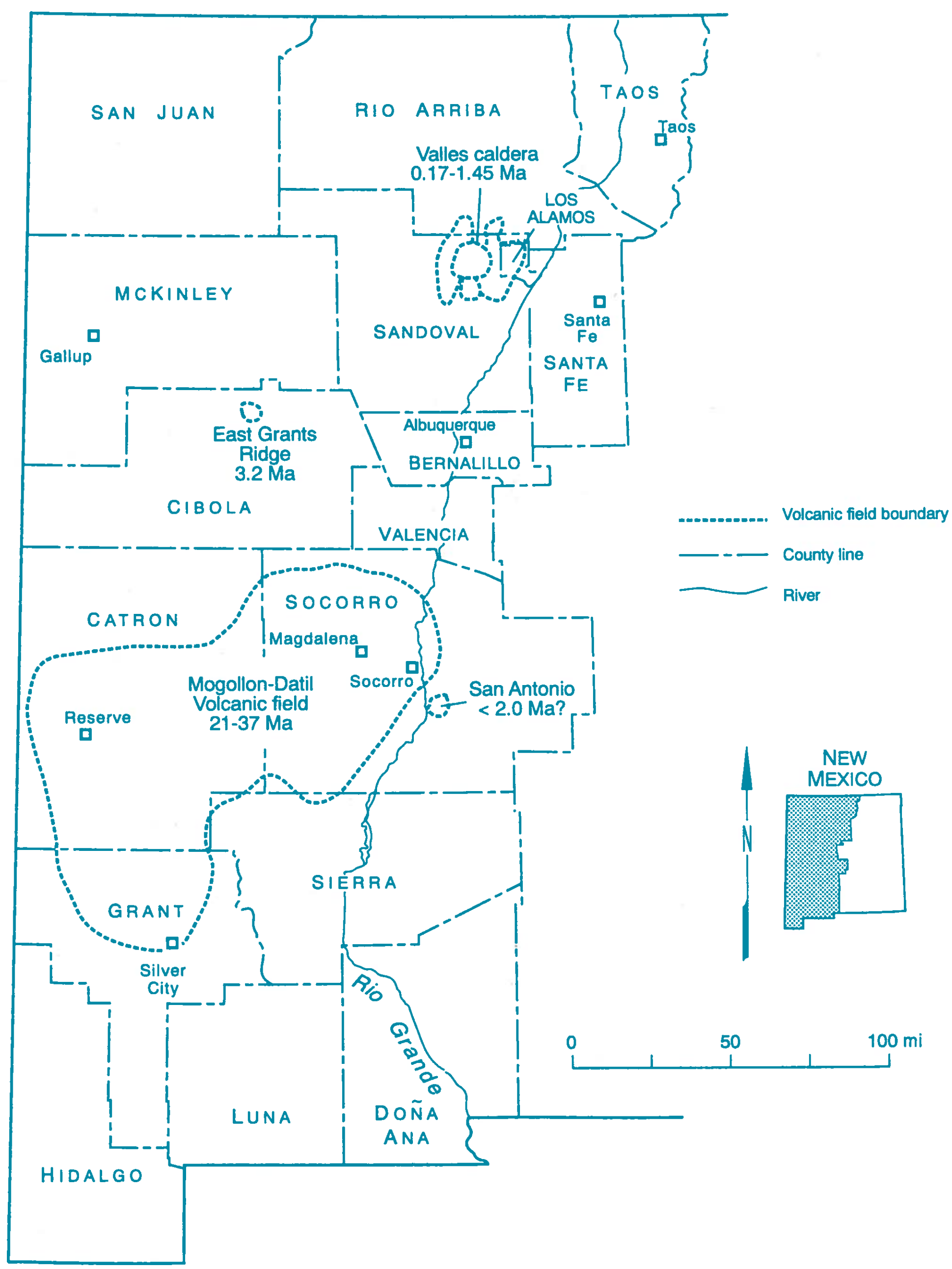
Pumice and Pumicite in New Mexico

by Jerry M. Hoffer



BULLETIN 140 New Mexico Bureau of Mines & Mineral Resources 1994

A DIVISION OF
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

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SOCORRO 1994

NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY
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Original Printing

Published by Authority of State of New Mexico, NMSA 1953 Sec. 63-1-4
Printed by University of New Mexico Printing Services, December 1994

Available from New Mexico Bureau of Mines & Mineral Resources, Socorro, NM 87801

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Acknowledgments

Special thanks are extended to Mitch Brasington, former president of East—West Apparel, Inc., El Paso, who first introduced the author to the use of pumice in stone-washing and who provided funding for the development of a set of physical property specifications that could be used to evaluate the quality of laundry pumice. The author would also like to thank James M. Barker, George S. Austin, and Virginia T. McLemore of the New Mexico Bureau of Mines and Mineral Resources who reviewed drafts of the paper and supplied pumice and pumicite reports and maps from Bureau files for this study. Wayne Brown (Copar Pumice), Dan Warner, II (Utility Block), R. W. Alley (General Pumice), and L. R. Stokes (U.S. Gypsum) allowed access to their pumice properties. Frank E. Kottlowski, Emeritus Director, NMBMMR, provided funds for visiting the principal pumice deposits to collect samples. Finally, thanks to my wife, Dr. Robin L. Hoffer, who has listened to my pumice problems for the last eight years and has tolerated the pumice testing in our library and kitchen.

Abstract

New Mexico has ranked in the top three states in the production of pumiceous materials in the United States since 1980. In 1986, the state produced nearly half, 255,000 mt, of the total U.S. production; during subsequent years production has decreased to a low of 48,000 mt in 1991. In 1993, production increased significantly to 100,000 mt. From 1980 to 1993, New Mexico mines produced 1,382,000 mt of pumice and pumicite with an estimated value of approximately $19,700,000.

The principal domestic uses of pumiceous materials include concrete admixtures and aggregates, building block, abrasives, laundry use, and landscaping. In 1993, nearly 60% of the production was used for making concrete and blocks. Since 1987, the use of pumice as an abrasive has increased rapidly because of the demand in the laundry industry to produce faded denim fabrics. New Mexico pumice is well positioned to serve the El Paso area which consumes 750,000 lb/month in the production of designer jeans; however, more than 50% of the pumice utilized in El Paso is currently imported from foreign sources.

The principal pumiceous deposits in New Mexico occur within the volcanic units related to the resurgent Valles caldera in the Jemez Mountains. Present production is approximately 2,500 yds^3/day from two Plinian ash-fall units: (1) the 0.17 Ma El Cajete Pumice of the Valles Rhyolite and (2) the 1.45 Ma Guaje Pumice Bed, within the Otowi Member of the Bandelier Tuff in Santa Fe, Sandoval, Rio Arriba, and Los Alamos Counties. Currently, four active mines are operated by Copar Pumice Company, Inc., Utility Block Company, and General Pumice Corporation.

Physical properties of the New Mexico pumiceous materials indicate they are suitable for use in concrete aggregate, in Portland-pozzolan cements, and as abrasives. The coarse-particle pumice of the El Cajete Pumice is the most promising for laundry use.

Introduction

Terminology and Origin

Pumice and pumicite are pyroclastic materials produced by the rapid expansion of dissolved gases in a viscous siliceous magma generally ranging from rhyolite to dacite composition. This group of pyroclasts is distinctive because they are glassy and consist of a cellular structure composed of numerous thin-walled vesicles. Pumicite originates when dissolved gases in the viscous magma produce a froth or a large quantity of bubbles in a short period of time followed by rapid rupture of the vesicles. If fewer bubbles develop in the magma, and the glass vesicle walls are allowed to solidify rapidly enough to prevent collapse, then pumice will form (Verhoogen, 1951; Chesterman, 1956). An academic classification of pyroclastic and pumiceous fragments, which defines the fragments based upon size (Fisher, 1961), is in Table 1.

Block pumice has commonly been used to refer to lump pumice; however, the term block has been defined legally as a pumice fragment possessing one dimension equal to or exceeding 50.8 mm (2 in.) (Federal Register, 1990). The laundry industry utilizes only coarse pumice ranging from 19 to 76 mm (3/4 to 3 in.) in diameter; fragments smaller than 19mm (3/4 in.) would disintegrate completely before the completion of the 15- to 50-min washing cycle. The proportion of coarse pumice in a typical pumiceous deposit is generally less than 10%. A survey of 58 deposits in the western United States shows that more than 30% contain no pumice fragments coarser than 19 mm (3/4 in.). The average percent of fragments sized greater than 19 mm (3/4 in.) for all of the deposits is 7.3% (Table 2).

Geologic Setting and Occurrence

Pumiceous materials are formed in areas of explosive volcanism where high-silica materials (65 to 75% SiO_2) have erupted. Such areas occur in the western United States and include the active volcanoes of the Cascade Mountains in northern California, Oregon, and Washington. In addition, numerous deposits have been produced from siliceous calderas and volcanic dome complexes in California, Nevada, Arizona, New Mexico, and Idaho. An index map showing the major pumiceous deposits and occurrences in New Mexico is given in Figure 1.

TABLE 1—Classification of pyroclastic and pumiceous fragments (after Fisher, 1961).

Clast size (mm)	Clast size (in.)	Pyroclastic Fragments	Pumiceous Fragments
> 64 mm	> 2.6	Bomb, block	Lump pumice
64–4	0.16–2.6	Lapilli	Pumice
< 4	< 0.16	Ash	Pumicite

All glasses are amorphous and are therefore unstable in nature over geologic time if in the presence of water. Pumice and pumicite, which are natural glasses, are susceptible to alteration by chemical weathering at the earth's surface. Weathering of the pumice will denitrify the glass, form clay materials, and destroy the physical properties that make the pumice useful as an aggregate and abrasive. Therefore, fresh, unaltered pumice and pumicite are generally restricted to strata of late-Tertiary to Quaternary age or to older strata that has escaped alteration.

Physical and Chemical Properties

Pumice and pumicite are either vesicular volcanic glass or fragments of such glass. Vesicles can range in size from less than 0.01 mm (0.0004 in.) to over 20 mm (0.8 in.) but commonly range from 0.1 to 0.6 mm (0.004 to 0.024 in.) in diameter with equidimensional to highly elongate shape. Pumice has a white streak and a Mohs hardness of 6.0. The fracture is irregular, and the tenacity is generally brittle. Pumice usually has a silky luster whereas pumicite is more earthy (Williamson and Burgin, 1960). Pumice and pumicite are usually light colored, commonly light gray to white, but shades of light buff, brown, and pink are common. The density of the unexpanded glassy materials is about 2.5 g/cm^3 (156 lbs/ft^3) but, because of their cellular structure, the apparent density is generally less than 1.0 g/cm^3 (62.4 lbs/ft^3). Apparent density measurements of more than 250 pumice samples (Hoffer, 1989) show a range from 0.35 to 1.20 g/cm^3 (21.8 to 74.9 lbs/ft^3) with an average of 0.70 g/cm^3 (43.7 lbs/ft^3).

Fragments of quartz, feldspar, hornblende, biotite, augite, and magnetite are commonly found as phenocrysts in pumice and pumicite. Generally, these minerals are most abundant in pumice with high apparent density.

Pumiceous materials are inert to most chemicals and are composed primarily of $Si0_2$. Williamson and Burgin (1960) reported that the $Si0_2$ content of 92 pumice and pumicite samples ranged from 54 to 77.6 wt% with a median of 71.3 wt%. Chesterman (1956), based on chemical analyses

TABLE 2—Percentage of coarse pumice in pumiceous deposits of California, Idaho, New Mexico, Oregon, and Washington ([1]Chesterman, 1956; [2]Asher, 1965; [3]Clippinger and Gay, 1947; Kelley, 1949; [4]Walker, 1951; [5]Carithers, 1946).

State (County)	Number of Samples	Number of samples containing no 3/4 in. fraction	Percentage of coarse fragments in samples (3/4 in. or 19 mm)	
			range (%)	average (%)
California[1] (Siskiyou, Mono, and Inyo)	6	0	2.0–20.3	9.5
Idaho[2] (Owyhee, Twin Falls, Power, Oneida, Teton, Bonneville, Blane, and Camas)	9	7	0.0–69.3	10.4
New Mexico[3] (Santa Fe, Rio Arriba, Cibola, and Sandoval)	15	1	0.0–35.4	11.4
Oregon[4] (Klamath)	3	1	0.0–5.6	2.0
Washington[5] (Lewis, Skamania, and Snohomish)	25	10	0.0–18.8	3.4
	58	19	0.0–69.3	7.3

of 80 pumice samples, states that the average SiO_2 value is approximately 70.4 wt% (Table 3). Typically, pumiceous materials contain from 65 to 75 wt% SiO_2. The second most abundant compound is $A1_20_3$, followed by the alkali oxides of potassium and sodium.

The chemical analyses of New Mexico pumice samples, which are from the pumice deposits associated with the Valles caldera and the East Grants Ridge area, are comparable to those of average pumice. The loss on ignition (LOI) values of New Mexico pumice are much higher than average pumice as shown in Table 3. LOI represents the liberation of volatiles such as $\mathbf{H_20}$ and CO_2 during heating above 100°C and is calculated as the difference in the sample weight before and after heating.

TABLE 3—Chemical composition, as weight percent (wt%), of averaged pumice and New Mexico pumice ([1]from Chesterman, 1956; [2]from Goff et al., 1989; Self et al., 1988; Kelley, 1949; Swineford, 1949; Johnston, 1953). nr = not reported; LOI = loss on ignition.

Chemical Oxides	Averaged Pumice (80 samples)[1]	Averaged New Mexico Pumice (7 samples)[2]
SiO_2	70.38	70.41
TiO_2	nr	0.16
Al_2O_3	15.82	13.92
FeO	2.92	2.13
MgO	0.48	0.48
CaO	1.56	1.21
Na_2O	3.70	4.02
K_2O	4.10	4.03
MnO	nr	0.06
P_2O_5	nr	0.04
LOI	0.53	4.15

Deposits

Pumice and pumicite deposits can be classified on the basis of mode of deposition and origin. A working classification, modified from Chesterman (1956), is given in Table 4.

Pyroclastic-fall deposits are formed after material has been explosively ejected from a vent into the atmosphere and falls to the surface under the influence of gravity. Fall deposits locally maintain a relatively uniform thickness over the topography and are generally well sorted with the majority of the fragments between 1 to 8 mm (0.04 to 0.3 in.) in diameter (Figure 2a). Near the vent some fall deposits are welded (Cas and Wright, 1987).

Pyroclastic-flow deposits result from surface flow of hot pyroclastic debris and gases which travel as a high-particleconcentration medium. The deposits are topographically controlled and fill valleys and depressions (Cas and Wright, 1987). The pyroclastic units are generally massive and poorly sorted (Figure 2b). The individual clasts may show rounding and the effects of abrasion. In addition, lithic fragments, which range widely in abundance, show normal grading, whereas pumice clasts display inverse grading (Hickson and Barnes, 1986). Units formed by pyroclastic flows are commonly referred to as ignimbrites, ash-flow tuffs, or welded tuffs.

Surge deposits are emplaced as a relatively cool, turbulent mixture of gas and clasts. The resulting deposits mantle the topography but are generally thicker in valleys and in depressions and usually contain abundant lithic fragments (Cas and Wright, 1987). Characteristically, the units show directional sedimentary bed forms such as low-angle cross-bedding and dune and anti-dune forms.

TABLE 4—Classification of pumiceous deposits (modified from Chesterman, 1956).

Origin	Example
Subaerial	
Pyroclastic fall	Lower Bandelier Tuff, NM
Pyroclastic flow	Upper Bandelier Tuff, NM; Mt. St. Helens, 1980
Pyroclastic surge	Base of the upper Bandelier Tuff, NM
Flow and dome	Glass Mountain and Mono Craters, CA
Subaqueous	Japan, Grenada Basin, Krakatoa (Indonesia), Phillippines
Epiclastic-mainly fluvial, but may include mass movements, ice or wind.	San Antonio, NM

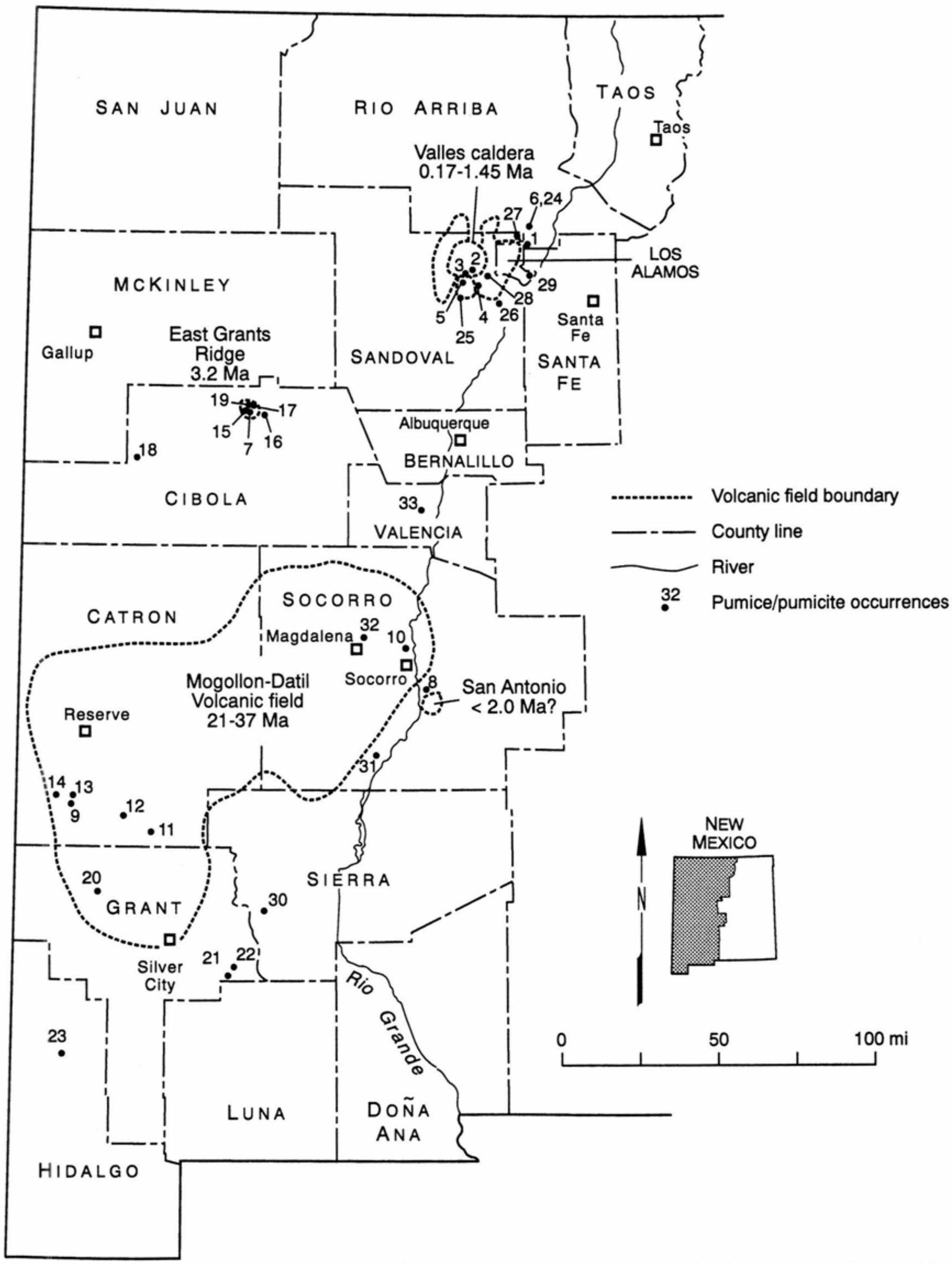


Figure 1—Index map of New Mexico showing major deposits and occurrences of pumice and pumicite. Numbers are at locations listed in Tables 10 and 11.

Pumice deposits that exist as vesiculated surfaces of obsidian flows and domes have been observed at Glass Mountain and Mono Craters in California (Chesterman, 1956). The pumice formed by quiet vesiculation of viscous glassy lava as it rose to the surface. The pumice occurs in blocks, several inches to 1.5 m (5 ft) in diameter, and grades downward into unexpanded obsidian.

Subaqueous pyroclastic deposits can form in both marine and lacustrine environments from accumulation of ejecta from subaerial and submarine eruptions. Typical features associated with subaerial eruptions include plane-parallel beds, normal grading from crystal- and lithic-rich bases to shard-rich tops, inversely graded pumice, and good-to-poor sorting (Fisher and Schmincke, 1984). Subaqueous pyroclastic eruptions consist mainly of debris flows which form massive to poorly bedded and poorly sorted lower units with a thinly bedded upper unit. When present, pumice is inversely graded in the lower layer (Fisher and Schmincke, 1984).

Epiclastic deposits represent any of the above materials that have been eroded, transported, and redeposited by running water, glaciers, mass movements, or wind. Reworked materials deposited by streams commonly show many of the same features as fluvial clastic sedimentary rocks. Such features include crossbedding, interbedded nonpyroclastic materials, and rounding of fragments.

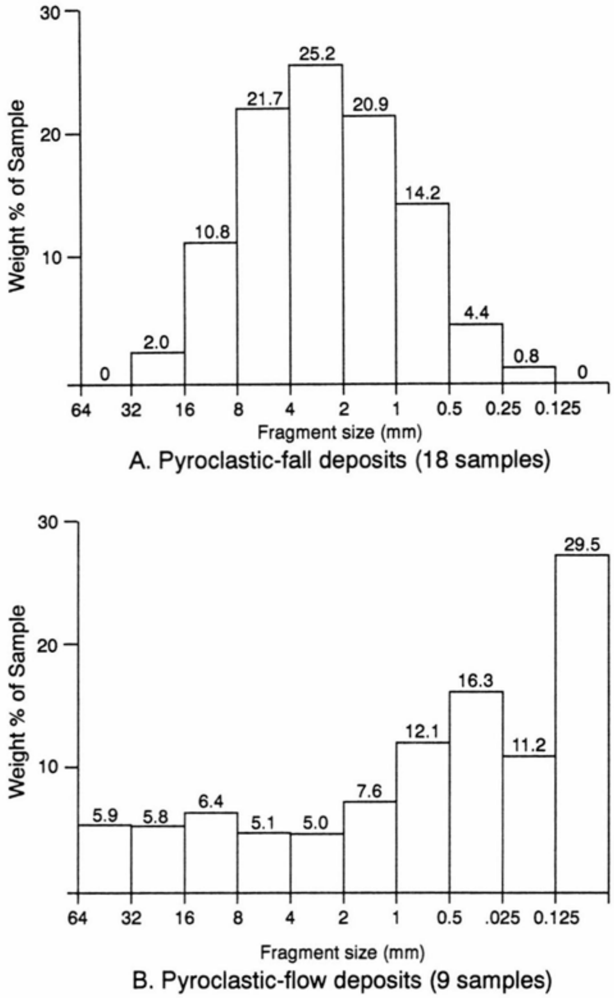


Figure 2—Size distribution of (A) pyroclastic-fall and (B) pyroclastic-flow pumice deposits (from Moore, 1937).

TABLE 5—New Mexico production of pumiceous materials, 1980–1993 in thousand metric tons (mt) and thousand dollars (from Meisinger, 1983, 1988, 1989; Bolen, 1991, 1992, 1993, 1994; Hatton, 1993). e = estimated.

Production Year	Quantity (1000 mt)	Value (1000 $)	U.S. Rank	U.S. Percentage
1980	76	814	2	14
1981	85	919	1	17
1982	88	809	1	21
1983	100	1070	1	22
1984	120	1269	1	24
1985	138	1114	1	27
1986	232	2370	1	46
1987	79	991	2	22
1988	84	852	2	24
1989	77	1086	2	18
1990	60[e]	1496	3	14
1991	48	1511	3	12
1992	95[e]	2900	2	20
1993	100[e]	2530	2	21

Production

Many commercial pumiceous deposits are unconsolidated and have a minimum of overburden. Open-pit mining can easily be carried out with conventional loading equipment. The material is removed in bulk and screened on site into various size fractions as required by the construction and laundry industries. Pumice, after separation from the pumicite, may undergo a gravity separation to remove pumiceous fragments that contain lithic fragments and obsidian.

Since 1980, New Mexico has ranked from third to first in the production of pumiceous materials in the United States. Before 1980, volcanic cinder and scoria were lumped together with pumice and pumicite making it impossible to determine the actual production of pumiceous materials from the individual states. Other important pumice-pumicite producing states include Oregon, California, Arizona and Idaho. A summary of the United States and New Mexico production from 1980 to 1993 is given in Table 5 and Figure 3.

New Mexico's production of pumiceous materials increased steadily from 1980 to 1986. In 1986, 46% of the U.S. production was from New Mexico with 255,000 mt. In 1987, domestic production of pumiceous materials declined by 29%, whereas New Mexico's production declined even more dramatically by 66%. The decline in production paralleled the weakened U.S. demand for pumice aggregate in concrete (Meisinger, 1988). Production continued to decline during the next four years reaching a low of 48,000 mt in 1991. In 1993 the state's production of pumiceous material increased to 100,000 mt due to recently opened mines in Sandoval County and the strong demand for laundry pumice.

From 1980 to 1993, New Mexico mines produced more than 1,380,000 mt of pumice and pumicite with a value of approximately 20 million dollars. The major producers include Copar Pumice Company, Inc., Santa Fe; General Pumice Corp., Santa Fe; and Utility Block Company, Albuquerque.

The 1993 domestic production is estimated at 469,030 mt and apparent consumption at 594,000 mt (Bolen, 1994). Major sources of imported pumice and pumicite during the last three years have been from Greece (77%), Mexico (6%), Ecuador (6%), and Turkey (4%). In 1993 imports totaled 25% of the domestic consumption.

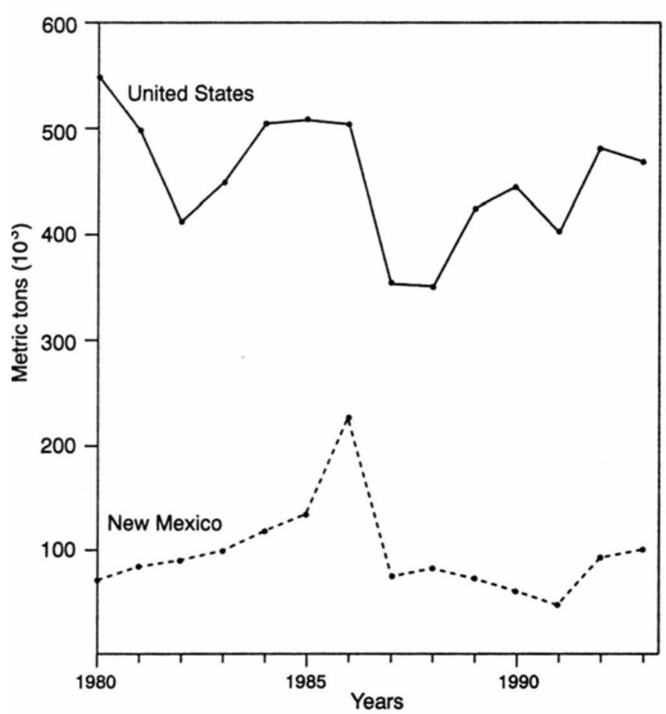


Figure 3—Pumice-pumicite production in United States and New Mexico, 1980–1993 (from Meisinger, 1983, 1988, 1989; Bolen, 1991, 1992, 1993, 1994).

Consumption and use

Principal domestic uses of pumiceous materials include concrete admixtures and aggregates, light-weight building block, abrasives, laundries, and landscaping (Figures 4 and 5; Table 6). In 1993, nearly 70% of the production was used for making concrete and building blocks.

Concrete and Aggregate

In the construction industry, pumice and pumicite are used primarily to produce light-weight concrete aggregate. The major advantages of using pumice in concrete include:

1. lighter weight—pumice weighs one-third to two-thirds as much as quartz sand, gravel, or crushed stone, thereby decreasing the need for structural steel;
2. high insulation value—pumice concrete is six times more efficient as a heat insulator than ordinary concrete;
3. high elasticity—pumice concrete is six times as resilient as ordinary concrete and is therefore more resistant to earthquakes and other shocks; and
4. heat resistance—pumice undergoes no volume change below 760°C and therefore less spalling or structural damage occurs during building fires (Chesterman, 1956, 1966).

Major disadvantages of pumice concrete include minor moisture absorption that causes volume change and significantly lower compressive strength than ordinary concrete (Bates, 1960).

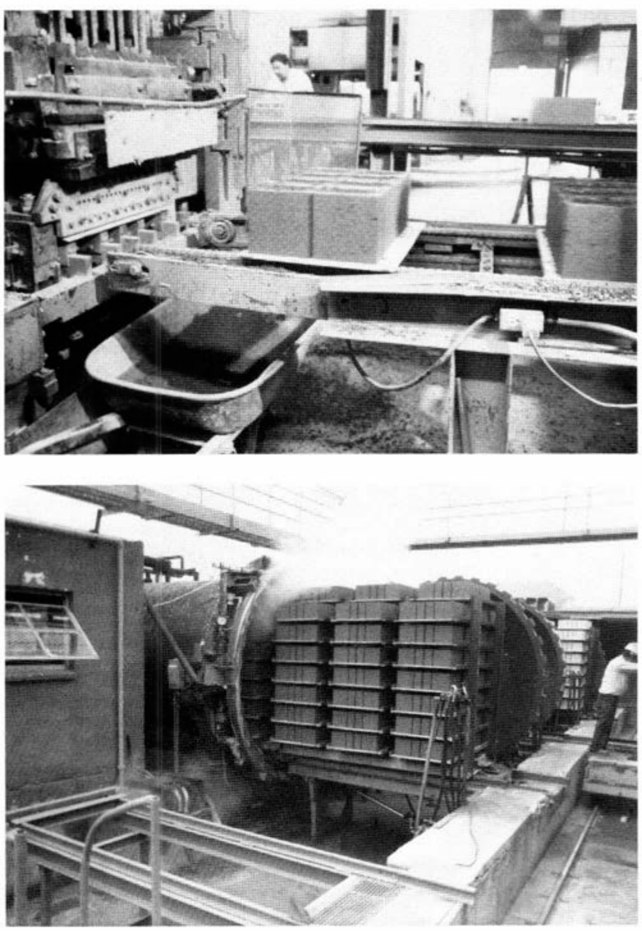


Figure 4—Manufacturing of pumice-cement blocks at Utility Block Co., Inc., Albuquerque. Top, concrete blocks released from molding machine (left) moving on conveyor to be stacked on pallets. Bottom, the blocks are placed in a steam-bath oven at 160°F for 10 hr to cure.

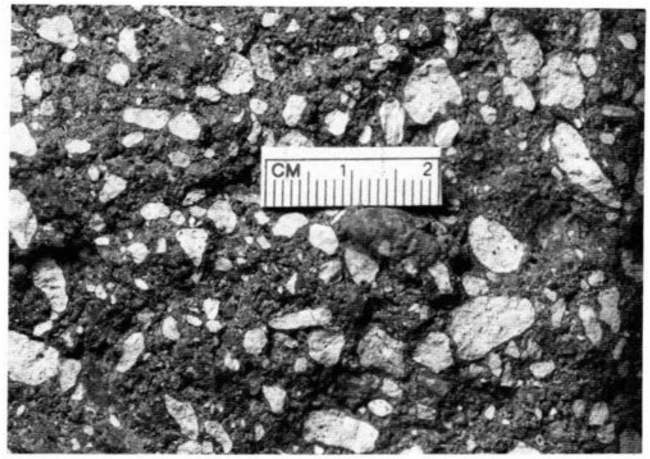


Figure 5—Texture of pumice-cement building block showing the distribution of rounded to subangular pumice fragments. The original pumice fragments were crushed and screened to obtain 7.9 mm (0.31 in.) diameter fragments and were blended with cement.

Pumice used for lightweight aggregate should possess vesicles of uniform size and shape which should not be interconnected. The pumice fragments should be inert and free of contaminating substances such as clay, organic materials, chemical salts, and amorphous silica (Walker, 1951). The aggregate should be well sorted with fragments ranging in size from 0.16 to 0.64 cm ($^{1}/16$ to $^{1}/4$ in.).

A Portland-pozzolan cement is formed when finely ground pumice or pumicite is added to Portland cement. The pumiceous fragments, in the presence of water, combine with calcium hydroxide that is liberated from the cement to form compounds with additional cementious properties (Harben and Bates, 1990). The chemical reaction forms an insoluble hydrous calcium silicate which reduces the porosity and permeability of the concrete and thus prevents deterioration of the concrete by chloride or sulfate salt solutions or acid waters (Bates, 1960; U.S. Bureau of Mines, 1969). In addition, Portland-pozzolan cements reduce the effect of alkali reactions in concrete that cause expansion and cracking. In the U.S., Portland-pozzolan cements have been used in the construction of concrete dams, canals, tunnels, reservoirs, and other structures exposed to corrosive waters.

The suitability of pumiceous material utilized in Portland-pozzolan cement is determined by testing. Minimum

TABLE 6—Consumption of pumice and pumicite by end use in the United States, 1993 (Bolen, 1994).

Use	Quantity (1000 mt)	End use Percentage	Cost per Ton ($)
Concrete admixtures and aggregates	43	9.2	20.53
Decorative and building block	279	59.6	13.48
Abrasives	316	6.6	109.36
Laundry	42	9.0	44.40
Landscaping and horticulture	57	12.0	26.77
Other (road construction, insulation, pesticide carriers, etc.)	17	3.6	36.35
Total	469	100	

criteria of the American Society for Testing and Materials (ASTM) standard C618-78 include: (1) compressive strength of 2600 psi for 28 days; (2) less than 115 wt% water requirement for flow when compared to normal Portland cement; (3) drying shrinkage of less than 0.03%; and (4) reduction, if needed, of alkali reactivity by 75% (U.S. Bureau of Mines, 1969). Tests on pumice and pumicite samples from deposits in Rio Arriba (sec. 23, T2ON, R7E), Sandoval (sec. 33, T17N, R5E), and Santa Fe (sec. 32, T19N, R7E) counties indicate suitable sources of pumiceous materials exist for manufacture of Portland-pozzolan cement in New Mexico (U.S. Bureau of Mines, 1969).

Building Block, Decorative Stone, and Landscaping

In 1993, the principal use of pumice was in the construction of building block (Bolen, 1994). Many of the larger pumice blocks, up to 1.5 m (5 ft) or more in diameter, are sold as decorative stone either rough or with one or two edges sawed. These blocks are used for wall or other surface coverings such as suspended ceilings.

The rough, uncut blocks are often used in landscaping and for sculptured pieces (Peterson and Mason, 1974). The low specific gravity of block pumice makes it easy to transport large boulders, 0.9-1.2 m (3-4 ft) in diameter and emplace them by hand.

Abrasives

Pumice and pumicite have been used as abrasives for nearly 90 years; before 1940, this was their chief use. High-quality pumiceous materials, free of crystals (quartz, feldspar, etc.) and alteration products (clay minerals and iron oxides), have been used for scouring and fine-polishing operations. High-quality pumice abrasives should be uniform in texture and particle size; size and shape of the vesicles should be uniform (Walker, 1951).

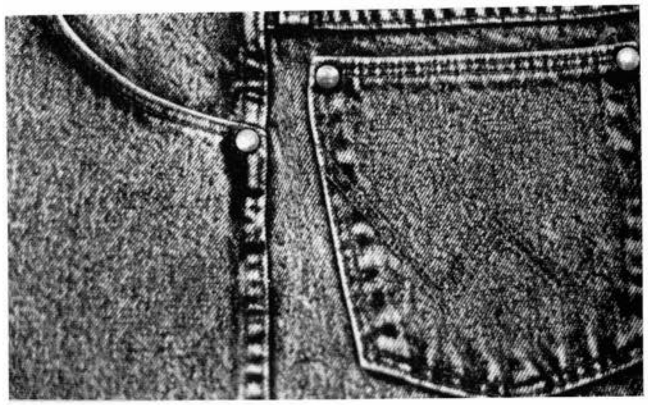
Since about 1985, clean lump pumice has been employed as an abrasive in the production of designer jeans in a process called stone-washing (Picciotto, 1988). From 1986 to 1987, pumice use as an abrasive increased 71% primarily because of the demand in the laundry industry to produce faded denim fabrics (Meisinger, 1988). In El Paso alone, more than 2500 mt of lump pumice were consumed in laundries each month during 1988.

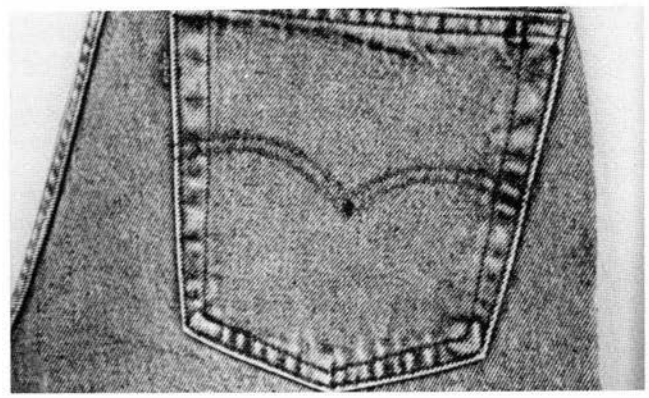
Prior to 1990, the U.S. Bureau of Mines in their annual Mineral Industry Surveys included laundry pumice in the abrasive category. However, because of the increasing consumption of pumice in denim finishing, a laundry category was established in 1990. Table 7 summarizes the consumption by laundry use from 1988 to 1993.

As an abrasive in the laundry industry, pumice is utilized in two distinct processes: acid- and stone-washing (Figures 6 and 7). In acid-washing, pumice is impregnated with oxidizing chemicals (potassium permanganate and/or bleach) and then tumbled dry with the denim fabric. The chemicals are slowly released from the pumice and bleach the fabric. In stone-washing, the pumice (unimpregnated with chemicals) is tumbled with the fabric and water and the bleached

TABLE 7—Domestic laundry pumice consumption, 1988–1993 (Bolen, 1991, 1992, 1993, 1994). e = estimated

Year	Percent of Total Consumption	Estimated Value (1000 $)
1988	2.8[e]	3,259
1989	5.0[e]	6,990
1990	8.8	10,285
1991	9.5	9,217
1992	14.4	15,235
1993	9.0	11,088





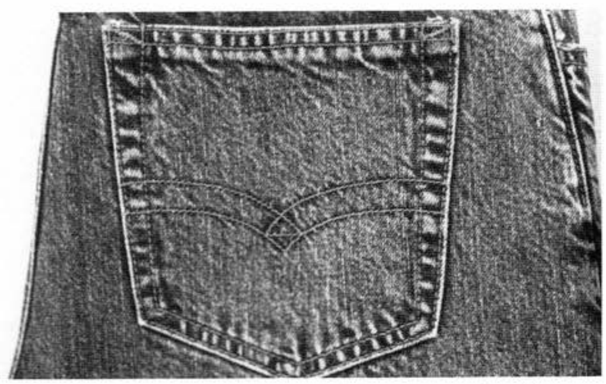


Figure 6—Top, acid-washed denim with high contrast produced by tumbling of potassium permanganate impregnated pumice with denim; middle, acid-washed denim with less contrast from longer tumbling time; bottom, stone-washed denim produced from abrasion by unimpregnated pumice during wet tumbling.

look is produced by the abrasion of the outer surface of the fabric. The net result of both processes is to soften the denim fabric and impart a worn look to the garment. There are a multitude of looks that can be produced by the pumice, ranging from a splotchy pattern of high contrast to an even finish of light blue to nearly white.

Before mid-1988, no specifications existed that would aid in the identification of pumice suitable for denim washing; acceptable pumice was determined in the industry by trial and error. Since late 1988, the author has tested more than 400 pumice samples from the United States (California, Idaho, Oregon, Utah, Arizona, Hawaii, Washington, and New Mexico), Indonesia, Turkey, Ecuador, Guatemala, Canada, Greece, Panama, and Mexico in order to develop a set of physical property specifications that could be used to identify suitable pumice for acid- and stone-washing. The major physical properties that were found to be useful in selecting a specific pumice for washing use include moisture content, apparent density, abrasion loss, absorption capac-

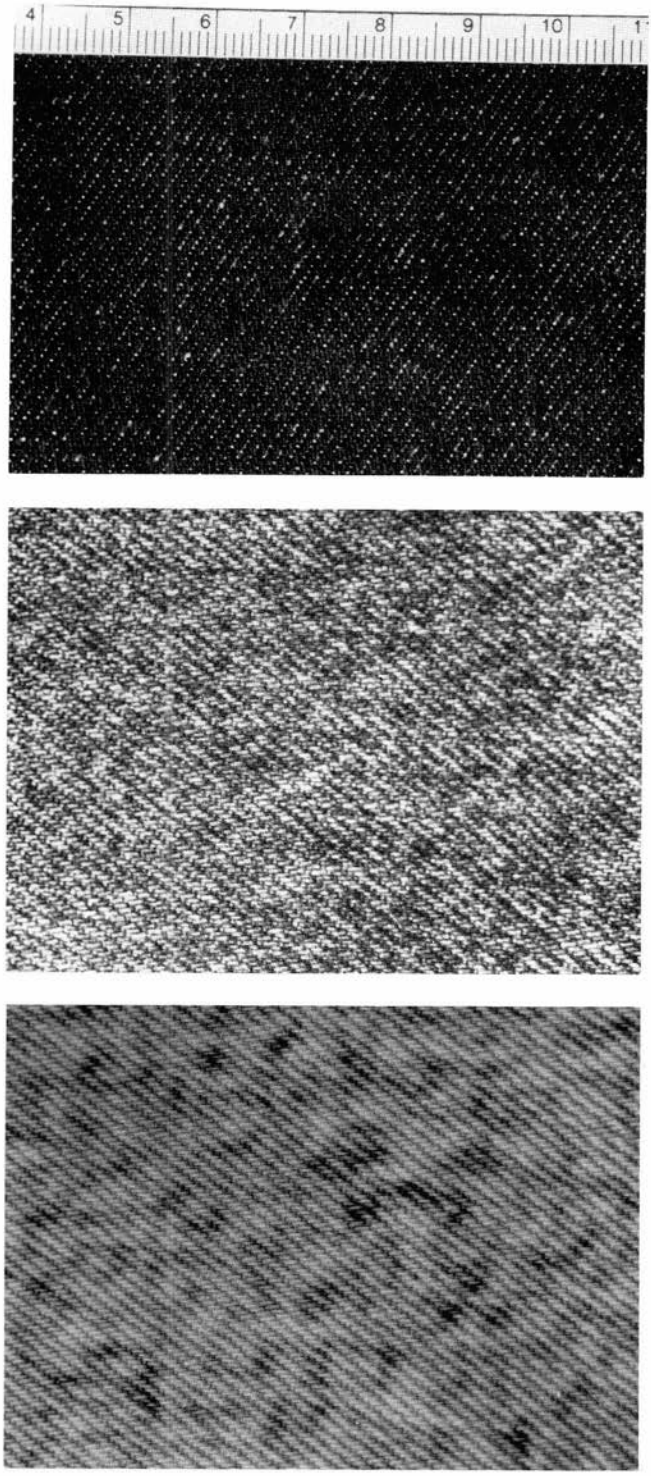


Figure 7—Close-up of untreated, stone-washed, and acid-washed denim fabric. Top, untreated denim; middle, stone-washed denim—bleaching is from pumice abrasion; bottom, acid-washed denim—bleaching is from oxidizing chemicals, potassium permanganate or bleach, released from the pumice (scale in centimeters).

ity, impregnation rate, and surface fines and coloration (Hoffer, 1989).

In addition to these physical properties, pumice size is a significant factor. Pumice fragments in the industry are referred to as small (1.9-3.2 cm, 0.75-1.25 in. in diameter), medium (3.2-5.1 cm, 1.25-2.00 in.), or large (5.1-7.6 cm, 2.0-3.0 in.). The small diameter fragments, when tumbled with denim fabric, will produce an even worn look, whereas the coarser fragments will produce a splotchy pattern.

Pumice properties and laundry use

The various physical properties are not of equal importance in evaluating a pumice for laundry use. Absorption capacity, apparent density, and abrasion loss are the most useful overall.

Another point to consider in evaluating a pumice is its intended use. If the pumice is to be used for stone-washing, abrasion-loss and density are most important. Absorption capacity and impregnation rate are not factors because the pumice carries no chemicals. If the pumice is used in acid-washing, then absorption capacity and impregnation rate are the important properties. A classification of the physical properties of pumice is shown in Table 8, and procedures for measuring the following physical properties of pumice are described in Appendix I.

Moisture content

A common problem with pumice is its moisture content. Pumice absorbs moisture during periods of precipitation. The amount of moisture entering the rock depends on the size of the vesicles and the amount of time it is in contact with water.

Moisture in pumice, which has been measured as high as 40 wt%, can affect processing in two ways: (1) if the pumice is to be impregnated with an oxidizing chemical for acid-washing, moisture will dilute the concentration of the chemical; and (2) if the pumice is purchased by weight, the buyer is paying for water not rock. The ideal pumice should contain not more than 5 wt% moisture.

Pumice moisture can be eliminated by heat drying, but this is relatively expensive. It can be reduced by air drying, but this is time consuming and generally ineffective for fragments with a diameter greater than 3.8 cm (1.5 in.) in diameter (Hoffer, 1993).

Apparent density

Although the true density of unexpanded volcanic glass is about 2.5 g/cm^3 (156 lb/ft^{-3}), the cellular structure gives pumice an apparent density of less than 1.0 g/cm^3 (62.4 lbs/ft^3). A wide range of densities can be tolerated in the washing process, but the most acceptable are those between 0.5 and 0.85 g/cm^3 (31.2 and 53.0 lbs/ft^3). Pumice fragments with densities greater than 0.85 g/cm^3 (53.0 lbs/ft^3) have relatively low porosity and are unsuitable for acid-washing. In addition, they will generally increase in density to over 1.0 g/cm^3 (62.4 lbs/ft^3) as they absorb water during washing and sink. Low density pumices, less than 0.50 g/cm^3 (31.2 lbs/ft^3), will generally produce only a small amount of abrasion and are undesirable for stone-washing.

Pumice samples measured in this study have apparent densities ranging from 0.39 to 1.14 g/cm^3 (24.3 to 71.1 lbs/ft^3); the average value is 0.70 g/cm^3 (43.7 lbs/ft^3). Approximately 62% of the densities measured occur within the interval of 0.50 to 0.80 g/cm^3 (31.2 to 49.9 lbs/ft^3).

Abrasion loss

The rate of disintegration of the pumice fragments during tumbling in a laundry rifle machine is referred to as the abrasion loss. The pumice fragments are weighed before and after tumbling for 15 minutes, and the loss of weight is reported as a percentage. Low-abrasion loss indicates hard pumice with slow disintegration, whereas high loss indicates softer pumice with more rapid disintegration during the washing process. Measured abrasion losses range from 8 to 70%; the average, based upon 240 samples, is 31%.

TABLE 8—Classification of pumice physical properties; see text for an explanation of each property.

	Designated Classes				
Properties	High	Medium-high	Medium	Medium-low	Low
Moisture Content (wt%) 175 samples tested	> 20	16–20	11–15	5–10	< 5
Apparent Density (g/cm³) 325 samples tested	> 1.0	0.85–1.0	0.60–0.84	0.40–0.59	< 0.40
Abrasion Loss (wt%) 240 samples tested	> 44	36–44	25–35	15–24	< 15
Absorption Capacity (wt%) 320 samples tested	> 30	25–30	20–24	10–19	< 10
Impregnation Rate (wt%/minute) 275 samples tested	> 5.5	4.5–5.5	3.5–4.4	2.0–3.4	< 2.0
Surface Fines (wt%) 200 samples tested	> 6.0	4.0–6.0	3.0–3.9	1.0–2.9	< 1.0

Absorption capacity

The absorption capacity of pumice is defined as the amount of liquid that is absorbed by the pumice during submergence. Factors that influence absorption include the size, shape, and the amount of vesicles in the pumice. In general, pumice with large vesicle diameters possess the highest absorption values. Absorption capacity is very important in acid-washing, because it determines the amount of oxidizing liquid, either potassium permanganate or bleach, that can be absorbed and then released onto the garment by the pumice. An absorption capacity of 30% or above is preferred for acid-washing. In general, pumice with high absorption capacity are those of low-apparent density, i.e. < 0.60 g/cm³ (<37.4 lbs/ft³). For stone-washing, pumice absorption is not a factor. Measured pumice absorptions from more than 320 samples range from 1 to 56%; the average value is 23%.

Impregnation rate

The impregnation rate represents the rate of liquid absorption by the pumice. By knowing the amount and rate of liquid absorption, one can estimate the rate of chemical release from the pumice during acid-washing. Large vesicles and high-absorption capacity correlate with high-impregnation rate. The impregnation rate is estimated by calculating the percentage of weight gain from liquid absorption during a five minute period. Measurements from 275 pumice samples show that the impregnation rate ranges form 0.6 to 11.3; the average is 3.9.

The recommended physical properties for pumices utilized in acid- and stone-washing are summarized in Table 9. Once the physical properties of a pumice are measured, the table can be used to determine if the pumice is suitable for washing use and if it is best suited for acid- or stone-washing.

Surface fines and coloration

Surface fines include fine-particle glass fragments or clay minerals that adhere to the outer surface of the pumice. The glass fragments result from fragmentation of the vesicle walls and, when abundant, tend to plug the vesicles reducing the porosity and the amount of chemical the pumice can carry. Alteration products, such as smectile clay minerals, occasionally adhere to the outer surface of the pumice. The clay particles not only reduce the pumice porosity, but in acid-washing, they will absorb the oxidizing chemical and release it faster than pumice alone during contact with a garment. The result is a highly bleached streak across the fabric which will cause the garment to be rejected. If these surface fines exceed 5 wt%, they should be removed by washing or tumbling the pumice prior to its use.

Pumice that contains more than 5 wt% yellowish- or reddish-brown iron oxides should be avoided. These iron oxides become mobilized during acid-washing and are subsequently deposited on the garment during tumbling. The result is a light yellow or brown color on the finished garment which will cause it to be rejected.

Pumice and pumicite deposits and occurrences in New Mexico

Introduction

The principal pumice-pumicite deposits occur within the volcanic units associated with the Jemez Mountains in Santa Fe, Sandoval, Rio Arriba, and Los Alamos counties of north-central New Mexico. Formation of the Jemez Mountains occurred during the last 13 million years, culminating in the development of the resurgent Valles caldera with associated ash-flow tuffs (Smith and Bailey, 1966; Self et al., 1988).

Other areas of the state that contain pumice or pumicite deposits or occurrences include: (1) an epiclastic deposit just east of San Antonio in Socorro County; (2) East Grants Ridge area, Cibola County; and (3) the Mogollon—Datil volcanic field in the southwest part of the state, mainly in Catron, Grant, Sierra, and Socorro counties.

Jemez Mountains

Current production of pumice is derived from volcanic units associated with the Valles caldera. These units consist of Plinian pyroclastic ash-fall deposits of the 1.45 Ma lower Bandelier Tuff and the post-caldera 0.17 Ma, El Cajete Pumice, east, west, and south of the volcano. Current production is from the lower Bandelier Tuff east (Pajarito Plateau) and from the El Cajete Pumice south of the caldera.

The rocks of the Pajarito Plateau consist of nearly horizontal Quaternary volcanic rocks (upper and lower Bandelier Tuff) underlain by Tertiary fluvial sands and gravels of the Puye Formation (Figure 8). The lower Bandelier (Otowi Member) is composed of a basal pumice-fall unit (Guaje Pumice Bed), intermediate flow and surge deposits, and an upper series of lithic-rich ash-flow units (Self et al., 1986). The Guaje Pumice Bed averages 7.6 m (25 ft) in thickness, is only slightly indurated, and consists of an off-white pumiceous tuff of pyroclastic-fall origin. Coarse pumice (greater than 19 mm or 3/4 in.) comprises about 6 wt% of the pumice bed (Figure 9).

TABLE 9—Physical properties recommended for acid- and stone-washing pumice.

Properties	Acid-Washing	Stone-Washing
Moisture content	< 5 wt%	Not a factor unless purchased by weight
Apparent density	0.50–0.70 g/cm^3 (31.2–43.7 lbs/ft^3)	0.70–0.85 g/cm^3 (43.7–53.0 lbs/ft^3)
Abrasion loss	35 wt%	< 20–25 wt%
Absorption capacity	> 30 wt%	Not a factor
Impregnation rate	4.0–7.0 %wt increase/min.	< 4.0 %wt. increase/min.
Surface fines and coloration	If fines exceed 5 wt%, wash before use; reject if iron oxide stain exceeds 5 wt%.	

The Guaje Pumice Bed is exposed on the topographic flats and benches where the upper Bandelier Tuff has been stripped away by erosion; a thin veneer of overburden, 0.30.6 m (1-2 ft) in thickness, generally occurs on the pumice bed. In the northeast portion of the Pajarito Plateau, Kelley (1949) estimates the reserves of the Guaje Pumice Bed to be approximately 55,539,000 mt. An additional 2 billion mt of pumice are estimated to exist under the upper Bandelier Tuff on the Pajarito Plateau. Copar Pumice Company, Inc. and General Pumice Corporation are currently producing from the Guaje Pumice Bed of the lower Bandelier Tuff in Santa Fe County, sec. 31-32, T2ON, R7E (Figure 8) and Rio Arriba County, sec. 34, T21N, R7E, respectively (Figure 9).

Directly south of Redondo Peak scattered outcrops of the lower Bandelier Tuff overlie Tertiary volcanic rocks of the Paliza Canyon Formation. Utility Block Company is mining pumice from the Guaje Pumice Bed in this area of Sandoval County, sec. 35, T18N, R3E.

The Valles Rhyolite is one of the youngest units associated with the Valles caldera. It consists of a basal pyroclastic-fall unit, El Cajete Pumice (Figure 10), which also contains pyroclastic flow and surge deposits; the Battleship Rock ignimbrite; and the Banco Bonito rhyolite lava flow (Figure 11; Self et al., 1988). The El Cajete Pumice is widespread, with coarse particles, and has the general characteristics of a typical Plinian deposit (Walker, 1981). Deposits occur east and south of the Jemez Mountains at distances of up to 43.4 km (27 mi) from the vent, which may be located along the southern ring-fracture zone of the caldera (Self et al., 1988).

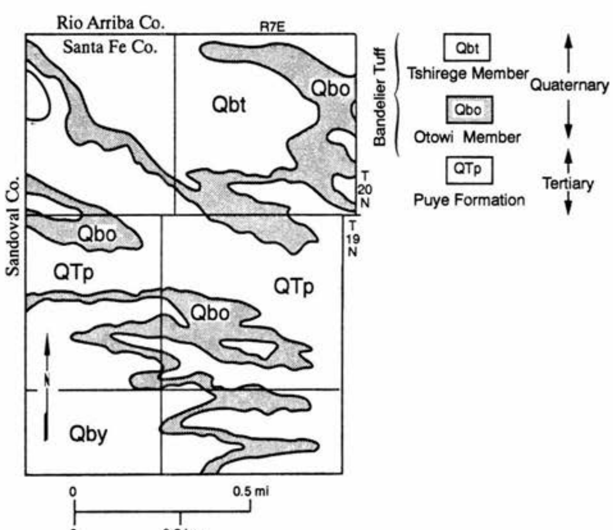


Figure 8—Geologic map showing the distribution of the Guaje Pumice Bed (Otowi Member) of the Bandelier Tuff, east of the Valles caldera (Kelly, 1949).

The El Cajete Pumice consists of interbedded tan to white pumice-fall units and white to pink, nonwelded pyroclastic-surge deposits (Self et al., 1988). The unit ranges in thickness from 1 to 9 m (3 to 30 ft) with an estimated volume of 4 km^3 (0.9 mi^3) and an estimated weight of 341,000 mt.

Copar Pumice Company, Inc. is currently mining pumice from the El Cajete Member south of the East Fork of the Jemez River (sec. 5, T18N, R4E) (Figure 11). Their plan to expand the mining to the east has met with stiff resistance from local environmental groups who want to preserve the scenic beauty of the area. In early 1990, legislation was introduced and passed in the U.S. Congress to declare an

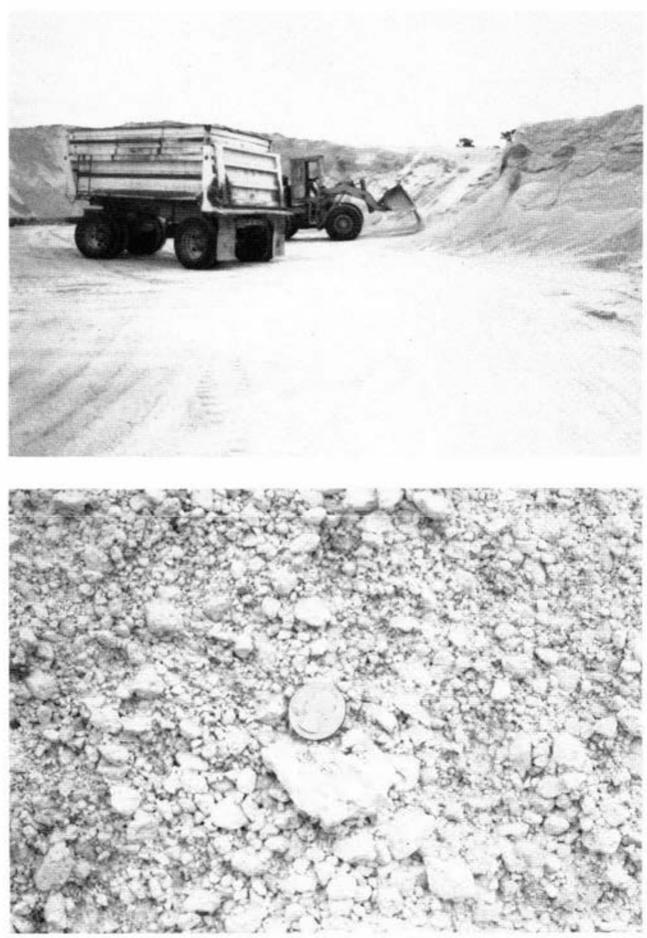


Figure 9—Guaje Pumice Bed, at the base of the Otowi Member, Bandelier Tuff, sec. 32, T20N, R7E, Santa Fe County. Top, approximately 10 yd^3 of pumice per load are trucked to the screening plant at Cuayamungue, 7 km (12 mi) north of Santa Fe. Bottom, close-up of pumice fragments from the Guaje Pumice Bed; coarse fragments (19 mm, 3/4 in) comprise about 6% of the deposit.

Figure 10—El Cajete Member of the Valles Rhyolite, sec. 5, T18N, R4E, Sandoval County. Top, approximately 1,800 yd³ are mined per day from this quarry and trucked to a screening plant at San Ysidro, 40.2 km (25 mi) northwest of Bernalillo. Bottom, close-up of pumice fragments from the El Cajete Member; coarse fragments (19 mm, 3/4 in.) comprise 45% of the deposit.

additional 99,000 acres in the region off limits to mining (Austin, pers. comm., 1993).

San Antonio area

An epiclastic pumice deposit 3.2 km (2 mi) east of San Antonio is currently under development by Mission Mining of Las Cruces (secs. 27 and 34, T4S, R1E). The deposit is composed of cobble-sized pumice lumps, 2 to 16 cm (0.8 to 6.3 in.) in diameter in a matrix of fluvial sediments and volcanic ash. The pumice layer, averaging 2 m (6.6 ft) in thickness, is overlain by 0 to 1.8 m (0 to 6 ft) of river sands and gravels and underlain by a thin ash-rich fluvial flood deposit (Figure 12; Cather, 1988a). Mission Mining reports that the deposit contains 55% coarse pumice (3.8 cm; 1.5 in.) with total reserves of lump pumice at approximately 56,000 mt.

The pumice was reportedly derived from the Jemez Mountain area by a single flood event 1.1 to 1.5 m.y. ago that transported the pumice fragments 212 km (132 mi) downstream from their source (Cather, 1988b). The San Antonio pumice has a very high apparent density, which is significantly higher than any pumice from the Jemez area tested by the author; it averages 0.91 g/cm³ (55.8 lbs/ft³). The majority of the pumice fragments sink within a few seconds when placed in water and, therefore, probably could not have floated downstream any great distance. The pumice was probably transported from the Jemez Mountains as a debris flow (Cather 1988b).

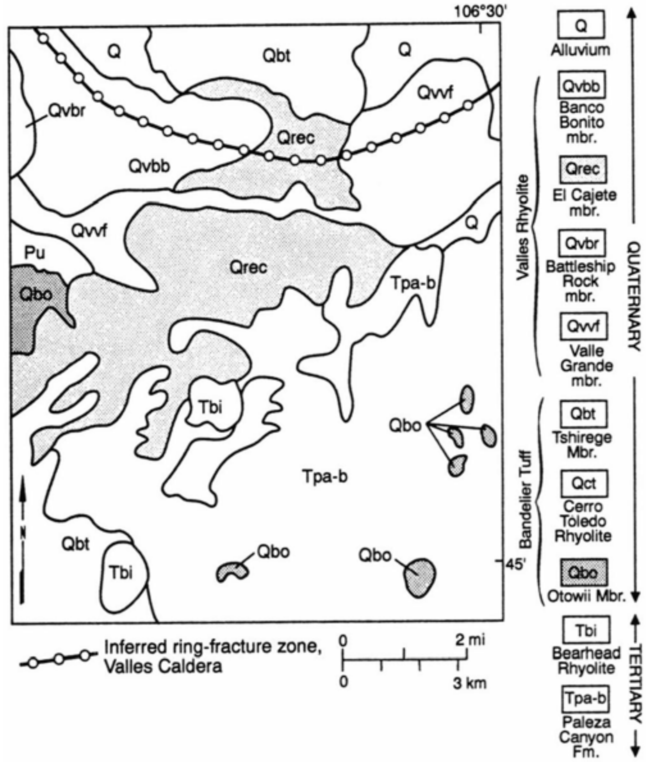


Figure 11—Geologic map showing the distribution of the El Cajete Member of the Valles Rhyolite south of the Valles caldera (modified from Smith et al., 1970).

East Grants Ridge

Pumiceous lapilli tuffs in East Grants Ridge (Figure 13) about 8 km (5 mi) northeast of Grants in Cibola County, were formerly a source of high-quality abrasive pumice (Weber, 1965). From July 1946 to 1952, a total of 59,472 mt of pumice was produced by the Pumice Corporation of America. The rhyolite pumice occurs in blocks and lumps along with fragments of rhyolite and other rocks in a matrix of pumicite. Bassett et al. (1963) describes the pumiceous occurrences as consisting of an upper reddish pumice breccia, an intermediate layer of bedded ash, and a lower rhyolitic tuff; the pumice was mined from the lowest tuff layer which has a K—Ar age of 3.2-0.3 Ma (Bassett, et al., 1963).

U.S. Gypsum purchased the pumice claims in 1953, but no production has been reported (Barker et al., 1989). Large reserves remain in the deposit, but the pumice is overlain by a 6-9 m (20-30 ft) thick basalt lava flow which would make open-pit mining very expensive (Figure 14).

Mogollon—Datil Volcanic Field

The Mogollon Plateau forms the core of the Mogollon-Datil volcanic province in southwestern New Mexico. The

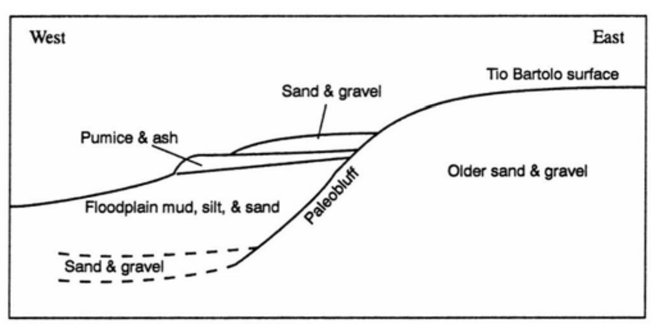


Figure 12—Sketch cross section of the San Antonio pumice deposit, no scale (from Cather, 1988b).

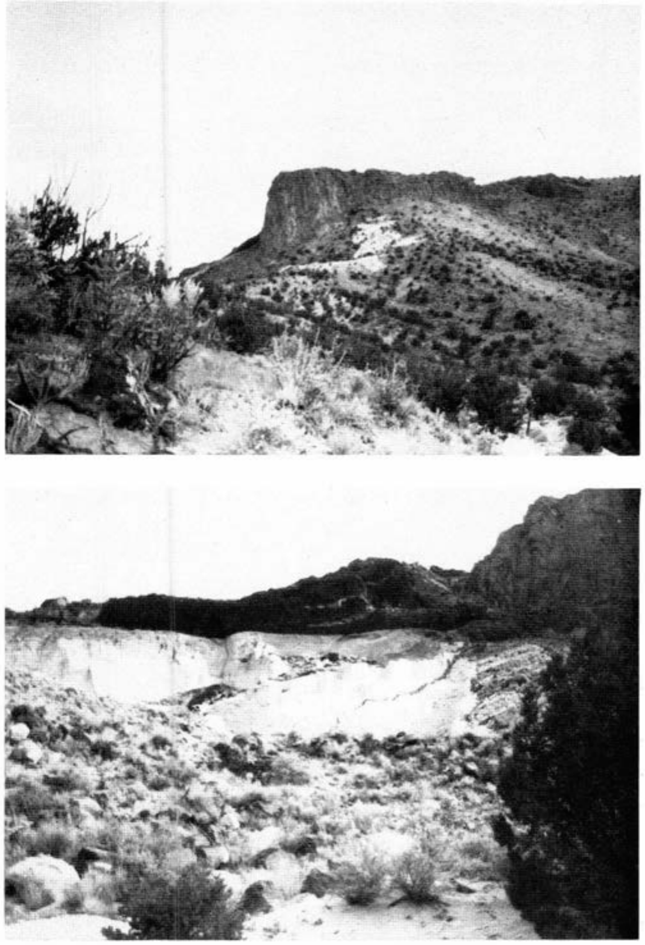


Figure 13—East Grants Ridge pumice deposit. Top, pumice layers (white) capped by basaltic lava flows; basalt plug on left side of hill. Bottom, inactive pumice quarry overlain by a basaltic lava flow, basaltic plug to right. This property is currently owned by U.S. Gypsum Corporation.

field is made up of mid-Tertiary lava flows, epiclastic rocks and pyroclastic units which include voluminous and extensive ash-flow tuffs (Elston et al., 1976). The source of the ash-flow tuffs appears to be from calderas, 22 of which have been identified in southwestern New Mexico (Elston et al., 1976). The existence of three overlapping magma suites were responsible for the volcanic rocks in the region (Elston et al., 1976). The three proposed magma suites include: (1) an

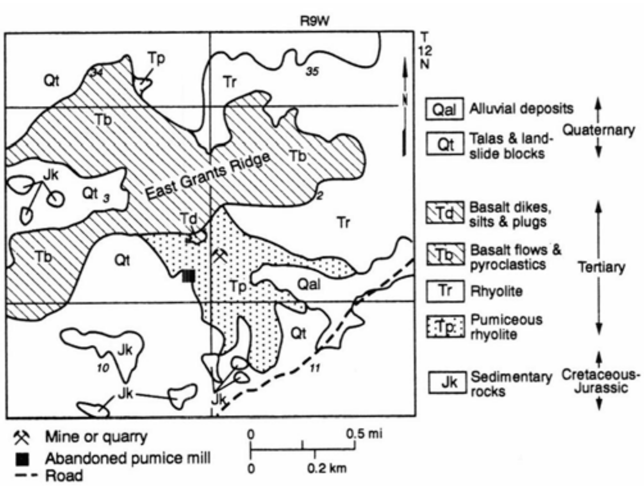


Figure 14—Geologic sketch map of the East Grants Ridge pumice deposit (modified from Barker et al., 1989; and from Thaden et al., 1961).

early calc-alkalic, andesite to rhyolite suite; (2) a high silica alkali rhyolite suite, and (3) a basalt and basaltic andesite suite.

Recent $40^{Ar}/39^{A}r$ dating and paleomagnetic analyses by McIntosh et al. (1991) indicate that the Mogollon—Datil ignimbrite activity was strongly episodic and confined to four brief (< 2.6 m.y.) eruptive periods separated by 1-3 m.y. lulls in activity. The ignimbrite volcanism generally migrated from southeast toward the north and west during the following episodes: I = 36.1-33.5 Ma; II = 32.0-31.3 Ma; III = 28.9-27.3 Ma; and IV = 24.3 Ma (McIntosh et al., 1991).

Pumice is a common occurrence in high-silica rhyolitic-tuffs such as those associated with eruptive episodes III and IV. A survey of the stratigraphic terms published on the Mogollon—Datil volcanic field indicates that rhyolitic pumice and pumicite do occur in the region, predominantly associated with the 21-37 Ma alkali-rhyolite suite. The dis-, tribution of high-silica alkali-rhyolite ash-flow tuffs are shown in Figure 15.

Table 10 summarizes the pumice-pumicite mines in New Mexico, including information on location, operators, current status, and production, where available. The locations of all known pumice-pumicite occurrences in New Mexico reported in the literature or from the New Mexico Bureau of Mines and Mineral Resources files are summarized in Table 11.

Physical properties of selected New Mexico pumice deposits

Twenty-six pumice samples have been tested from the Bandelier Tuff (Guaje Pumice Bed), El Cajete Member of the Valles Rhyolite, the epiclastic Jemez-derived San Antonio deposit, and the East Grants Ridge deposit. A sum-

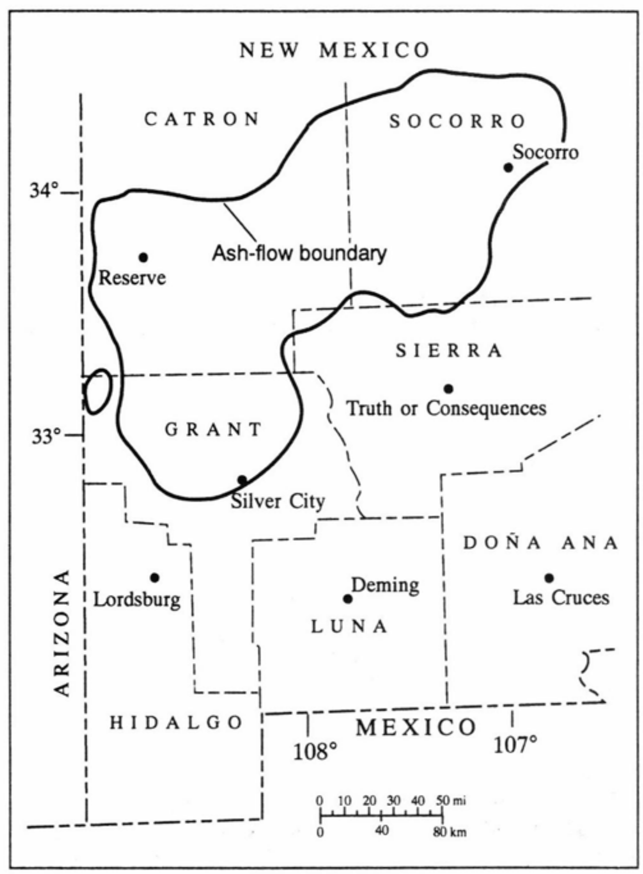


Figure 15—Generalized distribution of high-silica alkali-rhyolite ash-flow tuff sheets Mogollon–Datil volcanic province (Elston et al., 1976).

TABLE 10—Pumice and pumicite mines and deposits in New Mexico (modified from Hatton et al., 1993). Map Number refers to locations in Fig. 1.

County	Map Number	Location	Operators	Address	Status	Production
Santa Fe	1	T20N, R7E, secs. 31, 32	Copar Pumice, Inc	Box 38, Española, 87532 Wayne Brown 505/455–2145	active	100 mt/day (200 yd³/day)
Sandoval	2	T18N, R4E, sec. 5	Copar Pumice, Inc.	same as above	active	600 mt/day 1,250 yd³/day)
Sandoval	3	T18N, R4E, sec. 7	Mission Mining, Inc.	Box 455 Las Cruces, 88004 Ben Schaberg 505/526–5276	inactive	
Sandoval	4	T18N, R4E, sec. 14	Mission Mining, Inc.	same as above	inactive	
Sandoval	5	T17N, R3E, sec. 3	Utility Block, Co.	7200 2nd St., NW Albuquerque, 87197 John Duran 505/753–2145	active	31 mt/day (60 yd³/day)
Rio Arriba	6	T21N, R7E, sec. 34	General Pumice Corp.	Box 5135 Santa Fe, 87502 R.W. Alley 505/982–0411	active	124 mt/day (240 yd³/day)
Cibola	7	T11N, R9W, sec. 2, 3, 11 T12N, R9W, sec. 34	U.S. Gypsum, Co.	Box 216 Grants, 87020 L.R. Stokes, 505/287–4211	inactive since 1953	
Socorro	8	T4S, R1E, sec. 27, 34	Mission Mining, Inc.	Box 455 Las Cruces, 88004 Ben Schaberg 505/526–5276	inactive	

mary of the physical properties from each occurrence is given in Table 12.

The Guaje Pumice Bed contains light-gray to white lump pumice and ranges in thickness from 8 to 12 m (24 to 36 ft); the pumice lumps occur up to 7.6 cm (3 in.) in diameter (Griggs, 1964). The pumice is of average density, is moderately hard, and displays a low-abrasion loss during tumbling. Its average absorption capacity of 25 wt% would make it marginal for acid-washing; it appears to be more suited for stone-washing.

The pumice of the El Cajete Member is light tan to gray and ranges in thickness from 1 to 9 m (3 to 30 ft). The physical properties of this pumice are very similar to the Guaje Pumice Bed, except that the 0.3% of fines is much lower than the 1.8% of Guaje pumice. Its absorption capacity averages 24 wt%, and therefore it rates marginal for acid-washing use. Because the El Cajete pumice is much coarser than the Guaje pumice, i.e. 32% vs 5% greater than 19 mm (3/4 in.), it is a more desirable source for laundry use (Figure 16).

The pumice clasts of the San Antonio deposit are light-gray to white and occur in fragments up to 15.2 cm (6 in.) in diameter. The pumice fragments possess high-absorption capacity and impregnation rate which are suitable for acid-washing. Because of its high density of 0.91 g/cm³ (56.8 lbs/ft³), it tends to sink after absorbing chemicals or when in contact with water and is therefore undesirable for either stone- or acid-washing. Its higher-than-normal apparent density is from the occurrence of up to 15%, by weight, crystalline materials which include small crystals of quartz, feldspar, and minor mafic minerals (Figure 16).

The pumice from East Grants Ridge is hard, has a low abrasion loss, and has less than 10% absorption capacity. These properties indicate that the pumice should be excellent for stone-washing.

New Mexico producers and markets

Producers and current markets

Presently, four active mines produce pumice and pumicite from deposits on the eastern and southern flanks of the Valles caldera in Santa Fe, Sandoval, and Rio Arriba counties with pumice mills in Bernalillo, Sandoval, and Santa Fe counties (Barker et. al., 1993).

Copar Pumice Company, Inc., produces from two separate mines. One quarry is located east of the caldera in Santa Fe County, and the pumice (Guaje Pumice Bed of the Otowi Member, Bandelier Tuff) is marketed for light-weight aggregate. Current production is approximately 76,500 m³ (100,000 yd³) per year. The second quarry is extracting pumice from the El Cajete Member of the Valles Rhyolite located in Sandoval County on the south flank of the caldera, 33 km (20 mi) west-southwest of Espanola. Approximately 60% of the pumice is marketed for laundry use and the remainder is sold for landscaping, horticultural use, lightweight aggregate, and erasers (McMichael, 1990).

General Pumice Company is mining the Guaje Pumice Bed east of the caldera approximately 16 km (10 mi) northwest of Espanola in Rio Arriba County. Production is approximately 45,900 m³ (60,000 yd³) per year, and the pumice is marketed for dental polishes, soaps, and light-weight aggregate (McMichael, 1990).

Utility Block Company mines approximately 22,950 m³ (30,000 yd³) per year from the Guaje Pumice Bed south of the caldera in Sandoval County. All the production is utilized by the company in the construction of light-weight building blocks.

Two additional pumice properties were under development by Mission Mining, Inc., of Las Cruces in 1991. One property in Sandoval County is associated with the El Cajete Member of the Valles Rhyolite. The second property

TABLE 11—Pumice and pumicite occurrences in New Mexico. Map Number refers to locations in Fig. 1; NMBMMR = information derived from the files of the New Mexico Bureau of Mines and Mineral Resources.

County	Map Number	Location	Material	Reference and Comments
Catron	9	T11S, R19W, sec. 3	Pumice	Bedded pumice deposits in the Deadwood Gulch Rhyolite; 26.9 Ma (McIntosh et al., 1991)
Catron	10	T2S, R1W, secs. 25, 26, 30	Pumice-Pumicite	Minor ash-fall tuff (Elston, 1976)
Catron	11	T11S, R14W, sec. 25	Pumice	Pumiceous rhyolite tuff of Jordan Canyon Formation, 26.1 Ma (McIntosh et al., 1991)
Catron	12	T11S, R16W	Pumicite	Jerky Mountain Rhyolite, flow banded rhyolite and associated pumiceous tuff; 23–26 Ma (Elston, 1976)
Catron	13	T10S, R19W, secs. 28, 33	Pumice	Fanney Rhyolite, banded pumice-flows at base of flow-banded rhyolite; 27–28 Ma (Elston, 1976)
Catron	14	T11S, R20W T12S, R20W	Pumice	Mule Creek deposits, NMBMMR
Cibola	15	T11N, R9W, secs. 3, 4	Pumicite?	NMBMMR
Cibola	16	T11N, R8W, secs. 1, 2, 10, 15	Pumicite?	NMBMMR
Cibola	17	T12N, R8W, sec. 29	Pumicite?	NMBMMR
Cibola	18	T10N, R15W, sec. 34	Pumicite?	Mineral Products Co., NMBMMR
Cibola	19	T12N, R9W secs. 34, 35, 36	Pumice	Pumice Corporation of America, NMBMMR
Grant	20	T15S, R17W, T15S, R18W	Pumicite	West side of Duck Creek in northwest Grant Co.; 6–15 m (20–50 ft) exposed along highway above Cliff (Ellis, 1930)
Grant	21	T19S, R10W, sec. 28	Pumice	Ash-fall and water-laid tuff of the Sugarlump Tuff, 35.1 Ma (Elston, 1989; McIntosh et al., 1991).
Grant	22	T19S, R10W, sec.8	Pumice	Mimbres Peak Formation rhyolite flows, domes, pumiceous tuffs; 34.5 Ma (Elston, 1989; McIntosh, 1991).
Hidalgo	23	T24S, R19W, secs. 12, 13, 15	Pumice	Pyramid Mtns.; small amounts of pumice mined in 1950 (Weber, 1965)
Rio Arriba	24	T21N, R7E, secs. 32, 33, 34, 35 T20N, R7E, sec. 17	Pumice-Pumicite	Kelly (1949)
Sandoval	25	T17N, R3E, secs. 10, 11	Pumice	NMBMMR
Sandoval	26	T17N, R5E, secs. 16, 27, 28, 34	Pumice	NMBMMR
Sandoval	27	T20N, R6E, secs. 1, 2, 12	Pumice-Pumicite	Kelley (1949)
Sandoval	28	T18N, R4E, sec. 13	Pumice-Pumicite	NMBMMR
Santa Fe	29	T19N, R7E, secs. 4, 5, 6, 8	Pumice	Kelley (1949)
Sierra	30	T16S, R8W	Pumicite	Pumicite on both sides of Percha Canyon between Hillsboro and Kingston, 5 m (15 ft) thick (Ellis, 1930).
Socorro	31	T8S, R3W	Pumice	Near Ft. Craig, NMBMMR (Cather (1988a, b).
Socorro	32	T1S, R3W	Pumice	Bedded pumiceous tuff 7.2 km (4.5 mi) northwest of Magdalena; impure pumice (Weber, 1965).
Valencia	33	T7N, R1E	Pumicite	8 km (5 mi) west of Los Lunas; Gold Seal Products, Albuquerque (Talmage and Wootten, 1937).

Table 12—Physical properties of selected New Mexico pumice deposits. R = range; H = high; MH = medium high; M = medium; ML = medium low; L = low. See Table 5 for classification scheme.

	Bandelier Tuff Otowi Member Guaje Pumice Bed sec. 31, T20N, R7E; sec. 33, T21N, R7E; and sec. 3, T17N, R3E 7 samples	Valles Rhyolite El Cajete Member secs. 5, 7, and 14 T18N, R4W 10 samples	San Antonio secs. 27 and 34, T4S, R1E 7 samples	East Grants Ridge Lower rhyolitic tuff sec. 3, T11N, R9W 2 samples
Surface Fines (wt%)	R 0.4–4.3 Avg. 1.8 ML	R 0.1–0.5 Avg. 0.3 L	R 0.6–1.1 Avg. 1.0 ML	R 0.1–0.2 Avg. 0.2 L
Apparent Density (g/cm^3)	R 0.60–0.84 Avg. 0.74 M	R 0.64–0.79 Avg. 0.73 M	R 0.68–1.04 Avg. 0.91 MH	R 0.74–0.78 Avg. 0.76 M
Abrasion Loss (wt%)	R 21–34 Avg. 27 L	R 20–30 Avg. 23 M	R 34–40 Avg. 37 MH	R 15–19 Avg. 17 ML
Absorption Capacity (wt%)	R 7–51 Avg. 24 M	R 15–30 Avg. 24 M	R 24–41 Avg. 30 MH	R 7–8 Avg. 8 L
Impregnation Rate (wt% increase/minute)	R 1.3–10.2 Avg. 4.8 MH	R 3.1–6.0 Avg. 4.8 MH	R 4.8–8.3 Avg. 7.0 H	R 1.5–1.7 Avg. 1.6 L
Particle size (% $\geq$ 29 mm or 3/4 in.)	R 1–8 Avg. 5	(sec. 5) R 29–59 Avg. 44	> 38 mm (1.5 in.) R 45–60 Avg. 55	R 7–21 Avg. 14

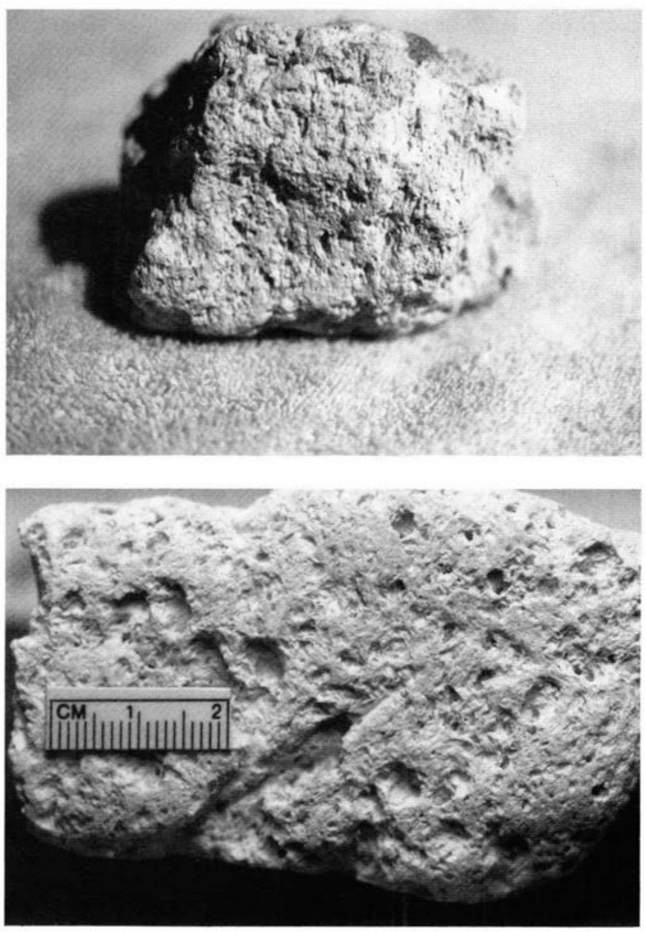


Figure 16—Top, El Cajete Member pumice fragments, 7.6 cm (3 in.) maximum diameter, from the Las Conchas mine, Sandoval County. The pumice has small equidimensional vesicles with an absorption capacity of approximately 25 wt% with a density of 0.75 g/cm^3 (47 lb/ft^3). Bottom, pumice fragment from the San Antonio deposit, Socorro County. The pumice contains small to large irregular-shaped vesicles; the absorption capacity is 35 wt% with an apparent density of 0.91 g/cm^3 (55.8 lb/ft^3).

is an epiclastic deposit in Socorro County approximately 16 km (10 mi) east of San Antonio. Neither of the above properties produces pumice commercially and are inactive at present.

Future markets

Prior to the late 1980's, the vast majority of New Mexico's pumice was utilized in the construction industry. In 1987, pumice production in the state dropped more than 60% because of decreased construction use. However, during this same period, pumice used as an abrasive increased more than 70% because of the large demand for acid- and stone-washed jeans.

The largest current markets for laundry pumice are in Los Angeles and El Paso. In El Paso, more than 2500 mt (5 million lbs) per month are consumed by laundries; the majority of the pumice is imported. The price of bagged laundry pumice in 1992 delivered in El Paso ranges from $0.08 to $0.13/1b; the price variations are due to pumice quality and amount purchased. The largest factor that influences the selling price of the pumice is the transportation cost. Most of the foreign pumice delivered to El Paso is from Ecuador, Turkey, and Mexico with lesser amounts from Guatemala. The Central American and Turkish pumice is shipped to ports in Houston and New Orleans and then trucked to El Paso. Shipping charges to Houston or New Orleans range from $0.05 to $0.07/1b. Additional freight charges from Houston or New Orleans to El Paso are $0.02/1b or $0.03/1b, respectively.

The major pumice deposits in New Mexico are associated with the Valles caldera in the Jemez Mountains west of Los Alamos, a distance of approximately 563 km (350 mi) from El Paso. Transportation costs to El Paso would be about $0.01/1b compared to the $0.05—$0.07/1b for the imported pumice. In addition, the $130 to $285/mt paid for laundry pumice in El Paso greatly exceeds the $10 to $15/mt offered for pumice in the construction industry. Therefore, because of significantly lower transportation costs, New Mexico pumice should compete favorably with imported pumice in the El Paso market. A discussion of trends in the El Paso laundry market from 1984 to 1994 is found in Appendix B.

Summary

Pumice and pumicite resources are abundant in New Mexico which in 1993 ranked second in U.S. production. The principal commercial deposits are primarily pyroclastic-fall in origin and are associated with the Valles caldera in the north-central part of the state.

Currently, four active mines produce pumiceous materials from the 0.17 Ma El Cajete Member of the Valles Rhyolite (Copar Pumice Company, Inc.), and the 1.45 Ma Guaje Pumice Bed in the lower part of the Otowi Member of the Bandelier Tuff (Copar Pumice Company, Inc., Utility Block Company, and General Pumice Corporation). Additional occurrences include an epiclastic deposit near San Antonio, Socorro County, and a pyroclastic-fall deposit near Grants in Cibola County.

The principal uses of New Mexico pumice-pumicite are in the production of light-weight concrete, building blocks, and as abrasives. The use of pumice as abrasives has increased in the past several years in the U.S. because of the demand in the laundry industry to produce faded denim fabrics.

The quality and potential use of the New Mexico pumices has been determined by testing their physical properties, such as apparent density, absorption capacity, abrasion loss, surface properties, and impregnation rate. The results, based upon the analyses of 26 representative samples, indicate that New Mexico pumices are of average to good quality. Most of the pumices are suitable for concrete aggregate and Portland-pozzolan cements; the El Cajete pumice, because of its above average coarseness and overall acceptable physical properties, is the best pumice for laundry use.

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Appendix A
Procedures for measuring pumice physical properties

Apparent density

The apparent density of the pumice is measured by weighing the pumice and then submerging it in water (1000 ml graduated cylinder) and recording the number of cm^3 (1 ml = 1 cm^3) displaced by the fragment. In order to minimize the effect of infiltration of water into the pumice, the displaced volume of water is recorded within 5 seconds of submergence.

$$\textit{Apparent Density} = \left(\frac{\textit{Initial pumice weight, g}}{\textit{Volume of displaced water, cm}^3} \right)$$

Abrasion loss

The pumice abrasion loss is determined by the weight loss of pumice during tumbling for 15 minutes in a laundry rifle machine. The initial pumice sample is weighed (4–5 lb sample) and then reweighed after tumbling. The percent loss of weight during tumbling represents the percent abrasion loss.

$$\textit{Weight Percent Abrasion Loss} = \left(\frac{\textit{Weight loss}}{\textit{Initial weight}} \right) \times 100$$

Absorption capacity

The absorption capacity is measured by weighing the dry pumice fragment and then submerging it in water for 5 minutes. The pumice fragment is reweighed after the surface is dried. The increase in weight from absorbed water is used to calculate the absorption capacity. The time of 5 minutes is used because laundries commonly submerge pumice for 4–5 minutes to impregnate it with oxidizing chemicals.

$$\textit{Weight Percent Absorption Capacity} = \left(\frac{\textit{Submerged weight—Dry weight}}{\textit{Submerged weight}} \right) \times 100$$

Impregnation rate

The impregnation rate refers to the rate of liquid absorption by the pumice. It is calculated by dividing the percent weight gain after submergence by 5 minutes, the time of submergence.

$$\textit{Impregnation Rate} = \left(\frac{\textit{\% Weight gain with submergence}}{\textit{5 minutes}} \right)$$

Surface fines

Pumice surface fines are measured by weighing the pumice fragment and then removing the fines with a soft brush. The pumice is then reweighed and the weight loss represents the weight percentage of surface fines.

$$\textit{Weight Percent Surface Fines} = \left(\frac{\textit{Weight loss}}{\textit{Initial weight}} \right) \times 100$$

Surface coloration

The surface coloration is reported as the percentage of the pumice surface covered by iron oxides. The percentage of surface stains are visually estimated on 5 or more fragments and then reported as an average.

Appendix B
El Paso laundry pumice market: 1984-1994

The garment industry is one of El Paso's major employers and is the closest major market for New Mexico's laundry-grade pumice. In 1994, over 20,000 people were employed in the garment manufacturing and finishing fields (Table 13). Major U.S. clothing manufacturers such as Levi Strauss, Wrangler, Lee, and Farah have plants in the city. Approximately 25 laundries are involved in producing acid- and stone-wash finishes on the manufactured garments for both local and out-of-state companies and several in foreign countries. Most of the denim articles involve the use of pumice, with or without chemicals, to produce a faded or "bleached" look on the garment.

Laundry finishers work for the garment manufacturers on a contract basis. The manufacturer furnishes the laundry

Table 13—Garment industry employees in El Paso, 1994 (*El Paso Times*, September 11, 1993; February, 20, 1994; and July 10, 1994). e = estimated.

Company	Employees
Levi Strauss Company	4,600
Wrangler	2,400
Lee Company	1,740
American Garment Finishers	1,650
Border Apparel	1,500
Farah Manufacturing	850
International Garment Finishers	700
East-West Apparel	600e
Others (less than 600 employees)	6,460e
Total	20,500

a "standard" displaying the desired finish, and the laundry will develop a method to duplicate the "look" on the unfinished garments at a reasonable cost. If successful, the laundry will receive a contract to finish so many garments at a specific price and time. The major laundry finishers in El Paso include American Garment Finishers, Border Apparel, International Garment Finishers, East—West Apparel, and Border Apparel.

One of the first companies to enter the domestic market of supplying laundry pumice in El Paso was Ashco Industries. In mid-1984, Ashco retained the author to find a suitable source of pumice for fading denim garments. At that time, the major domestic source of laundry-grade pumice was distributed by U.S. Pumice in California under the product name Featherock; the pumice sold for approximately $0.40 per pound. Pumices were tested for Ashco from Arizona (Tufflite), New Mexico (Copar and Utility Block) and Mexico. The Mexican pumice was selected by Ashco, and they initialized local sales in 1985. Ashco's local sales did not remain successful, but they did develop a large market for their pumice in the eastern U.S.

Acid-washing

In 1986, the El Paso pumice market was served by Dyadic Industries (Chicago), Big Chief Stone (Las Cruces, distributor for Arizona Tufflite), and Ashco. In 1987 Dyadic controlled an estimated 50% of U.S market, followed by Big Chief Stone (bagged Arizona Tufflite)—Arizona Tufflite (bulk pumice) at 20% and the remaining 30% shared by 20 to 30 other distributors. In January 1987, Arizona Tufflite sold for approximately $0.08/1b in El Paso, whereas Dyadic's Glass Mountain and Ecuadorian pumices brought $0.17/1b. During this period of time, acid-washing was popular, and it required pumice with high-absorption capacity. The Ecuador pumice possessed very high, rapid, absorption capacity in contrast to the slower absorption of the Tufflite pumice. The Glass Mountain pumice was popular because laundries claimed it produced a "unique" acid-wash finish. For most of 1988, several El Paso laundries worked three 8-hour shifts per day to keep up with the demand for acid-washed garments. Pumice consumption by the El Paso laundries was estimated at three million pounds per month.

During the last quarter of 1988 and into 1989, because of a slow down in laundry finishing business, the list of pumice suppliers was reduced from approximately 25 to 8 major distributors. The eight remaining suppliers were Dyadic Industries (Chicago), Central Trading (Chicago), Stone Co. (Chicago), Ashco (El Paso), Omicron (El Paso), Denim Finishing Supply (Mobile), Touchstone (Chicago), and Arizona Tufflite (Flagstaff). All the above suppliers sold pumice to El Paso laundries except Ashco and Denim Finishing Supply who sold their pumice to laundries in the southeastern U.S. Dyadic, who controlled over half the El Paso market, was selling the Glass Mountain and Ecuador pumices for about $0.14—$0.16/1b. Also in 1988, Featherock ceased to sell laundry pumice; Ashco folded in late 1989. In 1990, the suppliers and pumice prices remained about the same as in the previous year.

In late 1990 and early 1991, El Paso pumice suppliers included Dyadic, Arizona Tufflite, Omicron, Central Trading, Stone Co., and a number of new distributors that included Quimica Minera (Mexico), Copar (New Mexico), and Phoenix Ash (El Paso). Because of the increased competition among suppliers, the average pumice price dropped from $0.14 to $0.12/1b. In April of 1991, Arizona Tufflite informed me that it would sell its pumice as low as $0.05/1b bulk, in El Paso.

In late 1991, the acid-washing process began to decline; this occurred because of two factors. The first is attributed to the environmental effects of acid-wash chemicals, and the second to a lawsuit (still pending as of August, 1994) involving a claim of patent infringement between a major U.S. clothing manufacturer and an El Paso garment finisher.

Stone-washing

With the decline in the production of acid-wash garments in late 1991, stone-washing production increased in popularity among the processors. This situation produced a couple of problems for the laundries. One, the profit margin is much less for stone-wash finishes than for acid-wash. Second, stone-washing requires a different pumice than is used in acid-washing. In the stone-wash processes, the rock is not impregnated with a chemical because the bleaching effect is produced mechanically by abrasion on the fabric. The desired pumice is generally hard with low abrasion loss to withstand the longer wash cycles and has an apparent density from 0.85 to 0.95 g/cm^3. This is in contrast to the lighter acid-wash pumice with high absorption capacity and only moderate abrasion loss. The problem is that there is a shortage of hard, domestic pumices; the best of these include the Arizona and New Mexico pumices produced by Arizona Tufflite and Copar, respectively.

Some El Paso laundries are hesitant to purchase the New Mexico pumice that sells for $0.10 to $0.12/1b. because of (1) environmental concerns in northern New Mexico, such as the effect of mining on scenic areas, plant and animal habitats, and runoff into streams and the effect of heavy equipment on roads (Austin, 1994) and (2) adverse publicity that can attach to a company using pumice from northern New Mexico. Their alternatives include using a softer, less-efficient pumice, such as Dyadic's Ecuador (selling for $0.13/1b), thereby consuming up to one and one-half times more pumice to produce the desired look at a net cost of $0.20/1b. The other option is to purchase the hard Turkish rock distributed by Premium Pumice (London) or Icefields (Atlanta). The cost to produce the Turkish pumice and deliver it in El Paso is about $0.115/1b; it currently sells in El Paso from $0.13 to $0.14/1b.

Enzymes

During 1992 and 1993, the use of enzyme powders has become popular with laundry finishers in El Paso. Cellulase enzymes attack and degrade the cloth dye chemically with a minimal effect on the denim itself. The use of the enzyme reduces the amount of pumice needed to bleach the denim. The enzymes are biodegradable and, therefore, can be placed directly in the municipal sewer system. Reducing the quantity of pumice will result in less drum damage in the rotary washers and formation of smaller quantities of sludge from the abraded pumice that cannot be flushed into the sewage system.

Some laundries have tried to eliminate all pumice in processing and use only enzymes. However, several laundries have indicated that eliminating all pumice is a mistake because the abrasive action of pumice helps in the removal of enzyme weakened surface fibers which results in a cleaner and smoother surface appearance. In addition, it is claimed that pumice-abraded denim takes up dye more efficiently than nonabraded cloth.

Current status

Currently research is being directed toward developing synthetic pumice or pumice substitutes to eliminate the environmental problems associated with natural pumice. The environmental problems include the derivation of large quantities of fines and impregnated chemicals which are released into the municipal sewage systems or dumped into overcrowded landfills. No completely satisfactory substitute has been identified or produced to date.

Although actual figures on the consumption of pumice by the individual El Paso laundry finishers are difficult to obtain, it appears that the pumice market is shrinking. Interviews with two major finishers indicate a significant reduction in pumice consumption during the last quarter of 1992; decreases are reported as high as 50%.

In May, 1994, the U.S. Bureau of Mines reported that the consumption of pumice by domestic laundries had declined from 69,000 mt in 1992 to 42,000 mt in 1993, a drop of nearly 40% (Bolen, 1994). The dramatic decrease in laundry pumice use correlates with the increased use and efficiency of enzymes, environmental concerns, and the acceleration of free trade with Mexico through the implementation of the North American Trade Agreement (NAFTA).

The enzymes, which were in use before 1990 in Europe, did not become popular in El Paso until late 1991 and 1992. Initially, the chemicals did not make much of an impact on pumice because the finishers were unfamiliar with their use. As the laundries became more knowledgeable, less pumice and more enzymes were employed in garment finishing. Several companies went to enzyme only and placed labeled their garments finished "stone free". The increasing use of enzymes decreased the consumption of pumice and, thereby, reduced the amount of machine damage and the environmental problems associated with the generation of pumice fines from the stones.

The February 20, 1994, issue of the *El Paso Times* reports that as free trade with Mexico picks up, the current flow of garment cutting and sewing jobs into Mexico will eventually be followed by jobs in laundry and related services. At the present time, two major domestic garment companies have established finishing facilities in Mexico.

Table 14—Pumice distributors serving the El Paso laundry market, 1994.

Pumice Distributor	Pumice Source	Use
Premium Pumice, Ltd. (London)	Turkey	Stone-wash
Dyadic Industries, Ltd., Inc. (Juniper, FL and El Paso)	Ecuador	Stone- and acid-wash
	California	Acid-wash
Omicron Industries, Inc. (El Paso)	New Mexico	Stone-wash
	Mexico	Acid-wash
	Arizona	Stone-wash
Phoenix Ash, Inc. (El Paso)	New Mexico	Acid- and stone-wash
Big Chief Stone, Inc. (Las Cruces, NM)	New Mexico	Acid- and stone-wash
Quimica Minera, Ltd. (Mexico)	Mexico	Acid-wash
Arizona Tufflite, Inc. (Flagstaff, AZ)	Arizona	Stone-wash
Icefields Pumice, Inc. (Atlanta, GA)	Turkey	Stone-wash

Today, El Paso's garment finishing industry is in a deep slump, which started in September, 1992, because of a "softening" in the denim market. The popularity of the Levi's Dockers, which is finished without enzymes or pumice, has added to the decrease in demand for stone-washed denim fabrics. The current slump has continued for the last seven months and shows no signs of a quick turn-around. It is estimated that denim finishing as of May, 1994, is down over 50% from 1992.

It is for all of the above factors that the demand for pumice by garment finishers has dramatically decreased during late 1992 through 1993, and will probably continue through most of 1994.

The current price for good stone-washing pumice is in the range of $0.12 to $0.14/1b. Lesser-grade pumices are selling for much less, from $0.05 to $0.10/1b. In the foreseeable future, I would not expect these prices to fall significantly, especially the Turkish stone-washing pumice which costs $0.115/1b just to get it to El Paso. A list of the current distributors, including those providing New Mexico pumice, to the El Paso laundries is included in Table 14.

Selected conversion factors*

TO CONVERT	MULTIPLY BY	TO OBTAIN
Length		
inches, in	2.540	centimeters, cm
feet, ft	3.048×10^{-1}	meters, m
yards, yds	9.144×10^{-1}	m
statute miles, mi	1.609	kilometers, km
fathoms	1.829	m
angstroms, Å	1.0×10^{-8}	cm
Å	1.0×10^{-4}	micrometers, μm
Area		
in^2	6.452	cm^2
ft^2	9.29×10^{-2}	m^2
yds^2	8.361×10^{-1}	m^2
mi^2	2.590	km^2
acres	4.047×10^{3}	m^2
acres	4.047×10^{-1}	hectares, ha
Volume (wet and dry)		
in^3	1.639×10^{1}	cm^3
ft^3	2.832×10^{-2}	m^3
yds^3	7.646×10^{-1}	m^3
fluid ounces	2.957×10^{-2}	liters, l *or* L
quarts	9.463×10^{-1}	l
U.S. gallons, gal	3.785	l
U.S. gal	3.785×10^{-3}	m^3
acre-ft	1.234×10^{3}	m^3
barrels (oil), bbl	1.589×10^{-1}	m^3
Weight, mass		
ounces avoirdupois, avdp	2.8349×10^{1}	grams, gr
troy ounces, oz	3.1103×10^{1}	gr
pounds, lb	4.536×10^{-1}	kilograms, kg
long tons	1.016	metric tons, mt
short tons	9.078×10^{-1}	mt
oz mt^{-1}	3.43×10^{1}	parts per million, ppm
Velocity		
ft sec^{-1} (= ft/sec)	3.048×10^{-1}	m sec^{-1} (= m/sec)
mi hr^{-1}	1.6093	km hr^{-1}
mi hr^{-1}	4.470×10^{-1}	m sec^{-1}
Pressure, stress		
lb in^{-2} (= lb/in^2), psi	7.03×10^{-2}	kg cm^{-2} (= kg/cm^2)
lb in^{-2}	6.804×10^{-2}	atmospheres, atm
lb in^{-2}	6.895×10^{3}	newtons (N)/m^2, N m^{-2}
atm	1.0333	kg cm^{-2}
atm	7.6×10^{2}	mm of Hg (at 0° C)
inches of Hg (at 0° C)	3.453×10^{-2}	kg cm^{-2}
bars, b	1.020	kg cm^{-2}
b	1.0×10^{6}	dynes cm^{-2}
b	9.869×10^{-1}	atm
b	1.0×10^{-1}	megapascals, MPa
Density		
lb in^{-3} (= lb/in^3)	2.768×10^{1}	gr cm^{-3} (= gr/cm^3)
Viscosity		
poises	1.0	gr cm^{-1} sec^{-1} *or* dynes cm^{-2}
Discharge		
U.S. gal min^{-1}, gpm	6.308×10^{-2}	l sec^{-1}
gpm	6.308×10^{-5}	m^3 sec^{-1}
ft^3 sec^{-1}	2.832×10^{-2}	m^3 sec^{-1}
Hydraulic conductivity		
U.S. gal day^{-1} ft^{-2}	4.720×10^{-7}	m sec^{-1}
Permeability		
darcies	9.870×10^{-13}	m^2
Transmissivity		
U.S. gal day^{-1} ft^{-1}	1.438×10^{-7}	m^2 sec^{-1}
U.S. gal min^{-1} ft^{-1}	2.072×10^{-1}	l sec^{-1} m^{-1}
Magnetic field intensity		
gausses	1.0×10^{5}	gammas
Energy, heat		
British thermal units, BTU	2.52×10^{-1}	calories, cal
BTU	1.0758×10^{2}	kilogram-meters, kgm
BTU lb^{-1}	5.56×10^{-1}	cal kg^{-1}
Temperature		
°C + 273	1.0	°K (Kelvin)
°C + 17.78	1.8	°F (Fahrenheit)
°F − 32	5/9	°C (Celsius)

**Divide by* the factor number to reverse conversions.
Exponents: for example 4.047×10^{3} (see acres) = 4,047; 9.29×10^{-2} (see ft^2) = 0.0929.

Editor: Nancy Gilson
Drafter: Kathy Campbell

Typeface: Palatino

Presswork: Miehle Single Color Offset
Harris Single Color Offset

Binding: Saddlestitched with softbound cover

Paper: Cover on 12-pt. Kivar
Text on 70-lb White Matte

Ink: Cover—PMS 320
Text—Black

Quantity: 1000