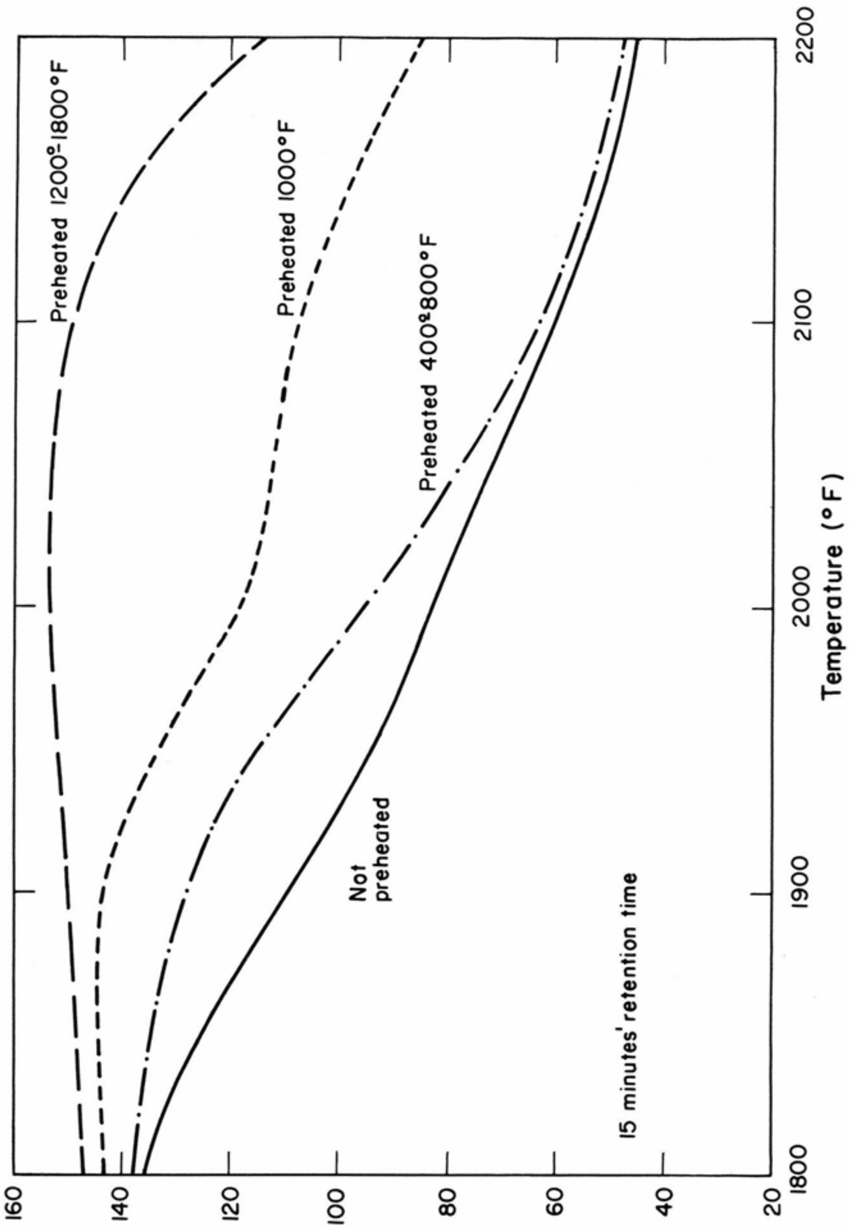

Figure 16

EXPANSION CURVES OF 66-1-15 AND 66-1-15 PREHEATED

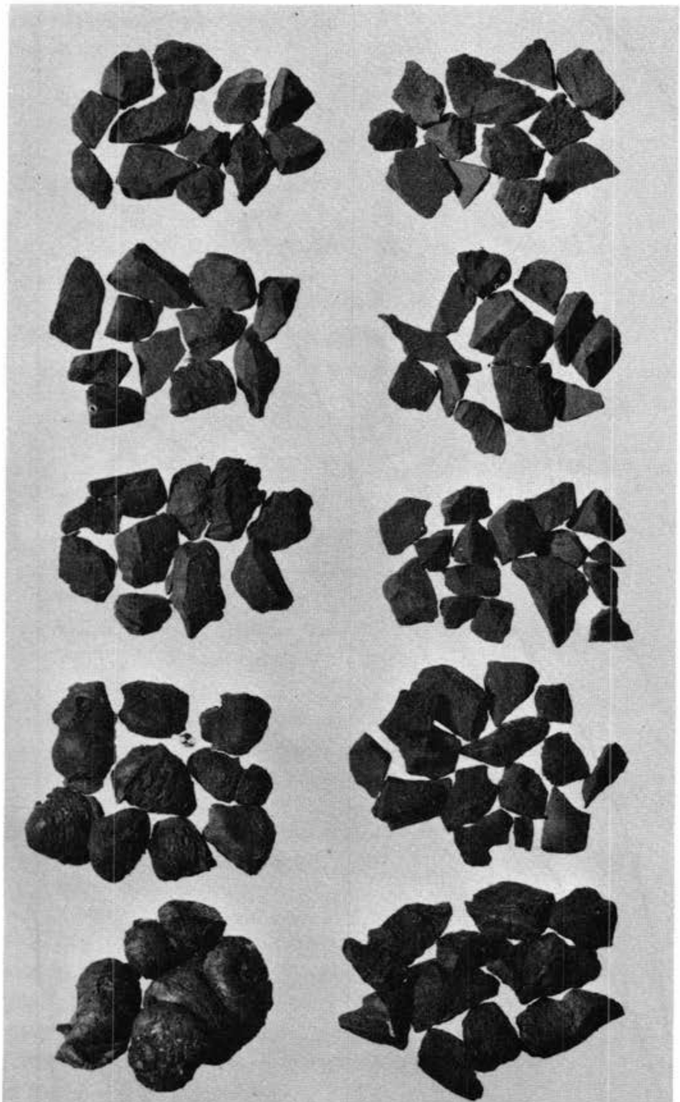

Figure 17

EXPANSION CHARACTERISTICS OF 66-1-15 AND 66-1-15 PREHEATED TO 1200° F

(15 minutes' retention time)

F and below have expansion properties similar to those of the raw shale at the higher test temperatures, but the raw shale begins to expand at much lower temperatures. Weights at 2200° F for the raw shale and the specimens preheated up to 800° F are less than 60 pounds per cubic foot. The sample preheated to 1000° F falls between the two groups of samples preheated between 1200° and 1800° F and 400° and 800° F. The reason for this is not entirely understood, but the results seem to indicate that chemically combined water in the clay minerals is at least in part responsible.

Specimens preheated up to 800° F and those not preheated have good pore development at 2000° F. At preheat temperatures of 1000° F, very small pores form in the center of the particles at 2000° F flash-heat temperatures. The number, size, and sphericity of pores decrease with higher preheat temperatures, although there may be slight variations depending on the chemical composition of the samples. The exterior slightly porous rim of the particles increases in thickness as higher preheat temperatures are used. As noted, slight pore development does take place in specimens preheated at 1200° F and above when flash-heated at 2200° F. However, it is doubtful that higher temperatures would result in appreciable increase in expansion, for it is apparent that melting takes place at temperatures slightly in excess of 2200° F, even though preheating apparently increases the melting point of these shales to some extent.

The data suggest that chemically combined water plays an important part in the expansion of this shale. Similar tests conducted on samples from locality 113-1 indicate improved expansion when the shale has been preheated above 1200° F. In this instance, gases other than water are being evolved at higher temperatures and are primarily responsible for the expansion. The data also indicate that shales from locality 66-1 would have to reach the high temperature zone of a rotary kiln fairly rapidly, or the expansion would be greatly reduced.

SAMPLE LOCALITY 31-2

Samples of Pennsylvanian shales were collected from outcrops near the southern end of the Sangre de Cristo Mountains along the road from Pecos to Vallecitos in the 5E1/2 sec. 12, T. 16 N., R. 12 E. The shales are medium gray (N5), silty, micaceous (muscovite), and calcareous, and contain numerous fossil fragments. The area is heavily timbered and outcrops are sparse. It does not appear that any thick strippable beds are present, and exploration would be difficult. For purposes of evaluating this part of the Pennsylvanian sequence at this locality, a series of expansion tests was made on the samples collected. The shale agglomerated when fired at 2200° F, so tests were run only to 2100° F, 15 minutes' retention time.

From curve 31-2 in Figure 14, it can be seen that the expansion range is quite short, with a temperature of about 2075° F needed to obtain a product with a weight of 85 pounds per cubic foot. Slight to moderate agglomeration is evident at 2100° F, 15 minutes' retention time. With a retention time of 10 minutes, a weight of 80 pounds per cubic foot is obtained at 2100° F without agglomeration. Pores develop at 2100° F and are fairly uniform in size and distribution at 10 and 15 minutes' retention times. Some melting and extrusion, apparently caused by discrete particles of calcite, were noticeable at 2100° F. Water absorption ranges from 5 to 11 per cent.

SAMPLE LOCALITY 42-5

Steeply dipping beds of the Mancos Shale flank intrusive igneous rocks north of the town of Cerrillos. The shale is dark gray (N3) and is crisscrossed by gypsum veins. Preliminary firing tests resulted in complete melting of the shales, so no further tests were conducted.

SAMPLE LOCALITY 42-6

Several representative shale samples were collected at the Kinney Clay Pit in sec. 18, T. 9 N., R. 6 E. on the west side of N. Mex. 10, south of the village of Cedro. Preliminary tests indicated that the material probably is not suitable for expanded shale. Temperatures above 2100° F may result in adequate expansion but further tests were not conducted.

SAMPLE LOCALITY 42-7

Eight samples were collected from roadcuts on N. Mex. 44 across from the entrance to Doc Long Campground. In this part of the Sandia Mountains, the basal Pennsylvanian section consists of interbedded shales, limestones, and sandstones of the Sandia Formation. At the campground, this interval is 60 feet thick and contains 28 feet of shale, 20 feet of which occur in one unit near the base of the section. Shales are dark to medium light gray (N3.5 to N6.5), silty, and micaceous (muscovite) and contain a few thin laminae of very fine- to medium-grained quartz sandstone. Only one of the samples was calcareous.

Based on preliminary tests, expansion was not uniform. Some of the shales overexpanded and began to agglomerate while others exhibited no expansion. Further tests were not conducted.

SAMPLE LOCALITY 42-8

Samples of the Mancos Shale were collected from outcrops along N. Mex. 10 in the Ortiz Mountains. The location is 0.8 mile north of the junction of N. Mex. 10 and 22 and 5 miles south of Madrid. Tonnage available in the Ortiz Mountains is somewhat limited, but the Mancos underlies a large area to the south and southeast of the range beneath a thin soil cover. Shales are dark gray (N3.5), silty, and slightly to strongly calcareous. Kaolinite and montmorillonite are present in what appears to be approximately equal amounts. A strong illite peak was observed in the diffraction pattern for one of the samples.

A series of tests was run on these samples up to 2100° F, 15 minutes' retention time. At this temperature, agglomeration began to occur in most of the samples and it was decided not to fire the specimens at higher temperatures. A composite curve of the five samples fired (42-8) is given in Figure 14. This curve indicates the type of expansion that was fairly common in the Mancos shales that have been tested. This expansion is characterized by a slow reduction in weight up to 2000° F, followed by rapid expansion and melting. Each of the five samples tested gave somewhat similar results. At 2100° F, 15 minutes' retention time, a weight as low as 48 pounds per cubic foot was obtained for one of the samples. There was little agglomeration at this temperature, but at temperatures slightly above 2100° F, this would be a controlling factor. To obtain a product of about 80 to 90 pounds per cubic foot, the furnace temperatures would have to be closely controlled over a range of less than 25° F just below 2100° F. Obviously, control of this type is not very practical for a commercial operation. The short expansion range is evident also from a study of pore development. In all but one of the samples, pores did not form until the material was fired at a temperature of 2000° F and a retention time of 10 minutes. The distribution and size of the pores are not uniform and the structure of the particle is weak because of overexpansion.

SAMPLE LOCALITY 42-9

West of Cerrillos, a thick sequence of nearly flat-lying Mancos shales is exposed on the north side of the main line of the Santa Fe Railway. The shales are dark gray (N3), silty, calcareous, gypsiferous, and montmorillonitic and contain sparse fossil fragments. X-ray diffraction patterns disclosed the presence of small amounts of dolomite. Gypsum occurs in lesser quantities in the Mancos at this locality than at section 42-5, a little more than 3 miles to the east. Test-fired at 2100° F, most of the samples exhibited moderate to heavy agglomeration and very little expansion.

SAMPLE LOCALITY 42-10

One sample of the Abo Formation of Permian age was collected on the east side of the Sandia Mountains in the NW1/4 sec. 24, T. 11 N., R. 5 E. The shale is moderate reddish brown (10R4/6) and highly silty. Small green spots occur in the specimens where the ferric iron has been reduced. X-ray studies indicate a very low clay-mineral content, most of the rock being made up of quartz silt and clay. There was no evidence of expansion or vitrification during preliminary firing tests at 2100° F, but the shale melted at a slightly higher temperature.

SAMPLE LOCALITY 54-1

In the southern Manzano Mountains, Pennsylvanian shales crop out along the road to Capillo Peak northwest of the village of Manzano. Five samples were collected in the SE1/4 sec. 11, T. 5 N., R. 5 E. The shales are medium dark to medium light gray (N4.5 to N6), highly silty to sandy (very fine- to fine-grained quartz), micaceous (muscovite), and calcareous. Preliminary expansion tests indicated a short bloating range for some of the material and no expansion in other samples. Some agglomeration and local melting also were observed. The material probably varies too much in composition to produce a uniform product.

SAMPLE LOCALITY 65-1

Massive limestones stratigraphically above the shales at locality 66-1 were traced south to U.S. 60, where younger Pennsylvanian shales could be sampled in excellent roadcuts. Nineteen samples, representative of shales up to the top of the Pennsylvanian section, were collected from these cuts. The shales are medium to light gray (N5 to N7) and silty. Muscovite flakes and fossil fragments are fairly abundant in several beds, and all the samples were calcareous. Even with the fairly high per cent of calcium carbonate in the samples, there was little evidence of melting at 2100° F. Expansion was low at this temperature, and additional tests for use as a lightweight aggregate were not continued.

SUMMARY

From an investigation of the stratigraphy and expansion properties of shales in the Santa Fe—Albuquerque—Belen area, further testing should be restricted to Cretaceous and Triassic rocks. Shales thick enough to be stripped in the Pennsylvanian interval are limited in extent and most of them do not exhibit good expansion properties. Based on the tests conducted for this report, shales from locality 66-1 would make the best lightweight aggregate thus far discovered in the state. Available reserves without removing excessive overburden are large but not so extensive as at other favorable localities. Nearness to markets, transportation facilities, and natural-gas pipelines may outweigh this factor, as well as the more selective mining that would be involved.

LAS CRUCES—EL PASO

Shale that might be suitable for lightweight aggregate is limited in this area. Shales occur in the stratigraphic section at Bishops Cap, at the north end of the Franklin Mountains, in the Robledo Mountains, in the Potrillo Mountains, and at Brickland across the Rio Grande from El Paso. The thick sedimentary section in the San Andres Mountains northeast of Las Cruces is within White Sands Proving Grounds and is not open to exploration. Except for the Potrillo Mountains, not examined during this investigation, the section at Bishops Cap and that near Brickland appear to contain the only shale beds of adequate thickness and extent for the production of shale aggregate, and sampling was restricted to these two localities.

The Las Cruces—El Paso area is served by major highways (U.S. 62, 70, 80, 82, 85, and 180 and Interstate 10 and 25), railroads (Southern Pacific and Santa Fe), and natural-gas pipelines (two 123A-inch, one 26-inch, and one 30-inch).

SAMPLE LOCALITY 1 1 3-1

Thick Pennsylvanian-age shales are exposed on the southeast flank of Bishops Cap in the SW1/4 sec. 25, T. 24 S., R. 3 E. Seventeen channel samples were taken in this area where thin overburden had been removed by a bulldozer. The shales are medium dark gray (N4), silty, platy, and hard. Sample 11 contained some very fine-grained quartz sand laminae and is in part calcareous. The principal clay mineral is illite.

Preliminary expansion tests indicate that a lightweight aggregate might be produced from this material if the problem of excessive popping could be overcome. When placed in the furnace at preset temperatures of 1800° F and higher, specimens exploded, often leaving too small an amount of material for a study of expansion properties. Specific gravities of less than 1.0 were noted for the lower part of the section, and there was no indication of agglomeration.

PREHEAT TESTS

Several sample intervals from this section were flash-fired at various temperatures to determine at what heat popping occurred. This was done by placing weighed samples in the furnace at preset temperatures of 900°, 1000°, 1100°, 1200°, 1300°, and 1400° F. There was no appreciable loss until samples were fired at 1200° F and above. At 1100° F, weight loss from a sample weighing 9.63 grams amounted to only 2.4 per cent and in another sample weighing 6.33 grams, the loss was only 3.3 per cent. At 1200° F, losses were 48.0 per cent from an original weight of 10.90 grams and in a second sample, 89.4 per cent from an original 7.08 grams. There is no apparent pattern to increasing losses at temperatures above 1200° F. In this particular shale, most of the gas, probably from chemically combined water, comes off rapidly between 1100° and 1200° F.

Samples from unit 10 were preheated by the same procedure used for 66-1-15 except that the maximum temperature was set at 1600° F. Weights obtained when the samples were flash-fired at 2100° F, 15 minutes' retention time, ranged from 62 to 79 pounds per cubic foot for samples preheated up to 1200° F (table 3). The lowest weights

TABLE 3. PREHEAT TESTS; SAMPLE 113-1-10*

FLASH TEMP. (°F)	PREHEAT TEMPERATURE (°F)						
	400	600	800	1000	1200	1400	1600
2100	1.10 68.8	1.17 73.1	0.99 61.9	1.27 79.4	1.21 75.6	0.85 53.1	0.89 55.6

* First number listed is bulk specific gravity; second number, weight in pounds per cubic foot.

measured were from samples preheated to 1400° F (53 pounds per cubic foot) and 1600° F (56 pounds per cubic foot). The raw shale fired at 2100° F had a weight in excess of 100 pounds per cubic foot (curve 113-1, fig. 18). In part, the lower weights at the higher preheat temperatures are caused by lower water absorption, 4 to 4.5 per cent compared to 6 to 12 per cent for samples preheated at lower temperatures. The primary reason, however, appears to be splitting of the particles in specimens preheated up to 1200° F. This splitting results in alternate layers of dense and porous material. In addition, pore development in most particles is more uniform in samples preheated to 1400° and 1600° F than for samples preheated at lower temperatures or not preheated. Photomicrographs of 113-1-10 without preheating show very little pore development through 2000° F (fig. 19). At higher temperatures, pore distribution is fairly good but pores remain very small. In the same sample preheated to 1600° F, a few pores begin to form at 1900° F. At 2000° F, pores are larger and more numerous but are flattened parallel to the bedding in the shale. At higher temperatures, pore development is fairly complete and most pores have taken on a spherical shape. The exterior rim of the particle is fairly thick at 2100° F and particle strength is correspondingly high. A comparison of the expansion properties can be seen in Figure 20. All samples were originally screened to minus 0.575 inch, plus 0.375 inch. Shale fired raw breaks up into many small fragments and there is little evidence of expansion. Shale from the same interval preheated to 1600° F does not break up, and expansion is evident from the rounding of the particles beginning at 2000° F.

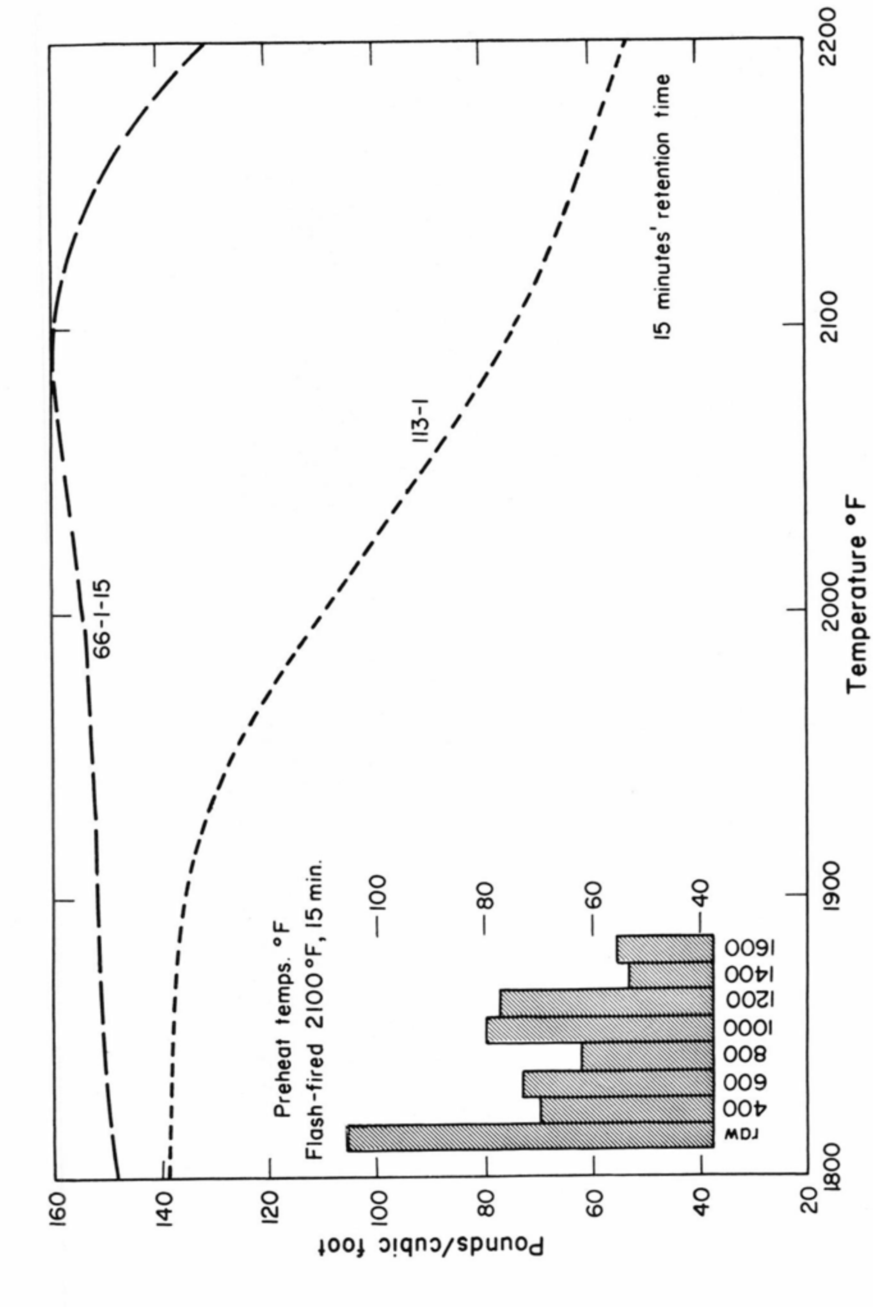

Figure 18

EXPANSION OF 113-1 COMPARED TO 66-1-15 (BOTH PREHEATED TO 1600° F) AND WEIGHT OF 113-1-10 PREHEATED AT VARIOUS TEMPERATURES

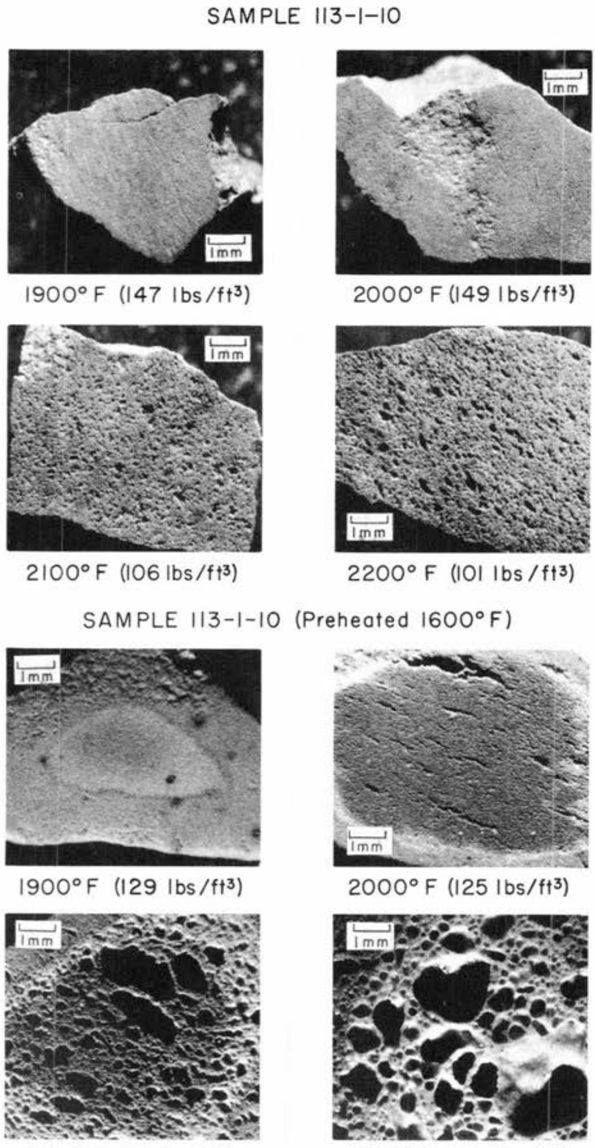

Figure 19

PORE DEVELOPMENT OF PENNSYLVANIAN SHALES, BISHOPS CAP

(15 minutes' retention time)

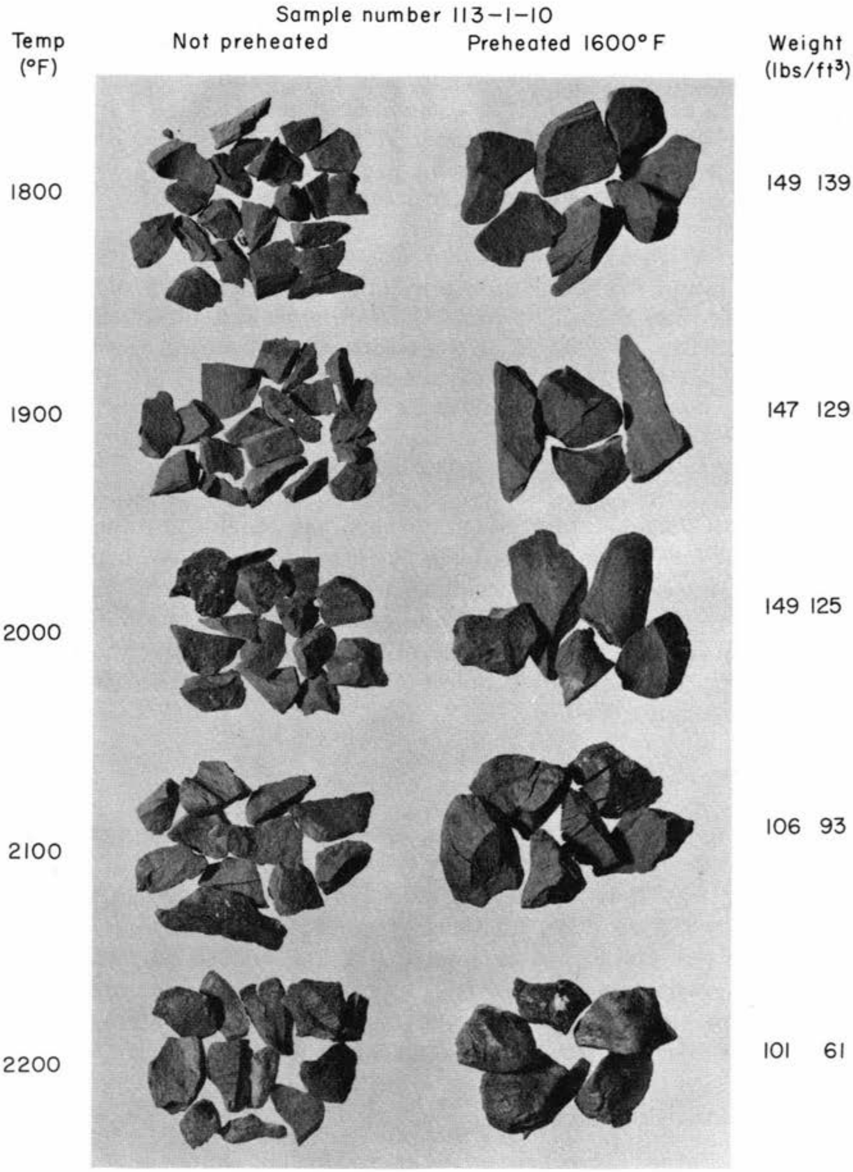

Figure 20
EXPANSION CHARACTERISTICS OF 113-1-10 AND 113-1-10 PREHEATED TO 1600° F
(15 minutes' retention time)

Sample 113-1-10 also was preheated to 1200° F and retained at this temperature for more than twelve hours. When flash-fired at 2100° F, 15 minutes' retention time, the weight was 116 pounds per cubic foot. Pores began to develop at 2100° F but were small and few. Fairly uniform pore development occurred at 2200° F, but agglomeration was moderate to heavy. When the same sample was preheated for three hours to 1200° F and flash-fired, the sample had a weight of 76 pounds per cubic foot.

Following these preliminary preheat tests, specimens from all seventeen samples collected at locality 113-1 were preheated to 1600° F. Each sample was then flash-fired for 15 minutes at 100° F increments between 1800° and 2200° F. A composite curve based on the average weights of all these samples is given in Figure 18, and the data for individual samples are given in Table 4. The basal part of the section had the best expansion properties (fig. 21), with most of the remainder developing fair pore structure at 2000° F or slightly higher. The average weight of the aggregate fired at 2100° F was 72 pounds per cubic foot. At this temperature, slight to moderate agglomeration occurs only in the lower four sample intervals. Moderate to heavy agglomeration was observed in all specimens when flash-fired at 2200° F, 15 minutes' retention time. It is of interest that no agglomeration occurred in 113-1-10 at this temperature when the sample was fired without preheating (fig. 20), while in sample 66-1-15, preheating raised the temperature of agglomeration.

SAMPLE LOCALITY 113-2

Shale samples from younger Pennsylvanian strata were collected on the south side of Bishops Cap in the NEIA sec. 35, T. 24 S., R. 3 E. The shales are grayish red (10R4/2), light brownish gray (5YR6/1), and medium dark gray (N4), highly silty, and fossiliferous and contain numerous veinlets of gypsum. Some expansion was observed after test-firing the gray shales, but bloating properties varied considerably. The mixed nature of the expansion and the high gypsum content appear to rule out this material for shale aggregate.

SAMPLE LOCALITY 125-2

Samples of Lower Cretaceous shales were collected from the stock-pile of the NuTex Brick Plant near Brickland. The shales are medium dark gray (N4), silty, and partly calcareous and contain kaolinite as the principal clay mineral. Rather high temperatures (almost 2200° F) are required to obtain an aggregate with a weight of slightly more than 80 pounds per cubic foot. The shale flakes severely, producing many very thin plates. This might be overcome by preheating the shale to a predetermined temperature before flash heating. No agglomeration was observed at the highest test setting of 2200° F, 15 minutes' retention time. Slight sticking that occurred at this temperature was caused by local melting, apparently around fragments of calcite, by extrusion of this melted material, and by welding to adjacent particles.

TABLE 4. EXPANSION DATA FOR 113-1 PREHEATED TO 1600° F*

SAMPLE NUMBER	FLASH TEMPERATURE (°F)				
	1800	1900	2000	2100	2200
113-1-1	2.06 128.8	1.92 120.0	1.21 75.6	0.94 58.8	0.57 35.6
113-1-2	2.03 126.9	1.82 113.8	1.16 72.5	0.68 42.5	0.49 30.6
113-1-3	1.79 111.9	1.70 106.3	1.30 81.3	0.80 50.0	0.55 34.4
113-1-4	1.77 110.6	1.87 116.9	1.24 77.5	0.68 42.5	0.59 36.9
113-1-5	2.03 126.9	1.99 124.4	1.09 68.1	0.82 51.3	0.63 39.4
113-1-6	2.29 143.1	2.22 138.8	1.60 100.0	1.17 73.1	0.93 58.1
113-1-7	2.36 147.5	2.32 145.0	1.97 123.1	1.32 82.5	1.06 66.3
113-1-8	2.46 153.8	2.44 152.5	2.40 150.0	1.76 110.0	1.36 85.0
113-1-9	2.40 150.0	2.45 153.1	2.27 141.9	1.50 93.8	0.90 56.3
113-1-10	2.23 139.4	2.07 129.4	2.00 125.0	1.49 93.1	0.98 61.3
113-1-11	2.40 150.0	2.32 145.0	2.13 133.1	1.58 98.8	0.87 54.4
113-1-12	2.25 140.6	2.24 140.0	2.00 125.0	1.54 96.3	1.17 73.1
113-1-13	2.37 148.1	2.55 159.4	2.25 140.6	1.07 66.9	1.17 73.1
113-1-14	2.47 154.4	2.17 135.6	1.60 100.0	0.87 54.4	0.65 40.6
113-1-15	2.43 151.9	2.27 141.9	1.73 108.1	2.05 128.1	0.68 42.5
113-1-16	2.39 149.4	2.18 136.3	1.89 118.1	1.09 68.1	0.71 44.4
113-1-17	2.17 135.6	2.08 130.0	1.54 96.3	1.09 68.1	0.77 48.1

* First number listed is bulk specific gravity; second number, weight in pounds per cubic foot.

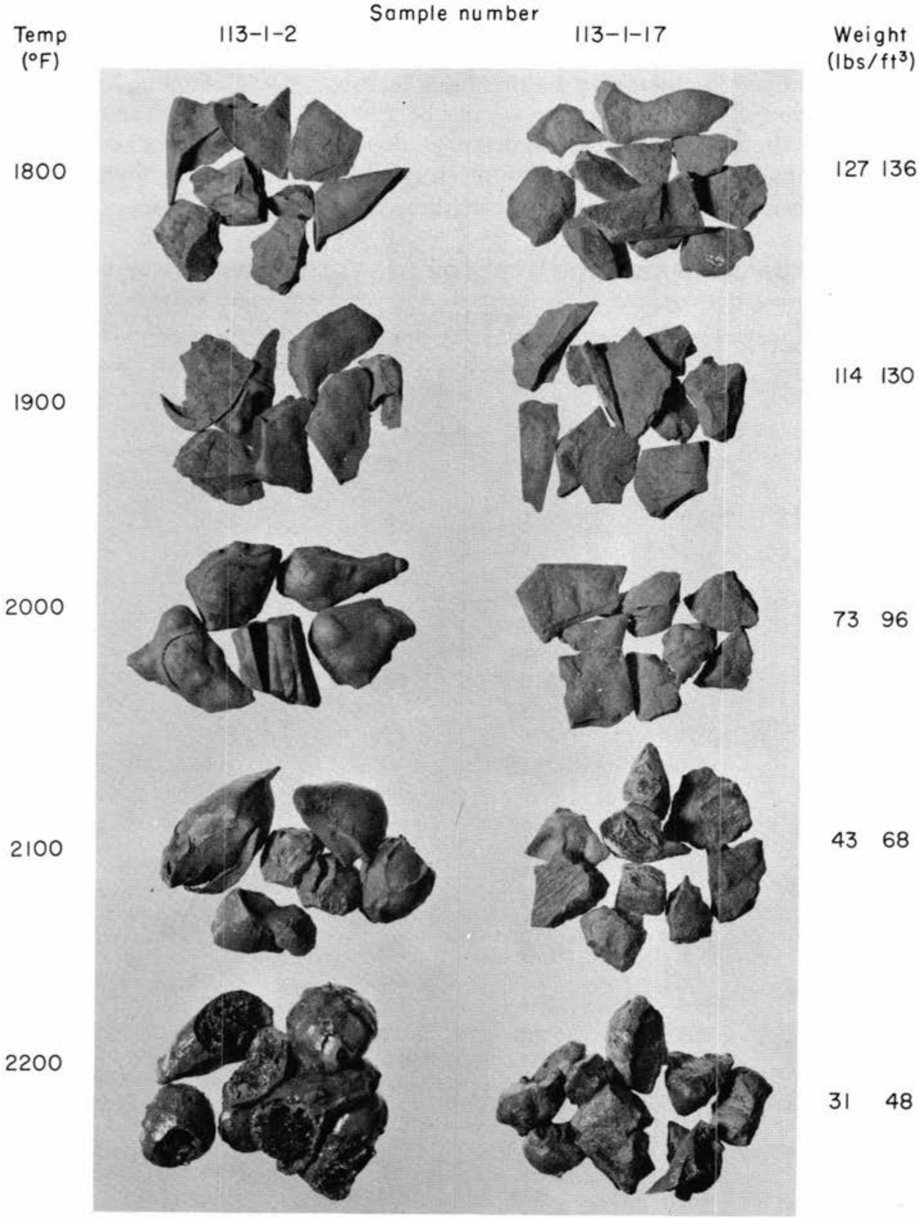

Figure 21
EXPANSION CHARACTERISTICS OF PENNSYLVANIAN SHALES AT BISHOPS CAP PREHEATED TO 1600° F
(15 minutes' retention time)

SUMMARY

Additional sampling in the Las Cruces—El Paso area could be done in the Potrillo Mountains west of Las Cruces and in the Franklin Mountains north of El Paso. Some of the fired specimens from locality 125-2 seemed to have good expansion properties, and lithologic variations in the shales, collected from a mixed stockpile, indicate that detailed sampling on the outcrop may result in the discovery of raw material suitable for expanded aggregate.

According to the data collected for shales from locality 113-1, it appears that, to produce a good aggregate, transmission rates in a rotary kiln would have to be fairly slow. These rates could be determined only through experimentation. Although it seems likely that a good aggregate can be produced from this shale, the weights will be higher than those obtained for some of the other shales tested for this report.

MISCELLANEOUS AREAS TESTED

Because of the limited number of suitable lightweight shale aggregates found in the Albuquerque and Las Cruces areas, additional sampling was conducted in the intervening area outside the limits of the arbitrary 50-mile radius. It also was desired to conduct some preliminary tests on the predominantly shale section that comprises the Devonian System in south-central New Mexico, on the thick shales exposed in the eastern part of the San Juan Basin, and on the metamorphosed argillaceous sediments of Precambrian age south of Taos. Samples were collected, therefore, from Pennsylvanian strata in the Mud Springs Mountains (88-2), Upper Cretaceous beds at Carthage (77-1), Devonian shales at Sawpit Canyon in the Black Range (99-1) and in the Mud Springs Mountains (88-1), Upper Cretaceous Lewis shales near Chama (4-4), and Precambrian phyllites in the Picuris Mountains (19-5).

SAMPLE LOCALITY 4-4

Samples from the upper part of the Lewis Shale were collected at a roadcut on N. Mex. 17, half a mile west of Dulce in the SW1/4 sec. 12, T. 31 N., R. 2 W. Shales are light olive gray (5Y6/1), very silty, and slightly carbonaceous and contain a few calcareous fossil fragments. Of the six samples collected, a full series of tests was conducted on only the lower three. Upper samples contain appreciable amounts of very fine- to fine-grained sand composed of quartz and feldspar; preliminary tests indicated very low expansion for these samples.

Fired Data

Pores begin to form at 2000° F, 10 minutes' retention time, and have fairly uniform size and distribution through 2200° F. Pores range from less than 0.05 millimeter in diameter at 2000° F up to a few pores greater than 2.0 millimeters in diameter at 2200° F, 15 minutes' retention time. Particle strength is moderate to high through firings at 2100° F, decreasing markedly at 2200° F, 10 minutes' retention time. Slight to moderate agglomeration occurs in all the samples fired at 2200° F at retention times of more than 5 minutes. Weights obtained at 2100° F, 15 minutes' retention time, ranged from approximately 56 to 63 pounds per cubic foot, but kiln temperatures in excess of 2050° F are necessary to obtain an aggregate with a weight of 85 pounds per cubic foot or less (fig. 22, table 1). The expansion range, however, is fairly long, based on temperature and retention times required for agglomeration. When test-fired at 2100° F, 15 minutes' retention time, the upper samples, collected just below the Pictured Cliffs Sandstone, had weights from 88 to 138 pounds per cubic foot. Water absorption for the lower samples ranged from 7 to 15 per cent and averaged about 14 per cent at expansion temperatures.

SAMPLE LOCALITY 19-5

A fairly thick sequence of phyllite occurs in the Picuris Mountains south of Taos. This interval was named the *Pilar Phyllite Member* of the Ortega Formation by Montgomery and was formerly called the *Hondo Slate* by Just (1937). As pointed out by Montgomery in a footnote, "the term slate is not satisfactory as the rock has undergone middle-grade metamorphism together with associated staurolite-bearing schists." Montgomery describes the phyllite as being gray-black to black and containing minute muscovite flakes on cleavage surfaces. In thinsection, the rock is very fine-grained with streaky patches of carbonaceous material, muscovite flakes, and elongate quartz grains.

Samples were collected from roadcuts along N. Mex. 75 in the SW1/4 sec. 24, T. 23 N., R. 10 E. Samples 1 and 2 were from the phyllite and sample 3 was from a gouge zone in the phyllite. The bulk specific gravities of samples 1 and 2 test-fired at 2100° F, 15 minutes' retention time, were exceptionally high at 2.78 and 3.18. The gouge-zone material had a bulk specific gravity of 2.03. Absorption per cent for the phyllite samples was 5.8 and 7.4 and for the gouge material, 12.8. No pores had formed at the test temperature, so additional tests for its use as an expanded aggregate were not conducted.

SAMPLE LOCALITY 77-1

Shales from the Mancos and Mesaverde intervals of Upper Cretaceous age were sampled in the Carthage area southeast of Socorro.

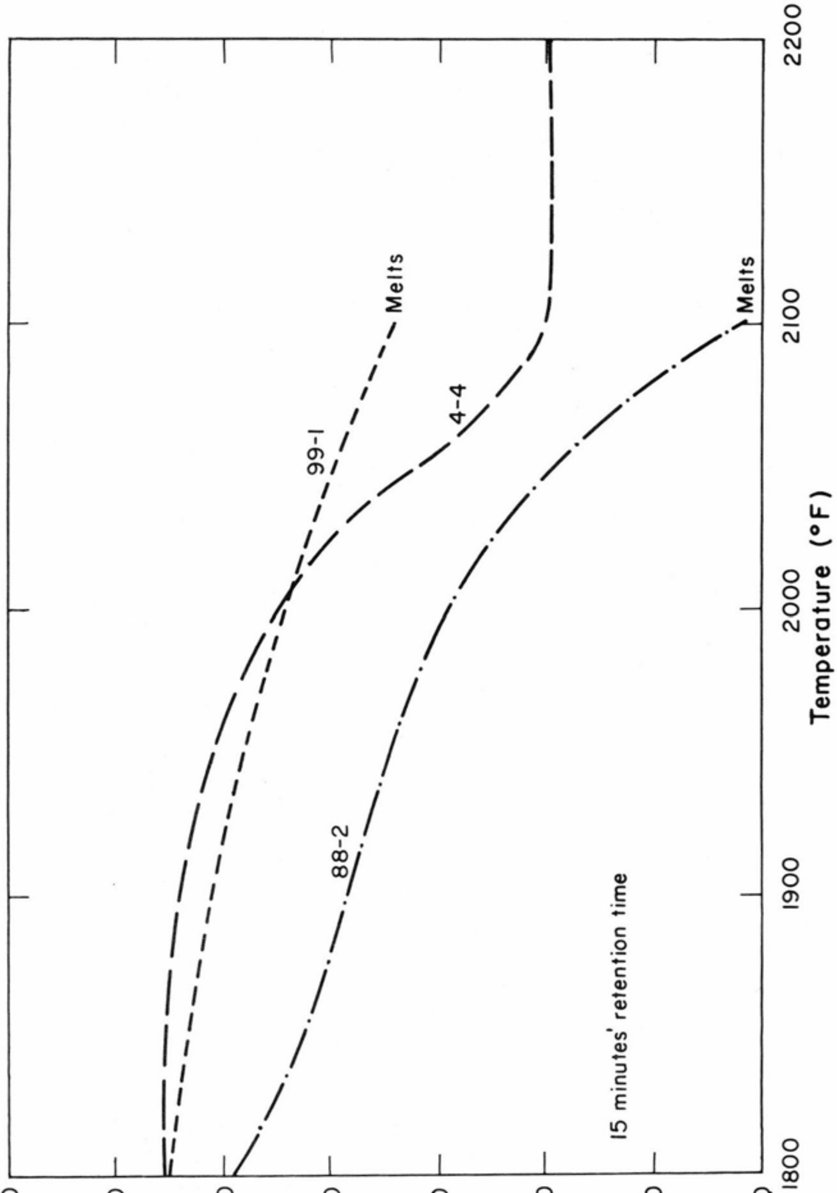

Figure 22

EXPANSION CURVES OF LEWIS (4-4), PENNSYLVANIAN (88-2), AND DEVONIAN (99-1) SHALES

Six samples of Mancos shales were collected from exposures in the upper part of this interval in secs. 8, 16, and 21, T. 5 S., R. 2 E. The shales are medium to light gray (N5 to N6.5), silty to sandy (very fine-grained quartz), and, except for interval 5, calcareous. Test-fired at 2100° F, 15 minutes' retention time, the three upper samples gave weights of from 38 to 78 pounds per cubic foot without any evidence of agglomeration. Water absorption was fairly high, ranging from 14 to 19 per cent. If this shale is uniform in its expansion properties along the strike, considerable easily mined raw material is available.

Fourteen samples of shale were collected from the overlying Mesaverde Formation in a section consisting of interbedded sandstones, shales, and coal. The shales are dark gray (N3), silty, and highly carbonaceous. Most specimens were too refractory for expansion purposes. The only evidence of bloating involved the development of a few small pores.

SAMPLE LOCALITY 88-1

The material collected consisted of eight channel samples of Devonian shales from the Mud Springs Mountains northwest of Truth or Consequences. Sample locality is in the center of sec. 24, T. 13 S., R. 5 W. near the top of a prominent ridge about half a mile north of Cuchillo Negro. Twenty-four feet of Devonian shales and nodular limestones are exposed in several small gullies. The shales are pale olive and light gray (10Y6/1 and N7), silty, and calcareous; the principal clay mineral is illite. Preliminary firing tests gave no indication of expansion. Slight melting was noted in only two of the samples, but complete melting occurred at temperatures slightly above 2100° F and when slow-heated below 2100° F.

SAMPLE LOCALITY 88-2

Pennsylvanian shales were sampled immediately above the Devonian beds at 88-1. Exposures were limited to a thin interval of shale above a monzonite sill. The shale is medium gray (N5), silty, and calcareous. Preliminary firing tests disclosed good pore development with minor cracks parallel to the shale laminations, and a full series of tests was conducted.

Pores began to form at **1900°** F, 5 minutes' retention time. Uniform size and distribution of pores developed at temperatures of 2100° F and higher. The pore size increased from 1.0 millimeter at 2000° F to more than 4.0 millimeters at 2200° F. Particle strength is low and slight agglomeration occurs at 10 and 15 minutes' retention times at 2100° F. Agglomeration is heavy at 2200° F, and the curve data presented are limited to weights obtained through 2100° F (curve 88-2, fig. 22). From the curve, it appears that a fairly good lightweight aggregate of from

50 to 80 pounds per cubic foot could be produced between 2000° and 2050° F. An extremely light weight of 22 pounds per cubic foot was obtained with this shale at 2100° F, 15 minutes' retention time. Particles have a spherical shape above 2000° F and there is only slight flaking during heating. Water absorption between 1800° and 2200° F increased from 12 to 18 per cent.

SAMPLE LOCALITY 99-1

Twenty-five channel samples of Devonian shale were collected in Sawpit Canyon about 2 miles north of Kingston in the SW1/4N1/4 sec. 5, T. 16 S., R. 8 W. The section consists primarily of shale with thin zones of limestone nodules increasing in frequency just beneath massive limestone cliffs of Mississippian age. Shales are grayish olive (10Y4/2) and olive gray (5Y4/1), silty, calcareous, and fossiliferous. X-ray diffraction patterns were prepared for each of the samples and, based on the relative intensities of the peaks, chlorite is the principal clay mineral in twelve samples, illite in eight, and kaolinite in one. The remainder have approximately equal amounts of chlorite and illite.

Preliminary firing tests indicated that several of the samples expanded at 2100° F, 15 minutes' retention time, with little evidence of fusion. The only problem encountered involved popping and extreme flaking of the shale particles. This was a serious problem throughout tests on this sequence of samples, and the data presented here are not considered highly reliable.

The average weight of the aggregate at 2100° F, 15 minutes' retention time, was 88 pounds per cubic foot (curve 99-1, fig. 22) with a range from 70 to 110 pounds per cubic foot. It had already been determined during preliminary tests that expansion at 2100° F was low, as indicated by pore development, but it was hoped that the expansion range might be fairly long. During final testing, it was discovered that pore formation did not begin until a temperature of 2100° F had been reached and that the shales melted completely at 2200° F, 10 minutes' retention time. An aggregate produced from these shales would be fairly heavy and the expansion range exceedingly short.

SUMMARY

Two possible sources for lightweight shale aggregate were found between Las Cruces and Socorro (77-1 and 88-2), but considerable testing and tracing of beds would be necessary to determine the extent of suitable material. Preliminary tests indicate that raw material with fair expansion properties occurs in the Lewis Shale of northwestern New Mexico (4-4) which is approximately 2000 feet thick. The Lewis Shale is equivalent in part to the Pierre Shale of northeastern New Mexico and may have very similar expansion properties.

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Numbers in **boldface** indicate main sections