MP-21

Proceedings of the 22nd Forum on the Geology of Industrial Minerals

May 4-8, 1986
Little Rock, Arkansas

G. W. Colton, Editor

Published by Arkansas Geological Commission
Little Rock, Arkansas
1988

Cover: This one-room building is located on the Crater of Diamonds State Park property in Pike County, Arkansas--the site of the only commercial production of diamonds in North America. Originally built before 1913 as a miner's shack, it was modified in 1919 to house the draw works for a vertical mine shaft.

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MISCELLANEOUS PUBLICATION MP-21

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Norman F. Williams, State Geologist

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STATE OF ARKANSAS
Bill Clinton, Governor

ARKANSAS GEOLOGICAL COMMISSION
Norman F. Williams, State Geologist

PREFACE

The 22nd Forum on the Geology of Industrial Minerals was held May 4 through May 8, 1986 in Little Rock, Arkansas. It was sponsored by The Arkansas Geological Commission, Norman F. Williams, Director. The Forum consisted of 2 days of technical sessions during which 22 papers were presented. In addition, pre-meeting and post-meeting field trips were conducted to half a dozen mining operations in Arkansas, and 3 excursions for spouses were provided.

The keynote presentation by Dr. Eugene N. Cameron of the University of Wisconsin at Madison was a sobering evaluation of the recent history, present status, and the future of the United States' minerals industry. His prediction for the future stressed the need for national recognition of the industry's problems, noting that the mineral, financial, and technical resources are still in existence.

While the majority of papers dealt with the mineral industry or mineral deposits of Arkansas, others dealt with mineral deposits in the states of Idaho, Indiana, Texas and Virginia, and in one paper, marble in the Kingdom of Nepal was discussed. Of a broader nature were several papers concerned with the overall problems of several specific industrial mineral commodities. Another paper was devoted to the strategy of entering into the minerals industry as a new producer.

This proceedings volume contains one half of the papers presented as well as abstracts of the remaining papers. All have been edited -- but lightly --, mainly for standardization of stylistics, as in figures, figure captions, and lists of references.

We extend thanks to the Society of Economic Geologist's Foundation, Inc., for extending a grant to partially defray operating costs. Many helped in the planning and in the conduct of the activities of the 22nd Forum. Mary Finch, Katherine Headrick, and Oleta Sproul, all three with The Arkansas Geological Commission, conducted the trips for spouses. Susan Young, also of the Commission, was instrumental in preparing displays for the meetings and guidebooks for the field trips. The various field trips to the mining, processing, and producing facilities were led, in alphabetic order, by the following:

Benjamin F. Clardy, Arkansas Geological Commission
Murray Harding, Manager, Smith Whetstone, Inc.
J. Michael Howard, Arkansas Geological Commission
Leendert Krol, Consulting Geologist
John Long, Manager, Geomex Mine Services, Inc.
Wallace Mitchell, Consulting Geologist
Billy McNish, Alcoa Bauxite Co.
Larry P. Renard, General Manager, Gypsum, Weyerhaeuser Co.
Richard Smith, President, Smith Whetstone, Inc.
Beal Snodgrass, Mine Superintendent, Weyerhaeuser Co.
Charles Steuart, Mine Superintendent, Malvern Minerals Co.
Charles G. Stone, Arkansas Geological Commission
Norman F. Williams, Arkansas Geological Commission

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George W. Colton	Mary Finch
J. Michael Howard	Susan Young
John D. McFarland, III	Molly Snyder

ANNUAL MEETINGS OF THE FORUM ON THE GEOLOGY OF INDUSTRIAL MINERALS

1st	1965	Columbus, Ohio
2nd	1966	Bloomington, Indiana
3rd	1967	Lawrence, Kansas
4th	1968	Austin, Texas
5th	1969	Harrisburg, Pennsylvania
6th	1970	Ann Arbor, Michigan
7th	1971	Tampa, Florida
8th	1972	Iowa City, Iowa
9th	1973	Paducah, Kentucky
10th	1974	Columbus, Ohio
11th	1975	Kalispell, Montana
12th	1976	Atlanta, Georgia
13th	1977	Norman, Oklahoma
14th	1978	Albany, New York
15th	1979	Golden, Colorado
16th	1980	St. Louis, Missouri
17th	1981	Albuquerque, New Mexico
18th	1982	Bloomington, Indiana
19th	1983	Toronto, Ontario
20th	1984	Baltimore, Maryland
21st	1985	Tucson, Arizona
22nd	1986	LITTLE ROCK, ARKANSAS
23rd	1987	Chicago, Illinois
24th	1988	Columbia, South Carolina

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Dr. Eugene N. Cameron of the Department of Geology and Geophysics at the University of Wisconsin -- Madison, the Keynote Speaker at the 22nd Forum on the Geology of Industrial Minerals. An outstanding authority in the area of mineral economics, Dr. Cameron is the author of *At the Crossroads -- the Mineral Problems of the United States.*

KEYNOTE ADDRESS

Some thoughts on our mineral future

EUGENE N. CAMERON
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Madison, Wisconsin 53706

I am very pleased to be invited to give this introductory address to the Forum on the Geology of Industrial Minerals. I have long had an interest in the work of the Forum, and I made extensive use of its proceedings in teaching economic geology at the University of Wisconsin. My work at the U.S. Geological Survey, and especially my term as Commodity Geologist for Industrial Minerals, gave me a lasting interest in industrial mineral deposits. For years it has troubled me that those deposits are given such scant attention in most American universities.

The title of my talk is that of the final chapter of my book "At the Crossroads - The Mineral Problems of the United States" (Cameron, 1986). The topic seems timely, because the past five years have seen hard times in many mineral industries, and we have

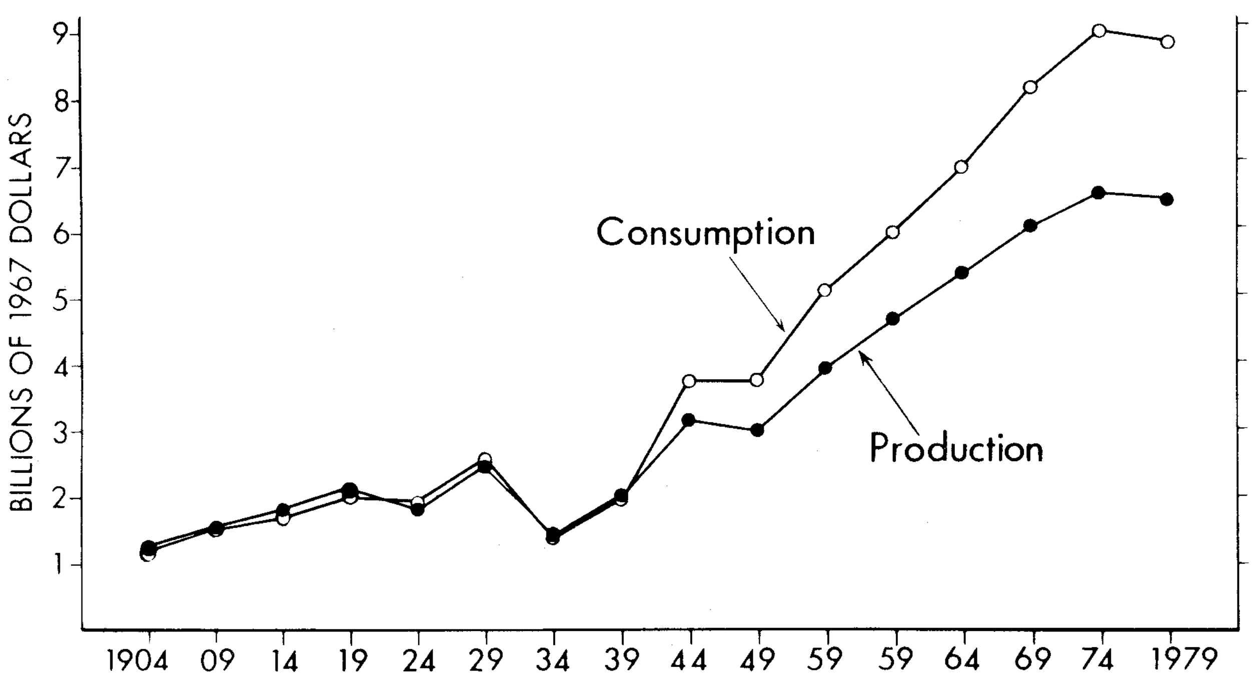

Figure 1. *U.S. production and consumption of nonfuel minerals, 1900-1979. Each point on a curve is the average for the 5-year period ending with the year for which the point is plotted. Data from U.S. Bureau of Mines Mineral Commodity Summaries and Minerals in the U.S. Economy and from Spencer (1972). From Cameron (1982), by permission of Elsevier Publishing Company, Amsterdam.*

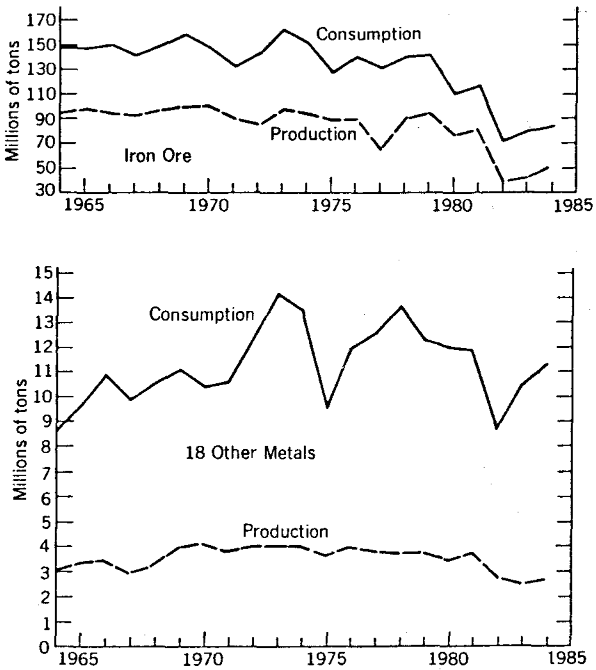

Figure 2. *U.S. production and consumption of iron ore and 18 other metals. Data from U.S. Bureau of Mines, Mineral Commodity Summaries and Minerals in the U.S. Economy. From Cameron (1986), by permission of John Wiley and Sons, New York.*

all been wondering what the future will bring. Today I wish to give you my own thoughts on our mineral future.

First, some facts. Let us look briefly at the background of the present mineral situation, considering all the nonfuel minerals. Figure 1 shows U.S. production and consumption of nonfuel minerals, in constant 1967 dollars, from 1900 to 1979. Each point on a curve is the average for the 5-year period ending with the year for which the point is plotted. The chart shows that during the period both mineral production and mineral consumption rose, but after World War II a gap between production and consumption appeared and steadily increased. The gap was filled, of course, by imports of nonfuel minerals.

Figures 2 and 3 show U.S. production and consumption of metals and industrial minerals, in tons, from 1964 to 1984. In Figure 2 we see the graph for iron ore, above, and for 18 other metals, below. U.S. metal-mining industries were hard hit by the 1981-1983 recession. The chart shows that there was little recovery during 1983-1984, and the same is true for 1985. Note that since the Arab oil embargo of 1973-1974, both production and consumption of metals have irregularly declined.

In Figure 3 we see the picture for the industrial minerals. Industrial mineral industries were also hit by the recession, but there has been substantial recovery during 1984-1985. Note, however, that both production and consumption have leveled off. From this and the previous figure it appears that U.S. mineral industry cannot count on a future increase in domestic demand comparable to that which occurred from 1948 to 1974.

The charts give a general picture, but let us look at the recent record for individual commodities, by comparing metal and nonmetal production for 1985 with that for 1980, the last relatively normal year before the recession. Table 1 shows data for production of newly mined metals in 1980 in the second column and data for 1985 in the third column. The fourth column shows the change in

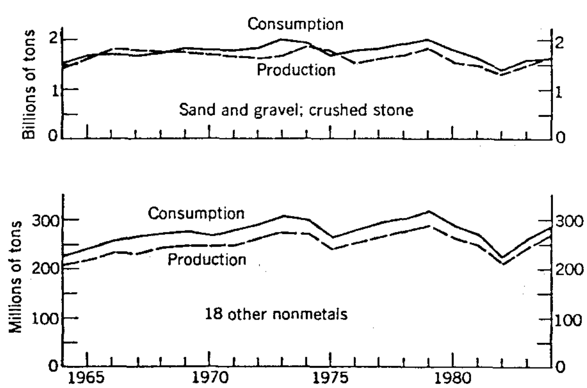

Figure 3. *U.S. production and consumption of sand, gravel, and crushed stone, and 18 other nonmetals. Data from U.S. Bureau of Mines Mineral Commodity Summaries and Minerals in the U.S. Economy. From Cameron (1986), by permission of John Wiley and Sons, New York.*

Table 1. -- *U.S. mine production of metals or ores (thousands of short tons)*

	1980	1985	% Change
Bauxite	1,718	623	-64
Chromium	0	0	0
Cobalt	0	0	0
Copper	1,300	1,158	-11
Iron ore	77,152	53,750	-31
Lead	606	440	-27
Magnesium	170	150	-12
Manganese	0	0	0
Mercury (flasks)	30,657	15,100	-51
Molybdenum	75	50	-33
Nickel	15	7	-53
Silicon	483	400	-17
Tin	0	0	0
Tungsten	3	1.2	-60
Vanadium	5	2	-60
Zinc	349	248	-29

Data from U.S. Bureau of Mines, Mineral Commodity Summaries, 1985, 1986.

production of various metals from 1980 to 1985. It is a sorry picture. For copper the percentage change would be much worse if I had chosen to compare 1985 production with the peak production of 1,894,000 tons in 1973.

Table 2 gives data for important industrial minerals. The picture is quite different. For 7 of the 22 commodities in the table, production was actually greater in 1985 than in 1980. For 4 others, 1985 production was unchanged or only 1 to 5 percent less than 1980 production. The table indicates, however, that for 6 commodities, notably barite, potash, and sodium sulfate, recovery has been poor. Thus the picture of recovery for the nonmetals is mixed, but it is certainly far brighter than that for the metals.

What about the future of mineral industry in the United States? That is no easy question to answer. Aside from predicting the behavior of the stock market, I know no easier way of losing credibility than making firm forecasts of future mineral supply and demand. I shall not attempt a forecast. I suggest instead that we look at certain facts of our mineral situation and try to assess their implications for the future. There are four sets of facts to be considered:

1. The mineral reserve base of the United States as estimated by the U.S. Geological Survey and the U.S. Bureau of Mines.

2. Current U.S. production and consumption of minerals.

3. Trends in mineral production and consumption in recent years.

4. The record of success or failure in mineral exploration in the United States.

We have already looked at mineral production and consumption trends of the past 20 years. Let us next examine the reserve base for various mineral commodities. We must remind ourselves that the estimated reserve base for a mineral includes those identified resources that are currently economic, i.e., true

Table 2. -- *U.S. mine production of industrial minerals (thousands of short tons)*

	1980	1985	% Change
Barite	2,245	890	-60
Boron[a]	783	630	-20
Cement	75,224	80,000	+6
Clays	48,791	45,630	-6
Diatomite	689	637	-8
Feldspar	710	700	-1
Fluorspar[b]	162	180	+11
Gypsum, crude	12,736	14,400	+13
Lime	19,010	15,800	-17
Magnesium compounds	800	630	-21
Ammonia	16,244	14,100	-13
Phosphate rock	59,987	56,222	-6
Perlite	638	512	-20
Potash	2,468	1,461	-41
Pumice	543	556	+2
Salt	41,480	39,600	-5
Sand and gravel	763,100	800,000	+5
Sodium carbonate	8,275	8,500	+3
Sodium sulfate	583	375	-36
Sulfur	13,081	12,512	-4
Crushed stone	984,000	1,006,000	+2
Talc-pyrophyllite	1077	1079	0

a - Boric oxide.
b - Includes fluorspar equivalent of flousilicic acid recovered from phosphate rock.
Data from U.S. Bureau of Mines, Mineral Commodity Summaries, 1985, 1986.

reserves, and identified resources that are marginally economic or even subeconomic. Proportions of these components in the reserve base vary from commodity to commodity. For example, the reserve base for copper is estimated at 99 million tons. A significant portion of this consists of true reserves. On the other hand, the reserve base for cobalt, estimated at 950,000 tons, consists entirely of subeconomic material.

With these caveats in mind, let us compare the U.S. reserve base for metals with current annual consumption. The simplest way is to divide the reserve base by annual consumption. This gives us a ratio which is the reserve base/consumption index. The index is simply a measure of the size of the reserve base relative to current consumption.

Table 3 shows reserve base/ consumption indices for 18 metals or their ores. In columns 2 and 3, the 1984 reserve base and average 1974-1984 consumption of primary metal are given for each metal or ore. The fourth column gives the reserve base/consumption indices. There is a wide range, from infinity or very large for magnesium and silicon to zero for chromium and manganese. What about the metals in between, with indices ranging from 212 to 1? The actual record of U.S. production indicates that when the reserve base/consumption index for a mineral falls to about 50 or below, production will no longer keep up with

Table 3. -- *U.S. reserve base/consumption indices for metals, 1984. From Cameron (1986), by permission of John Wiley and Sons, New York*

	Reserve base[a] 1984	Average consumption primary[a] metal 1974-1984	RB/Cp 1984
Magnesium	**	92.5	**
Silicon	Very large	570	Very large
Molybdenum	5,900	28	211
Iron ore	24,800,000	120,000	207
Lithium	460	3.4	135
Copper	99,200	1,755	56
Zinc	53,000	1,036	51
Lead	27,000	661	41
Tungsten	320	9.6	33
Vanadium	240	7.6	32
Cobalt[b]	192	7	27
Nickel[c]	2,800	160	18
Antimony	100	14.9	7
Mercury[d]	200	35	6
Aluminum	12,000	4,881	2
Tin	55	44	1
Chromium	0	485	0
Manganese	0	1,115	0

** - Infinite
a - Thousands of tons, except mercury.
b - The cobalt reserve base consists entirely of subeconomic resources.
c - The nickel reserve base consists largely of subeconomic resources.
d - Thousands of 76-pound flasks.
Source: Data for reserve base and consumption from U.S. Bureau of Mines, Mineral Commodity Summaries.

consumption. The chart thus shows that the U.S. position in metals is weak. Indices for 11 of the 18 metals are below 50.

This is borne out by the fact that the metals figure prominently in Figure 4, which is the 1984 Bureau of Mines chart of net import reliance of the United States. Of the 18 metals shown in the previous figure, 14 appear in this chart.

Let's look now at the industrial minerals (Table 4). Here the picture is quite different. For most of the 19 commodities in the table the indices in column 4 are comfortably large. Only 5 commodities have indices below the critical level. As would be expected from the table, the United States supplies most of its needs for industrial minerals and is actually an exporter of 9 of the commodities listed in the table. The U.S. position in industrial minerals is therefore very strong.

What we have now discussed is only a start toward appraising mineral prospects for the future. For a firm forecast we would also have to consider future levels of demand for minerals, the probable success of future mineral exploration, and the possible impact of future changes in the technology of mineral extraction and use. All these will be profoundly influenced by the nature and scale of economic development both in the world and in the United States. All these are variables in the

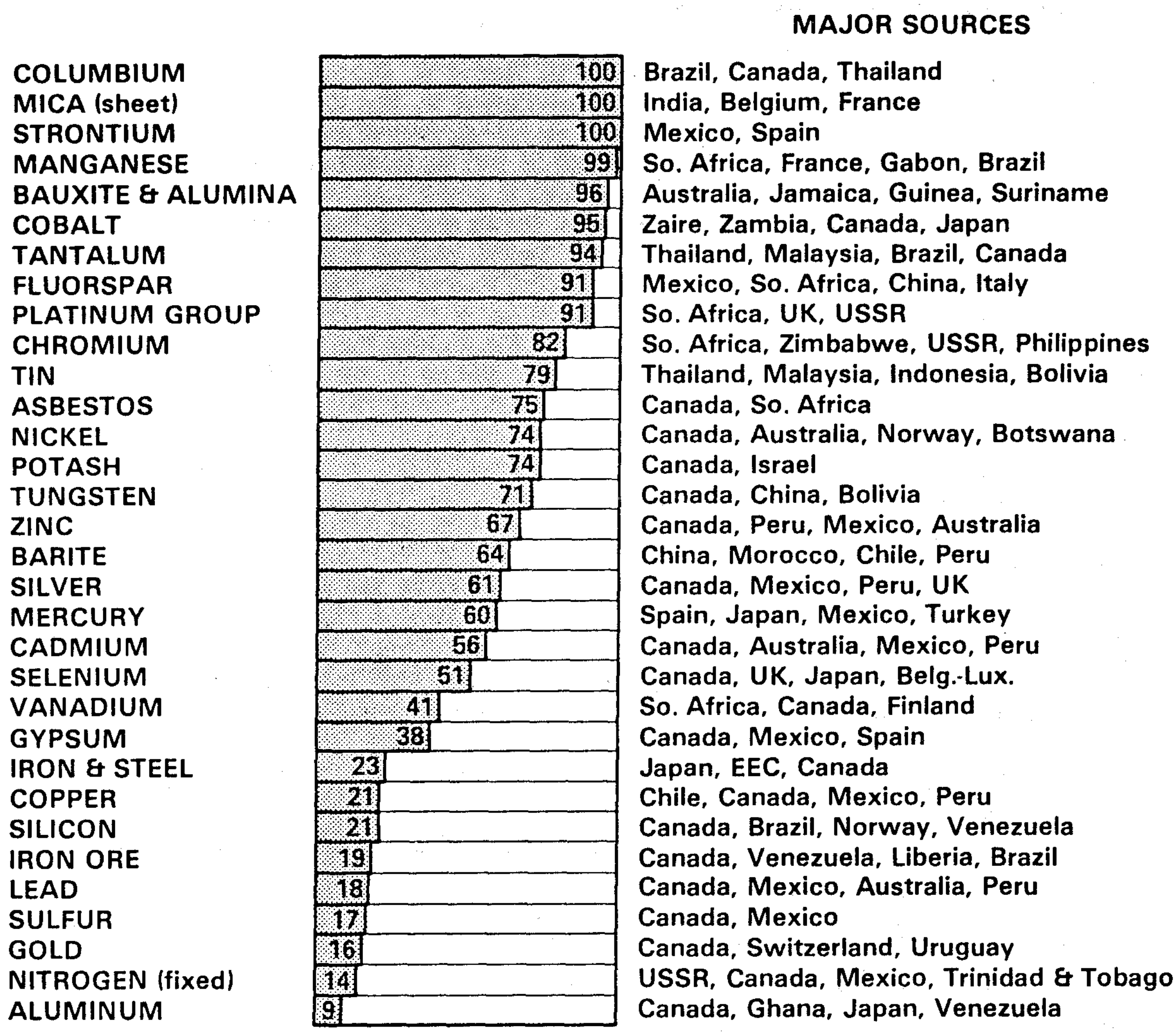

Figure 4. *U.S. net import reliance (imports minus exports) in 1984 for 32 mineral commodities. U.S. Bureau of Mines, courtesy of J.D. Morgan, Jr.*

equation for future mineral supply and demand. Unfortunately, none of the variables can be quantified, and I don't intend to try.

I do not believe that a firm forecast of future U.S. mineral production is possible, but the facts we have enable us to answer a question that has important implications for the future. The question is this: Given the present reserve base of the United States, what are the chances that present levels of U.S. mineral production can be maintained during the next 20 years? We can examine this question in terms of the impact of production on the reserve base and the changes in the reserve base/production indices that would take place between now and the year 2005. As an example, let us take the case of copper. The 1984 reserve base for copper (U.S. Bureau of Mines, 1985) is given as 99,200,000 tons. Dividing this by the average annual production of primary copper during 1974-1984, we get a reserve base/production index of 69. If production during 1985-2005 were to continue at the 1974-1984 rate, total production would be 30,093,000 tons. The remaining reserve in

Table 4. -- *U.S. reserve base/consumption indices for industrial minerals, 1984. From Cameron (1986), by permission of John Wiley and Sons, New York*

	Reserve Base[a] 1984	Average Consumption 1974-1984	RB/Cp 1984
Salt	**	44,561	**
Cement	Very large	79,478	Very large
Clays[b]	Very large	48,212	Very large
Lime	Very large	18,792	Very large
Sand and gravel	Very large	807,556	Very large
Stone (crushed)	Very large	940,963	Very large
Sedium carbonate	36,600,000	7,043	5,196
Diatomite	500,000	533	938
Perlite	200,000	555	360
Feldspar	200,000	700	288
Boron[c]	18,000	106	170
Phosphate rock	5,400,000	38,327	141
Titanium[d]	50,000	482	112
Potash	360,000	6,425	56
Gypsum	500,000	20,252	25
Barite	60,000	2,987	20
Asbestos	4,400	303	15
Sulfur	175,000	12,911	14
Fluorspar	8,000	1,112	7

** - Infinite
a - Thousands of tons.
b - Clays of all types.
c - Boron content of boron ores or concentrates.
d - Titanium content of titanium minerals and slags used for nonmetallic purposes.
Source: Data for reserve base and consumption from U.S. Bureau of Mines, Mineral Commodity Summaries.

2005 would then be 69,107,000 tons, and the reserve base/production index would then be 48.

Let's look at the metals first. In Table 5, column 2 gives RB/P indices for various metals for 1984. In this table the index is the ratio of the reserve base to production of newly mined metal; i.e., primary metal. The third column gives reserve base/production indices for 2005, assuming that production in the interval is at the average 1974-1984 rate. By 2005 indices for 9 out of the 18 metals will have dropped below 50, which simply means that production of these metals until 2005 at the 1974-1984 rate is impossible out of the present reserve base. We should add a 10th metal to the list--tungsten. Much of the reserve base for tungsten consists of uneconomic material. Even in times of high prices, domestic mines have never produced more than 50 percent of U.S. requirements.

The table shows that unless there are marked additions to the U.S. reserve base for metals through discoveries or through technologic advance, the U.S. position in metals, already weak, will be very much weaker in the year 2005.

What about the industrial minerals? In Table 6, column 3 shows that even in 2005, the U.S. position in industrial minerals will be strong. There should be no difficulty in maintaining 1974-1984 production rates for all but 5 of the 19 commodities, and I suspect that the position for gypsum will be much better

Table 5. – *U.S. reserve base/production indices for metals: Year 2005 compared with 1984. From Cameron (1986), by permission of John Wiley and Sons, New York.*

	1984	2005*
Magnesium	Infinite	Infinite
Silicon	Very large	Very large
Vanadium	480	459
Iron Ore	332	311
Nickel	233	212
Zinc	138	117
Tungsten	107	86
Molybdenum	104	83
Lithium	77	56
Copper	69	48
Lead	48	27
Aluminum	34	13
Tin	50?	5?
Mercury	8	0
Antimony	8	0
Chromium	0	0
Manganese	0	0
Cobalt	0	0

* - Assuming production at average 1974-1984 annual rate during 1985-2005.

than indicated in the table. The one reservation that is necessary here, however, is that some of our industrial mineral industries face problems of rising costs, environmental problems, and increased competition from imports. The phosphate, potash, and titanium mineral industries are examples.

With regard to the future, I think there are two main points brought out by an analysis of this kind. One is that for a number of mineral commodities, both metals and nonmetals, present levels of production cannot be maintained without substantial additions to the reserve base through mineral exploration and through technological advances in extractive processes. This is especially true for the metals, but it is true also for some nonmetals.

The second and obvious point is that the real strength of the U.S. mineral position lies in its resources of industrial minerals. This is a critical point that is often overlooked in discussions of U.S. mineral resources.

What are the chances for additions to the reserve base through new discoveries? For the metals, the chances are not very good. For some of them--chromium, cobalt, manganese, tin, bauxite, and mercury, prospects for discovery of significant new deposits are dim. For others,--zinc, lead, copper, molybdenum, antimony, and tungsten, the geologic potential for further discoveries is high, but exploration for these metals faces formidable institutional barriers. The first of these is the land policy of the United States. The lands having greatest potential for discovery of new metal deposits lie mostly in the western states and Alaska. Their total area is about 1,118,000,000 acres. Of this, about 582,000,000 acres, about 52 percent, belongs in the public domain. Since 1964, when the Wilderness Act was passed, the land policy of the United States has moved steadily toward restricting access to the public domain for purposes of mineral exploration and development, through the creation of wilderness areas, new national parks, wildlife refuges, and so on.

Table 6. -- *U.S. reserve base/production indices for industrial minerals: Year 2005 compared with 1984. From Cameron (1986), by permission of John Wiley and Sons, New York.*

	1984	2005*
Salt	Infinite	Infinite
Cement	Very large	Very large
Clays	Very large	Very large
Lime	Very large	Very large
Sand and gravel	Very large	Very large
Crushed stone	Very large	Very large
Sodium carbonate	4,939	4,918
Diatomite	772	751
Perlite	325	304
Feldspar	307	286
Potash	172	151
Titanium (ilmenite)	151	130
Talc, pyrophyllite	133	112
Phosphate rock	113	92
Boron	87	66
Asbestos	57	21
Fluorspar	46	25
Gypsum	43	22
Barite	40	19
Sulfur	17	0

* - Assuming 1974-1984 average annual production rate during 1985-2005.

In 1976, a task force on the Availability of Federally Owned Mineral Lands reported to the Office of Technology Assessment that in 1974, location under the Mining Law of 1872 was formally prohibited on 41 percent of the public domain, severely restricted on 18.2 percent, and moderately restricted on another 11.4 percent. Exploration and development under the mineral leasing laws were formally prohibited on 36 percent of the public domain, severely restricted on 22.7 percent, and moderately restricted on 6.6 percent. Since 1974 there have been large additional withdrawals of lands from mineral entry. About 300 million acres of the public domain are under the jurisdiction of the Bureau of Land Management: 174 million acres of this is in the western states exclusive of Alaska. Articles in the Wall street Journal on April 23 and April 24, 1986, graphically describe how these lands have become a battleground between environmental groups and those who wish to develop the resources of the lands. In Alaska, 141,000,000 acres of the public domain are now closed to mineral entry for nonfuel minerals under the Alaska National Interests Land Act of 1980 (Cameron, 1986, p. 217).

Even on lands that by law are open to mineral activities, exploration and development are hampered by administrative regulations and often opposed by environmental groups. Environmental regulations add to the time, the cost, and the uncertainty of mineral development. The situation in my own state of Wisconsin is a prime example. A major zinc-copper deposit was discovered at Crandon, Wisconsin, in 1975. Exxon has spend $70,000,000 in exploration, evaluation, and engineering and environmental studies. At this date, 11 years after discovery, there is still no assurance that a permit to mine will be granted.

A major obstacle to future exploration for metals is the financial health of much of the American metal-mining industry. It can be characterized in one word--bad. The glut of metals on world markets has depressed prices, measured in constant dollars, to levels not seen since the Great Depression. Competition with foreign producers, some of them subsidized by their governments or even by the United States, has destroyed the profitability of much of the metal-mining industry of the United States. Except for gold, exploration for metals is virtually at a standstill. Smelting and refining industries are moving abroad. In my judgment, we have reached the point at which the national security is threatened. The arsenal of democracy of which we boasted in World War II is being progressively dismantled. Yet there is little interest in the fate of U.S. mining industry at national policy-making levels. In a world in which few nations are really interested in free trade, the U.S. is still firmly committed to the free-trade policy that was adopted in 1934. In the words of the Presidential spokesman, Mr. Speakes, market forces must prevail. The latest to feel the impact of this policy is the petroleum industry. Yet in 1985, petroleum imports contributed about 50 billion dollars to the U.S. international trade deficit, and imports of nonfuel minerals contributed about 17 billion dollars more. Except for the steel industry, which has received limited aid, U.S. metal mining industry has been strictly on its own.

In short, future prospects for the American metal mining industries are bleak. It is thus a relief to turn to the industrial mineral industries. Though tough competitive years appear to lie ahead, the future for industrial minerals seems to me relatively bright. We have large reserves of many major industrial minerals. We still have the plants that are needed to convert them into consumer goods. Furthermore, developments in materials science are creating a new generation of ceramic and other materials that could offer new markets for industrial minerals. The best chance for improving the mineral position of the United States appears to be through increased use of our industrial mineral resources. American technology should be adapted, so far as possible, toward minimizing the use of those minerals, especially the metals, that cannot be produced from domestic mineral resources in adequate amounts, and toward maximizing the use of the industrial minerals that we possess in great abundance. Materials science already points the way. It should be encouraged by a positive, carefully directed national mineral policy. Part of that policy should be support of essential domestic mineral industries. Our trade policy should be revised. It flies in the face of the realities of international trade. It is no longer consistent with our needs for mineral supplies and mineral industries that are vital to the national security. The problem of instability of mineral markets, the prime source of distress in mining industry and the largest single cause of loss of mineral resources, must be addressed. Land policy must recognize the essential role that minerals play in the economy and national security of the United States. We cannot afford to close vast areas of the United States to mineral exploration and development. Environmental regulation is necessary and must be continued, but it must be streamlined to reduce its costs both in money and in loss of exploration opportunities. These are costs to society, not just to mining companies, and they are costs that society can ill afford to bear.

For some thirty years I have been concerned with the progressive deterioration of the mineral position of the United States. The events of the last ten years have heightened that concern. I believe that the time has come when the nation must come to grips with its mineral problems. We have the resources, mineral, financial, and technological, that are needed to resolve them. We need only a national recognition of our problem and a national commitment to address them.

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Mineral raw materials for flat glass manufacturing[1]

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ABSTRACT

Raw materials used by the flat glass industry are known in the industrial minerals geology sector as specialty products. These products must meet specification limits usually not the same for all glass manufacturers. Evolving new glass compositions will require mineral concentrates of consistent purity being produced within economic limits that will assure market viability of the resulting glass product.

The amount of success the flat glass industry will achieve by developing and maintaining domestic production centers will be determined by many economic factors which affect the costs of doing business. Technological developments by mineral processors must continue in order to achieve more efficient production of high quality glassmaking raw materials.

INTRODUCTION

In the market place, there is a continuing demand for higher quality and more sophisticated flat glass products which are economically attractive to the consumer. What is flat glass, what is the future of flat glass, and what impact will mineral raw material producers have on flat glass manufacturers achieving their future goals?

In general, most flat glass is produced on a continous basis in ribbon form having plane and parallel surfaces. The processes employed are the Fourcault, Colburn, rolled plate, and more recently the float process. Primary applications of flat glass include the automotive, architectural (both residential and non-residential), mirror, and furniture markets. The amount of glass distributed to each market is shown in Figure 1. A variety of base glass colors having varying spectral properties are available to meet consumer requirements. The addition of thin metallic films to the glass substrate by vacuum deposition or chemical vapor deposition processes, has added to the versatility of flat glass, particularly in the architectural market. As a result of glass' unique properties, there has been a demand for new and more sophisticated applications; a real challenge to glass scientists.

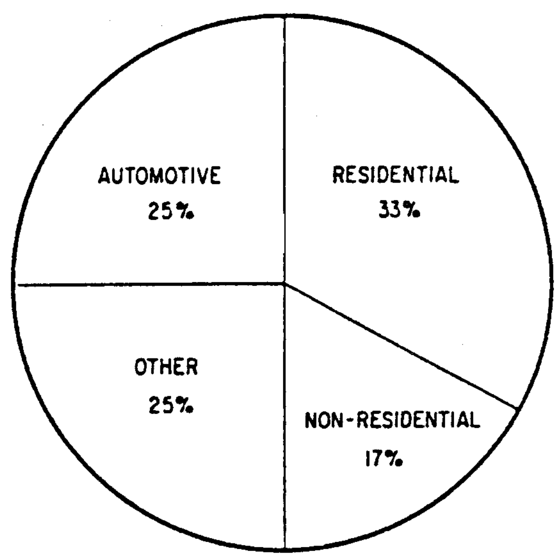

Figure 1. *Major flat glass markets and share (From White, 1983).*

The manufacturers of flat glass in the United States include the following: LOF Glass, PPG Industries, Ford Motor Co., AFG Industries,

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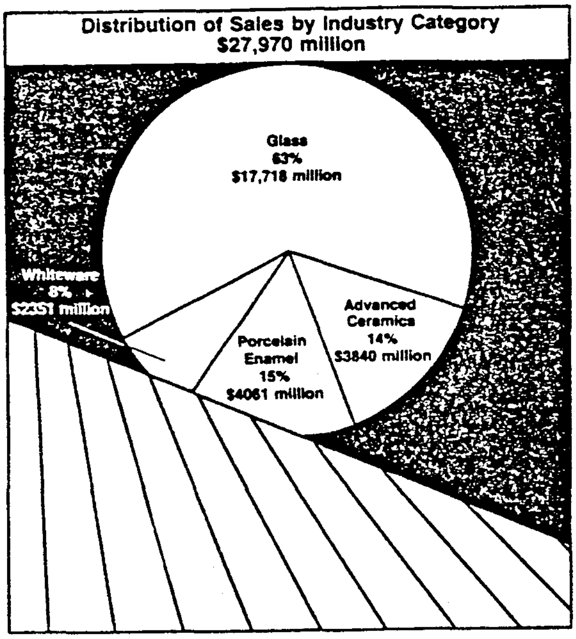

Figure 2. *Distribution of glass sales (From Ceramics Industry Magazine, August, 1985).*

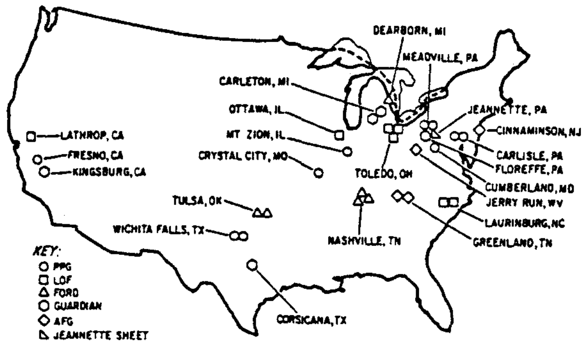

Figure 3, *Location of flat glass manufacturing furnaces. (From White, 1983)*

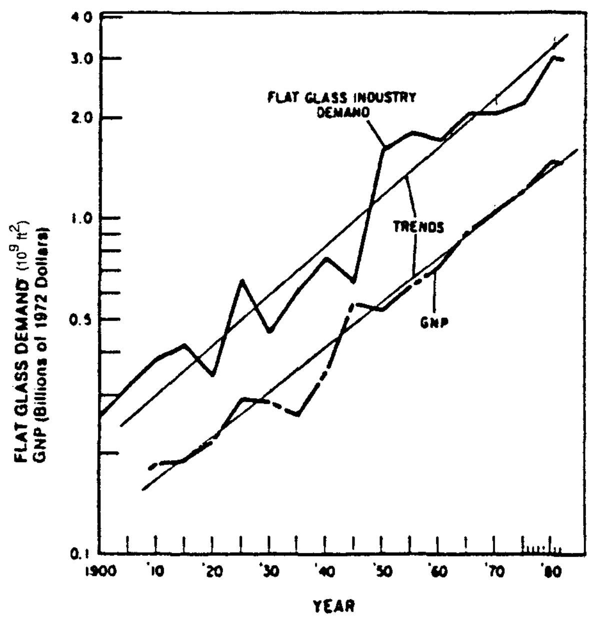

Figure 4. *Flat glass industry demand vs. Gross National Product (GNP). (From White, 1983)*

and Guardian Industries. Based on data supplied by the U.S. Department of Commerce, approximately 3,200,000 metric tons of flat glass was produced domestically in 1984. As shown in Figure 2, flat glass sales for 1984 represented 27% of $17,718 million total glass sales or approximately $4,784 million. It has been projected that total output for 1985 will exceed that experienced in 1984. The general locations of flat glass producing facilities in the U.S. are shown in Figure 3. The selection of a location for building a glass melting furnace has been based on one of two basic requirements--proximity to major markets and proximity to raw material sources.

RAW MATERIALS FOR FLAT GLASS MANUFACTURING

As has been discussed, the flat glass industry is healthy, is growing, and is becoming more sophisticated. Historically, based on data provided by the U.S. Department of Commerce, the demand for flat glass, as shown in Figure 4, has paralleled the Gross National Product during the period from 1900 to 1980. Continued growth for the balance of the century, based on a study published by PPG Industries (White, 1983), is shown in Figure 5. The projections appear to be valid. The continued success of the industry will be greatly influenced by the ability of raw material suppliers to meet the ever increasing material quality requirements without major changes in price structures.

What are the current basic requirements for materials used in manufacturing flat glass and what are the anticipated changes in requirements that need

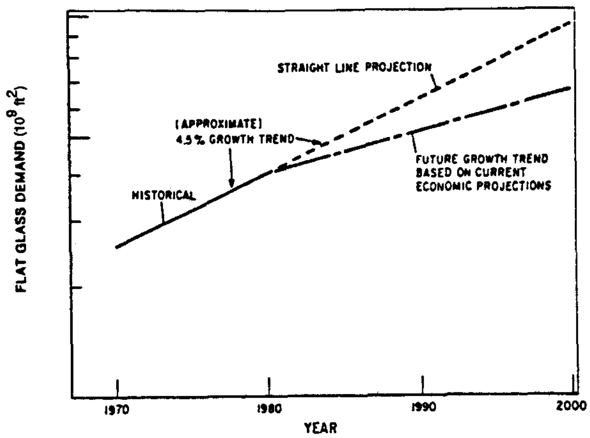

Figure 5. *Growth trends for flat glass industry. 1980 to 1990 is estimated, based on a 3% compounded growth rate. (From White, 1983)*

to be addressed for the future? First, let's review in general terms a typical flat glass batch.

Table 1 is a typical formulation for a high-iron glass commonly referred to as soft-ray glass, generally used in automotive applications. Using the above formulation along with the previously mentioned total tonnage produced in 1984, an indication as to the amount of mineral raw materials consumed by the flat glass industry in 1984 is listed in Table 2.

Table 2 does not include small quantities of materials used in the production of specialty glasses such as niter, cobalt oxide, nickel oxide, selenium, and sea coal or carbon. The quantity of materials listed in Table 2 indicates that the flat glass industry will have some impact on the mineral industry.

With the relatively limited sources of high purity mineral raw materials currently available to the flat glass industry, along with the sometimes long shipping distances involved between source and end-use, there is an obvious need for mineral processing development in order to produce high quality products from lower grade deposits closer to the glass manufacturer.

Table 1: *Typical flat glass batch formulation*

MATERIAL	POUNDS	SOURCE OF
Sand	1000	SiO_2
High calcium limestone	73	CaO
Dolomitic limestone	252	MgO & CaO
Soda ash	323	Na_2O
Salt cake or gypsum	8	Na_2O/CaO & SO_3
Rouge	7	Fe colorant

MINERAL RAW MATERIAL REQUIREMENTS

With the quantities of materials consumed annually to produce a high quality flat glass product, there obviously must be specifications established for each individual material which must be met on a continuing basis in order for the glass melting operations to be successful. Following is the basic philosophy of LOF Glass used in developing raw material specifications for its operations.

LOF Glass has been producing flat glass since the 1920's. Based on, (1) many years of experience, (2) thousands of chemical and physical analyses, and (3) correlating material analyses to glass quality, model specifications have been developed for each individual raw material. These model specifications provide general guidelines in determining if a material, particularly a new source, will be compatible with our operations. Upon acceptance of a material, a specification is written for that given material. These specifications are reviewed bi-annually and up-dated if necessary to reflect changes in chem-

Table 2: *Total mineral raw materials used by the flat glass industry in 1984*

MATERIAL	TOTAL TONS
Sand	2,590,720
High calcium limestone	190,080
Dolomitic limestone	654,720
Soda ash	837,760
Salt cake or gypsum	21,120

Table 3: *Acceptable variance (percent by weight)*

Constituent	Symbol	Maximum allowable concentration (%)
Silica	SiO_2	.15
Total iron	Fe_2O_3	.040
Alumina	Al_2O_3	.07
Calcia	CaO	.10
Magnesia	MgO	.10

Table 4: *Critical control limits (percent by weight)*

Constituent	Symbol	Maximum Limit
Total iron	Fe_2O_3	.080
Alumina	Al_2O_3	.30
Chromium	Cr_2O_3	.0002
Cobalt	Co_3O_4	.0002
Manganese	MnO_2	.0020
Moisture	H_2O	.05

istry of the deposit or possible process improvements. It is critical to the glass melting operation that any material is consistent day to day, week to week, and month to month in order to maintain consistent glass composition and quality.

TO ILLUSTRATE THE PROCESS USED IN DEVELOPING A SPECIFICATION, GLASS SAND WILL BE USED AS AN EXAMPLE.

First, acceptable variance limits are given for the major constituents as defined in Table 3.

Most glass sands have a minimum silica (SiO_2) content of 99.40% to 99.70%. Operational requirements necessitate maximum limits on certain critical constituents defined in Table 4.

The limits imposed on iron, chromium, cobalt, and manganese are a result of their influence on glass color. Alumina affects glass viscosity, thus having a significant influence on the forming and fabricating processes. Since sand is the major batch ingredient, control of moisture is critical due to not only handling but more importantly in maintaining glass composition.

Certain minerals of a refractory nature resist solution during the melting process. A flowsheet illustrating the analytical procedure followed in the quantification and identification of trace contaminants contained in raw materials is shown in Figure 6. In Table 5, attention is directed specifically to those particles exceeding .0082 inches in their least dimension (U.S. Standard Mesh). The undesired refractory minerals are listed in Table 5.

In the glass melting operations, sulfur is present, thus metal particulates containing 1% or more copper or nickel and exceeding .0029 inches (75 micrometers) in the least dimension must be excluded. The basis for this requirement is the formation of copper sulfide blisters in the glass ribbon resulting in an esthetic defect or the formation of nickel sulfide pellets which, upon going through transformation changes, can cause fracture problems in tempered glass products. Thus it becomes important in the initial design of a material processing plant, as well as during routine maintenance, to select the proper materials directly involved in the processing stream.

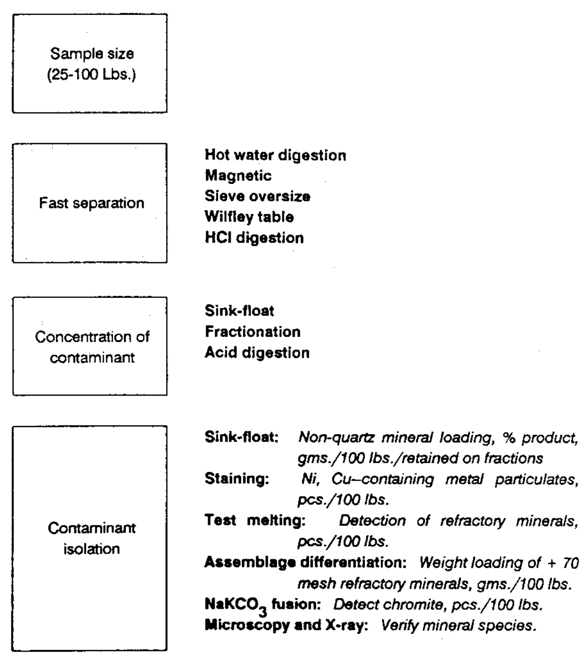

Figure 6. *Analytical procedure for trace contaminant identification.*

Table 5: *Total refractory content / 100# sand*

Requirement	Mesh Size	Maximum Limit
Cum. retained on:	U.S. Std. 70-mesh (0.0083 inches; 212 micrometers)	.200 grams

Undesired refractory minerals:

Chromite*	$FeCr_2O_4$	Sillimanite	Al_2SiO_4
Corundum	Al_2O_3	Zircon	$ZrSiO_4$
Andalusite	Al_2SiO_5	Zirconia	ZrO_2
Kyanite	Al_2SiO_5		

* Also other spinels

Table 6: *Acceptable mesh distribution for glass sand*

Requirement	U.S. Standard Limits	
Cumulative retained on:	16-mesh	Not one piece
Cumulative retained on:	20-mesh	.01% max.
Cumulative retained on:	40-mesh	5.0-15.0% max*
Cumulative retained on:	140-mesh	92.0% min.
Cumulative retained on:	200-mesh	99.5% min.
Cumulative retained on:	325-mesh	100.0% min.

*The amount of +40 mesh material acceptable is generally dependent on the amount of +70 mesh refractory particles contained in the product.

One other important criteria for a glass batch material is the particle size distribution. The particle size distribution is important for a number of reasons. First, oversize particles, particularly in the case of sand, must be excluded to prevent individual grains from surviving the melting process. Second, the total glass batch particle size distribution is designed to result in an homogeneous mixed batch being delivered to the furnace. Third, the -200 mesh material must be minimized to prevent problems resulting from dusting. Table 6 defines the desired mesh distribution for a glass batch sand.

Assuming one or two initial test samples meet the above criteria, a 50-to 100-pound sample of the product taken weekly for a period of six weeks is then carefully evaluated. If the material meets all the requirements, the material is then introduced into the melting operations at a level of 25% of the total required for a period of one month. During this period, samples from incoming shipments are analyzed and glass quality monitored. If no problems occur, the quantity of material is then increased to 50%, 75%, then to 100% of the total required for similar time periods and types of evaluation. If no problems are experienced, it is at this time that the material is given technical acceptance and a specific specification is generated based on all the data accumulated during the evaluation period.

The above example is typical of the procedure used by LOF Glass for acceptance of any raw material into its glass melting operations. The procedure may seem to some to be rather extensive and expensive; however, if one considers the consequences of using inferior or variable raw materials in flat glass manufacturing, there is indeed justification. Current float glass operations, for example, produce between 500 to 1000 tons of glass per day. Due to the size of the glass melting furnaces and the inertial effect in re-establishing satisfactory conditions, several days and sometimes up to a week of production can be lost at a significant economic penalty.

SUMMARY

In summary, the flat glass industry is alive, healthy, growing, and responding to the needs of the consumer in producing more sophisticated and higher performing flat glass products. It is not only a challenge to the glass scientist, but also to the scientist and engineers in the mineral raw material segment of industry. The continued success of the glass industry will depend on the technological achievements of the mineral industry to develop and provide high quality raw materials economically. To those not familiar with the mineral industry, little thought is given to the amount of technology involved in meeting customer requirements.

Certainly, the above illustration with respect to glass batch sand proves otherwise.

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Cause and effect of jointing in quarries in central and northern Indiana

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INTRODUCTION

Joints are ubiquitous features that are found wherever bedrock is exposed. In central and northern Indiana, which is mostly covered by glacial deposits of Pleistocene age, some of the largest bedrock exposures are in active crushed-stone quarries, where carbonate rocks of Silurian, Devonian, and Mississippian age are exposed to depths of more than 250 feet (Table 1). Joints, which are defined for this study as fractures or partings in rock without displacement, are present in all quarries in varying numbers and patterns. The most prominent joints are designated as primary, and other joints are designated as secondary. Secondary joints commonly butt against primary joints, but complex butting relationships may result from several episodes of joint formation.

Joints directly effect energy efficiency from blasts, direction of propagation of blast energy, placement of blastholes, size of rock fragments, floor conditions, appearance and safety of quarry faces, and blasting noise and air vibration. Joints may also be the principal control for direction of water influx into many quarries and may be the loci of clay-filled solution channels. Many of the negative effects of joints on the operations of quarries can be alleviated by proper orientation of quarry faces and judicious placement of blastholes. To achieve optimum conditions for new quarries or for reorientation of faces in active quarries, a knowledge of the local and regional joint directions and patterns is necessary.

CAUSES OF JOINTING

In recent years the cause and the orientation of jointing in much of the central United States have become better understood. Although many joints in tectonically active areas are directly associated with the stresses producing faulting and folding, most joints in flat lying or nearly flat lying rocks, as in much of Indiana, are caused by erosional unloading of bedrock. This unloading results in expansion and tensional stress that is relieved by the formation of joints. Engelder (1982) found that joint sets in the northeastern United States that are not genetically related to local structures are oriented and related to regional compressive stress in the lithosphere. Ault and others (1985) indicated that much of the primary jointing in southwestern Indiana is parallel or subparallel to regional compressional stress in the Midcontinent Stress Province as defined by Zoback and Zoback (1980) and Zoback and Zoback (1981).

With some exceptions, primary joints in central and northern Indiana are vertical or nearly vertical, some to depths of more than 200 feet, and are oriented east-northeastward in a direction parallel or subparallel to the direction of regional compressional stress. Secondary orthogonal joints are generally less prominent than the primary joints and probably formed shortly after the primary joints and following further erosional unloading, a method of joint formation discussed by Price (1966). These two joint sets, at right angles or nearly right angles to each other, are present in outcrops (Figure 1) and in the quarries studied

Table 1. *Outcrops and active quarries studied in central and northern Indiana. (See Figure 4.)*

Figure 4 Number	Location Sec.-Twp.-Rng.	Company	Rock units exposed in quarry or outcrop.
1.	16-29N-4W Pulaski County	Ward Stone, Inc.	Muscatatuck Gr. (Devonian) Wabash Fm. (Silurian)
2.	28-28N-2W White County	Vulcan Materials Co	Reef facies of Wabash Fm.
3.	19-25N-2W Carroll County	Delphi Limestone, Inc.	Reef facies of Wabash Fm.
4.	15-22W-6WW Tippecanoe County	(Outcrop)	Borden Gr. (Mississippian)
5.	20-27N-4E Miami County	Rock Industries, Inc.	Wabash Fm.
6.	29-26N-4E Miami County	Mill Creek Stone and Gravel Corp.	Traverse Fm. (Devonian) Wabash Fm.
7.	3-23N-3E Howard County	Martin Marietta Aggregates	Wabash Fm.
8.	12-23N-6E Grant County	Pipe Creek Jr.	Reef facies of Wabash Fm.
9.	12-28N-9E Huntington County	Erie Stone, Inc.	Reef facies of Wabash Fm. Pleasant Mills Fm. (Silurian) Salamonie Dol. (Silurian)
10.	11-27N-10E Huntington County	Erie Stone, Inc.	Reef facies of Wabash Fm. Pleasant Mills Fm.
11.	23-31N-14E Allen County	The France Stone Co.	Traverse Fm. Detroit River Fm. (Devonian) Salina Gr. (Silurian)
12.	33-26N-13E Adams County	Meshberger Bros. Stone Corp.	Pleasant Mills Fm. Salamonie Dol.
13.	4-26N-15E Adams County	Meshberger Bros. Stone Corp.	Pleasant Mills Fm. Salamonie Dol.
14.	8-16N-5W Putnam County	Russellville Stone Div., Kentucky Stone Co., Inc.	St. Louis Ls. (Mississippian) Salem Ls. (Mississippian) Harrodsburg Ls. (Mississippian)

Table 1. *(cont.) Outcrops and active quarries studied in central and northern Indiana. (See Figure 4.)*

Figure 4 Number	Location Sec.-Twp.-Rng.	Company	Rock units exposed in quarry or outcrop.
15.	9-17N-4E Hamilton County	American Aggregates Corp.	Wabash Fm. Pleasant Mills Fm. Salamonie Dol.
16.	3-18N-5E Hamilton County	Stony Creek Stone Co., Inc.	Wabash Fm. Pleasant Mills Fm.
17.	10-18N-7E Madison County	Irving Materials, Inc.	Jeffersonville Ls. (Devonian) Wabash Fm.
18.	25-21N-10E Delaware County	Irving Bros. Stone and Gravel	Pleasant Mills Fm. Salamonie Dol.
19.	30-23N-14E Jay County	Meshberger Bros. Stone Corp.	Salamonie Dol.
20.	11-21N-12E Randolph County	Meshberger Bros. Stone Corp.	Pleasant Mills Fm. Salamonie Dol.
21.	12-21N-13E Randolph County	Meshberger Bros. Stone Corp.	Salamonie Dol. Salamonie Dol.
22.	1-12N-4W Putnam County	The France Stone Co.	West Baden and Blue River Grs. (Mississippian)
23.	8-12N-9E Rush County	Rush County Stone Co., Inc.	Jeffersonville Ls. Waldron Sh. (Silurian) Salamonie Dol.
24.	1-14N-1W Wayne County	Middleboro Stone Corp.	Salamonie Dol.

in central and northern Indiana (Figures 2 and 3). In quarries with steeply dipping beds on reefal flanks, the direction of some primary joints may be deflected somewhat from the overall regional pattern (Figure 4 and Table 1). The joint patterns in quarries 2 and 10 in Figure 4, both measured in reefal-flank rocks, may have been deflected by the reefal structure. Other joint sets in reefs, however, do not appear to vary much from the regional pattern (for example, quarries 3, 8, and 9 in Figure 4).

Most fractures caused by blasting in quarries can be differentiated from natural joints by fracture patterns and by stains, weathered zones, and mineral coatings on natural fractures. Natural fractures near quarry faces are nearly always more persistent than blast fractures. Blast fractures radiate for a short distance from blasthole sites on quarry faces and in places on quarry floors. Most fractures adjacent to a shothole on a quarry face should therefore be suspect, but such fractures are concentrated and generally are not apparent in

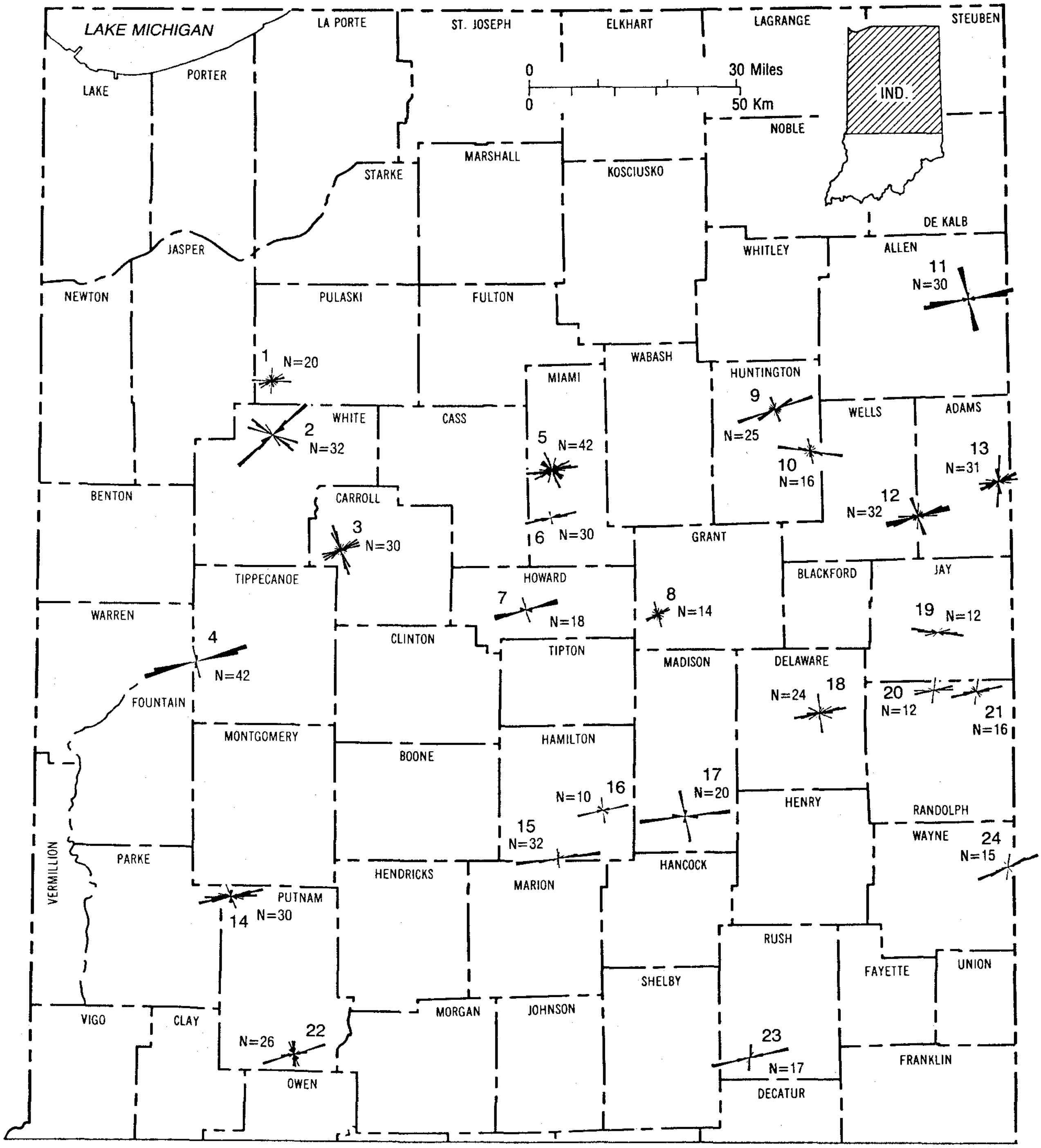

Figure 4. *Map of central and northern Indiana showing rose histograms of jointing at an outcrop and at active quarries. N = number of measured joints. See Table 1 for specific locations and rock units exposed at each location.*

any number farther than a few feet from the shothole. Fresh fractures that are persistent near quarry faces are commonly aligned with prominent joint directions. This alignment suggests that the bedrock stress that controlled the direction of joints also exerts some control over the orientation of fresh fractures.

MEASUREMENT OF JOINT ORIENTATION

In central and northern Indiana outcrops are few, glacial deposits are thick in most areas, and many joints in quarries, where most measurements are made, are in inaccessible faces. Notwithstanding the scarcity of data in some areas, regional patterns and directions are generally predictable, and with some searching, sufficient exposed bedrock can be found in many areas to give accurate directions of jointing.

Measurement of joint directions in quarries and outcrops by use of a good surveying compass makes determination of joint patterns rapid and inexpensive. Various grids and measured traverses have been used in attempts to prevent bias in joint measurement in Indiana (Foote, 1980; Pentecost and Samuelson, 1979; and Powell, 1976), but the measurement of joint frequencies and directions is still an inexact science. Reproducibility of measurements of the prominent directions of jointing is much better than the reproducibility of the proportionate number of joints in each direction, especially in active quarries, where the mining of rock constantly exposes new joints while removing others.

Joints can be measured by laying a surveying compass directly on a joint surface, by laying a flat object, such as a field notebook, on the surface of a joint and laying the compass on the notebook, or by sighting along a joint with a surveying compass. Joint surfaces are commonly thought of as nearly a plane surface, but small irregularities can throw off measurements by several degrees by the first two methods (see Figure 11b for example). Sighting along a joint with a surveying compass was found to be quite accurate, commonly reproducible within 1^{o} or 2^{o}, and nearly all measurements shown in Figure 4 were obtained by this method. In some quarries the joints exposed on high quarry faces are the only joints that can be measured. Floors of quarries are commonly covered with loose, finely crushed stone, and the bedrock surface around the top of most quarries is commonly covered with soil or other loose material, even where stripped for quarrying. A close approach to a high face in a quarry is dangerous, but the sighting method, which can be used from several tens of feet or even farther away from the face, is accurate for prominent joints and for many small joints.

The number of measurements that must be made to be representative of a site is as much a matter of judgment as a matter of statistics. The number of joints measured at each site shown in Figure 4 ranged from 10 to 42; the actual number was dictated mostly by the number of reliable joint surfaces that could be found at each site. Measurements were made on all quarry faces to compensate for joints that were at acute angles or parallel to any one or two faces. There is a point of diminishing returns for joint measurements. Prominent joints are easily measured (Figs. 1, 2, and 3), but smaller joints or fractures may be difficult to measure accurately and they vary more in direction. Further, even at sites that have many joints, the most prevalent directions of jointing are commonly evident after a minimum number of measurements. The number varies from quarry to quarry because of a number of factors, including the difference in lithologies of exposed rock and the influence of local structures, such as reefs.

Although individual joints are given equal weight in most statistical presentations, Pentecost and Samuelson (1979) divided joints in east-central Indiana into three categories of persistence according to the length of the joints. They determined that the dominant two directions of all of the jointing were also seen in the data for each category, which indicates that the dominant directions can be determined without categorizing. Joint measurements for this study were plotted on rose histograms (Figure 4), which represent the number of joint measurements in each 5^{o} arc by the length of each of the bars. All measurements of joints, whether large or small, prominent or obscure, are given equal weight in each histogram. The histograms are most useful in showing the dominant directions of jointing, which information can be used to predict the general direction of jointing in other nearby rocks or quarry sites that are not affected unduly by reef structures.

No attempt has been made to categorize the joints because accurately determining joint persistence is difficult and because the direction of jointing is more important to the purpose of this study than other less determinable factors. Notwithstanding the difficulty of quantifying joint persistence, it can be stated in a general way that the most prominent joints at quarries and outcrops in central and northern Indiana are more numerous in one direction, commonly parallel to the direction of regional stress (Figs. 5,6, and 7).

EFFECTS OF JOINTS IN QUARRIES

Blasting energy

Efficient blasting in a crushed-stone quarry produces pieces of rock that are an optimum size for rapid processing through crushers and screens. In homogeneous rock much expense of mechanical crushing and rehandling can be avoided by using proper shothole patterns, calculating efficient amounts and types of explosives for shots, and using appropriate sequential timing of shots. Jointing is one of the major factors that controls the breakage of rock in blasting operations (Davenport, 1979).

Shotholes placed some distance from prominent joints will allow blast energy to fragment the surrounding rock before breaking through to the joints. As a matter of practice, one blaster (the person blasting the bedrock in a quarry) in northern Indiana drills shotholes at least 5 or 6 feet from prominent joints. Although other important considerations are obviously necessary to determine the best pattern and geometric arrangement of shotholes in a quarry bench, the presence of persistent joints should greatly influence such decisions.

Joints and fractures in and near the quarry face to be blasted can allow significant amounts of energy from the blast to escape. Escaping blast gases from joints can and have caused damage to distant structures (Richard Kauppila, written commun., 1986). In one instance related to me, a shot was made, but nearly all of the blast gases escaped through joints and fractures and no rock fall occurred (Mark Sereno, oral commun., 1986). Joint faces reflect energy that strikes them at obtuse or right angles. and this too should be taken into account by blasters.

Size of blasted rock

Where prominent joints are parallel to the quarry face, explosive gases may widen joints in the direction of the quarry face, and cause large blocks to be pushed into the quarry (Figure 8). Even where a prominent joint set is perpendicular to the quarry face, improperly placed shotholes may produce oversize shot rock at the joint surfaces. Collections of oversize blocks can be seen in many quarries. "Headache" balls or air hammers will be required to break the blocks before they can be fed to the primary crusher. Some quarries hold a rather large collection of these blocks that are the result of jointing and other causes (Figure 9). Many operators feel that it is less expensive to waste the large blocks than to break them into smaller sizes for the crusher.

Appearance and safety of quarry faces

One quarry superintendent told me that a prominent joint surface makes a fine quarry face. It is relatively smooth with no loose rock and appears quite stable. The problem in an advancing quarry face is blasting to the joint surface in the first place. The shot preceding the exposure of the joint surface may have produced many of the difficulties discussed above, and a prominent joint at a quarry face indicates the likelihood of additional parallel joints behind the quarry face.

An advancing quarry face that is close to a parallel-joint surface may be particularly unstable where a well-developed secondary joint set accounts for presence of loose blocks at the face (Figure 10). Such faces are dangerous and difficult to work near. They are also particularly susceptible to freezing and thawing, which further increase the danger from falling rock. Orthogonal surfaces are commonly well exposed on such faces, and the orientation of the jointing can generally be determined accurately with a surveying compass.

Where a prominent joint surface is used as a sidewall perpendicular to the advancing face, however, the joint surface may make a convenient and safe wall if no close parallel joints or prominent secondary joints are present (Figure 11). At least one operator in northern Indiana follows this practice (Richard Kauppila, written commun., 1986).

Floor conditions

Perhaps of less importance than the above effects, jointed bedrock can contribute to the production of a rough, uneven quarry floor that will cause undue wear and tear on quarry equipment, particularly the tires on loaders and trucks. Where possible, blasters and quarry operators like a well-defined bedding plane for a floor. The base of shots can be set at certain depths in many quarries, so that the blasted rock separates from the floor of the quarry at a bedding plane that will result in a smooth floor. Joints can disrupt the effect of the blast to a bedding surface and result in a rough floor.

Blasting noise and air vibration

Most quarry operators and explosives experts agree that noise and air vibration from blasting cause more complaints from quarry neighbors than the actual vibration or shaking of the bedrock. Very low clouds or unfavorable wind directions can cause a rise in complaints from some quarry neighbors, even though the same procedure is used for blasting as on any other day. It is not known if the increased noise and air vibration caused by blasting gases escaping through joints increase and cause more problems with quarry neighbors, but any increase in noise and vibration is obviously undesirable.

Water influx

That joints are good passageways for water is unquestioned. In south-central Indiana, for example, the relationship of jointing and caves, the ultimate in good passageways in carbonate rock, has been investigated in detail (Powell, 1976), and it has been shown that there is a direct relationship between joint systems and the formation of some caves. A cave more than 45 feet long in the direction of prominent jointing was mapped in a quarry in Delaware County in northern Indianna (Figure 12). Ground-water movement can form solution channels of all sizes, and water-bearing channels and channels filled with unconsolidated clays and sands are common in quarries in carbonate rock.

Prominent joint sets generally have a large influence on water movement near quarries, although detailed investigations of water movement near any particular quarry site are necessary to determine actual volumes, directions, and depths of ground-water flows. On many joint surfaces, ground-water stains and mineral coatings testify to the passage of ground water. In northern and central Indiana, waterfalls can commonly be seen at some height on quarry faces where ground water flows through joints or channels into the quarry (Figure 13).

Quarry operators and their neighbors are concerned with the stability of the water table near quarries. A knowledge of the direction of the joint sets and their directions in and near a quarry is of value in evaluating the water regime of the area, particularly where a stream or river is near the quarry and where a direct connection by way of a joint set is a possibility.

Filled joints and solution channels

Solution channels filled with clay or other unconsolidated sediments may be the most undesirable aspect of jointing in some quarries in central and northern Indiana (Figure 14): The deposits can cause considerable expense to some quarriers, who must separate the broken rock from the clay, which may be present in considerable quantity. The unconsolidated material deposited in channels and joints can clog the screens used to size crushed stone and can discolor and contaminate the bedrock near joints to such an extent that it cannot be used for some products.

Some clay-filled joints can easily be seen at a bedrock surface that has been stripped for quarrying, but many others are not so obvious and are first encountered during blasting. A shot in one quarry in northwestern Ohio reportedly caused a clay "worm" to be expelled from a sediment-filled channel onto the bedrock surface some distance away from the blast (Bruce Mason, oral commun., 1985). Small joints are cleaned out by hand in some quarries in central and northern Indiana, but closely spaced joints filled with sediment may cause the operator to avoid quarrying that part of the bedrock altogether.

If the probable direction of such sediment-filled channels and joints can be determined by the direction of the jointing in the quarry, precautions can be taken, or test drilling in the suspected area may help determine the severity of the problem.

RECOMMENDATIONS

Prominent directions of jointing are generally locally consistent and measurements of exposed bedrock in outcrops or other exposures can be used to predict the jointing directions at a nearby prospective quarry site. Data derived from steeply dipping flank beds of Silurian reefs, many of which are exposed in northern Indiana (Ault and others, 1976), should be used with caution because of the possibility of some deflection of joint directions from the normal for the area. Similarly, data derived from normal, nearly flat-lying interreef rocks may not reflect well the direction of jointing that will be found in reef rocks being considered for a quarry site.

A new quarry may be strategically placed to avoid movement of water from a nearby stream, river, or lake through a prominent joint set into the quarry. As noted above, ground-water movement is not obvious at many sites, even where jointing directions may be well known, and direction of jointing should only be one of several important factors evaluated when determining water regimes.

Other considerations aside, a face in a newly opened quarry or the advancing face in an established quarry generally should be at right angles to the most prominent joint direction if there are only a few joints in other directions. This will minimize the effects of jointing that is parallel to the quarry face and will promote greater stability and safety of the quarry face, fewer large blocks blasted from the face, better fragmentation of the rock, and less noise and vibration resulting from escaping explosive gases. The shothole pattern and shot-delay sequence and their relation to jointing should be carefully considered to provide maximum confinement of the blasting energy and to prevent premature breakthrough of shots made near joints.

If there are two prominent joint sets, a quarry face oriented at 45^{o} or at the widest angles possible to the two sets will minimize the number of joints parallel or subparallel to the quarry face. Where more than two prominent joint sets are present, decisions may be difficult or of little practical importance, although if possible the quarry face should be at obtuse angles with the most prominent joints.

An important consideration in mining aggregate from shallow underground limestone mines, two of which are active in central Indiana, is the effect of joints in the roof rock. A prominent joint set parallel to corridors or room entrances tends to promote roof falls, especially if a well-developed secondary orthogonal joint set is also present. Although roof bolting or other means may sufficiently cure many such problems, orienting rooms and mine corridors at about 45o to prominent joint directions will provide better pillar support for jointed rocks.

ACKNOWLEDGMENTS

Richard Kauppila, explosives engineer with Irving Brothers Gravel Co., read the manuscript and made many valuable comments that were incorporated in the report. All operators of crushed-stone quarries in central and northern Indiana were courteous and cooperative during the gathering of data, and discussions with blasters and other quarry personnel greatly benefited the report.

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Figures 1, 2, 3, and 5 - 14 on following pages.

Figure 1. *Outcrop of well-jointed rocks of the Borden Group (Mississippian) near West Point, Tippecanoe County, showing prominent east-northeastward jointing.*

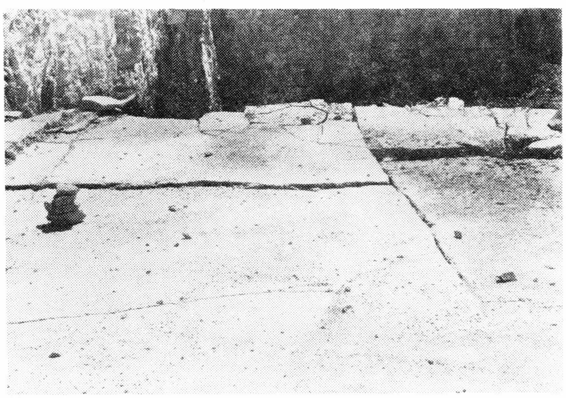


Figure 2. *Orthogonal joints and fractures in a quarry bench in central Indiana.*

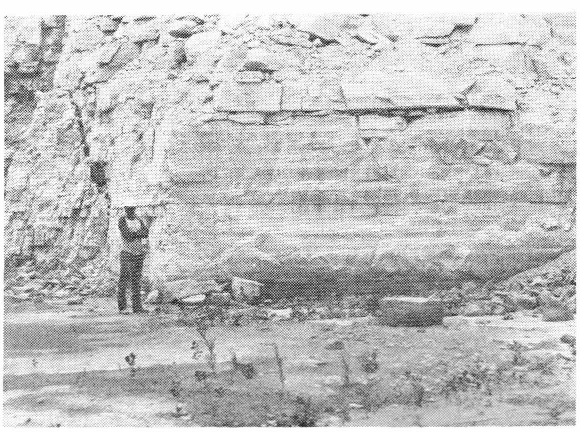


Figure 3. *Orthogonal joint surfaces exposed in a quarry in north-central Indiana. The prominent, relatively smooth joint to the right of the figure is at a right angle to the joint surface directly behind the figure.*

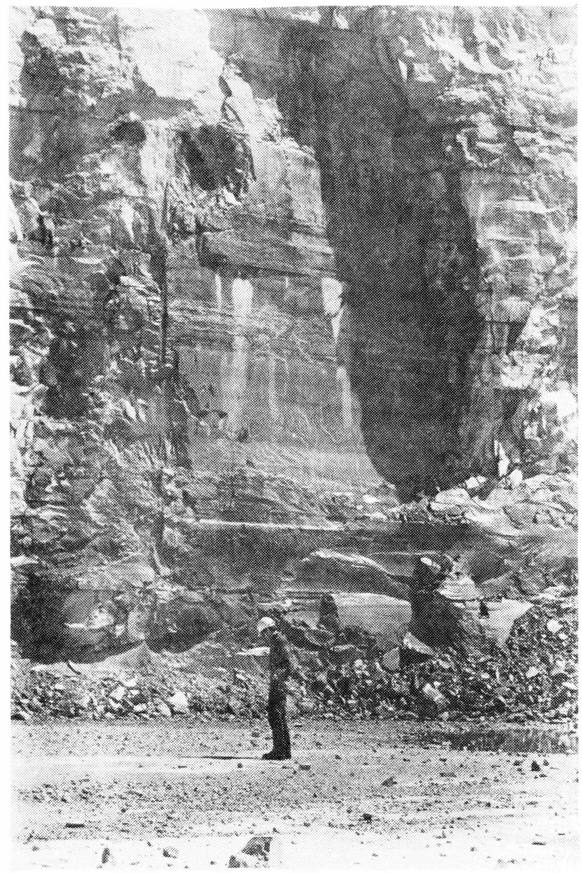


Figure 5. *Prominent joint surface in silty and argillaceous dolomite of the Mississinewa Shale Member of the Wabash Formation (Silurian) in a quarry in central Indiana.*

Figure 6. *Prominent joint in silty dolomite of the Louisville Member of the Wabash Formation in a quarry in northeastern Indiana.*

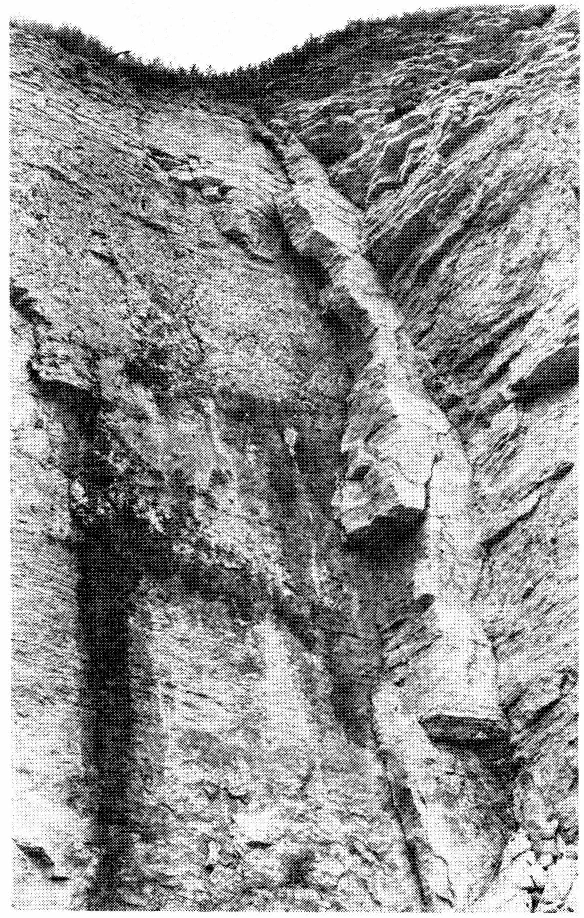


Figure 7. *Prominent joints in dolomite of the Wabash and Pleasant Mills Formations (Silurian) in a quarry in northeastern Indiana.*

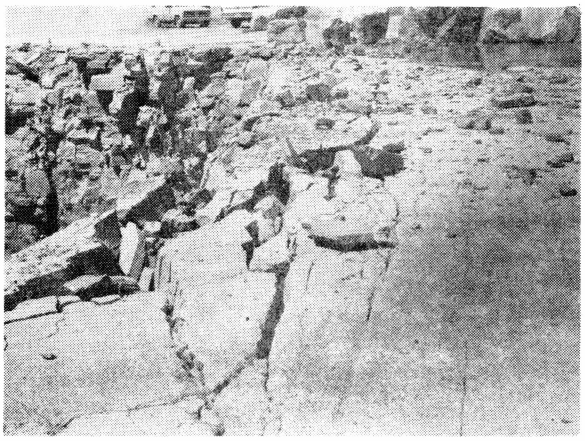


Figure 8. *Joints and fractures parallel to a quarry face in central Indiana.*

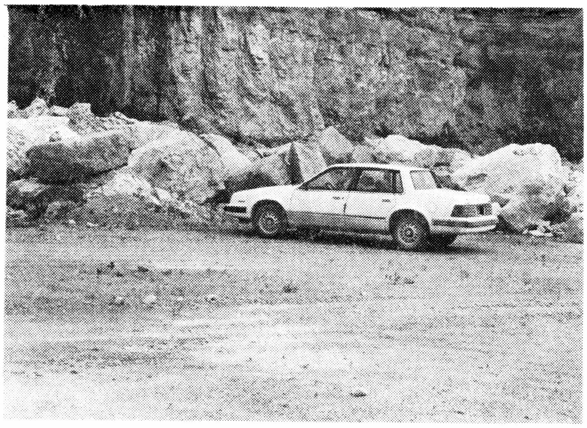


Figure 9. *Large waste blocks of dolomite resulting from joints and other causes.*

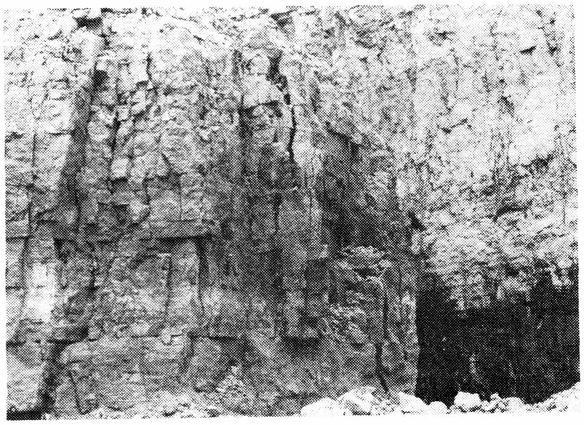
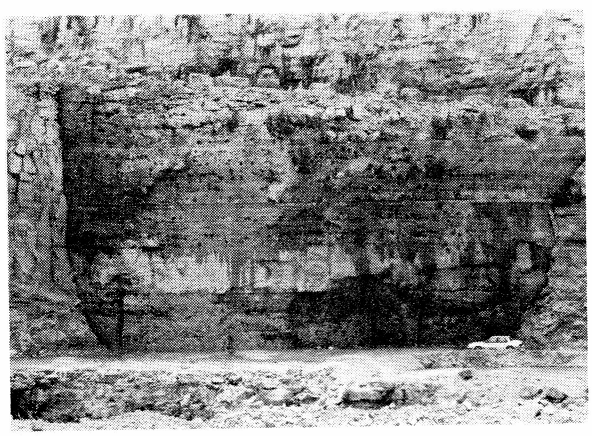


Figure 10. *Well-developed orthogonal joint systems in a quarry in northeastern Indiana producing loose blocks of dolomite on a rough quarry face.*

b



a

Figure 11. *Prominent joint surface used as a sidewall in a quarry in northeastern Indiana: a) far view showing large expanse of joint surface (for scale, note automobile in lower left of photograph); b) near view showing vugs and irregularities caused by ground-water solution affecting joint surface before it was exposed in the quarry.*

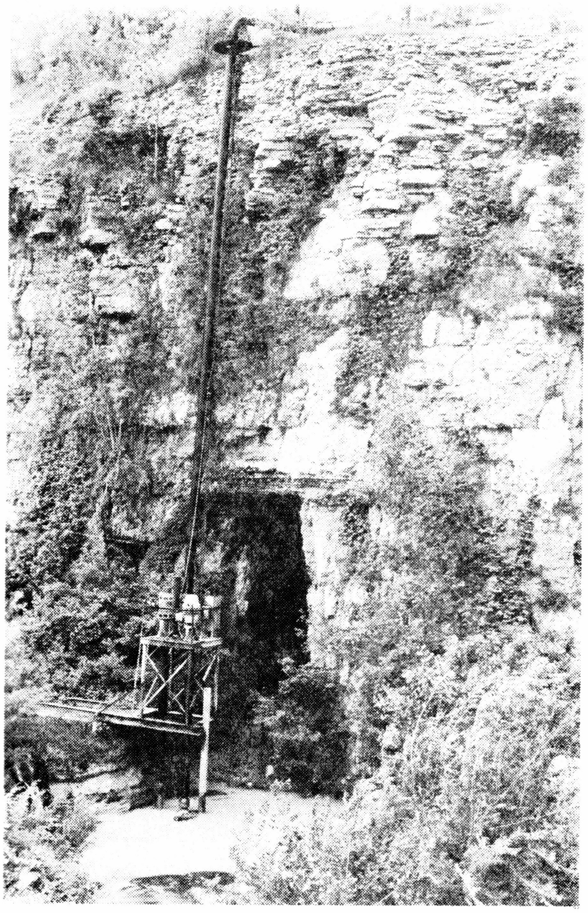


Figure 12. *Entrance to a 45-foot cave developed along a joint system in dolomite in a quarry in northeastern Indiana.*

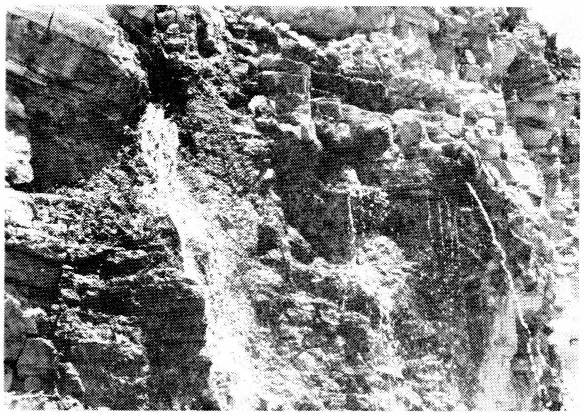


Figure 13. *Ground water entering a quarry in north-central Indiana through channels developed in well-jointed dolomite.*

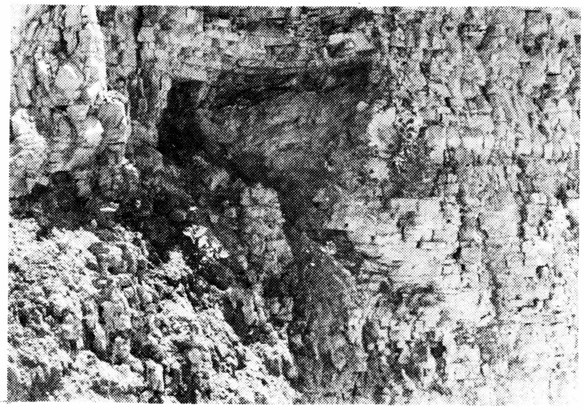


Figure 14. *Clay-filled solution channel (just above the center of the photograph) in well-jointed and bedded dolomite in a quarry in north-central Indiana.*

The cement industry and cement raw materials in Texas[1]

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ABSTRACT

Texas led the nation in cement production from 1980 through 1985. The value of cement produced in Texas in 1985 was slightly less than $600 million, more than 30 percent of the total value of Texas nonfuel mineral production. As of January 1986, Texas had 14 active clinkering plants and 6 plants acting as grinding/distribution terminals. Eleven of the active plants, located along a corridor from San Antonio to Dallas-Fort Worth, accounted for approximately three-fourths of the state's total cement production.

Texas has extensive deposits of raw materials suitable for cement manufacture. The calcareous resource most intensively used at present (approximately 7 million short tons in 1985) is the Upper Cretaceous Austin Chalk, which crops out in a band from San Antonio to Dallas. The Lower Cretaceous Edwards Limestone is used by some of the plants in the San Antonio area. Other Texas resource materials include the argillaceous, siliceous, and ferruginous materials needed for clinker, as well as gypsum, which is used for finished cement.

INTRODUCTION

Texas is now in its second century of cement production and has been the leading cement producer in the nation for the last 5 years. Such a history is due to: vast supplies of cement raw materials widely distributed throughout the state, a strong market for the product, past years of inexpensive fuel in the form of natural gas, planning by cement producers, and an excellent distribution network that includes water, rail, and highway.

In 1985, the value of cement production in Texas was more than $550 million. Cement in Texas is subject to a production tax of $0.0275 per 100 pounds; the total value of this tax in 1985 was $5.8 million. So, cement dollars are not something Texas takes lightly.

1/ Published with permission of the Director, Bureau of Economic Geology, The University of Texas at Austin. Research supported by U.S. Bureau of Mines grant no. G1154148 to the Texas Mining and Mineral Resources Research Institute.

LOCATION OF PLANTS

The market for cement is closely tied to construction, and construction is closely related to population distribution. Population in Texas is primarily distributed in the eastern half of the state, including the metropolitan areas of Dallas-Fort Worth, Houston, and Austin-San Antonio; therefore, the market for cement in Texas is concentrated in East Texas. Because raw materials used in cement manufacture occur throughout Texas (Gulf Coast calcareous resource materials being a notable exception), resources currently used are primarily in response to market demand and distribution networks.

Eleven of the 14 cement plants operating in Texas in 1986 (Fig. 1) are located in East Texas and the other 3 are in the West Texas-High Plains area. In addition, there are five plants along the Gulf Coast and one in El Paso that currently are not clinkering, but are acting as distrubution/grinding facilities.

Three of the inactive Gulf Coast plants are located in Houston, another at Corpus Christi and one at Orange. Several factors contributed to the demise of clinkering at these plants, such as the loss in the late 1970's of a nearby calcareous resource (oystershell dredged from dead reefs in Texas bays), the increased expense of urban environmental demands, rising fuel costs at older wet-process plants, and the downturn in the economy. But the increase of imported cement and clinker was the final blow to clinkering operations along the Gulf Coast. Imports into Houston, notably from Spain and Mexico, increased from a 1982 low of 20,000 short tons (st) to 691,500 st in 1985--almost 35 times the 1982 imports.

Although Gulf Coast cement plants may suspend or cease clinkering operations, they are ideally situated for product distribution. The Intercoastal Waterway, which serves long barge trains, runs the length of the Texas coastline and offers several facilities for loading and offloading barges. In addition, there are deep-water ports at Corpus Christi, Houston, and Port Arthur. Lone Star-Falcon has a terminal in Houston capable of holding 600,000 tons of cement and of handling ships as much as 700 ft. long. Centex is improving and deepening its dock facilities at Corpus Christi. All of the low-cost water transportation facilities have excellent connections with both rail and highway transportation networks.

Eleven plants along the central corridor extend from San Antonio north to the Dallas-Fort Worth metroplex. More than 75 percent of the cement produced within the state in 1985 came from these plants. The largest plant in the state is in Ellis County, south of Dallas, and a new plant in the same area is projected to open in late 1986 or early 1987.

Railroads and highways are extensive along this corridor, and all of these plants are located close to north-south interstate highways. An east-west interstate passes through San Antonio and another through Dallas-Fort Worth. Although transport from plants along the central corridor is largely by truck, there is also significant rail shipment.

The entire High Plains-West Texas area is served by three active plants. Not only do these plants supply construction needs, but they also manufacture oil-well cement. A plant in El Paso currently is grinding and distributing clinker and finished cement imported from Mexico.

STRUCTURAL SETTING

The most significant structural feature influencing the cement industry in Texas is the Balcones fault system, which trends in an arcuate pattern from west of San Antonio to north of Waco. This highly complex system of en echelon normal faults effectively delineates the Gulf Coast from topographically higher areas to the west and separates the present outcrop of poorly lithified Upper Cretaceous and younger formations to the east (downthrown) side from the well-lithified Lower Cretaceous and older rocks to the west (upthrown) side. The Balcones escarpment even influences rainfall patterns. Moisture from the Gulf of Mexico often does not lift over the fault zone; therefore, areas on the upthrown side of the system are more arid than those on the downthrown side. At the time Texas was settled, the differences in rainfall and lithology on opposite sides of the fault zone led to a more populous development of farming communities on the downside of the fault zone compared to the sparsely populated ranching and grazing lands on the west side. Later, the population difference encouraged development of transportation networks on the east. Thus, this fault system provides a major demographic, lithologic, and physiographic as well as structural influence on the state.

Outcrops within the Balcones fault zone are a crazy-quilt of Comanchean and Gulfian rocks, and Paleozoic and Precambrian rocks are at depths of only a few hundred feet.

The Luling-Mexia-Talco fault zone parallels the Balcones system through Central Texas and then curves eastward to separate the more structurally stable part of the state from the East Texas and Gulf Coast basins. Surface rocks in these basins, sites of subsidence and deposition since the Mesozoic, are essentially nonmarine clastic sediments of Eocene and younger age. The Gulfian Austin Group, with a main outcrop belt between the Balcones and

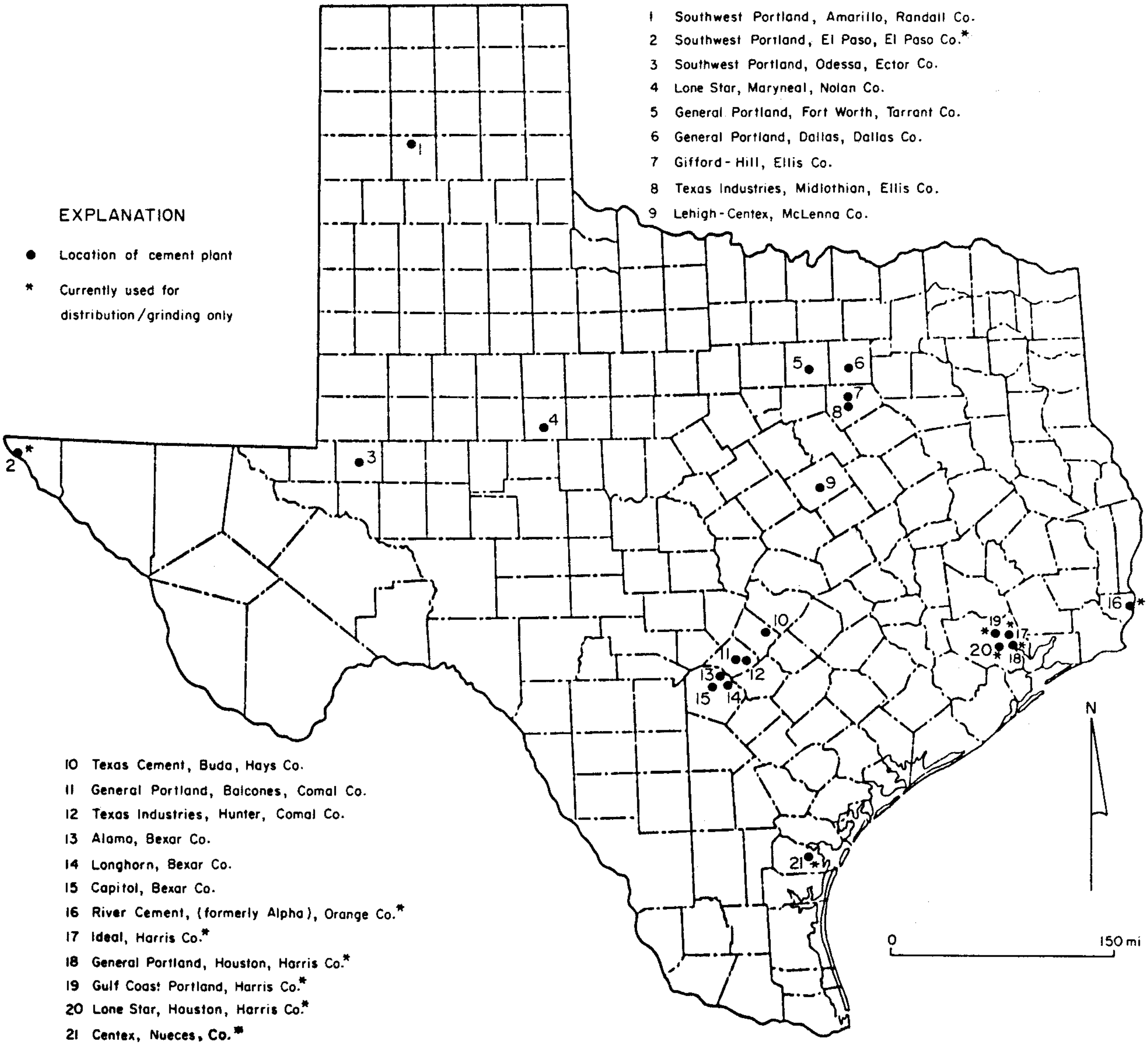

Figure 1. *Location of Texas cement plants.*

Luling-Mexia-Talco zones, is the youngest rock unit that contains major calcareous deposits.

Immediately west of the Balcones system, in Central Texas, is the granite massif, the "Central Mineral Region," which is characterized by outcrops of Precambrian and lower Paleozoic rocks. North of the Central Mineral Region are elongate outcrops of Pennsylvanian and Permian rocks. Broad outcrops of resistant Lower Cretaceous limestones form the plateau areas west and north of the Balcones fault zone. North of the plateau areas are outcrops of Permian and Triassic rocks and Neogene-Pleistocene gravels.

STRATIGRAPHY

Formation and group names of rock units having significance as cement resources are shown in Figure 2 and will be discussed by resource category.

Figure 2. *Stratigraphic association of cement raw materials currently used by Texas cement plants.*

Era	Period/Epoch	Group/Formation	Resource Material	Area of Outcrop
CENOZOIC	Quaternary /Holocene /Pleistocene		Clay, Sand	State-wide, River Terraces
	Tertiary — Neogene		Caliche	West Texas
	Tertiary — Paleogene	Claiborne /Weches	Iron	East Texas
		Claiborne /Carrizo	Sand	Central Texas
		Wilcox /Simsboro	Sand, Clay	East Texas
MESOZOIC	Late Cretaceous (Gulfian)	Taylor /Anacacho	Clay	South-Central Texas
		Austin /Atco	Limestone	Central Corridor
		Eagle Ford	Shale	Central Corridor
		Woodbine	Sand	North-Central Texas
	Early Cretaceous (Comanchean)	Washita	Limestone	Central Corridor
		Fredericksburg /Walnut /Edwards	Limestone, Gypsum	Central Corridor, West Texas
		Trinity /Paluxy-Antlers	Sand	North-Central Texas
PALEOZOIC	Permian	Briggs	Gypsum	West Texas
		Double Mountain	Shale	Northwest Texas
		Whitehorse /Blaine	Gypsum	Northwest Texas
	Pennsylvanian	Grayford /Chico	Limestone	North-Central Texas

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Calcareous Materials

The most commonly used cement calcareous resource is the Austin Group, or Austin Chalk, of Gulfian (Late Cretaceous) age. Most of the cement plants in the central and northern San Antonio-Dallas corridor use this rock. The second most commonly used material is from the Lower Cretaceous, Comanchean age, Edwards and associated limestones. The Austin Chalk and the Edwards provide more than 90 percent of the calcareous materials currently used by Texas cement plants. Other limestones being used include the Pennsylvanian Graford Formation, Lower Cretaceous Washita Group, the Gulfian Anacacho Formation, and a Neogene-Pleistocene caliche. The Anacacho, a marl to argillaceous limestone, provides both calcareous and argillaceous materials.

Deposited on a broad, shallow, tectonically stable shelf, the Comanche Platform, the Edwards and related limestones now have broad outcrops in Central and West Texas. However, they are used as cement raw materials only in the area along and within the southern Balcones fault zone (Bexar and Comal Counties) and in parts of northwest and West Texas (Nolan and Ector Counties).

The Edwards Limestone in the southern part of the Balcones fault zone consists of alternating evaporites and shallow-water carbonate mudstones and grainstones deposited in a lagoon developed in the central Comanche Platform (Fisher and Rodda, 1969). Most of the evaporites in this area subsequently were removed by weathering, and both solution porosity and local dolomitization are common. This limestone has extensive recrystallization (especially in areas of cavernous porosity), pockets of reefal material, and layers with burrowed surfaces. Some of the quarries show pockets of clay that are postdepositional fill of cavernous porosity. This part of the Edwards supplies the calcareous resource material for the new Alamo plant in San Antonio and the Balcones and Hunter plants in Comal County. An unusual mound of reefal material with a high degree of whiteness is used as the calcareous resource for Lehigh's white cement plant in Waco. This mound is within the Walnut Formation, which is stratigraphically above the Edwards of Central Texas, but is usually regarded as a facies of the Edwards. An elongated outcrop of the Edwards flanking and within the Balcones fault zone is quarried for crushed stone.

Two plants in the West Texas-High Plains area use the Edwards Limestone as a calcareous resource. Moore (1967) describes the Edwards near Lone Star Cement's Nolan County plant as a pellet grainstone to rudistid packstone varying to rudist fragment grainstone, all typical of shallow-water deposition. This area was along the northern margin of the Comanche Platform. In Ector County, where the Edwards occurs as an outlier southwest of Odessa, Rodda and others (1966) describe the limestone from the Southwest Portland Cement quarry as "buff to gray, fine to mostly coarse grained, partly crystalline, thick bedded; abundant fossils and fossil detritus." Although these rocks lack the well-developed rudistid reefs characteristic of the Edwards to the east, they are typical of the broad, shallow, stable platform that controlled deposition of this part of the Lower Cretaceous section in Texas.

The Austin Chalk, often described in the older literature as a naturally occurring cementitious rock, was the calcareous resource of all 19th and early 20th century cement plants in the state. The outcrop of the Austin Group used by the cement industry today extends from San Antonio through Austin, Waco, and Dallas. At its type section near Austin, this group has been divided into five formations, but these divisions are not mappable throughout the state. The lower Austin, or Atco Formation, represents about one-third of the thickness of the group and is the part most commonly used in cement. The Atco is composed primarily of coccolith plates and other pelagic planktonic debris, and is almost devoid of primary sedimentary structures, although bioturbation is common. Estimates of water depth are variable, ranging from 100 ft. to a few hundred feet. The absence of large-scale current features, such as channelling and winnowing, the preservation of massive bedding, and the cyclicity of the clay-rich intervals suggest that the Austin, with local exceptions, was deposited below wave base (Scholle, 1977). Bioherms and other indications of shallow-water deposition occur locally in Central Texas. The faunal assemblages indicate normal marine salinities. Regional to local structural features influenced thickness and lithology of the Austin Group.

A part of the significance of the Austin rocks as a calcareous resource is that immediately below are rocks of the Eagle Ford Group, which through South and Central Texas are shale, and immediately above are rocks of the Taylor Group. The Taylor of South and Central Texas is mainly marls, marly clays, and marly limestones. Thus, this outcrop band contains both calcareous and argillaceous resource materials, and many plants obtain both materials from one quarry.

These Gulfian rocks serve as resource materials for seven cement plants: two in San Antonio, one at Buda, one at Waco, two at Midlothian (south of Dallas-Fort Worth), and one at Dallas. Most of these plants take both calcareous and argillaceous materials from one quarry, and at the Waco plant iron content in the Austin Chalk is high enough that only a small amount of iron must be added. A new plant under construction along this trend will use these Gulfian resource materials.

Argillaceous Resource Materials

Argillaceous resources used by Texas cement plants range from the Permian Double Mountain Group of the Lone Star Industries plant in Nolan County to the Holocene silty overburden used by several plants. The Gulfian Eagle Ford and Taylor Groups provide the largest percentage of argillaceous material for plants that use the Austin Chalk as a calcareous resource. A white kaolinitic clay from the Eocene Wilcox Group is used at the white cement plant in Waco. This clay and an accompanying white sand, also used by the white cement plant, occur as lenses and pods in the interfluve areas of the fluvial Simsboro Formation of the Tertiary Wilcox Group.

Silica Resource Materials

Silica resources used by the Texas cement industry range in age from the Early Cretaceous sands of the Paluxy and Antlers Formations, used by the Nolan, Tarrant, and Ellis county plants, to the Pleistocene river-terrace deposits present along most of the major rivers in the state.

A ferruginous sand, the Upper Cretaceous Woodbine Formation, crops out west of the Austin Chalk in North Texas and is used at the Ellis County plants.

When silica enrichment is necessary, San Antonio area plants use sand from an outcrop of the Tertiary Carrizo Formation just south of town, or from the terraces of the Guadalupe River in Guadalupe County. Much of the sand in these terrace deposits is reworked from the Carrizo and Wilcox outcrops. The two Comal County plants and the Hays county plant also use sand from the Guadalupe terrace deposits.

Gypsum Resource Materials

Gypsum resources used in cement production are primarily from the northwest Texas outcrops of the Blaine Formation in the Permian Whitehorse Group or from the evaporitic facies of the Edwards Limestone in Central Texas. The extensive gypsum deposits of northwest Texas (Nolan, Fisher, and Stonewall Counties) are quarried primarily for production of wallboard. However, gypsum is also shipped to North Texas and Houston cement plants for finishing cement. Gypsum quarried from the caprock of one of the South Texas salt domes (Gyp Hill, Brooks County) is shipped into Houston for the manufacture of wallboard and is used by some of the Houston cement plants. The El Paso plant uses gypsum from a small deposit in the Permian rocks in the Finlay Mountains east of El Paso to finish-grind Mexican clinker imported into Texas.

Iron Resource Materials

The Tertiary Weches Formation of East Texas is the only naturally occurring iron resource used by Texas cement plants. The materials used are limonite and some siderite nodules formed from the weathering of a glauconitic (?) limestone.

CONCLUSIONS

Although the Texas cement industry has many of the same problems that are present nationwide--influx of imports, downturn in economy, and delay in release of Federal funds for highway and infrastructure improvement--the prospect for the future remains attractive. Since 1980, three Texas plants have increased their capacity, one has relocated to double its capacity, two plants at new locations have come on line, and an additional plant with an approximate capacity of 1 million tons will be on line in early 1987. Production of cement in Texas has outpaced the national average throughout the last decade. Because population growth in Texas is predicted to continue to surpass the national average at least until the year 2000, the Texas cement industry should continue to grow at a rate above the national norm. Natural resources necessary for cement manufacture are abundant and widely distributed in Texas and should foster the growth of this important industry throughout its second century in the state.

ACKNOWLEDGMENTS

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Virginia's lime industry

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INTRODUCTION

Lime is defined as calcined (burned) limestone, and marketed as quicklime or calcium oxide. It is made from a variety of calcareous materials such as limestone, dolomite, marble, chalk, shell, coral, aragonite, or by-product sludge from paper mills, carbide plants or other industrial plants. Quicklime, a white refractory, non-crystalline compound, is produced by calcining calcareous materials in a kiln at temperatures ranging from 1900 to 2400°F ($CaCO_3$ (limestone) + heat $\rightleftharpoons$ CaO + CO_2). Generally the term also includes hydrated lime (calcium hydroxide), a more stable lime produced by uniting quicklime chemically with water ($CaO + H_2O \rightarrow Ca(OH)$ + heat). Two basic types of limestone used for lime manufacture are high calcium and high magnesium (dolomitic). Dolomitic lime contains both the elements calcium and magnesium whereas high calcium contains only a small amount of magnesium; at least 97 percent combined carbonate content is considered necessary for salable lime.

Lime production in Virginia is again on the increase after four years of a decrease. Production tonnages and values are indicated in Table 1; 1984 production was 562,000 short tons with a value of $24.8 million. Preliminary data indicate 1985 production of 605,000 short tons at a value of $26.4 million. High production is noted during the war years with the increased use in the steel furnaces at the time. The year of largest lime production was 1969 when Virginia ranked fifth behind Ohio, Pennsylvania, Texas and Michigan with 1,072,000 short tons ($13.6 million). Wood (1958, p. 6) reports that Virginia ranked third in lime production in 1915 with 267,00 short tons from 40 plants. A record of almost $36 million of lime was produced in 1981 (824,000 short tons).

Table 1. *Lime production in Virginia*[1]

	Short Tons	Value ($)
1888	170,000 Bbls.	
1905	114,221	393,434
1910	141,257	563,567
1915	267,278	840,969
1920	251,052	2,201,724
1925	192,429	1,491,568
1930	146,996	960,219
1935	133,696	850,444
1940	178,036	1,044,229
1945	118,707	835,575
1950	428,339	3,861,932
1955	494,293	5,048,697
1960	711,000	8,028,000
1965	847,000	10,584,000
1969[2]	1,072,000	13,653,000
1970	1,046,000	14,090,000
1975	705,000	20,192,000
1976	878,000	25,993,000
1977	846,000	28,767,000
1978	832,000	30,578,000
1979	872,000	34,935,000
1980	824,000	33,872,000
1981	804,000	35,984,000
1982	641,000	31,721,000
1983	557,000	24,637,000
1984	562,000	24,799,000
1985	605,000	26,426,000

1 - Production data from annual editions of the U.S. Bureau of Mines Minerals Yearbook; Roberts, J.K., 1942, p. 431-432.

2 - 5th in production behind Ohio, Pennsylvania, Texas and Michigan.

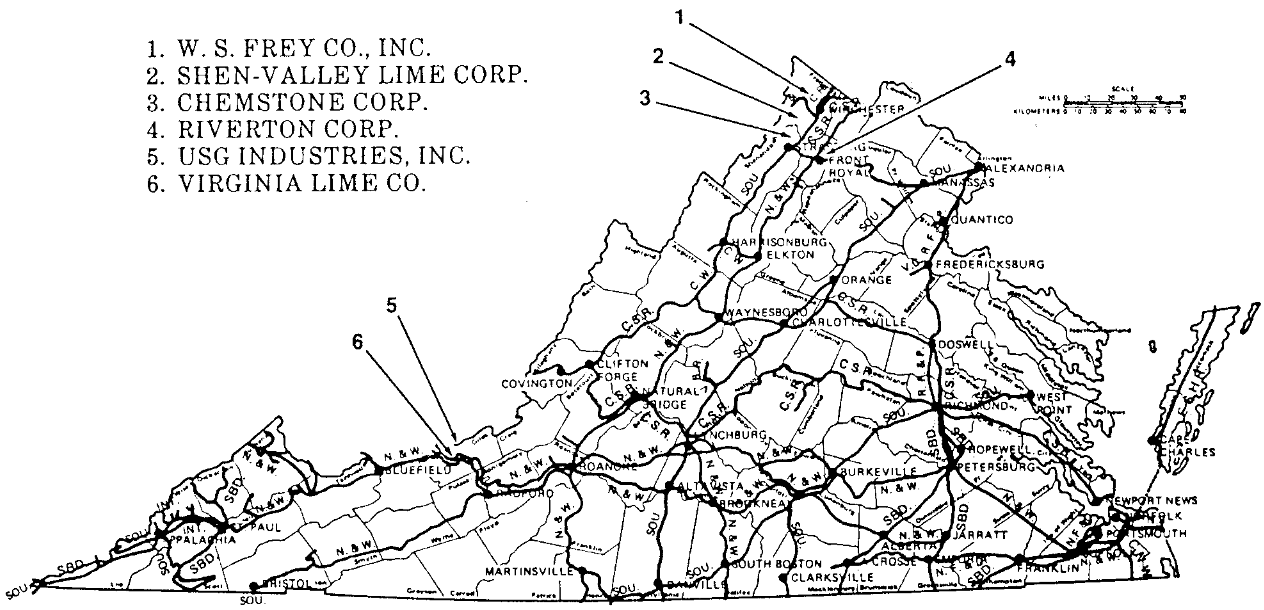

Figure 1. *Lime producers in Virginia. 1. W.S. FREY CO., INC., Frederick County. 2. SHEN-VALLEY LIME CORP., Frederick County. 3. CHEMSTONE CORP., Shenandoah County. 4. RIVERTON CORP., Warren County. 5. USG INDUSTRIES, INC., Giles County. 6. VIRGINIA LIME CO., Giles County*

Six companies (Fig. 1) in Virginia produce quicklime and or hydrated lime (Sweet, 1985) for a variety of markets. Both USG Industries, Inc. and Virginia Lime Company, subsidiary of the Rangaire Corporation operate underground mines in the Five Oaks Member (high-calcium limestone) of the Cliffield Formation of Ordovician age at Kimballton, Giles County near the West Virginia border. Both quicklime and hydrated lime are produced at both operations. In the northern section of Virginia, Chemstone Corporation in Shenandoah County and W.S. Frey Company, Inc. in Frederick County quarry the New Market (Mosheim) high-calcium Limestone of Ordovician age. This limestone is presently being calcined in rotary kilns by both companies; however only Chemstone Corporation produces a hydrated lime. Shen-Valley Lime Corporation in Stephens City, Frederick County hydrates purchased quicklime. Riverton Corporation, located in Warren County, north of Front Royal calcines a limestone from the Edinburg Formation of Ordovician age. This impure limestone is calcined in coal-fired vertical kilns, hydrated and mixed with portland cement to produce masonry cement.

PROCESSING

For burning (calcining) of the limestone, several types of kilns are utilized depending on capacity of operation, fuel costs, market requirements and air pollution regulations. Increasingly important is the amount of fuel required to convert each ton of limestone or dolomite to lime.

Vertical (shaft) kilns are elliptical or circular and may be of stone, masonry, reinforced concrete, or boiler plate construction. Kilns are refractory lined, usually with two layers, and are divided into three sections: preheating, calcining, and cooling. The top of the preheating section is where the limestone is put in the kiln. In the burning section, temperature varies depending on the physical and chemical properties of the limestone. If the fuel is coal, it is mixed in directly with the limestone, usually in a ratio of 1:5. Fuel requirements are usually under 5 million BTU per ton of lime. Large stone (3 inches - 12 inches) is fed into the kilns; more modern vertical kilns handle smaller (1 inch - 3 inch) sizes of stone. Advantages of vertical kilns include lower fuel cost through higher efficiency, less wear on the refractories, kilns can be stopped and started more easily, and there are lower pollution control costs. Figure 2 depicts vertical kilns presently in operation at Riverton Corporation, Warren County.

Calcimatic kilns were developed to utilize smaller sizes of stone; they can completely calcine the fines produced by other kilns. They have a circular hearth with a stationary bed of lime exposed to multiple burners which are usually gas-fired. The lime is usually carried in a thin layer; one revolution through the many burners constitutes a calcining cycle.

Rotary kilns were developed and utilized for plants needing greater capacity, to burn small stone readily, use less manpower, create a wider range of burn and produce a more uniform quality product. Longer rotaries were developed in the early nineteen sixties. They are able to burn smaller size material because a draft is not required. Stone as small as 1/4 inch can be burned as well as 2 1/4-inch material; however a 1:3 ratio of small to large feed is best. More segregation of particles would allow fine particles to sift to the bottom of the kiln and remain uncalcined. In contrast to vertical kilns that operate fully charged, the rotary has 90 percent of its volume filled with flame and hot gases; new surfaces of the stone are exposed as the kiln slowly rotates. As the area of solids exposed is small, this type of kiln is less efficient than a shaft kiln. A rotary kiln is utilized by W.S. Frey Company, Inc. (Fig. 3).

Rotaries vary in size, though most typically they are 8 to 10 feet in diameter, 150-200 feet long and producing 200-500 TPD. All types of fuel can be used, although with the less efficiency, powdered coal is the popular choice today. Coal can be pulverized more, by putting more crusher balls in the mill to effectively produce more coal particles. With the coolers associated with the rotaries, the hot gases are returned to the kiln as secondary air to increase fuel efficiency. Trends today are toward shorter kilns with a preheater in which exhaust gases may preheat the stone or fines are spread over coarser material as it is calcined, allowing the finer material to be calcined as it sifts through the kiln load.

After calcination, the lime is inspected for underburning or overburning and it is crushed and/or screened and classified:

* lump quicklime	up to 8 inches
* pebble quicklime	1/4 inch -- 2 1/2 inches
* ground quicklime	all minus 8 mesh
* pulverized quicklime	all minus 20 mesh

The fine fraction of lime is unwanted by the customer as it blows around. At plants where lime is not hydrated, fines usually end up in settling ponds. Fines are used in the hydrator, which consists of a revolving drum with stationary paddles to agitate the lime. A fine spray of water from a needle valve controlled by a flowmeter is added to lime that is weighed with feeders until a dry powder is produced. A continuous hydrator contains a screw conveyor which mixes the water with the lime. Water is controlled as too much will result in a wet, sticky lime and too little will result in an underslaked lime. The hydrated lime is usually separated by an air separator.

USES

An average of 150 lb. of pebble lime is used as a flux to produce a ton of steel in a basic oxygen furnace. The lime will flux out in the slag impurities such as silica, alumina, phosphorus and sulfur. For greater refractory life, steel companies substitute 10-30 percent of their high-calcium lime with high dolomitic lime. Refractory lime (dead-burned dolomite) is used to line the bottoms of open hearth steel furnaces to extend the life of brick linings. With the advent of basic oxygen furnaces, use declined until development of tar-bonded refractory brick, which is made from dead-burned dolomite.

Lime is used to neutralize the acidic effects of pyrites and maintain the proper pH in benefication of copper ores in the flotation process. Also, it is used to recover uranium from gold slimes in the flotation process, to neutralize sulfuric acid waste in ore extractive plants, control pH and curtail cyanide loss in gold and silver recovery, and as a flux in the recovery of nickel by precipitation.

The treatment of municipal potable water is done with lime to remove turbidity from river water and remove suspended solids from industrial water. In sewage treatment, lime is used in pH control in the sludge digester to remove dissolved and suspended solids that contain phosphates and nitrogen compounds. Other uses are to neutralize the acidic waste water in coal washing plants, wastes from sulfuric acid pickling plants, and plating wastes. Lime is also used in large quantities to recover ammonia for recyclical use in the manufacture of soda ash and bicarbonate of soda. Fourteen hundred pounds of quicklime are required to produce a ton of soda ash.

The fusion of coke and quicklime produces calcium carbide ($CaO + 3C \rightarrow CaC_2 + CO$), which is the chief source of acetylene. The ingredients are heated to 2000°C; molten carbide is removed from the furnace, solidified and crushed into desired sizes. Treating the fused carbide with nitrogen obtained from liquefying air produces calcium cyanamide, a nitrogen fertilizer. Introduction of chlorine and hydrated lime produces calcium hypochlorite and chloride of lime, which are dry sources of bleach. Various inorganic chemicals are also made from lime.

The paper industry uses lime in combination with chlorine to bleach paper pulp to obtain a desired degree of whiteness. It is also used when wood pulp is cooked in caustic soda (sodium hydroxide) and sodium sulfide. Sodium carbonate solution is recovered and reacted with quicklime to generate sodium hydroxide which is recycled to treat wood pulp again. Lime is also used in the clarification and color removal of paper mill wastes.

Dolomitic quicklime granules (10-100 mesh) are used as a flux raw material in the mix in the manufacture of glass. Lime is used to make calcium silicate building products (sand-lime brick) and hydrated lime is used to produce silica refractory brick.

Lime is necessary for sugar making to help purify the sucrose juices by removing phosphatic and organic acid compounds as insoluble calcium compounds which are removed by filtration. Most beet sugar plants make their own lime as they need about 500 pounds of quicklime per ton of sugar and since they also need CO_2 in their process and it is available from the lime kiln stack gases. Lime is used as a CO_2 absorbant for fresh fruit and vegetables to extend the freshness of the produce.

Hydrated lime with about 10% pebble quicklime is used for soils stabilization for highways and off-highway uses. Hydrated lime is also used with fly ash in the preparation of base material at mix plants, in asphalt mix (1.2%) to act as an antistripping agent, in exterior plaster or stucco in warm climates, and as a dependable plasticizer for mortar that makes it more workable. Air-slaked lime is used in agricultural liming rather than pulverized limestone as it reacts faster. Dolomitic lime is used in a sandy soil which is magnesium deficient.

Lime use has increased in scrubbers and fluidized bed injection to remove sulfur dioxide from stack gases of coal-fired electrical utilities, metallurgical and chemical plants. A potential use may be to reduce the effects of acid rain. Flue gas desulphurization is becoming more and more an issue and may lead to an expanded market for lime.

GEOLOGY

The high-calcium New Market (Mosheim) Limestone of Ordovician age is bluish to dove gray, compact, fine grained and has a glossy texture and conchoidal fracture. In most places in the Shenandoah Valley of Virginia, the unit is divided into two units: the upper half is thick bedded to massive and nearly free of insoluble matter and shows chalk-like material on weathered surfaces with 97 to 98 percent calcium carbonate. The lower zone contains some thin-bedded, shaly and dolomitic, and buff limestones. A dolomite pebble conglomerate is present at the base, which is an irregular surface on the underlying Beekmantown dolomite.

In the Shenandoah Valley, the thickness of the New Market Limestone is greater west of the Massanutten synclinorium (70 to 120 feet) than in the eastern belts, where measurements vary from less than 15 feet to no

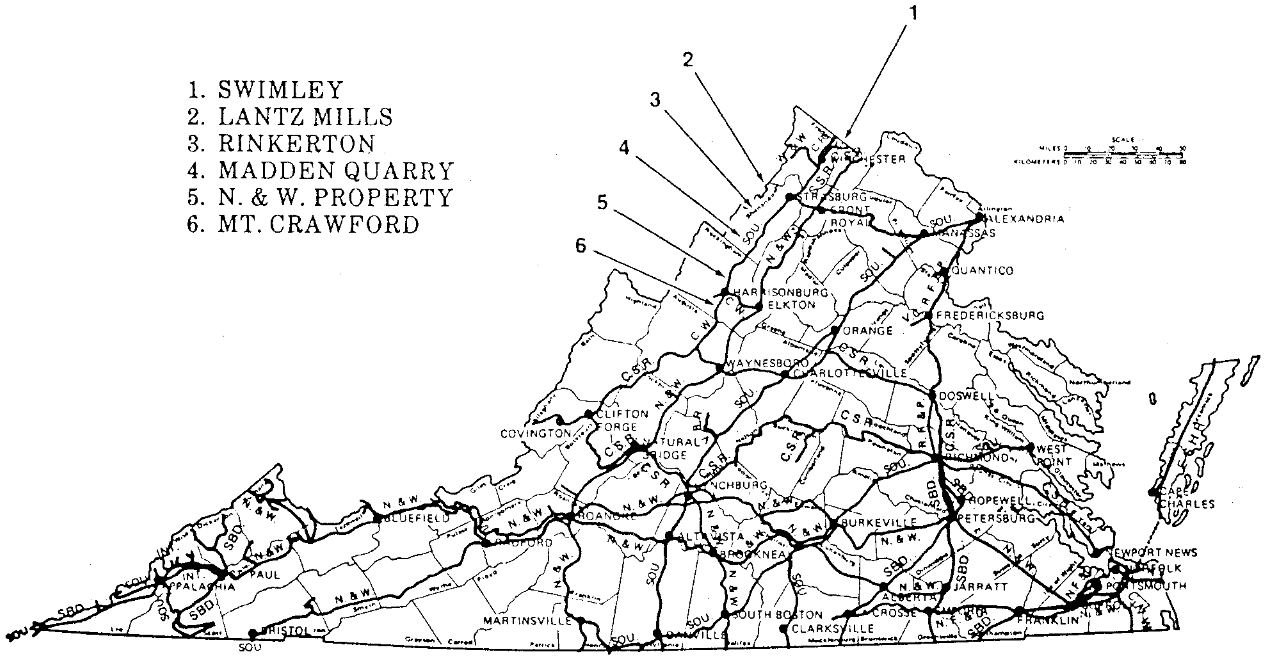

Figure 4. *Exposures of New Market limestone*

more than 50 feet. There are localized exceptions. Following are brief descriptions from north to south, by county, of some of the better deposits of the New Market Limestone.

Clarke County

The New Market is about 65 feet thick east of Opequon Creek about a mile south of Wadesville. The unit also thickens near the nose of several anticlines north of Virginia Highway 7 and near the West Virginia state line at Swimley (Fig. 4).

Frederick County

Both northeast and southwest of Winchester, the New Market ranges from 80 to a maximum of 2000 feet thick; around Stephenson it is 120 feet thick. The limestone is 125 feet thick on the east limb of an anticline at W.S. Frey's Clear Brook operation. The unit thins toward the axis and western limb of the structure.

Shenandoah County

Edmundson (1945, p. 59) notes a 218-foot section of New Market Limestone along Swover Creek, 2.5 miles north of Hamburg (Fig. 4) near the central part of the county. A composite analysis of the top 116 feet is 98.56% $CaCO_3$). This is the location referred to by Cooper and Cooper (1946), in Geologic Section 12, 4 miles west of Edinburg. A thick exposure of New Market is present in an abandoned quarry northwest of Mt. Jackson and just southeast of Rinkerton (Fig. 4). Due to the low dip in the northeast-plunging syncline, approximate thickness of 100 feet, and railroad accessibility, this may be a favorable deposit. Another location is about 1.5 miles southwest of Lantz Mills (Fig. 4) off State Road 693 in the nose of a shallow synclinal structure. Edmundson (1945, p. 55) notes an average analysis of 96.65% $CaCO_3$ in the 141-foot-thick eastern limb of the syncline; the western limb is about 180 feet thick. In northern Shenandoah County, Chemstone Corporation is quarrying an actual thickness of almost 150 feet just north of Strasburg. Fifty-five feet of high-calcium limestone is exposed along Tumbling Run, just southwest of Strasburg (Fig. 5).

A continuous section (80+ feet) of the New Market is present in the old Madden quarry (Figs. 4 and 6) just west of Interstate 81 west of New Market. Edmundson (1945, p. 52) notes an analysis of 98.15% $CaCO_3$ in the top 38 feet of the unit.

Rockingham County

Other exposures of New Market Limestone that may have a potential for commercial development are present in Rockingham County both north and south of Harrisonburg. The southern exposure is located east of Mount Crawford (Fig. 4) along Pleasant Run, where Gathright (1978) states that the unit is approximately 200 feet thick, dipping to the east with very little overburden. The site located northeast of Harrisonburg is presently owned by the N and W Railway Company. The New Market at this site is as much as 300 feet thick and averages 100 feet thick; it was quarried in the past for roadstone. The high-calcium limestone contains solution channels or tension fractures with some mud and shaly interbeds with small amounts of silica, and negligible pyrite. The black, cherty Lincolnshire Limestone overlies the New Market, which dips toward the west-northwest at this locality (Figs. 4 and 7). The outcrop belt along the ridge reportedly continues for 3.5 miles and reserves are noted to be about 500 million tons of high-calcium limestone. A sample across 12 feet near the top of the unit in the northwest wall produced an analyses of 98.02% $CaCO_3$ (W.F. Giannini, 1985, personal communication.).

Cooper and Cooper (1946) state that the lower unit of the New Market closely resembles and occupies the stratigraphic position of the dolomitic, shaly, cherty beds of the Blackford Formation in southwestern Virginia, Butts (1933) identified the New Market in northern Virginia as Mosheim and also the Five Oaks Limestone in southwest Virginia as Mosheim. The black, cherty Lincolnshire Limestone overlies the New Market in the central and northern Shenandoah Valley, while the high-calcium Five Oaks Limestone overlies the light-gray, black cherty, limestone beds of the Blackford Formation (Fig. 8)

Western belts of New Market Limestone in the northern and central Shenandoah Valley contain basal dolomitic limestone and pebble conglomerate that closely resemble the Blackford Formation of southwestern Virginia.

Five Oaks Member (Cooper, 1944) of the Cliffield Formation is being mined underground by USG Industries, Inc. and Virginia Lime Corporation in Giles County. The dove gray, dense, hard, high-calcium limestone varies in thickness from 40 to 100 feet and has a general dip of 15 degrees to the southeast. In the area of Kimballton, the Five Oaks has been twisted by a regional thrust from the east-southeast. Tension fractures may be filled with calcite or open with linings of red clay or silt.

CARBONATE PROJECT

The Division of Mineral Resources is involved in a long-term project that will provide new quantitative data on the location, thickness, and composition of limestone, dolomite and other carbonate units in Virginia. Acquisition of up-to-date location data and recent chemical, reflectance, and other data will lead toward a better understanding of the economic potential of the carbonate materials in Virginia. At the present time, almost 3000 samples have been taken in the last 5 years. During the course of this evaluation project, several dolomite units between Clarke County in the northeastern part of the Valley and Rife province and Lee County in the extreme southwestern part of the State were sampled. Samples were taken to determine their potential for refractory grade dolomite at six different locations from three different rock units (Fig. 9).

Chemical analyses and differential thermal analyses (DTA) performed on the six samples by the U.S. Bureau of Mines, Albany Research Center in Albany, Oregon are published in Sweet and Giannini (1985). Samples 135-C and 135-D produced the chemistry to meet specifications of a maximum of 0.75 percent $Si0_2$, less than 0.4 percent Fe_20_3 and less than 0.3 percent $A1_20_3$.

VIRGINIA LIME PRODUCERS

Chemstone Corporation

Chemstone Corporation is located in Shenandoah County just north of Strasburg. The company quarries the high-calcium New Market Limestone of Ordovician age which dips an average of about 35 degrees to the east. The high-calcium unit is underlain by the

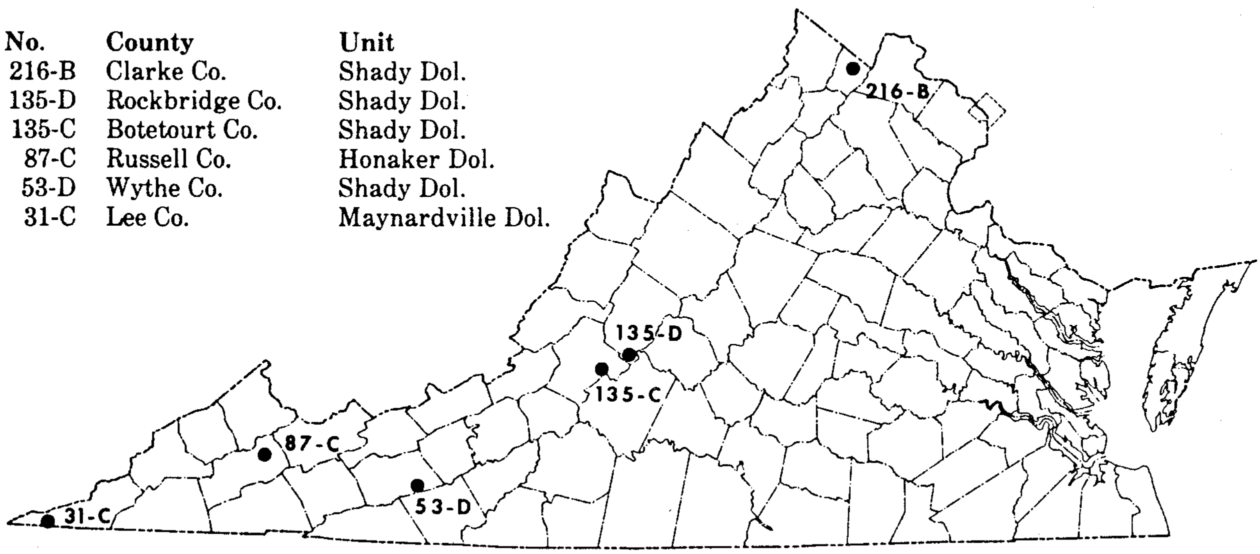

Figure 9. *Dolomite sample locations.*

Beekmantown Formation and overlain by the Lincolnshire Formation (Fig. 10). Present mining is both north and south from the center of the quarry. The limestone has an actual thickness of up to 150 feet at this locality; there tends to be more sulfur in the stone toward the north. It is shot, loaded, and transported to the primary crusher at the plant site (Fig. 11).

Some of the limestone is crushed into several sizes for roadstone as well as for introduction into the preheater where exhaust gases will preheat the stone in a refractory-lined box before it is fed into the rotary kiln (Fig. 12). Bituminous coal stored across State Road 629, travels by conveyor to a Raymond mill where it is pulverized to minus 200-mesh and then screw augured into the kiln.

There are also 5 vertical (shaft) kilns as well as one calcimatic kiln on the property, all of which are gas fired. The calcimatic kiln is presently in use by the company. Hydrated lime is also produced from some of the quicklime.

Markets for the quicklime and hydrated lime include water purification, sewage treatment, steel industry and various chemical uses.

W.S. Frey Company, Inc.

W.S. Frey Company, Inc., located about 7 miles north of Winchester in Frederick County, just east of Clear Brook, has been in operation at this site since 1961. Underground mining began south of the road in 1964; five tunnels were developed down dip to the east in the quarry. The underground mine was closed in the fall of 1967 and the mine is now flooded with water. An abandoned quarry north of the road was opened in the early 1960's (Figs. 13 and 14).

The company is presently quarrying on the eastern limb of a south-southwest-plunging anticline in the high-calcium New Market (Mosheim) Limestone of Ordovician age. The limestone is approximately 125 feet thick and thins toward the axis and nose of the anticline. The overlying Lincolnshire (Lenoir) limestone is being stripped toward the south; both the unit and the underlying Beekmantown Formation are being crushed for marketing as commercial crushed stone.

Stone is trucked to the crusher located east of the quarry hole. After crushing, the stone is calcined in a 165-foot bituminous-coal-fired rotary kiln, which is fired hot to drive off a significant amount of volatiles.

Markets are for fluxstone in the steel industry, as filler and feed ingredient, for the glass industry, and as an agricultural lime. The company does not hydrate lime, but they may in the future. Hydrated lime is needed for the water purification and in sewage treatment.

Riverton Corporation

Riverton Corporation, located in Warren County just north of the North Fork of the Shenandoah River, began production in 1863 and quarries the Edinburg Formation of Ordovician age. The stone is calcined in vertical kilns, hydrated, and added to portland cement to produce masonry cement. The black limestone with shale interbeds overlies the Lincolnshire limestone in the western side of the quarry (Fig. 15). The impure limestone is crushed to 1/2-inch to 4-inch size, transported and dumped into the top of the vertical kilns from small rail cars. Pea-size, low-volatile anthracite coal is placed both below and above stone in the kilns. Vertical kilns are used at this operation because of their effectiveness, using less than 4 million BTU per ton of lime produced and because of the capacity of the operation. There is a continuous feed into the kilns, which are operated during 2 shifts; retention time in the kilns is 72 hours.

After the material is calcined, it is pulverized and then hydrated with a controlled amount of water and sulfuric acid to produce a hydrated hydraulic lime. The use of sulfuric acid produces a cementatious quality in the batch. Hydraulic lime has the property of growing in strength year after year. The proprietary masonry cements produced by the portland cement industry reach their approximate ultimate strength in 28 days, growing only slightly in compressive strength in subsequent years. Hydraulic lime grows in compressive and bonding strength for an indeterminate number of years at a faster rate of growth than portland cement so that in 5 to 10 years, depending on atomospheric conditions, it may exceed a portland cement type mortar in compressive strength.

The company utilized 8-10 million pounds of pigments per year to produce many different colors of masonry cement. Several types of cement are manufactured by varying the percentage of portland cement to hydrated lime.

Shen-Valley Lime Corporation

Shen-Valley Lime Corporation is located in Frederick County, just west of Stephens City. The company has taken over the former operation of Genstar Stone Products, however they only produce hydrated lime, utilizing purchased quicklime. Lime comes to the plant (Fig. 16) by dump truck and is crushed and then put into a storage bin. Fines are a problem here as they continually sift to the bottom and have to be recycled.

Material is fed into the hydrator where water is added from the top; agitation during the process helps to hydrate the lime. Water supply is municipal and varying pressure can be a problem. From the hydrator, material is sent by a screw conveyer into the air separator. Here the powdery finished hydraulic lime is separated out; some coarse and waste materials are separated out and are recycled. Dust collectors are used to control some of the fines.

The hydrated lime is marketed in bulk and also sold in 10-, 20-,and 50-pound bags. Markets include water purification, sewage treatment plants, and resale by other retail outlets.

USG Industries, Inc.

USG Industries Inc. is located in Giles County near Kimballton, off the east side of State Road 635 (Fig. 17). The operation was acquired from Gold Bond Building Products of National Gypsum Company in early 1984.

The Company has up-graded the operation over the last year or so by adding dust collectors to satisfy air-pollution control regulations. The slope-entry underground mine is developed in the high-calcium Five Oaks Limestone of Ordovician age, which averages about 80 feet thick in this mine.

The mine has been developed on 12 levels in the past, with the top 6 levels having been mined out. Stone is presently crushed on the 10th level of the mine, being fed from the 9th and 10th levels. The limestone unit has a dip of 15 to 45 degrees to the east and appears to be twisted along its length, probably by local faulting.

After the stone is crushed, it is transported on a 36-inch conveyor to the surface when it goes to the screen house. Material has three potential routes from here: additional crushing, size grinding, and calcining. Material is fed into 3 bituminous-coal-fired rotary kilns. Limestone fines are pulverized and sold for agricultural use,etc. Quicklime is also hydrated at this plant (Fig. 18). Markets are to the pulp and paper industry, steel industry, for water purification, and for agricultural use.

Virginia Lime Company

Virginia Lime Company, subsidiary of the Rangaire Corporation (Fig. 20) is developed in the Five Oaks high-calcium limestone of the Cliffield Formation. The unit averages about 40 feet thick in this mine, which is developed on both limbs of a northeast-plunging syncline.

A thrust fault has created minor folding and open joints; some joints are filled with mud. The company is presently mining on the 240- and 300-foot levels; the mining plan calls for 50-foot rooms and pillars. Mining is now about 500 feet below the surface; future mining to the east will be to about 1500 feet below the surface.

Limestone is shot and trucked to the plant on the surface. After crushing, the stone (1/4 inch - 2 1/2 inch) is fed into bituminous-coal-fired rotary kilns; two kilns, one 396 foot long, are presently (September, 1985) running at the plant. Finer material that isn't put in the rotaries is considered waste and put into settling ponds. Lime is marketed in rail cars and tank trucks.

Quicklime is hydrated with water, air separated, and sold in bulk and in bags for municipal water purification and for sewage treatment plants. The ratio of quicklime to hydrated lime production is 5:1.

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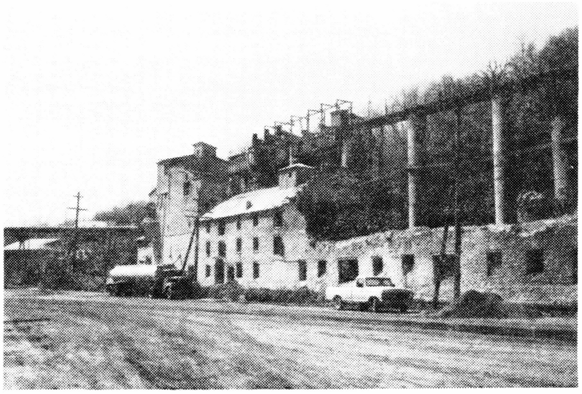

Figure 2. *Vertical kilns at Riverton Corporation, Warren County.*

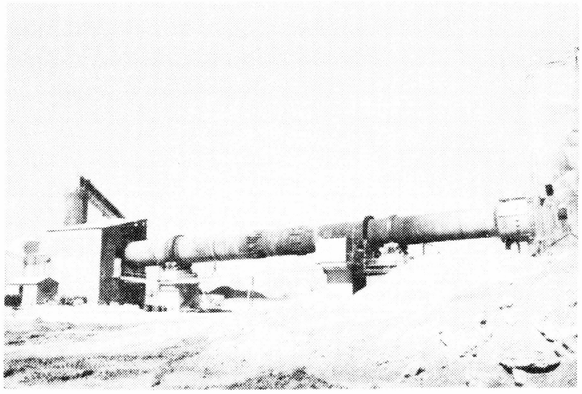

Figure 3. *Rotary kiln at W.S. Frey Company, Inc., in Clear Brook, Frederick County.*

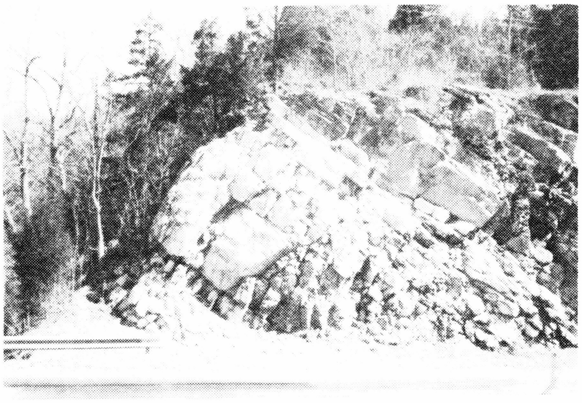

Figure 5. *New Market Limestone along Tumbling Run, southwest of Strasburg, Virginia.*

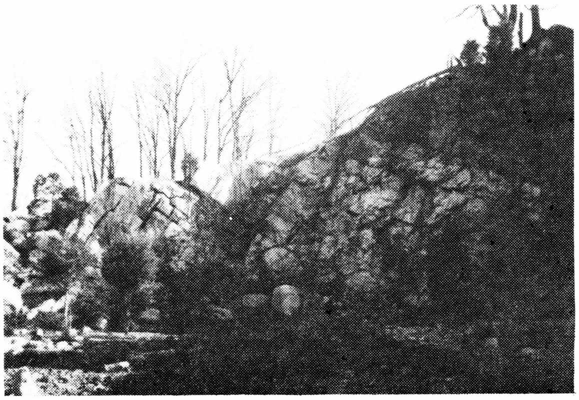

Figure 6. *Inactive Madden quarry, New Market, Virginia.*

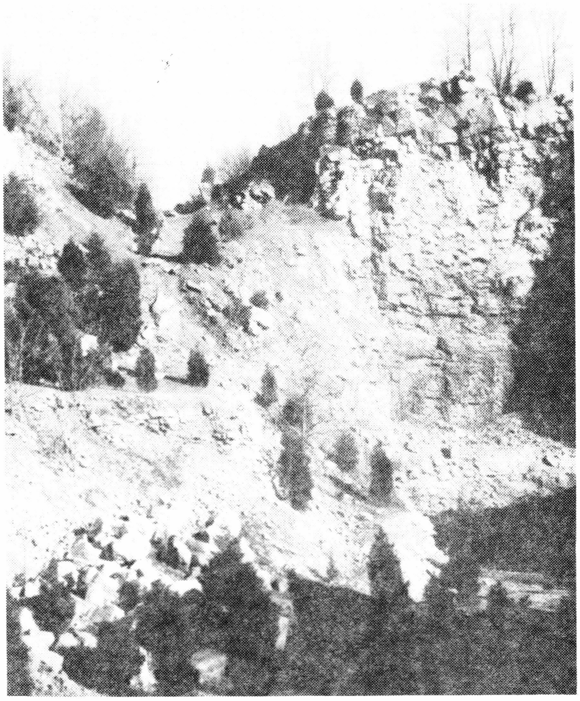

Figure 7. *Lincolnshire limestone overlying New Market Limestone, inactive N and W quarry, Rockingham County.*

Figure 8. *Cherty limestone beds of the Blackford Formation, near Klotz, Giles County.*

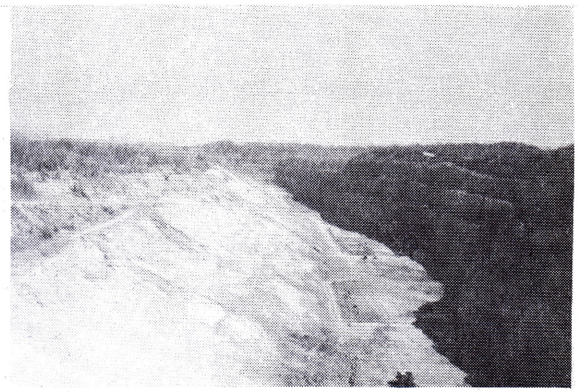

Figure 10. *Quarry of Chemstone Corporation, Strasburg, Virginia, looking northeast with dip-slope of Beekmantown Formation to left, underlying the New Market Limestone.*

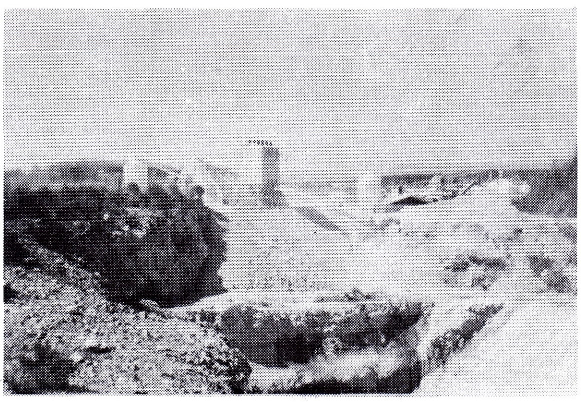

Figure 11. *Plant site of Chemstone Corporation, looking southwest from east rim of quarry.*

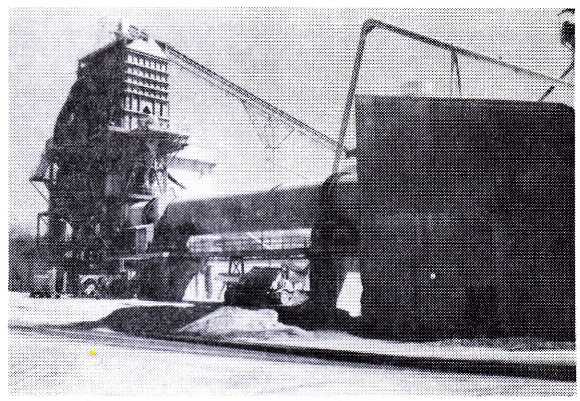

Figure 12. *Rotary kiln at Chemstone Corporation, Strasburg, Virginia.*

Figure 13. *Abandoned quarry of W.S. Frey Co., Inc., showing sharp contact of New Market Limestone with the overlying Lincolnshire limestone and underlying Beekmantown Formation.*

Figure 14. *Abandoned quarry of W.S. Frey Co., Inc. showing Lincolnshire limestone overlying New Market Limestone in nose of northeast-plunging anticline.*

Figure 15. *Quarry of Riverton Corporation, looking north.*

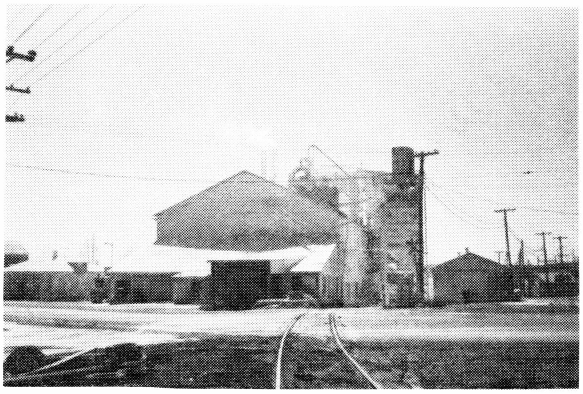

Figure 16. *Plant of Shen-Valley Lime Corporation, Stephens City, Frederick County.*

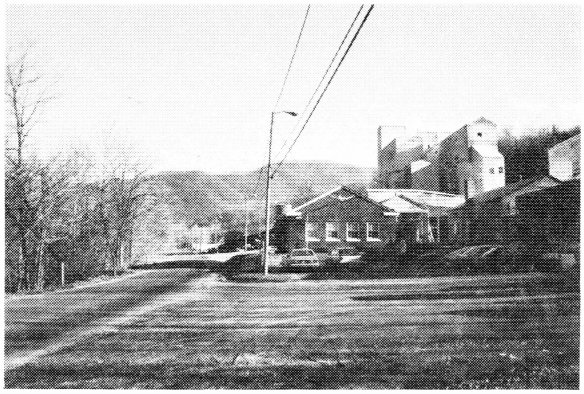

Figure 17. *USG Industries, Inc., Kimballton, Giles County.*

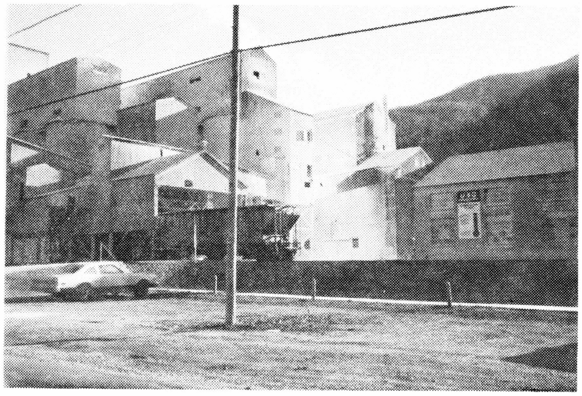

Figure 18. *Plant of USG Industries, Inc. at Kimballton, Giles County.*

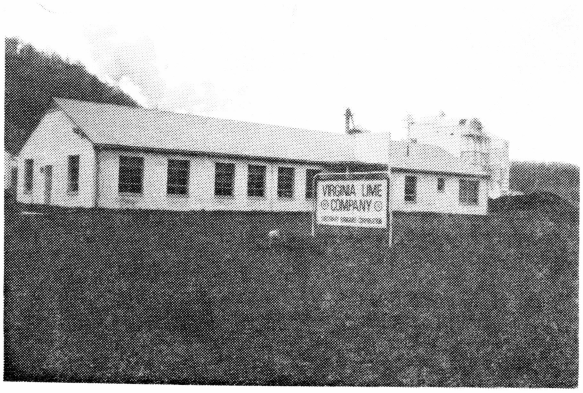

Figure 19. *Main office of Virginia Lime Company at Kimballton, Giles County.*

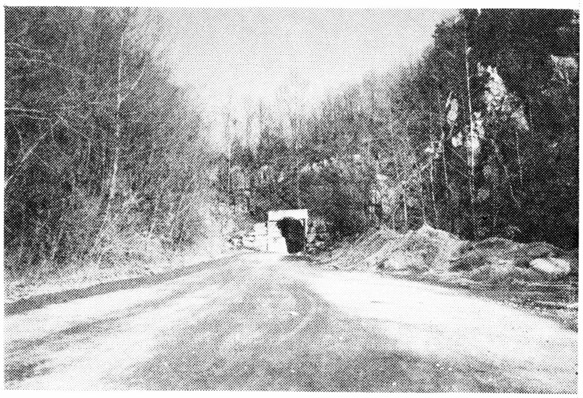

Figure 20. *Entrance to underground mine, Virginia Lime Company, Kimballton, Giles County.*

Tectonically emplaced serpentinites of the Benton uplift, Saline County, Arkansas.

By Timothy L. Cox
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Two occurrences of serpentine-soapstone bodies are located in the eastern end of the Benton-Broken Bow uplift of the Ouachita Mountains, 12 miles west of Little Rock, Arkansas (Figure 1). The bodies are along a fault contact between the Ordovician Womble Shale and the Bigfork Chert. This fault is parallel to the strike of the regional structure.

Foliations, folds, jointing, and mineral lineations within the soapstone-serpentine bodies indicate that the ultramafic rocks conform to the regional structural fabric of the enclosing sedimentary rocks. Hence, intrusion of the ultramafic rocks was pre-orogenic.

These serpentines have been mined for

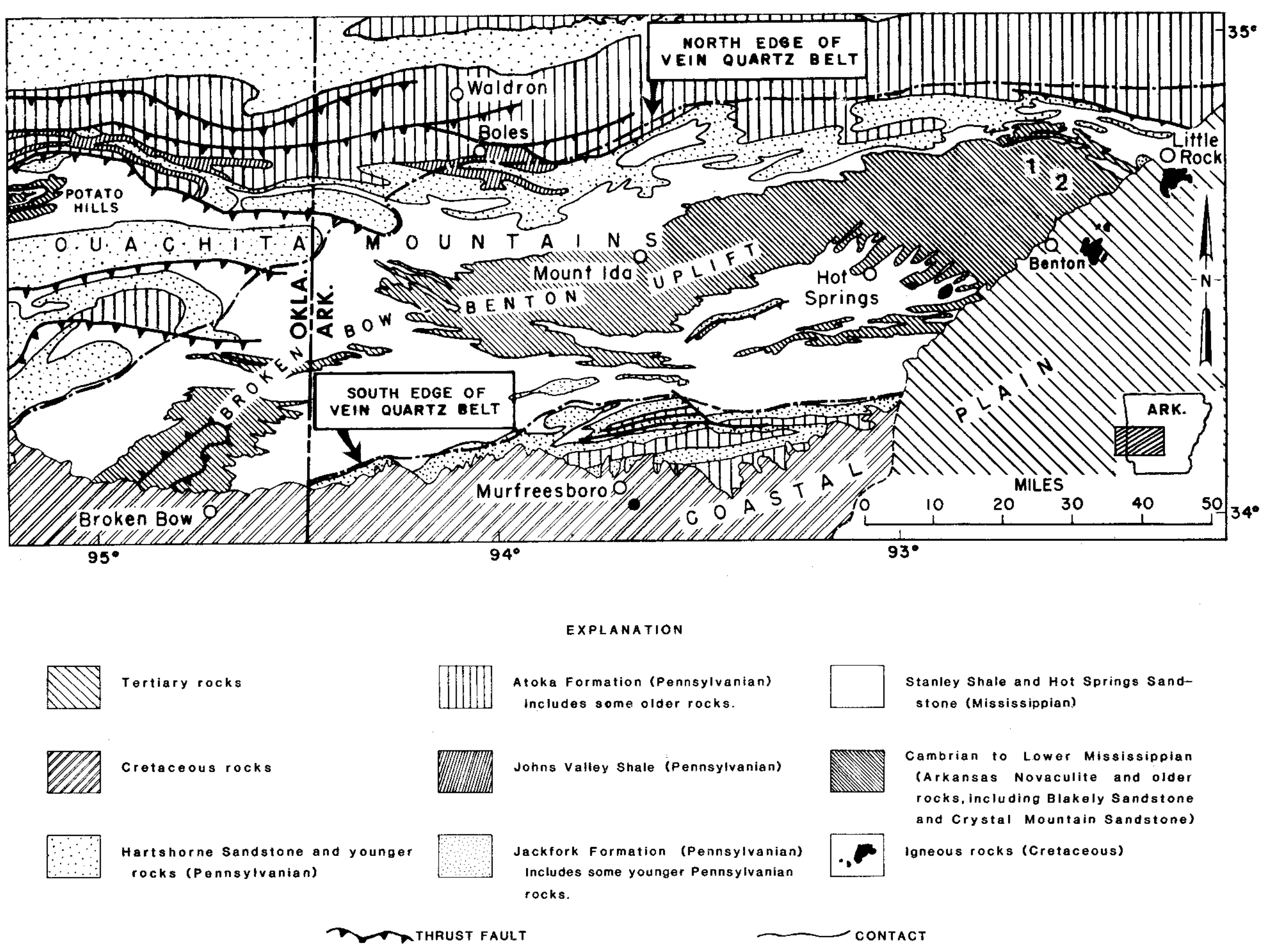

Figure 1. *General geologic map of the Ouachita Mountains of Arkansas and Oklahoma, showing the Benton-Broken Bow uplift, Saline County serpentine deposits (1), and the Hominy Hill gabbro (2). Adapted from Miser (1959).*

aggregates and fillers for a number of years. They contain some high-grade talc-pyrophyllite veins, and are an important local resource. Exploration along this and similar faults may reveal new deposits.

There have been several thoughts on the genesis of the soapstone pods ranging from metamorphosed shale, peridotite, ophiolite, sedimentary accumulation, and magmatic intrusion. Also the origin of the Ouachitas is still undisclosed and a topic of discussion among many geologist. Back-arc, fore-arc, north subduction, south subduction, or rift valley? Which style of tectonic activity is responsible for the Ouachitas? Several different theories of plate subduction mention peridotites as possible magmatic igneous rocks involved in the lithologic assemblages associated with each tectonic style. If we learn the origin these pods, it will help unravel some of the mystery of the Ouachitas.

From data collected and processed for this paper, I have come to the conclusion that the Saline County serpentine-soapstones are peridotitic in origin and were injected into the early pre-orogenic sediments of the Ouachita trough by diapiric rise from the mantle. The bodies were later folded and faulted with the sedimentary rocks during the Ouachita orogeny.

The Ouachita Mountains extend from Little Rock, Arkansas, west to southern Oklahoma (Figure 1). They are composed principally of lower to middle Paleozoic sedimentary rocks that are faulted and folded in an east-west trend. Igneous rocks mostly are Cretaceous, except in McCurtain County, Oklahoma (Morris and Stone, 1986a), the narrow strip of soapstone-serpentine pods in northern Saline County, Arkansas, and an outcrop of possibly related alkalic metagabbro of Precambrian age along the same structural trend as the serpentine-soapstone pods (Morris and Stone, 1986b).

The lower Paleozoic strata of Arkansas, consisting mainly dark shales, siltstones, mudstones, a few sandstones, and rare, thin local limestones, are generally thought to have accumulated in a slowly subsiding off-shore basin. The rocks are only moderately well exposed and structural complications are locally severe, so that stratigraphic relations and thicknesses are incompletely known.

The oldest exposed rock is the Cambrian Collier Shale, unconformably overlain by Ordovician rocks (Figure 2). Briefly, the Womble is similar to the Blakely and Mazarn; black to green clay shales predominate, with thin layers of blue-black limestone and, locally, some sandstone and conglomerate beds. The Womble is banded throughout the lower 200 feet of the formation. The position of the limestones in the Womble are also a matter of dispute among workers in the Ouachitas. Depending on who you read or talk to, they can be located anywhere in the 1200-foot thickness of the formation.

The Bigfork Chert, approximately 700 feet thick, conformably overlies the Womble and like its Ordovician predecessors, contains chert, dark shales, and limestones.

The serpentine and the metagrabbros of Oklahoma and Arkansas are located along the faulted contact of the Bigfork and the Womble. Further exploration along the boundary may reveal new occurrences of soapstone, talc, or serpentine.

Low - grade metamorphic rocks occur in two "metamorphic maxima" in the Benton - Broken Bow uplift (Figure 1), one near Little Rock and the other on the western end near Broken Bow,

SYSTEM	SERIES	FORMATION	THICKNESS (feet / meters)
ORDOVICIAN	MIDDLE ORDOVICIAN	Bigfork Chert	700 / 200
	LOWER ORDOVICIAN	Womble Shale	1,200 / 360
		Blakely Sandstone	500 / 150
		Mazarn Shale	1,100 / 330
		Crystal Mountain Sandstone	850 / 250
		unconformity	
CAMBRIAN		Collier Shale	200+ / 60+

Figure 2. *Stratigraphic column of Middle Ordovician-Cambrian sedimentary rocks, eastern Ouachita Mountains, Arkansas.*

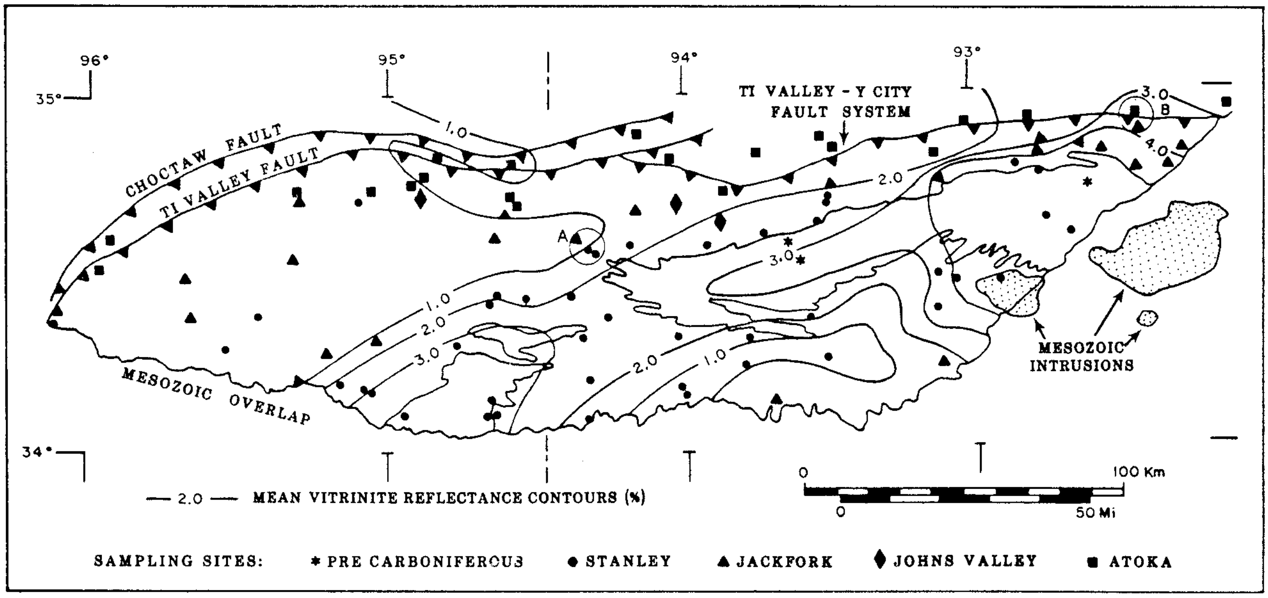

Figure 3. *Map of thermal maturity of exposed strata, Ouachita Mountains. Note how 2% contours closely follow outline of vein quartz belt of Miser, 1959. Asterisk (*) marks location of Saline County serpentine deposits. From Houseknecht and Matthews, 1985.*

Oklahoma.

An isotherm map compiled by Bence indicates that quartz veins were emplaced at very low temperature, ranging from 125^{o} C to 225^{o} C, with temperatures in the Benton quadrangle not exceeding 175^{o} C. A map by Houseknecht and Matthews (Figure 3), showing thermal maturities as measured by mean vitrinite reflectance indicates maximum temperatures in the Benton uplift as 230-240^{o} C by one technique and 250 to 275^{o} C by another technique. Also note the close similarity between the 2-percent contour line on the Houseknecht and Matthews map (Figure 3) and the edges of the quartz vein belt on the Miser map (Figure 1). Also note that the 4-percent contour, indicating higher temperatures, is around the Benton uplift metamorphic maxima of the eastern Ouachitas.

As indicated earlier, the area of study of the serpentine bodies is in the eastern end of the Ouachita Mountains in the northeast quarter of the Benton 15-minute quadrangle (Figure 4).

The Warner serpentine area, Saline County, is in Sec. 13, T. 1 N., R. 15 W. (Figure 5). At this time there are 3 open pits on the Warner property, the North, the Old, and the New. The main area of study was in the New Pit, because the North Pit is mined for Womble shale and the Old Pit is full of water. West of the Warner property is the Inman Pit, also full of water, with all surrounding rocks covered by grass. Westward in section 15 are the Anderson and Wallis mining Pits. The Wallis was opened in the 1880's and the old descriptions make it hard to tell its exact location.

The Anderson was the most extensively mined of the four, but except for modern mining in two places, it has not been operated for 20 to 30 years (Figure 6). At location A7, the Womble shale has crumbled into the pits making them useless for measurements and A13 is not believed to have yielded any serpentine or talc as it is an area of Womble slate.

The Womble in the area ranges from dark gray to black to medium brown, and at the A14 location it is even banded. At the southwest wall of the New Warner Pit it is black, hard, finely foliated, with laminations of graphitic-like dust. These shales are also

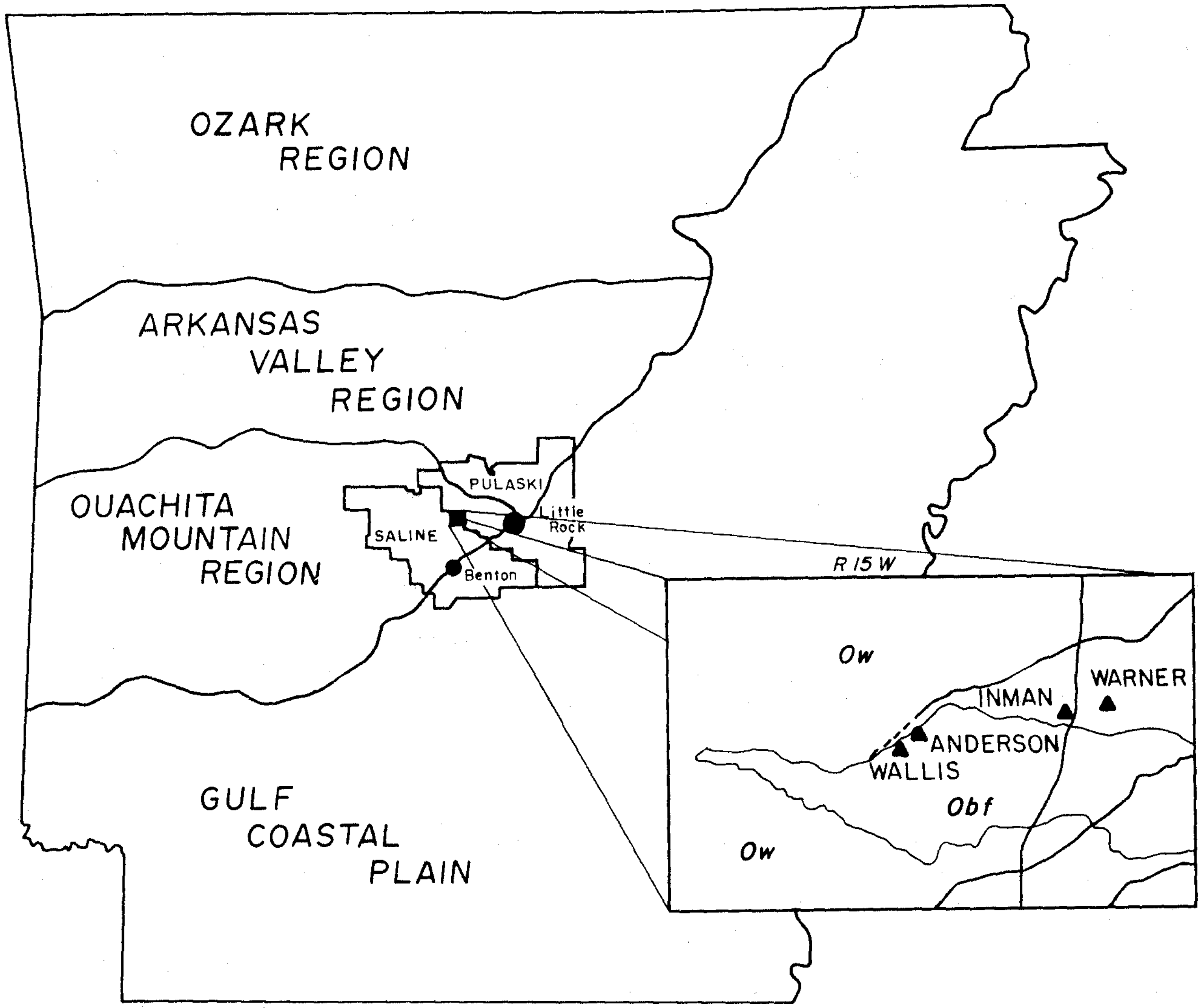

Figure 4. *Map showing location of study area.*

intensely folded and contain very thin veins of calcite and pyrite with disseminated grains of pyrite occurring irregularly throughout the exposure. In the creek flowing into the Old Warner Pit is a hard, black, homogeneous limestone which follows the shore of the pond to the north. The limestones and the calcareous shales have not revealed any fossils.

The Bigfork Chert surrounds the Anderson Pit and extends east below the Inman and Warner Pits. The Bigfork is very uniform in its appearance, being thinly foliated, dark-gray siltstone to a dark-brown to red chert layer interbedded locally between the shale layers.

The blackwall chlorite in the Warner area is a medium hard, aphanitic, dark-green to black rock with numerous medium-green, soft, aphanitic talc veins. It crops out in 4-to 6-foot wide band around the Old and New Warner Pits and in a very narrow band along the talc zone through the Anderson area.

The talc schist is a very fine grained white to brown to reddish thinly foliated unit with textural characteristics similar to the country rock shales. It rims the core of the serpentine rocks, continuously in the Warner Pit, but only on the east and west sides of the talc zone in the Anderson Pit.

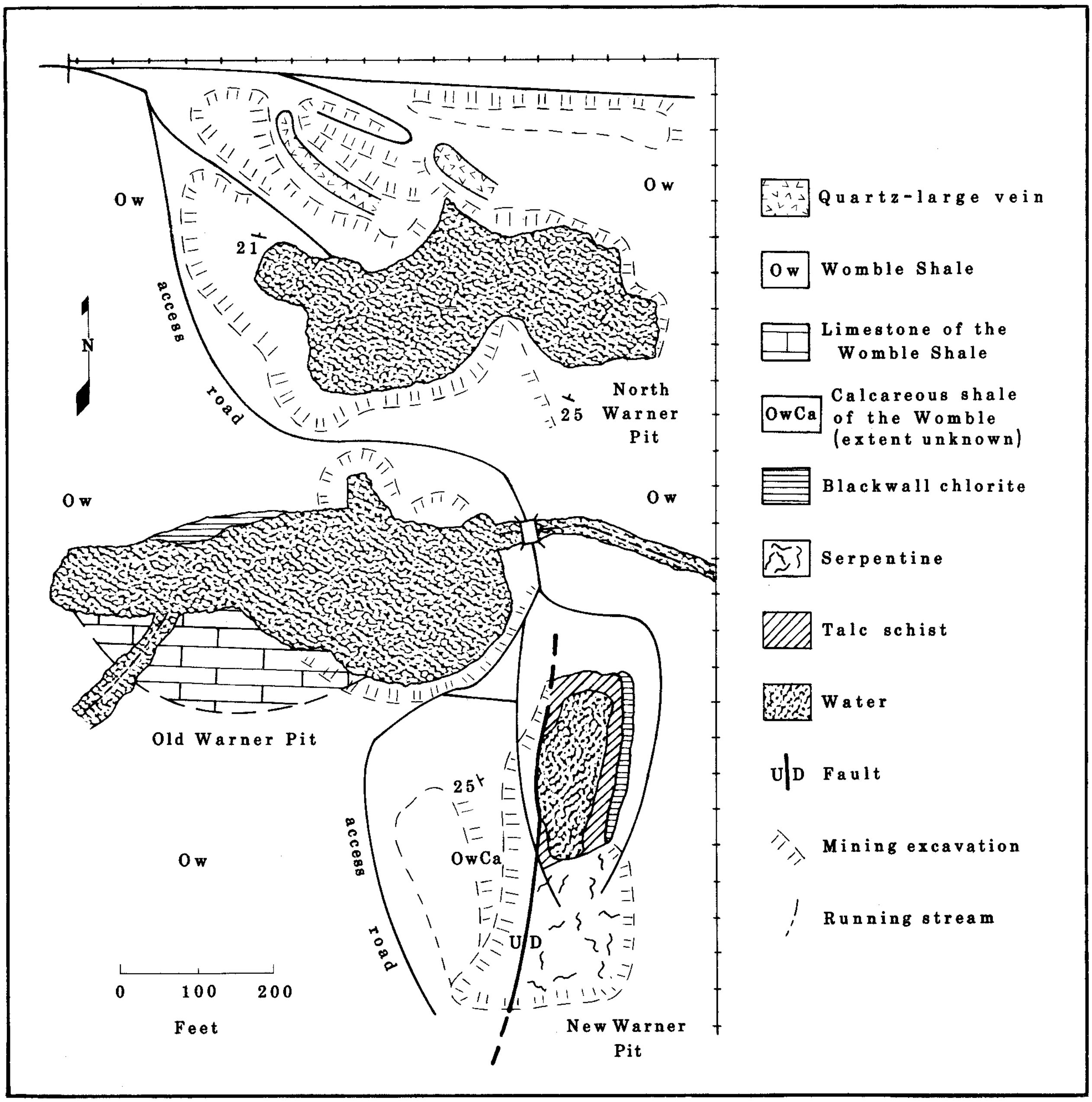

Figure 5. *Geologic map of the Warner Pit area.*

The serpentine is in the center of both pits, but extends southeast for an unknown distance away from the Warner Pit. It is a very fine grained, white to light to dark-green mottled, finely foliated rock with extensive very fine rust--red veining. The rocks exhibit a foliation which is resistant to weathering of the platy and fibrous minerals as emplaced by tectonic movement.

The serpentine rocks of Saline County are similar to alpine-type ultramafics, which may represent ophiolites, highly altered sedimentary accumulations, diapiric intrusions, or slivers of upper mantle tectonically emplaced by fault gliding. Whether alpine-type ultramafics represent fragments of upper mantle or accumulates from a basaltic magma, most authors consider them to have been emplaced in the upper crust as solid bodies.

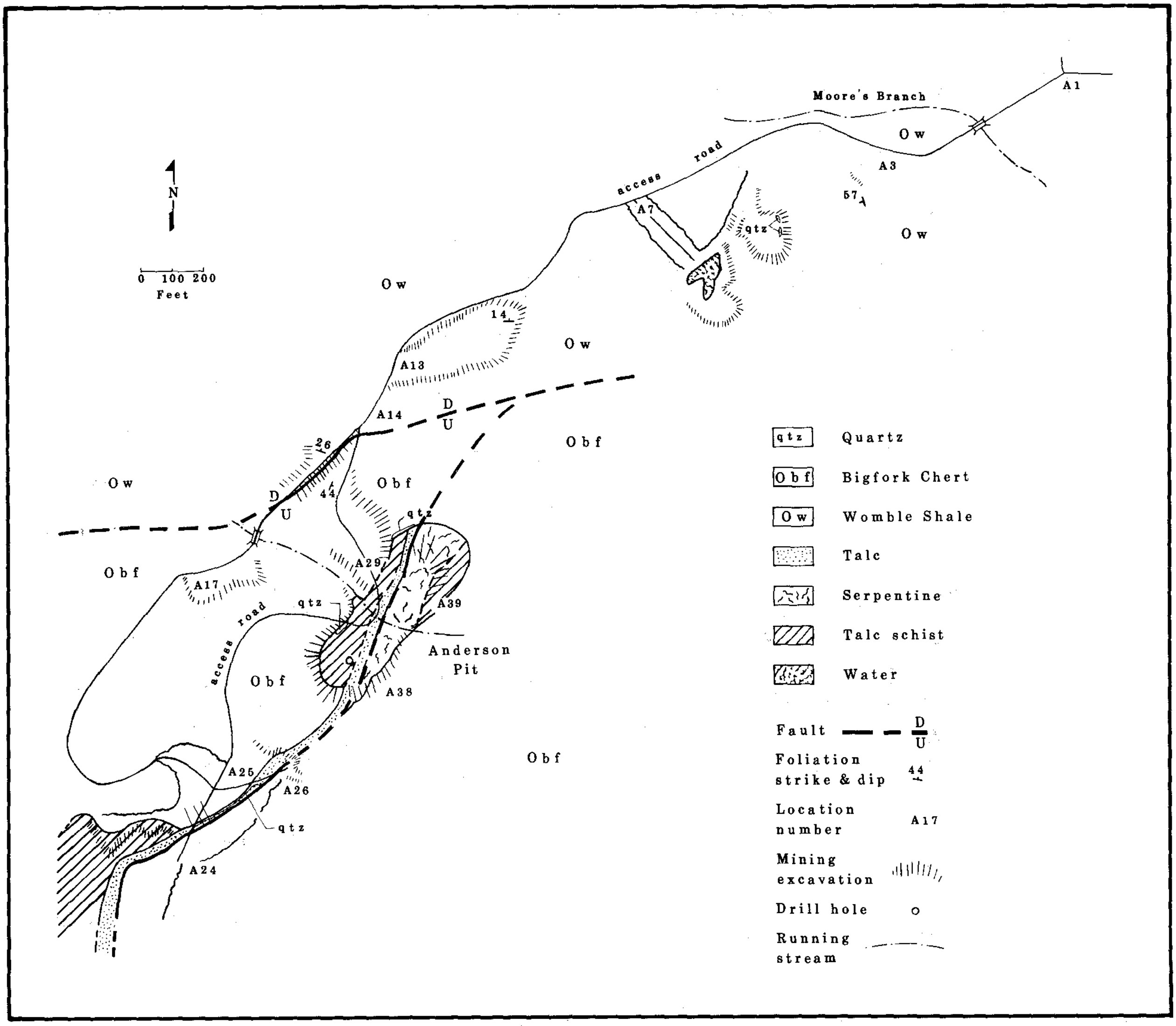

Figure 6. *Geologic map of the Anderson Pit area.*

Evidence for solid emplacement includes foliations in the ultramafic body concordant with the surrounding country rocks, sheared contacts, and a lack of thermal contact metamorphism of enclosing country rocks. The major problem in the solid state emplacement of an ultramafic body lies in accounting for its upward transport. At deeper levels, the upward movement of a peridotite body probably takes place by plastic flow; at shallower levels the movement is believed to take place under a tectonic stress gradient and is facilitated by serpentinization and weakening of the border zone due to high fluid pressures generated at the contact of the relatively hot peridotite body with wet sediments.

Antigorite-bearing serpentinites, which these are, must represent temperatures in excess of 300° C and perhaps as high as 550° C. In the case of small ultramafic bodies being serpentinized, it is not uncommon to have CO_2 or silica derived from the country rocks invade the ultramafic body at its borders to produce talc, chlorite, and carbonates within the serpentinite (Figure 7).

Several samples of the different rock units around the serpentine pits were studied by X-ray diffraction. The X-ray patterns and d-spacing values in angstroms were compared to data provided by other workers and to the

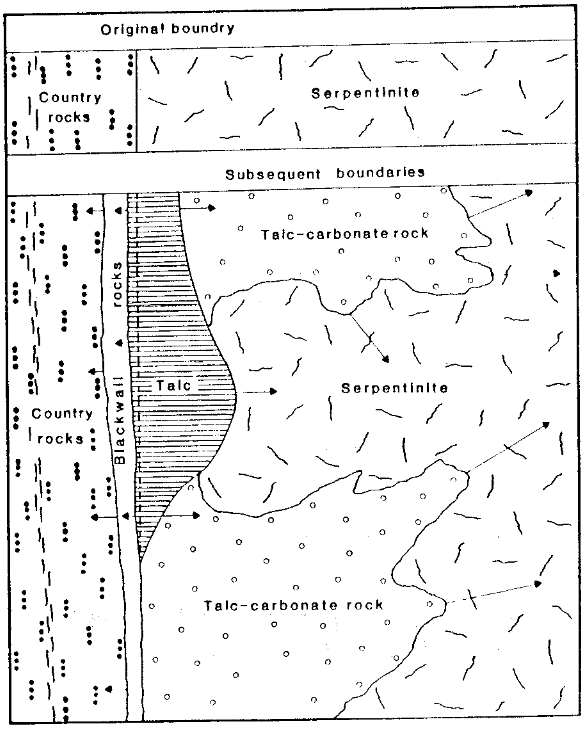

Figure 7. *Diagram showing typical movements of boundries between lithologic zones during alteration of serpentine bodies of Saline County, Arkansas. After Jahns, 1967.*

ASTM Guide to help determine mineralogies and as an aid in mapping the various rock units.

This study confirmed several preconceived thoughts and disallowed a few others.

1. The dominant serpentine mineral in the pits is antigorite, as no chrysotile patterns were seen in any of the samples run.

2. The second most abundant serpentine-related mineral is talc.

3. The light veins in the blackwall chlorite are talc rich.

4. The talc along the fault zone in the Anderson area is continuous from A24 to the north wall of the Anderson Pit.

5. The contact of Bigfork and Womble at A14 was confirmed as a fault. It is the only contact of Bigfork and Womble found in this area. This fault is confirmed by the physical appearance of the rocks, by structural measurements, and by X-ray diffraction analysis. The lower unit is black to dark-brown, medium-hard shale with very tight folds having small (1 to 3 in.) hinge lengths. They are pervasive throughout the unit. The upper unit is dark-gray to red, medium-hard shale with fewer folds whose hingelines are measurable in feet. The geometry of the folds and foliations in the two units also differs.

The d-spacings found from the X-ray patterns of samples at the A14 locality, and elsewhere for comparison, are close in value, but the intensity ranking is quite different. All the Womble samples have their highest intensity value in the 3.3 A^o range, but the second value for all Womble samples is 7.1 A^o, except for one in which the first two values are reversed. The patterns themselves, of Bigfork and Womble, are also similar in appearance, but close study reveals slight horizontal differences between peaks and differences in the relief of the peaks.

Within the Womble, the d-spacing is uniform and a definite pattern can be seen, while in the Bigfork, it is not as closely related and a pattern is more difficult to discern.

The conclusion at this locality is that the lower visible unit is in the lower or middle Womble and that it is in fault contact with the overlying Bigfork Chert Formation. However, the direction and amount of movement are not readily discernible owing to the poor exposures and the similarity of the two units. According to the interpretation of Sterling and Stone (1961), the soapstone deposits lie in the south limb of an overturned anticline near the Womble-Bigfork contact. The intense local shearing and small scale folding of beds suggest that there is much faulting in the area. The irregular lense-shaped soapstone deposits occur along an east-west trend. The ultramafic rock is dike-like in form, and in map view seems to be boudinaged, causing the soapstone deposits to appear as completely isolated bodies.

The main purpose of this study is to determine if the Saline County serpentines were emplaced into their present position within the surrounding rocks by magmatic intrusion or tectonic emplacement. Interpretation of structural measurements in and around the bodies should make it possible to determine if the country rocks and the ultramafics have the same deformational history or if the ultramafic body has its own unique history.

This problem is not unique to the Saline County soapstone-serpentines. Coleman (1971) listed structural studies related to the internal structure of the parent protolith and the external structure of the surrounding country rock as one of the approaches that future work on serpentines and their protolith rocks should be concerned with.

The structural fabrics of the Anderson and Warner areas were studied by means of stereographic projection. Fabrics measured and plotted by stereographic projection for this study include both planar and linear elements. Measurements included strike and dip of foliations. Foliation is used here because of the very dark color and fine-grained texture of most of the rocks makes it very difficult to distinguish bedding from cleavage with accuracy. Fabrics were measured in and around the Warner and the Anderson Pits as well as in the surrounding areas within a two-mile radius. These measurements are compared on a local scale and also on a regional scale to the published regional work of Viele (1966).

The Pi diagrams of Viele compared in this study are from measurements taken in local quadrangles. Viele's diagrams for the south half and the north half of the Benton quadrangle show that bedding and cleavage are concordant. The study area of this report is in the northeastern corner of the Congo 7 1/2-minute quadrangle (Figure 8).

In his diagram combining the Congo 7 1/2-minute quadrangle with the Ferndale, Alexander, and Pinnacle Mountain quadrangles, nearly all bedding poles indicate that the beds are striking northwest and dipping northeast (Figure 9). In the Anderson Pit area though, the Womble north of the pit strikes north with east and west dip. Many of the foliations are on the limbs of folds with hinge lines that plunge almost due north or south, which shows there are slight local variations to the regional trends as reported by Viele.

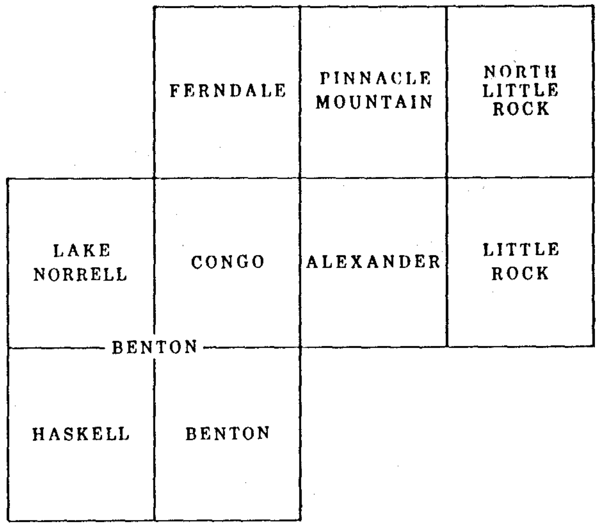

Figure 8. *Quadrangles surrounding the Saline County soapstone-serpentine pits.*

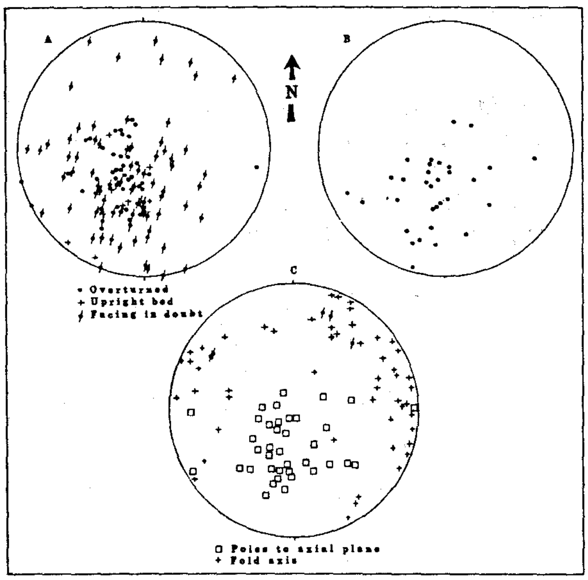

Figure 9. *Pi-diagrams for The Alexander, Congo, Ferndale, and Pinnacle Mountain quadrangles. See Figure 6 for index of quadrangles. A -- Pi-diagram of poles to bedding surfaces; B -- Pi-diagram of poles to cleavage planes; C -- Synoptic diagram of fold axes and poles to axial planes. From Viele, 1966.*

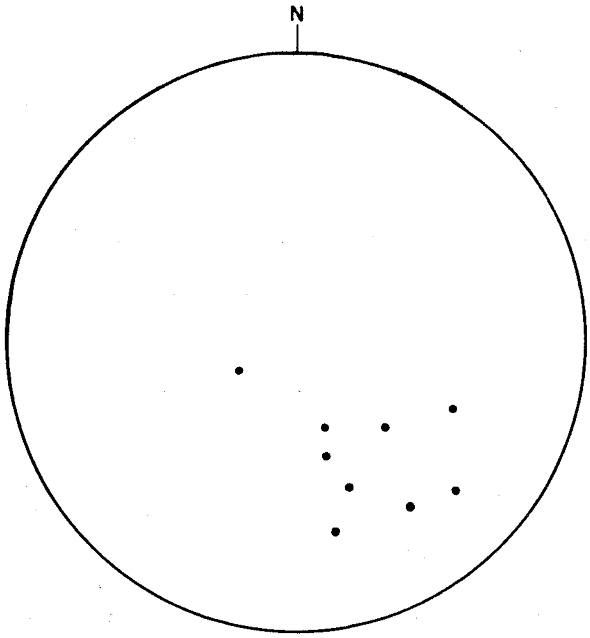

Figure 10. *Poles to foliations of the talc zone at localities A24 to A26, Anderson Pit area.*

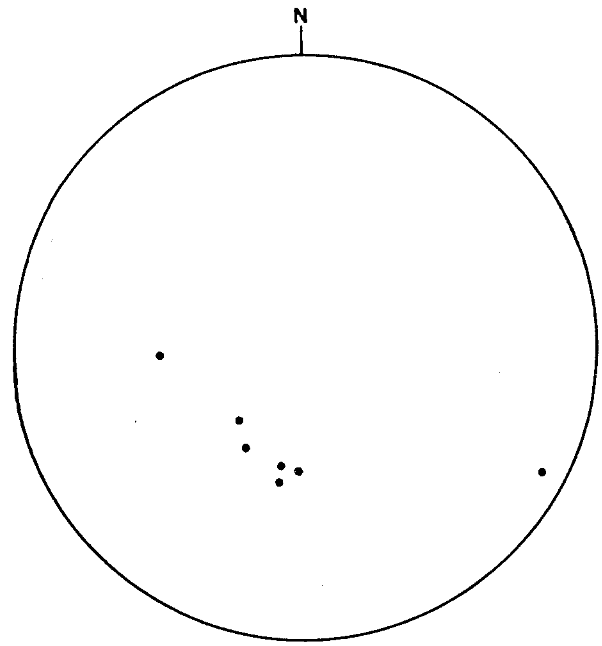

Figure 11. *Strike and dip of foliations in talc schist in the Anderson Pit area.*

The foliations in the talc zone at A24 to A26 (Anderson area, Figure 10) show moderate to gentle dips to the northwest and strike northeast. The local axial planes also dip northwest indicating that these folds are overturned to the southeast. Foliations in the talc schist of the Anderson area have northwest strikes and dip northeast similar to the trends of the adjacent Womble and Bigfork (Figure 11).

Figure 12 is a combination of foliation poles from the Congo and Ferndale quadrangles, the Womble from the Warner Pit area, and the talc schist and blackwall chlorite of the New Warner Pit. The foliations are all striking northwest and dipping northeast supporting the idea that the talc schist and blackwall chlorite are altered Womble Shale. The serpentine in both pits strikes north and dips predominately east (Figure 13), as represented by the platy foliation of the serpentine minerals. Folding in the Womble at the Warner Pit and in the Anderson area reveals differences which may indicate different tectonic phases.

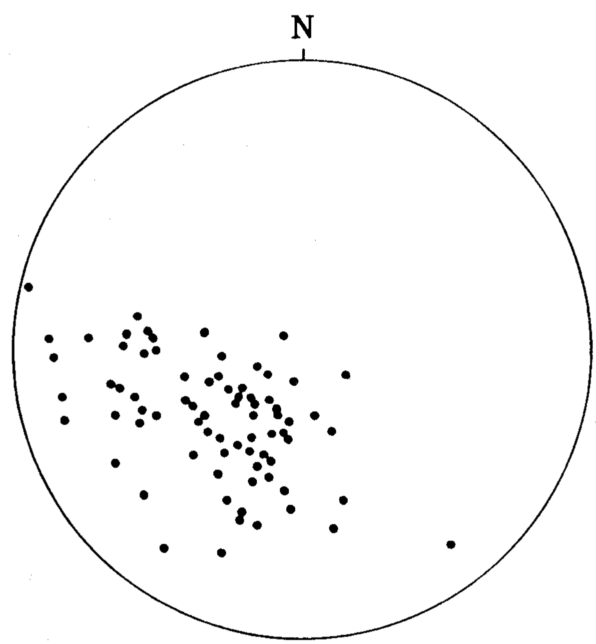

Figure 12. *Strike and dip of foliations in the Congo and Ferndale quadrangles, and in the Womble, talc schist and blackwall chlorite of the New Warner Pit.*

At several locations surrounding the serpentine pits, the jointing displays consistant

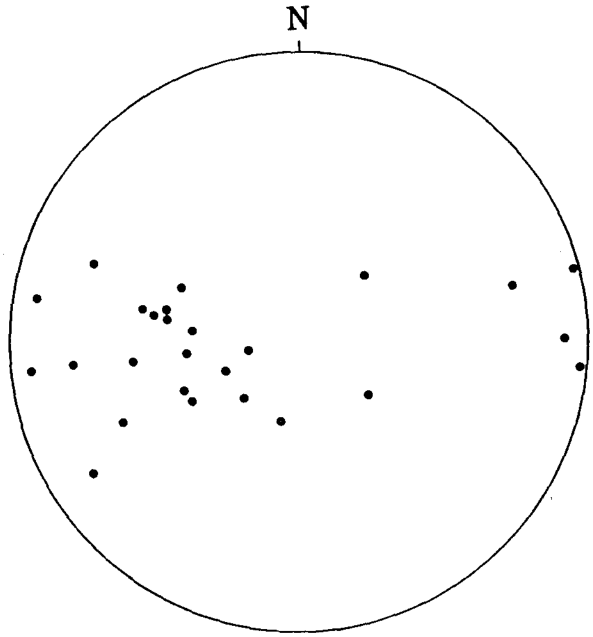

Figure 13. *Poles to foliations of serpentine in the New Warner and Anderson Pits.*

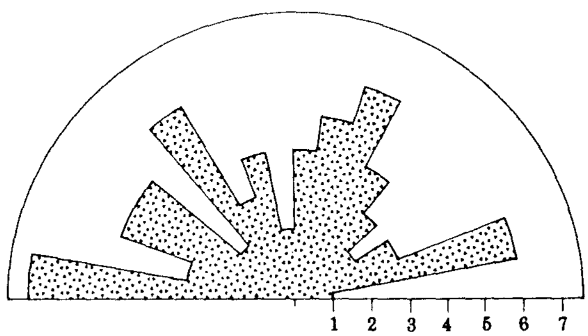

Figure 14. *Rose diagram of joint azimuths in the Ferndale and Congo quadrangles. Azimuths plotted in 10-degree increments. The longer the ray, the greater the number of joints in that increment. See index of quadrangles, Figure 6.*

trends (Figure 14). The same trends are repeated in the Womble of the Warner Pit, and in the serpentine and quartz veins of the Anderson area.

Veining is quite extensive in the area, the largest veins being quartz. One is up to 3 feet wide and 20 feet long. The talc-chlorite veins in the blackwall chlorite surrounding the New and Old Warner Pits trend northwest with most dips to the northeast, following the general strike and dip of foliations in the region. Calcite veins in the massive limestone along the south wall of the Old Warner Pit are of two generations. The older veins are black calcite showing strong deformation while the younger veins are white calcite, moderately sinuos, and cross-cut the older black calcite veins. The calcite veins show a wide range of azimuths.

Mineral elongation in the serpentine of both pits reveals a preferred northeast trend and minute pyrite crystals in the New Warner Pit both trend and plunge to the northeast (Figure 15).

Faulting is suspected to have played a part in the occurrence of the talc zone from A24 to the north corner of the Anderson Pit. A dominant quartz vein extends along the southern edge of the talc zone with stringers running northwest in the Bigfork, but none were seen going southeast. It seems entirely possible that a late episode of faulting after the deposition of the quartz could have raised the southeast portion of this zone carrying the quartz veins up to be eroded. The fact that the talc zone dips mostly to the northwest also supports lifting of the southeastern portion of the area.

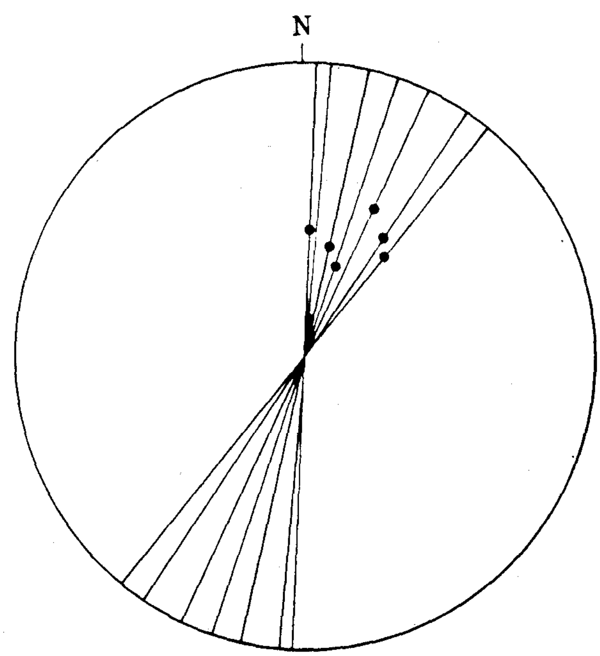

Figure 15. *Azimuths and point to plunge of pyrite crystals in the New Warner Pit.*

The talc zone of the Anderson area is traceable southwest of A24 into the valley below, but was not found on the opposing hillside. The talc zone, measured from the valley occurrence to the top of the hill at A26, shows a topographic height of about 180 feet, similar to the height measured from A26 to the floor of the Anderson Pit. Although it is not known how far the talc zone or the serpentine extend down into the country rock, a cross section by Wichlein (1967) shows that a diamond drill hole in the center of the Anderson Pit reached the Womble at 200 feet in depth. Proof of the presence of the Womble under the Anderson Pit, while Bigfork surrounds the pit on the surface, further enhances the possibility of major faulting in the area.

Along the south wall of the New Warner Pit is the contact of the black, calcareous shales of the Womble with the serpentine. This contact is very similar to the talc zone of the Anderson Pit area. The shale abuts a quartz vein which is in contact with a talc-carbonate zone which gradually grades into talc schist which, in turn, grades into serpentine. Another common feature of the contacts is the draping of the talc zone down and away from the country rocks. As explained in the discussion of the Anderson Pit area, this relationship can be explained by upward faulting. This is further support for the idea that the talc zone was a waterway for migrating fluids as indicated by the rapid mineralogic changes within short distances.

CONCLUSIONS

Serpentization

This study and previous work indicate that the serpentine in the Saline County serpentine-soapstone deposits is derived from peridotite. Petrographic and X-ray diffraction studies by this author confirm that the serpentine is antigorite and that it is rich in TiO_2, as described by Mullen (1984). Chrysotile, the low-temperature end member of the serpentine group, was not found in any of the X-ray diffraction patterns run by this author or others. As antigorite is the high-temperature end member of the serpentine group with a stability range of 460-550^{o}C, and the metamorphism of the country rocks is in the low greenschist facies, 250-300^{o}C, it is concluded that the serpentinization of the peridotite took place prior to its emplacement in the country rock.

The talc, talc schist, talc-chlorite, and the blackwall chlorite are the result of later metasomatic activities, while the clay minerals and sulfides in the area are believed to be hydrothermal in origin

Structure

All foliations in the Womble Formation follow the trend of regional foliation, striking northwest and dipping northeast,--as do the talc schist, and the blackwall chlorite. In the Anderson area the Bigfork strikes northeast but dips southeast. This was shown to be caused by local faulting and the possibility that some of the foliations represent the limbs of folds overturned to the southeast.

The majority of the foliations measured in the serpentine dip to the northeast, also following the regional trend.

Mineral elongation in the ultramafic bodies is to the northeast and is the result of stretching of folds along the northeast-trending hingelines. Foliations and mineral elongation and the other structural measurements presented earlier, all agree with the regional structure, implying that the serpentine was transported within the enclosing country rock by tectonic processes.

Origin of the Ultramafics

As described earlier, the diapiric rise and serpentinization of the ultramafics is established. Origin of the intruded diapir can be explained two ways (Figure 16): 1) The diapir rose and intruded the Ordovician sediments in the Ouachita trough as far up as the Bigfork (Middle and Upper Ordovician) and was then tectonically transported during the Ouachita orogeny to its present position, or 2) As a result of transform faulting or rift-zone emplacement as proposed by Thomas (1985) for the pre-orogenic Ouachitas.

Preference for these two models is based on analysis of the Hominy Hill gabbro (Morris and Stone, 1986b), which is believed to be related to the Saline County ultramafics. The Hominy Hill gabbro, 12 miles southeastward along strike from the Saline County bodies, is enclosed in Womble Shale and like the Saline County bodies, it is structurally conformable with the country rock. Field relations and petrography indicate the Hominy Hill gabbro also predated the Ouachita orogeny, is high in TiO_2, and has been metamorphosed to greenschist facies.

Model 1.

Stevens et al. (1974) described fossil ultramafic diapirs in the Appalachians with the following characteristics: 1) They are bounded by fault blocks (as are the Warner and Anderson bodies), 2) The ophiolite stratigraphy is never shown, but gabbro is sometimes present, and 3) The parental rock is clinopyroxenite rather than peridotite. Although it has not been determined what the parental pyroxene was, clinopyroxene by definition contains considerable Ca with or without Al, while orthopyroxene has no Ca and little or no Al. All previous studies and this study confirm the presence of Ca in the serpentinite body and talc rocks and the finding of pyrophylite, a hydrous aluminum silicate, establishes the presence of Al.

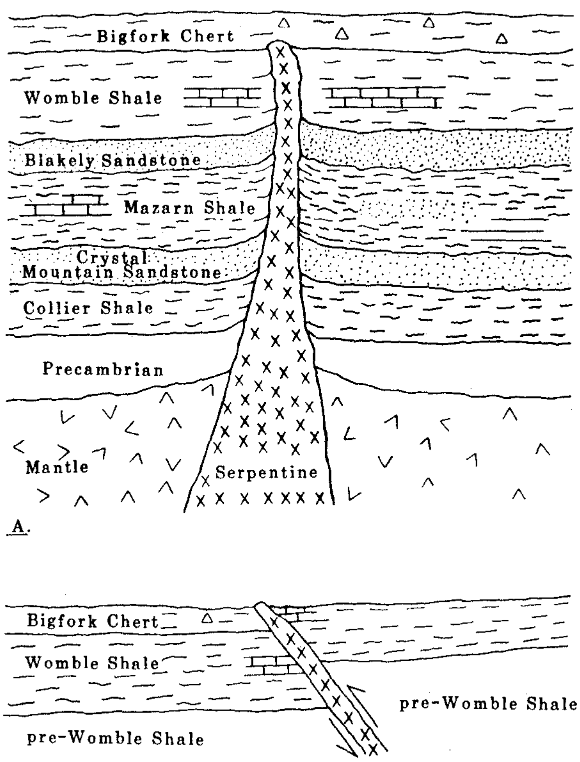

Figure 16. *A. Diapiric rise of an ultramafic body in Saline County through Ordovician sediments. B. Initial faulting of ultramafics and sediments.*

Model 2.

Thomas (1985) proposed a late Precambrian and Early to Middle Cambrian rifted continental margin (Figure 17), with rifts trending northeast in Alabama and southwest in Oklahoma going into Texas, with the transform fault connecting the two rifts forming the pre-orogeny continental margin, just south of the present location of the Ouachitas. In modern studies along the Mid-Atlantic Ridge, Bonatti (1976) found serpentine bodies, probably emplaced diapirically from the upper mantle, as solid protrusions and sills in the gabbroic-basaltic crust. These bodies were along narrow bands parallel to the axis of the mid-ocean ridge (Figure 18). Bonatti stated that no clear evidence of horizontal layering is apparent from the distribution of the various rock types and that serpentine outcrops are not restricted to any range of depths. They tend however to

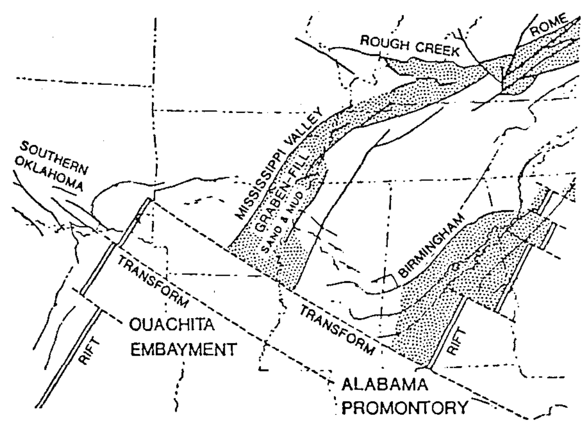

Figure 17. *Late Precambrian and Early to Middle Cambrian: rifted continental margin. Graben-filling sediments on continental crust (stipple). Transform fault between rifts forms the pre-orogenic continental margin just south of the present location of the Ouachita Mountains. (Thomas, 1985).*

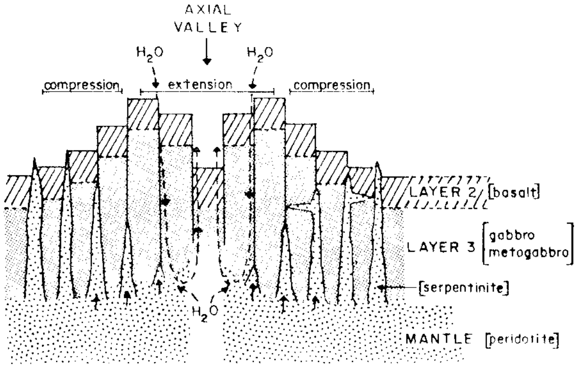

Figure 18. *Schematic model of the oceanic crust across the axis of the Mid-Atlantic Ridge showing the pattern of gradual diapiric emplacement of serpentine bodies in the oceanic crust. The serpentine bodies form narrow bodies parallel to the axis of the ridge. Note how serpentine rises above the basalt and becomes shallower with increasing distance from the axis. (Bonatti, 1976).*

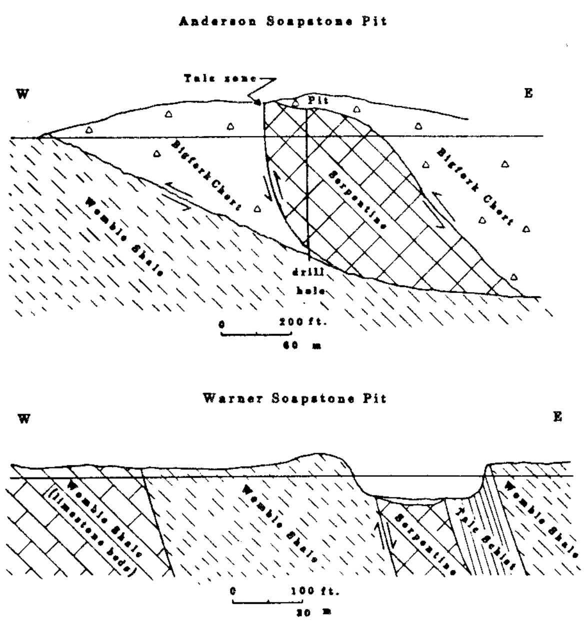

Figure 19. *Cross sections of the New Warner and Anderson serpentine-talc pits, Saline County, Arkansas. Datum lines are 500 ft. above mean sea level.*

become shallower with increasing distance from the axis of the ridge.

Geochemistry of the Saline County and the Hominy Hill ultramafic bodies fits either mid-ocean ridge of transform fault origins (Morris, personal commun., 1986). Both models place the ultramafic bodies into the pre-orogenic Ouachita trough to be faulted and folded into their present form and location by the Ouachita orogeny (Figure 19).

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Quartz crystal deposits of the Ouachita Mountains, Arkansas and Oklahoma

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ABSTRACT

Milky quartz veins are abundant in the complexly deformed Paleozoic rocks in the core of the Ouachita Mountains, occurring in a wide belt extending from Little Rock, Arkansas to near Broken Bow, Oklahoma. They may be as much as 60-100 feet in width. The veins typically have traces of adularia, chlorite, calcite, and dickite and may contain rectorite, pyrophyllite and cookeite. Certain metals, including lead, zinc, silver, copper, antimony, and mercury may be associated with the quartz veins.

The milky quartz and associated minerals are hydrothermal deposits of tectonic origin. The veins formed during the closing stages of the Late Pennsylvanian-Early Permian orogeny in the Ouachita Mountains. They commonly fill fractures and joints in the rocks and are closely associated with thrust-fault zones. Some smoky quartz crystals occur with vanadium, titanium, and lithium mineralization in the contact-metamorphosed Paleozoic rocks adjacent to Magnet Cove and are considered Late Cretaceous in age.

At certain localities, milky quartz veins have cavities containing crystal clusters suitable for mining. Individual quartz crystals up to 5 feet in length and weighing over 400 pounds and clusters 15 feet in length weighing over 5 tons have been produced from these mines. Most of the crystals mined have been from veins filling fractures in the Ordovician Crystal Mountain and Blakely sandstones near Mount Ida in central Montgomery County and near Jessieville in northern Garland County. Because of the aesthetic beauty of many of the crystals and crystal clusters, the principal market over the years has been as specimens in mineral collections worldwide. Other uses have been as oscillators in communications equipment during World War II, for fusing quartz, and as lasca--the chemical feedstock for vitreous silica or for growing cultured quartz. Some crushed milky quartz has been used as aggregate in precast concrete.

Geomex Mine Services, Inc. produced 2.5 million pounds of lasca in 1984, placing Arkansas at the forefront of the world's production of lasca. Coleman Crystal, Inc. of Arkansas was the other domestic producer in 1984. The five grades of quartz that have been produced are the feedstock for a variety of commercial applications, including cultured quartz, fiber optics, and vitreous silica.

Relatively simple open-pit mining operations are used to expose the crystal-filled cavities. The crystals are usually removed with hand tools and small equipment. Reserves of quartz in the Ouachita Mountains are impossible to calculate, but with the limited area mined to date and the difficulty in prospecting for suitable deposits, it is logical to assume that only a small percentage of the potential reserves has yet been mined.

INTRODUCTION

Quartz, or silica (SiO_2), is a hard, brittle, durable mineral that exhibits considerable resistance to weathering. It occurs in nature in many varieties, but is best known from Arkansas as prismatic, elongate, clear or colorless vitreous crystals (Figure 1). Quartz crystals from Arkansas have received worldwide recognition by the mineralogical profession. Because of this and the popularity of quartz with the many tourists who visit Arkansas each year, the Arkansas General Assembly of 1967

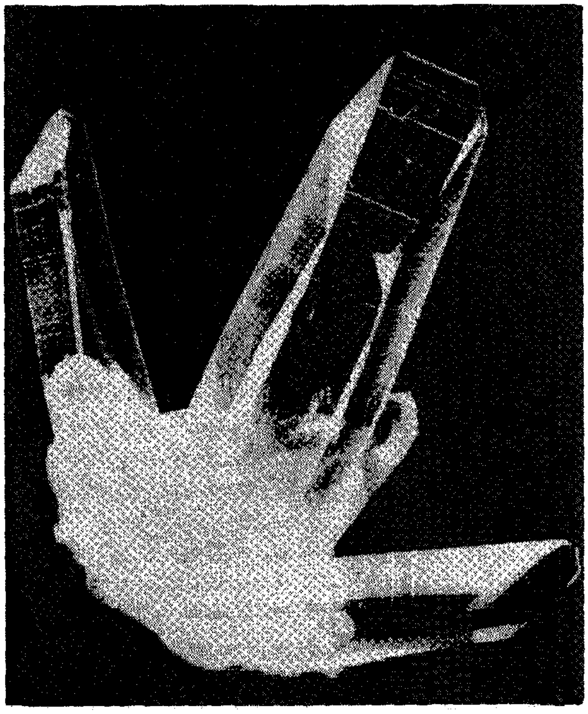

Figure 1. *Quartz crystal from the Crystal Mountains, Arkansas. Photograph by D.R. Hiens*

established Act 128, which designated quartz crystal as the official State Mineral.

HISTORY

The existence of quartz crystal in the Ouachita Mountains has been known since humans first occupied the area. According to H. D. Miser (1959), DeSoto's men in 1541 found that the Indians had been chipping arrowheads from quartz crystal.

Few restrictions or legal problems hindered the early miners, although most crystal deposits were on land owned by the Federal Government and by timber companies. As long as the timber was left undamaged and the openings did not become pitfalls for livestock, a miner was free to dig where he dropped his pick and scratcher (an iron rod, commonly 1 to 2 feet long and bent into a right angle several inches from the point, used to collect the crystals). Patented claims or leases were rarely obtained. During World War II, the critical need for oscillator grade quartz, used in communication equipment, brought about a rapid expansion in prospecting and mining. With Federal agencies and private mining companies participating, mining rights received more careful scrutiny and free-for-all operations dwindled. As a part of the Federal program to stimulate domestic production of oscillator quartz for the war effort, the Metals Reserve Company established a quartz-buying station in Hot Springs in June, 1943. About 75 percent of the oscillator quartz mined in the district during 1943, amounting to more than 4,000 pounds, was tested at this station. Following World War II, techniques were developed for growing quartz crystals artificially and the demand for Arkansas quartz was mostly limited to the expanding tourist and museum markets. Some crystals were cut into semi-precious "Hot Springs diamonds" for jewelry purposes. Crushed milky quartz for precast concrete products was produced from veins in northern Saline County. The present major commercial use of quartz is as a high purity feedstock (lasca) for the growth of synthetic quartz crystals. These man-made crystals have many chemical, thermal, and electrical applications.

With the increased demand by tourists, museums, and expanding commercial markets, the price of quartz crystals has continued to rise in recent years. Some exquisitely developed quartz clusters are reportedly valued at thousands of dollars.

GENERAL GEOLOGY

All the rocks in the Ouachita Mountains are of sedimentary origin, with the exception of several early Late Cretaceous igneous plutons (mostly of syenitic composition) and various related small dike swarms that occur primarily along the eastern margins of the region. The exposed sedimentary bedrock consists of shale, sandstone, chert, novaculite, limestone, conglomerate, and tuff. These rocks, which exceed 50,000 feet in thickness, are considered to be of deep-water marine origin. They are of Paleozoic age ranging from Late Cambrian (about 520 million years) to Middle Pennsylvanian (about 310 million years) (Table 1). The Ouachita Mountains were formed when these rocks were uplifted by northerly directed compressive forces during late Paleozoic time.

Table 1. Stratigraphic section of rocks exposed in the Ouachita Mountains

	Maximum Thickness in feet
PENNSYLVANIAN SYSTEM	
Atoka Formation--shale and sandstone	27,500+
Johns Valley Shale--shale, minor sandstone and limestone, and erratic boulders	1,500+
Jackfork Sandstone--sandstone and shale	6,000
MISSISSIPPIAN SYSTEM	
Stanley Shale--shale, sandstone, some chert and minor tuff	11,000
DEVONIAN AND MISSISSIPIAN SYSTEMS	
Arkansas Novaculite--novaculite, shale and conglomerate	950
SILURIAN SYSTEM	
Missouri Mountain Shale--shale with minor sandstone	250
Blaylock Sandstone--sandstone, siltstone and shale	1,500
ORDOVICIAN SYSTEM	
Polk Creek Shale--shale	175
Bigfork Chert--chert, limestone, and shale	800
Womble Shale--shale with some thin limestone and sandstone	1,900
Blakely Sandstone--shale, sandstone and erratic boulders	450
Mazarn Shale--shale with some sandstone and limestone	3,000
Crystal Mountain Sandstone--sandstone, shale and erratic boulders	850
CAMBRIAN AND ORDOVICIAN SYSTEMS	
Collier Shale--shale and limestone	1,000

The deformation caused extensive thrust faults and complex fold systems that trend nearly east-west. Some rocks were subjected to very low-rank metamorphism and related hydrothermal events as evidenced by locally pervasive shear planes, recrystallization, and numerous milky quartz veins. Steeply dipping fractures, closely related to the major folds, controlled the location of deposition of most of the quartz. Following the formation of the Ouachita Mountains there was a long period of erosion and minor arching with thousands of feet of rock being denuded from the area.

QUARTZ VEINS

Most of the quartz veins and crystals are restricted to a belt about 30 to 40 miles wide that extends for about 150 miles in a west-southwest direction from Little Rock, Arkansas to the vicinity of Broken Bow, Oklahoma (Figure 2).

The veins attain a width of as much as 60 feet in Arkansas and nearly 100 feet in Oklahoma. They are most numerous along the central core of the Ouachita Mountains, where they occur in Paleozoic shales, slates, sandstones, and other rocks. Along and near the borders of this region, the veins are usually confined to sandstone beds lying between thick intervals of shale.

Veins enclosed in shales typically are massive, milky vein deposits that yield relatively few faced crystals. Vein deposits in sandstone units of the Blakely and Crystal Mountain formations may also be in the form of sheeted zones, and/or stockworks. Although these forms may contain much less quartz volumetrically when compared to deposits in

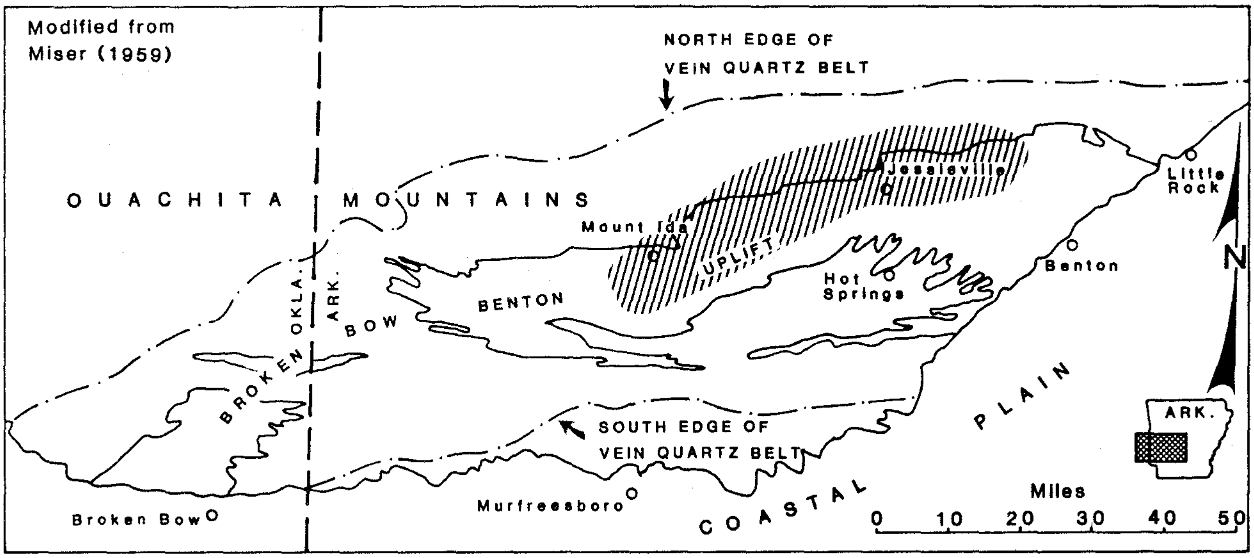

Figure 2. *Sketch map showing the extent of quartz occurrences in the Ouachita Mountains of Arkansas and Oklahoma. Diagonal lining marks area of significant quartz production.*

shale, they often yield a relatively high proportion of clear crystals in cavities or pockets. Many of the crystal-bearing pockets are distorted or crushed due to structural adjustment in the Ouachita Mountains that occurred after initial formation of the quartz veins. This deformation commonly causes the veins to exhibit complex fabrics.

The large, milky, "bull" quartz veins mostly in the highly deformed shale sequences of the Womble, Mazarn, and Collier formations, such as northeast of Jessieville, Arkansas and in the Broken Bow belt of Oklahoma, presently are being mined or investigated as a source of low-grade industrial quartz.

The quartz veins were formed by the filling of open fissures and show little evidence of significant replacement of wallrock. Milky quartz, quartz crystals, and associated vein minerals of the Ouachita Mountains were deposited from hot waters during the closing stages of the late Paleozoic mountain-building episode about 290-255 million years ago.

While most of the commercial quartz crystal is obtained from deposits in the Crystal Mountain and Blakely sandstones, attractive quartz crystal may be collected locally from any of the Paleozoic units.

PRINCIPAL QUARTZ-BEARING FORMATIONS

Although all the Paleozoic rocks in the Ouachita Mountains are cut at places by quartz veins containing some crystals, the chief producing deposits of clear quartz crystal occur in the Crystal Mountain and Blakely sandstones of Ordovician age in the "core" of the Ouachita Mountains.

At present there are two major localities for quartz crystal production (Figure 2). The Crystal Mountain locality contains the Fisher Mountain, Fisher Spur, High Peak, and other deposits, where generally rather small, clear crystals and some sizable clusters of crystals are present in veins dissecting the Crystal Mountain Sandstone. The Jessieville locality includes the Geomex, McEarl, Miller Mountain, and other deposits, where many of the large, clear quartz crystals and clusters are obtained from veins in the Blakely Sandstone. The apparent paucity of thick Ordovician sandstones in the Broken Bow belt of Oklahoma may preclude the occurrence of large cavities and associated crystals.

Crystal Mountain Sandstone

The Crystal Mountain Sandstone overlies the Collier Shale and was named for the massive sandstones that form the Crystal Mountains in Montgomery County, Arkansas.

The Crystal Mountain varies from approximately 550 to 850 feet in thickness. It is composed of very massive to thin-bedded quartzose, calcareous, light-gray to brown, sometimes conglomeratic, medium-grained sandstone. Interbedded black and gray to buff shales are present and are more common in the upper part of the formation. Intervals of thin, dense, very fine-grained to sandy, bluish-gray limestone and calcareous gray conglomerate and boulder-bearing breccia occur in the lower portions of the formation. Few fossils have been reported from the formation.

Blakely Sandstone

The Blakely Sandstone was named for the massive sandstones that form Blakely Mountain north of Hot Springs in Garland County, Arkansas. The formation ranges from 400 to 700 feet in thickness and consists of interbedded thin to fairly massive, fine to medium-grained, sometimes silty or calcareous, brownish-gray quartzose sandstone and black to green shale. A gray sandy limestone occurs locally in the upper part of the Blakely and a shale sequence ranging in thickness from 100 to 200 feet is present near the middle. Graptolite impressions occur in some of the shales. The Blakely forms high ridges with small, narrow, intervening valleys.

TYPES OF QUARTZ

Most of the quartz in the Ouachita Mountains occurs as white or milky veins. The primary difference between milky quartz and clear rock crystal is the presence of innumerable fluid-filled cavities in the former. These cavities scatter the light that otherwise would pass through as in clear crystal.

Although a variety of minerals are associated with vein quartz, coarsely crystalline milky quartz usually constitutes 90 percent or more of the cavity fillings. Clay minerals, including dickite and nontronite, are widespread. Calcite is a common associate, especially in the parts of the veins cutting limestone or calcareous siltstone. Adularia and chlorite are found in veins cutting certain shales. Carbonaceous material also is common. Less common accessory minerals are brookite, rectorite, the sulfides of lead, zinc, antimony and mercury, the lithium chlorite--cookeite and a lithium mica--taeniolite, and the carbonates ankerite, calcite, and siderite.

Colorless crystal or rock crystal occurs most commonly in comb pockets. Comb pockets are voids lined with opposed crystals oriented approximately normal to the vein walls. "Pockets," a crystal miners' term, are the result of incomplete filling of fissures in the fractured country rock, particularly sandstone. Individual crystals commonly exhibit an asymmetrical form due to the abnormal development or enlargement of at least one of the rhombohedral crystal faces. Individual crystals having essentially equal sized positive and negative rhombohedral faces so that the crystal appears morphologically symmetrical are rather scarce. Typically, growth was most rapid parallel to the C crystallographic axis, resulting in elongate prisms. The surface textures and features of quartz crystals vary from one deposit to another. The prism faces may display either growth lines consisting of innumerable parallel lines of varying intensity or major offsets--"stairsteps," both of which are expressions of rhombohedral faces. Many rhombohedral faces display triangular growth zones and/or minute triangular pits. Crystal luster varies from subvitreous, almost "frosted" in appearance, to vitreous. Individual crystals usually are milky at the base or point of attachment and clear at the termination. Occasionally, crystals are found that are almost entirely clear, tip to base. Aside from crystals that are attached to the sidewalls of the pockets, "free floaters" or unattached crystals occur, especially when the pockets are large enough to be filled with clay. Many unattached crystals occur as doubly terminated elongate prisms or highly distorted, bizarre forms. As the result of structural adjustment after the initial formation of the primary pocket, sheared-off pieces of crystals dropped into hydrothermal clays in the pocket and growth was reinitiated. These "free floaters" may be discovered suspended in the iron oxide-impregnated clay normally filling the quartz-lined cavities. Limonite, goethite, and lithiophorite are very common secondary minerals in the quartz veins, typically coating and staining the quartz. These oxides are easily removed by an acid bath treatment (usually oxalic).

Although many clusters or groups of crystals usually have a significant amount of sandstone matrix rock attached, shearing--often parallel to the vein walls--has removed the matrix from some. Minor growth in the vein results in a specimen consisting of a plate or sheet of quartz crystal with a very thin base.

Aside from the well known rock crystal, other varieties of quartz are found in this region. Quartz with water bubbles or fluid inclusions and negative crystal quartz are found near the edges or fringes of the area of major quartz deposition. Generally, these types of quartz resemble quartz from near Herkimer, New York, and form in calcite veins which are commonly weathered to clay, leaving the crystals suspended in clay where they wash out in loose soil. Phantom or zoned quartz is caused by temporary interruption of the growth process. Phantoms may be caused by small bubbles or inclusions of minerals adhering to the crystal faces. Across the northern limits of vein-quartz deposition, a type of quartz termed "solution quartz" by local collectors occurs. This quartz is unusual because much of it has grown as suspended or unattached crystals or clusters (burrs) in a clay-like material called rectorite. When rectorite is fresh, it has much of the appearance of petroleum jelly, but when dried it has the consistency of leather. It may weather to a tan or brown color. Specimens of these more unusual varieties are prized by collectors because of their beauty and scarcity.

Smoky quartz occurs near Magnet Cove, Hot Spring County, adjacent to an intrusion of Cretaceous igneous rocks. It is present as a gangue mineral in a contact-metamorphosed zone of the Arkansas Novaculite containing vanadium-, titanium-, and lithium-bearing minerals. The dark color is due to defects in the crystal lattice caused by radioactivity during the formation of the quartz. Banding or growth-zoning is not uncommon in well formed crystals from this area. Localities at Magnet Cove include the Hardy-Walsh titanium prospect, the Christy vanadium deposit, and other minor occurrences where the Arkansas Novaculite was intruded by igneous rocks. Alteration zones bearing smoky quartz, brookite, rutile, pyrite, eggonite, and taeniolite in a matrix of kaolinitic clay and vanadium-rich goethite extend several hundred feet into the highly shattered, faulted novaculite. Close to the contact, the novaculite has been recrystallized and some SiO_2 leached, yielding a rock that is quite vuggy and open spaced. Further away from the contact, the novaculite contains veins of smoky quartz--the site of deposition of the leached SiO_2 mentioned above. Essentially all of the smoky quartz has a dull luster, probably produced by etching after deposition, varies in color from a peculiar brown to coal black, and occurs as short stubby crystals. Rarely, more prismatic crystals are discovered. Selected pieces of this quartz have been faceted. Amethyst (purple or bluish-violet quartz) sparingly occurs associated with mafic igneous rocks, particularly as veins in lamproite at the Crater of Diamonds State Park and as veins in the serpentine bodies in northern Saline County.

MINING AND MILLING

Presently all commercial Arkansas quartz mines are open-pit operations. Commercial mining of quartz for lasca consists of: (1) locating suitable veins, (2) bulldozing next to the veins, (3) removing vein material by machinery or hand, (4) washing to remove bulk clay, (5) crushing, (6) treating in an acid bath to remove iron and manganese oxides, usually with oxalic or hydrochloric acid, (7) sorting on conventional belts and sorting tables under strong fluorescent lights. The standard product consists of several grades of +1/2" to 1 1/2" lumpy quartz. The high grade product consists of all "eye" or "water-clear" quartz.

USES

Quartz crystals have long been an important commercial mineral. The raw material (lasca) for "cultured quartz"--that is to say, quartz crystals grown in the laboratory--is natural quartz. Nearly all the natural crystals used to grow cultured quartz come from Brazil. The larger pieces which meet rigorous standards of quality are used for electronic and, to a lesser extent, optical components. Smaller pieces and fragments are used for vitreous silica, sometimes called "fused quartz" (Sosman, 1972, rev. 1965). The need for large quantities of high quality quartz crystal led the United States Government to sponsor research programs in the 1940s. This resulted in the "growing" in the laboratory of large crystals of prescribed shape, size, and quality.

Modern radio equipment is most often controlled as to frequency by the presence in the circuit of a separately added "crystal"--the 1918 discovery responsible for the existence and growth of the quartz industry. This component is a carefully oriented and prepared slice of a crystal--not a crystal as recognized by mineral collectors or as seen in museums.

Quartz belongs to that class of materials called dielectrics: those that do not conduct an electric current but permit electric fields to exist and act across them. Quartz shows the "piezoelectric effect," which means that when a quartz plate is mechanically deformed, one of its surfaces becomes negatively charged, the other, positively charged. An alternating current flowing through wires attached to this wafer responds to the mechanical oscillation of the plate and is keyed to this oscillation. By controlling the thickness of the plate, its mechanical vibration can be varied through a wide range of frequencies. At least 17 cuts or orientations have been studied for use in various applications. About 99% of United States' imports of quartz crystal comes from Brazil, with small amounts from the Malagasy Republic, the United Kingdom, Argentina, and West Germany.

PRODUCTION OF CULTURED QUARTZ

Presently there are two large and several smaller cultured quartz operations in the United States, and operations are reported in England, Japan, and Russia.

The manufacturing process makes use of "hydrothermal growth," so named because it involves an aqueous solution at elevated temperature and is similar to the "hydrothermal action" that forms crystals and ore bodies in the crust of the earth. The synthetic process may be briefly described as follows: A vertical steel vessel (pressure bomb) is provided with suitable internal fittings and pressure gauge, safety blow-off valve, thermocouples, and a source of electrical heating. The vessel is charged with (1) nutrient material (lasca) to about 1/4 of its volume, (2) dilute alkaline solution to about 3/4 full, and (3) an array of seed plates. The vessel is closed and brought to a temperature of about 350^{o}C in an autoclave, producing a high pressure. The heat source is adjusted to provide a temperature difference between the area of dissolution and the area of deposition and growth. Conditions of constant temperature and pressure are maintained for a period of weeks or longer. The status of the growing crystals can be monitored using radiography with cobalt-60. Vessels up to 10 inches inside diameter, and capable of operating at pressures up to 40,000 pounds per square inch, are in use.

In 1984, record-high United States production was set for both lasca and cultured quartz crystal. The lasca record was aided by the addition of a new mine in Arkansas and was fueled by a worldwide demand for cultured quartz crystal in electronic applications. Although overall consumption levels of natural quartz crystal fell in 1984, imported natural quartz crystal was still required as seed material for growing cultured quartz crystal.

DOMESTIC PRODUCTION

Production data of Arkansas lasca are for 1981--175,000 pounds, 1982--200,000 pounds, 1983--600,000 pounds, 1984--2,500,000 pounds, 1985--1,000,000 pounds (estimated).

The first full year of operation (1984) for the new mine in Arkansas, operated by Geomex Mines Services, Inc., P. O. Box 8388, Hot Springs Village, AR 71909, was the primary reason for the 1984 lasca production record. Presently, Geomex is temporarily inactive. The most consistent domestic producer and supplier of lasca to the United States' cultured quartz crystal industry is Coleman Crystal, Inc., Highway 7 North, Jessieville, AR. 71949.

The cultured quartz producers operated at near full capacity levels for most of 1984 because of the strong worldwide demand in the piezoelectric applications of quartz crystal. Seven companies produced cultured quartz crystal in the United States. The two largest, Sawyer Research Products, Inc., Eastlake, OH, and Thermo Dynamics Corp., Shawnee-Mission, KS, are independent growers who produced crystal bars for domestic and foreign consumers in the crystal-device fabrication industry. Motorola, Inc., Chicago, IL, and AT&T Technologies, Inc., North Andover, MA, produced for both in-house consumption and the domestic fabrication industry. The other three growers, Bliley Electric Co., Erie, PA, Electro Dynamics Corp., Shawnee-Mission, KS, and P. R. Hoffman Co., Carlisle, PA, produced only for in-house consumption.

TRENDS

Japan recently became the world leader in the production of cultured quartz crystal and the United States dropped to the number two position. The United States depended on small quantities of Brazilian natural quartz needed as seed material for growing cultured quartz and for a few direct applications such as deep-well pressure transducers.

Although worldwide estimates for lasca and cultured quartz crystal demand increased slightly in 1985 from their record setting levels of 1984, the United States quartz crystal industry suffered an overall decline in production, exports, and domestic consumption. By the end of 1985, most operations had experienced layoffs and some prices had been lowered slightly to compete in foreign markets. Although a number of factors were thought to be reasons for the downturn, including the double ordering of quartz crystal during the previous year's boom when there was a shortage of quartz crystal, increased lasca competition from Madagascar, the relative strength of the United States dollar compared with some foreign currencies, and the decline from projected sales forecasts for personal computers containing quartz resonators, the major factor was the doubling of autoclave capacity by the five largest Japanese quartz-growing companies. With the increased capacity, the Japanese companies were no longer as dependent on imports of cultured quartz from the United States. Demand for United States lasca for use as feedstock by the fused quartz industry also declined, but not to the extent that was experienced by the cultured quartz industry.

CONSUMPTION AND USES

United States consumption of lasca by the seven growers in 1984 was about 1.3 million pounds, a 92% increase from the 677,000 pounds reported in 1983. The substantial increase occurred because the quartz crystal industry operated at nearly full capacity in 1984 after recovering from a 2-year recession.

Quartz crystal was consumed by 28 companies in 11 States. Cultured quartz crystal is the primary quartz material used in electronic applications. Quartz resonators are uniquely suitable in application for very high selectivity in military, aerospace and commercial band-pass filters; and for very high stability oscillators. In addition, for many applications requiring only moderate stability, quartz resonators offer a unique combination of high performance, small size, and low cost. Quartz resonators are also used for many less demanding applications such as providing timing signals for watches, clocks, and microprocessors in industrial, automotive, and consumer products.

For very high frequencies (above 100 megahertz), the quartz wafer becomes too thin for practical use. At these higher frequencies, structures that use surface vibrations, in which the frequency is determined by electrode dimensions rather than wafer thickness, are becoming more important. These structures are called surface wave or surface acoustic wave (SAW) devices. In 1984, SAW devices amounted to only a few percent of the total industry usage for resonators.

Imported natural quartz crystal continues to be required as seed material for growing quartz crystal. It is also used in transducers for highly sensitive quartz pressure gauges, which have become the petroleum industry's standard for accurate and precise measurements in oil and gas wells.

PRICES

The average reported value of lasca consumed for production of cultured quartz crystal in 1984 was $0.57 per pound, 5 cents per pound below that of 1983. The average value of as-grown cultured quartz in 1984, based on reported sales of 264,435 pounds, was $24.18 per pound, up about 11% from that of 1983.

The average value of lumbered quartz, which is as-grown quartz that has been processed by sawing and grinding, was $54.90 per pound in 1984, an increase of about 12% from that of 1983. The average value of lumbered quartz was based on reported sales of 329,757 pounds.

FOREIGN TRADE

Sawyer Research Products and Thermo Dynamics, the two largest growers of cultured quartz crystal, accounted for all U. S. cultured quartz crystal exports in 1984. Japan received 79% and the Republic of Korea received 11% of the total exports reported.

Most of the natural quartz crystal exports were bought from the National Defense Stockpile and were in the 700- to 1,000-gram weight class or lower. This quartz was consumed primarily in nonpiezoelectric uses such as quartz carvings and figurines.

In 1984, imports of Brazilian lasca, designated "Crude Brazilian Pebble," reached their highest level since 1980 in response to the strong industrial demand for cultured quartz crystal.

ACKNOWLEDGEMENTS

We wish to express our deepest gratitude to those who have previously helped us in the evaluation of the quartz crystal occurrences in the Ouachita Mountains of Arkansas and Oklahoma. These include Hugh D. Miser, Charles Milton, Albert J. Engel, Boyd R. Haley, Drew F. Holbrook, Raymond B. Stroud, Ben F. Clardy, Robert O. Fay, Ocus Stanley, Jim Coleman, Ron Coleman, Gary Coleman, Don Burrows, Garland Milholen, Garfield Lewis, John Long, Paul Thompson, and many others. Thanks are also extended to George W. Colton for his editorial assistance.

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Prairie Creek kimberlite (lamproite)[1]

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The Prairie Creek peridotite pipe (73 acres), situated in Pike County, Arkansas, has been the site of the only commercial diamond mine in the United States. It had been recognized as a peridotite since 1842 when it was first cited by W. B. Powell (Miser and Ross, 1923). In 1889, after the discovery of diamond-bearing peridotites in South Africa, later named kimberlite, Branner and Brackett realised the significance of the Prairie Creek pipe. However, it was not until 1906 that John W. Huddleston found the first diamonds near the mouth of Prairie Creek.

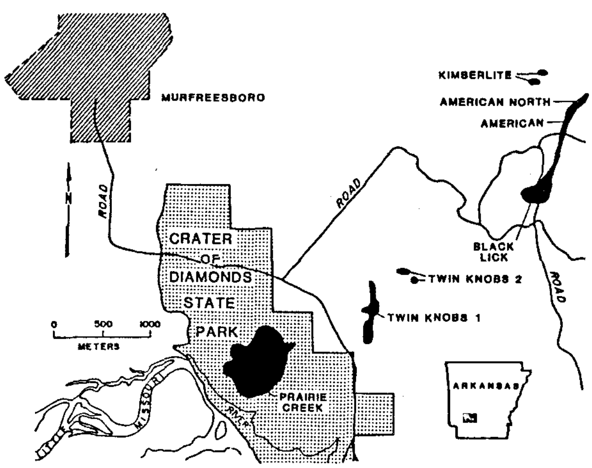

Figure 1. *Location of kimberlite (lamproite) bodies in Pike County, Arkansas. (From Michael A. Waldman et al., 1985)*

Since that time other smaller kimberlite bodies such as those at the American Mine and Kimberlite Mine, and others at Black Lick and Twin Knobs were discovered (Figure 1). Various efforts have been made to mine these bodies but, due to lack of adequate funding and experience, all failed sooner or later. The latest efforts were made by the Bureau of Mines in 1943-1944 and by the Glenn L. Martin Co. (the aircraft manufacturer) in 1948-1949. During the latter operation at Prairie Creek, approximately 125,000 short tons of kimberlite were treated with a disappointing recovery of only 246 carats. A company report stated that the extraction methods were not satisfactory and recommended numerous changes and alterations in mill design. However, after costly renegotiations the company decided to give up on this diamond venture.

At that time the Prairie Creek property was owned by Howard Millar and after failing to attract further interest, he converted the area into a tourist attraction. Finally, in 1972, the Arkansas Department of Parks and Tourism bought the property and made it a State Park (Figure 2) where the public can look for diamonds in exchange for a minimal entrance fee. Since the park was opened to the public in 1972, it has been visited annually by 60,000-90,000 people. Several hundreds of stones are found each year, culminating in a record 1501 stones in 1983.

In addition to the production reported by the Glenn L. Martin Co., the following production figures have been reported for earlier operations (Fuller and St. Clair, 1956) during the period 1907-1930.

Kimberlite treated (MT)	57,868
Number of diamonds recovered	14,026
Total wt. in carats (1 carat=0.2 gram)	7,845
Grade (carats/100MT)	13.56

The many modern improvements on recovery techniques and the resulting ability to recover smaller diamonds can possibly raise this grade significantly.

1/ - Reprinted from: Arkansas Geological Guidebook: 22nd Forum on the Geology of Industrial Minerals, Field Trip No. 3, p. 3-7.

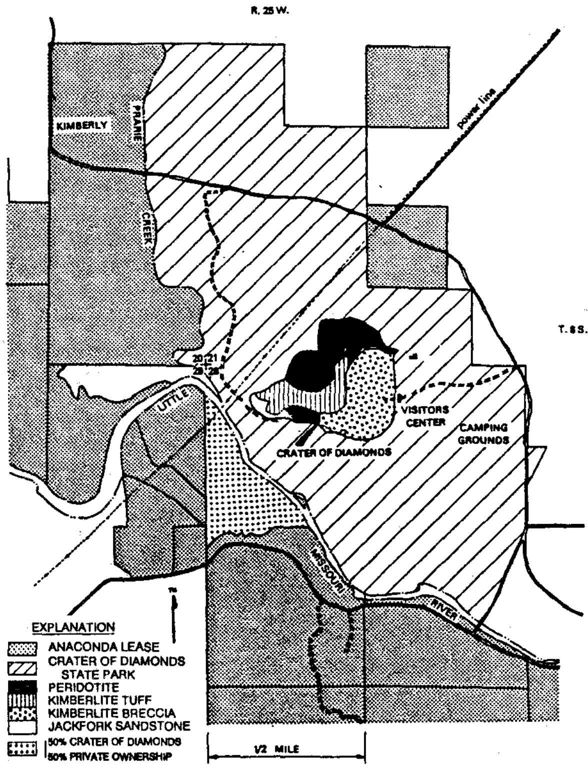

Figure 2. *Geology, land ownership, and lease holdings in the Prairie Creek area, Pike County, Arkansas.*

Estimates of how many diamonds have been produced from this area range from a conservative 25,000 stones registered by diamond buyers in New York up to the year 1940, to a very liberal figure of 300,000, including all illicit stones. A safe estimate is that approximately 50,000 stones have been produced to date. Some of the more famous are:

1. The Uncle Sam (1924)	40.42 carats
2. Star of Murfreesboro (1964)	34.25 "
3. Amarillo Starlight (1975)	16.37 "
4. Star of Arkansas (1956)	15.31 "
5. Gary Moore (1960)	6.43 "
6. Eisenhower (?)	6.11 "
7. unnamed (1981)	6.07 "
8. " (1983)	3.02 "

During the last decade several major mining companies, convinced of the potential of the Prairie Creek deposit, renewed their interest in the pipe and surrounding areas. Although some extensions of known kimberlite bodies were established, no major new discoveries were made. A proposal to evaluate the Prairie Creek pipe, put forward by one company in 1981, was turned down by the Department of Parks and Tourism and several later efforts also failed.

The Prairie Creek pipe has always been described as a micaceous peridotite or kimberlite intrusion because of the presence of diamonds, its peridotite composition, and its texture. Although it was recognized that the intrusion was not a true kimberlite (Lewis, 1977; Bolivar, 1977) because of the lack or rarity of picroilmenite, pyrope, chrome-diopside and enstatite, it took the discovery of diamond-bearing ultrapotassic lamproites in Western Australia before it was established by Scott Smith and Skinner (1984b) that the Prairie Creek pipe has a closer affinity to the Western Australian olivine lamproite than to kimberlite. This is summarized in the following abstract by Scott Smith and Skinner (1984a):

"A new look at Prairie Creek, Arkansas"

"Previous studies of the Prairie Creek occurrence have identified three main rock types namely: "volcanic breccias", "tuffs and fine-grained breccias" and "hypabyssal kimberlite or peridotite". Our investigation confirms the presence of three distinct rock groups which include both magmatic and crater-facies types. The so-called "volcanic breccias" and "tuffs" are both considered to be predominantly of pyroclastic origin. Many features of these rocks are atypical of kimberlite and indicate a complex intrusion history. The magmatic rocks contain two generations of relatively abundant olivine in a fine-grained matrix conposed of phlogopite, clinopyroxene, amphibole, perovskite, spinel, serpentine and glass. Although some petrographic features of these rocks are similar to those of kimberlites, the form of the euhedral olivine, presence of abundant glass and occurrence of potassic richterite are uncharacteristic of kimberlite but typical of lamproitic rocks. Both the groundmass phlogopite and the bulk rock have compositions intermediate between known lamproites and kimberlites. The data presented here shows that the Prairie Creek intrusion is not a kimberlite. Although in many respects Prairie Creek appears to be transitional between kimberlite and lamproite, it is considered that these rocks form an extension of the lamproite field."

The Arkansas lamproites are probably emplaced along mantle-tapping structures associated with the long-active Mississippi embayment rift system. This is suggested by the northeast alignment of the bodies parallel to the trend of the rift system. The more northerly trend within some of the lamproite bodies reflects a near-surface structural control.

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Barite in western Arkansas

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INTRODUCTION

Barite or $BaSO_4$, a heavy nonmetallic mineral used primarily as a weighting agent in drilling for petroleum, has been identified at several localities on the south flank of the Ouachita Mountains (Figure 1). The largest, Chamberlain Creek, is located near Magnet Cove on the east end of the Mazarn basin (Figure 2). This property for a number of years was the largest producing barite mine in the world ultimately producing over 9 million tons of barite. On the west end of the Mazarn basin, several barite occurrences have been identified west and north of Hopper, Arkansas in the Fancy Hill district. They are known as the Fancy Hill (Henderson), McKnight, Dempsey Cogburn, and Gap Mountain deposits. Barite also occurs near Pigeon Roost Mountain northeast of Glenwood and near Hatfield and Dierks, Arkansas. The properties near Hatfield occur in the Middle Division of the Arkansas Novaculite as small stratabound lenses of coarsely crystalline, black to gray-green barite. There are similar occurrences at Boone Springs and Polk Creek Mountain northwest of Fancy Hill. The occurrences at Dierks are Cretaceous gravels and sands cemented by barite.

The succession of Paleozoic and Mesozoic sedimentary rocks in the Ouachita Mountains and nearby part of the Gulf Coastal Plain is tabulated and briefly described below.

Barite occurs in three stratigraphic horizons in western Arkansas: (1) the Middle Member of the Arkansas Novaculite, (2) the lower 100 feet of the Stanley Shale, and (3) over about 500 feet of stratigraphic thickness in the Trinity Formation. In addition, barite is also found as cross-cutting veinlets associated with cinnabar mineralization, in the intrusive at the Crater of Diamonds State Park, and at other localities where it cross-cuts rocks of many different ages.

BEDDED BARITE

The commercial bedded barite deposits of the western Ouachita Mountains are restricted to the lower 100 feet of the Stanley Shale immediately above the Arkansas Novaculite. The novaculite is on the order of 900 feet thick in this area and consists of three units. The Lower Division is between 250 and 450 feet thick. The Middle Division is 210 feet thick at Fancy Hill, 390 feet thick at Gap Mountain, and 364 feet thick at Caddo Gap. The Upper Division is 70 feet thick at Fancy Hill, 120 feet thick at Gap Mountain, and 118 feet thick at Caddo Gap. The upper surface of the Novaculite in this area is an 18-inch-thick rubbly broken zone, in places cemented by pyrite (Figure 3). This zone is very well displayed at the Dempsey Cogburn mine on the exposed Novaculite wall and also at Chamberlain Creek. On a regional scale this stratigraphic horizon is represented by a chert pebble conglomerate of greatly varying thickness. At Hot Springs the zone is the Hot Springs Sandstone Member, which is mapped in the basal Stanley Shale. In the western Ouachitas the zone is from zero to 25 feet thick and consists of chert or novaculite clasts, usually one inch or less in size, in a siliceous matrix.

Above the Novaculite is the Stanley Shale, an approximately 11,000-foot-thick (Stone, 1984) turbidite sequence of shale and sandstone. It represents a radical change in depositional character from the Novaculite. Deposition changed from the very slow accumulation of mud to a rapid accumulation of turbidites with perhaps a ten-fold increase in

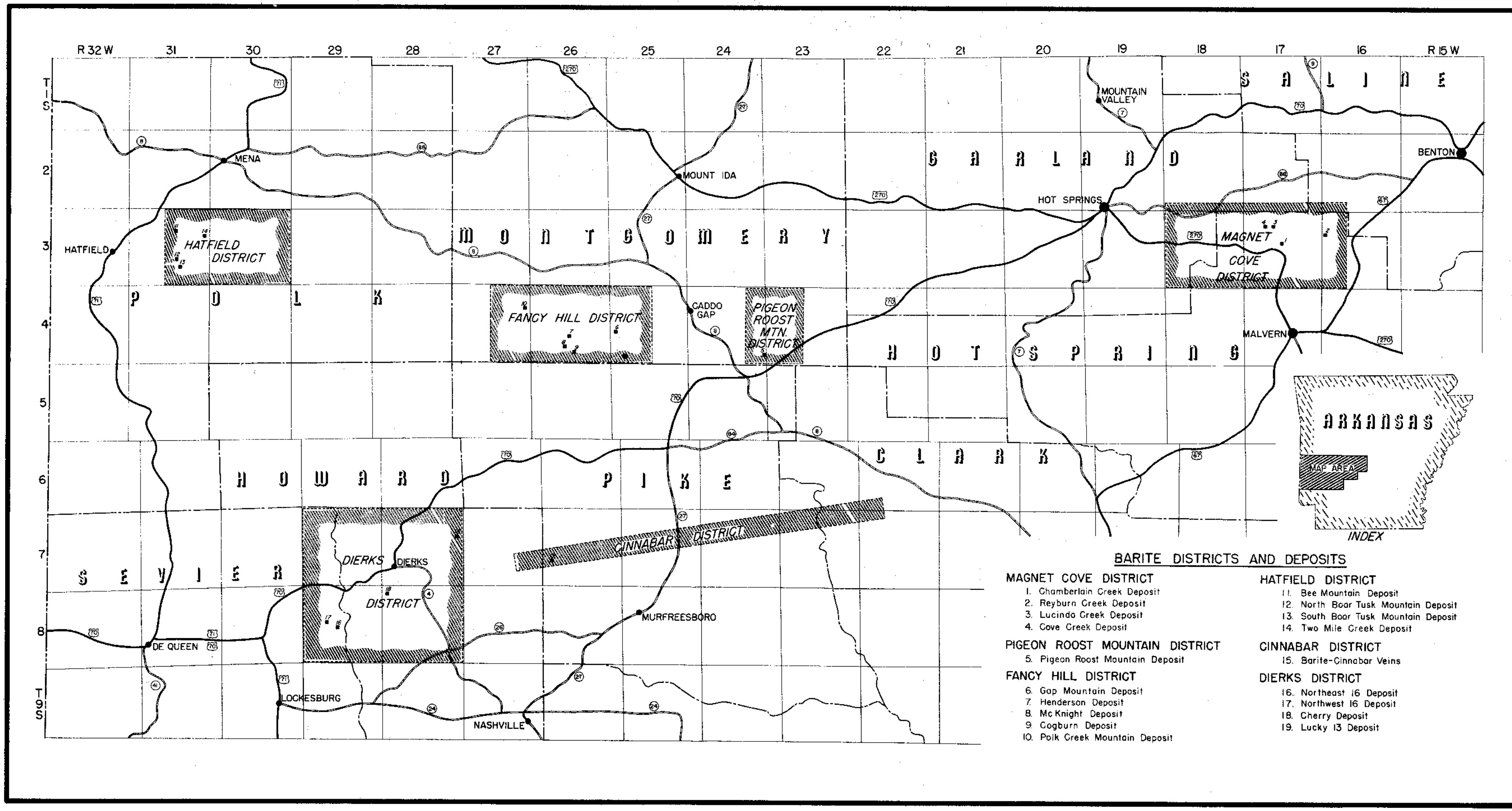

Figure 1. *Location map showing barite districts and larger known deposits in the Ouachita Mountains, Arkansas (from Scull, 1958).*

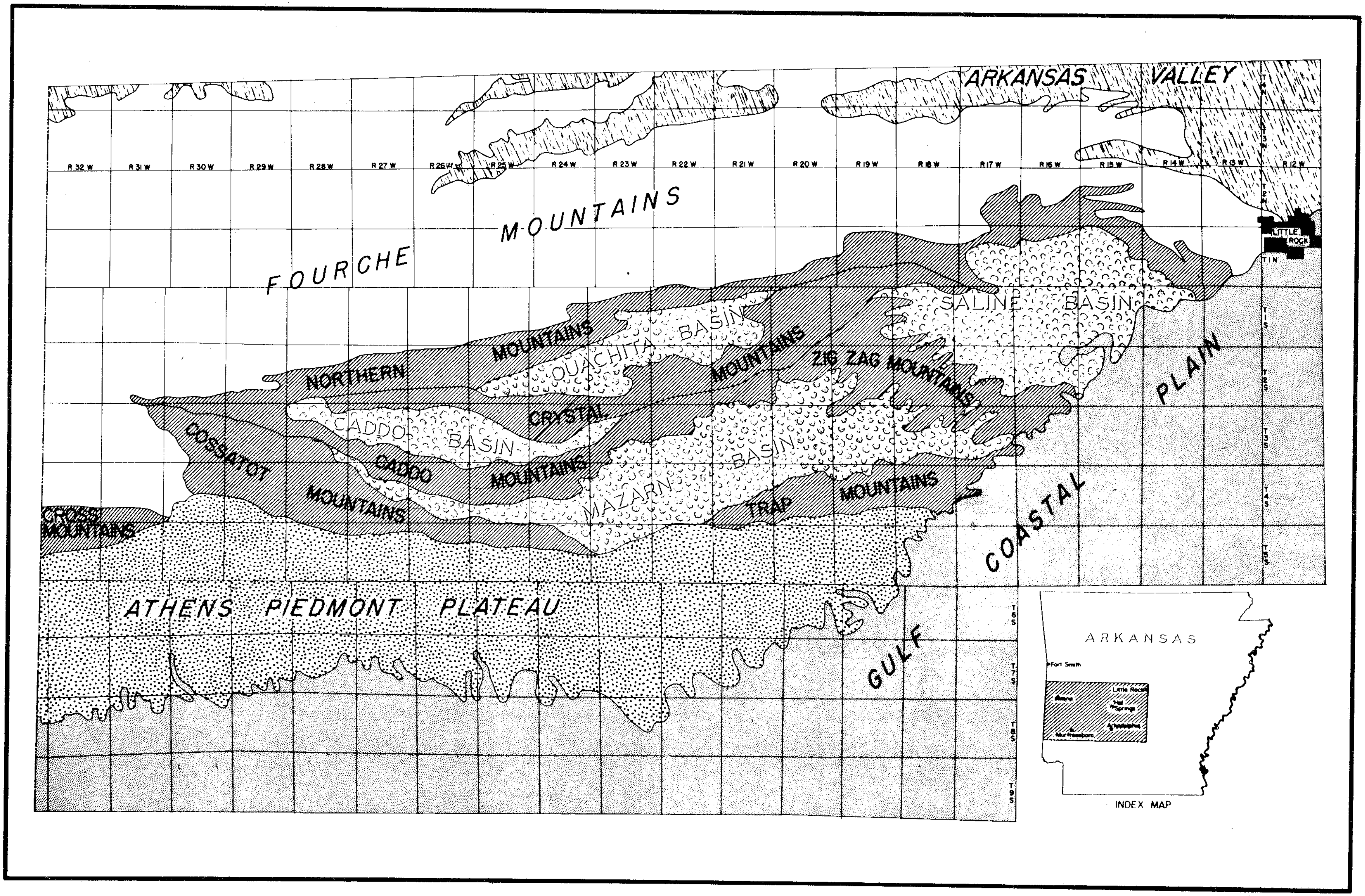

Figure 1. *Map showing major physiographic features in the Ouachita Mountain region of Arkansas. From Scull, 1958.*

Representative stratigraphic sequence encountered in the area of this study. [Modified from Scull, 1958]

Mesozoic

Upper Cretaceous

Woodbine Formation -- tuffaceous sands and clays

Lower Cretaceous

Trinity Group -- Pike Gravel at base, overlain by loosely consolidated sandstones; includes Dierks and DeQueen Limestones; some gypsum and celestite beds; maximum thickness 600 feet.

Paleozoic

Pennsylvanian

Jackfork Sandstone -- thick, massive sandstone units separated by thinner and less extensive shale units; maximum thickness 6000 feet.

Mississippian

Stanley Shale -- gray-green weathering dark-gray shale with thick siltstone and sandstone members; locally tuff beds near base; maximum thickness 11,000 feet.

Devonian-Mississippian

Arkansas Novaculite

Upper Division -- tan to gray, massive, calcareous novaculite; locally quartzitic; maximum thickness 120 feet.

Middle Division -- thin-bedded, dark-colored novaculite and shale; miximum thickness 450 feet.

Lower Division -- white to gray, dense, thick-bedded novaculiite; maximum thickness 450 feet.

Devonian

Missouri Mountain Shale -- black, green, and red fissile shale; maximum thickness 300 feet.

Silurian

Blaylock Sandstone -- tan to gray, fine-to medium-grained, thin-to medium-bedded quartzitic sandstone; intercalculated gray to black graptolitic shale; maximum thickness 1500 feet.

Ordovician

Polk Creek Shale -- contorted and crumpled black, graptolitic shale; maximum thickness 300 feet.

Bigfork Chert -- gray to black medium-bedded chert; thin black, graptolitic shale partings; strongly crumpled; maximum thickness 800 feet.

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the rate of accumulation. The lower 100 feet of the Stanley, where the barite occurs, is primarily shale, but some lenses of dense gray sandstone are present, and they increase in number and thickness upward from the barite.

STRUCTURE

The rocks in the Ouachita Mountains are folded into a series of tight isoclinal folds which trend east-west. South of Fancy Hill the folds have broken along axial planes into a series of stacked thrust sheets which repeat the section several times. The sheet containing barite south of Fancy Hill appears to have torn into several pieces. Seismic work has shown that the barite on Fancy Hill forms a synclinal trough in the Back Valley to the south (Figure 4). At Chamberlain Creek, folding of the barite caused development of a noticeable cleavage which was observed during the mining operation (Eugene Cameron, 1986, personal commun.). The presence of the cleavage in the barite indicates that the barite was present prior

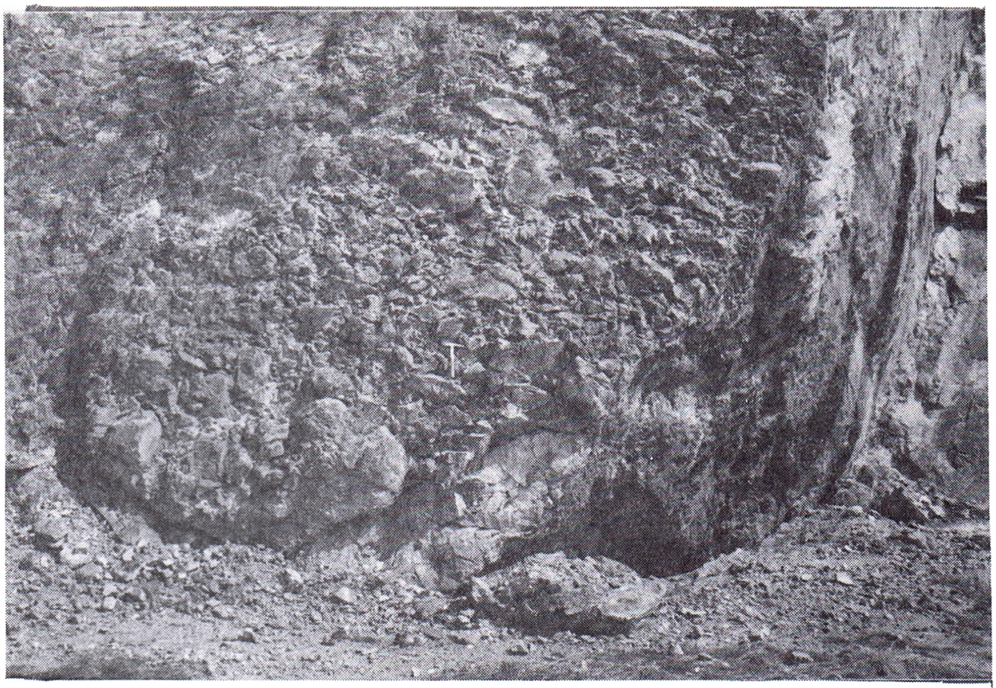

Figure 3. *Novaculite breccia at the top of the Upper Division of the Arkansas Novaculite at the Dempsey Cogburn mine. The face on the right is a cross fault showing novaculite below the breccia zone.*

to the folding rather than having been introduced later.

Just south of the Dempsey Cogburn mine the Blaylock is about 600 feet thick and only three miles north it is absent. The rapid thinning of the Blaylock indicates that a growth fault was probably present at the depositional site of these rocks during Silurian time. Another indication of a possible deep structure is the presence of hot springs at Caddo Gap, also two miles southwest of Caddo Gap, and 3 1/2 miles west of Fancy Hill. There are also two igneous dikes in the area, one at Pigeon Roost Mountain and one in Long Creek near the last hot spring mentioned.

The presence of the barite, hot springs, dikes, and the thinning Blaylock all seem to point strongly toward a growth fault, which was active during Silurian time and was sporadically reactivated, particularly at the end of Novaculite time. This reactivation caused the brecciation of the upper surface of the Novaculite and provided the conduit for hydrothermal fluids which precipitated sulfides in the form of pyrite, and later, barite. The growth fault also provided the relief necessary to form the chert pebble conglomerates and the Hot Springs Sandstone, which probably accumulated as lobes at the base of canyons cutting across the escarpment (Figure 5). Since this growth fault was a zone of weakness, it probably broke as a thrust fault during compression, and therefore cannot now be identified.

OREBODIES

The barite deposit at Fancy Hill follows a nearly straight line along the south side of Fancy Hill for over 9000 feet and dips to the south at 80 degrees. A series of northeast-trending cross faults of generally small displacement have offset the beds from one to ten feet. In a few places, much larger displacements can be seen.

The footwall of the deposit is primarily shale, 2 to 50 feet thick. On the east end, overlying the Arkansas novaculite, barite rests

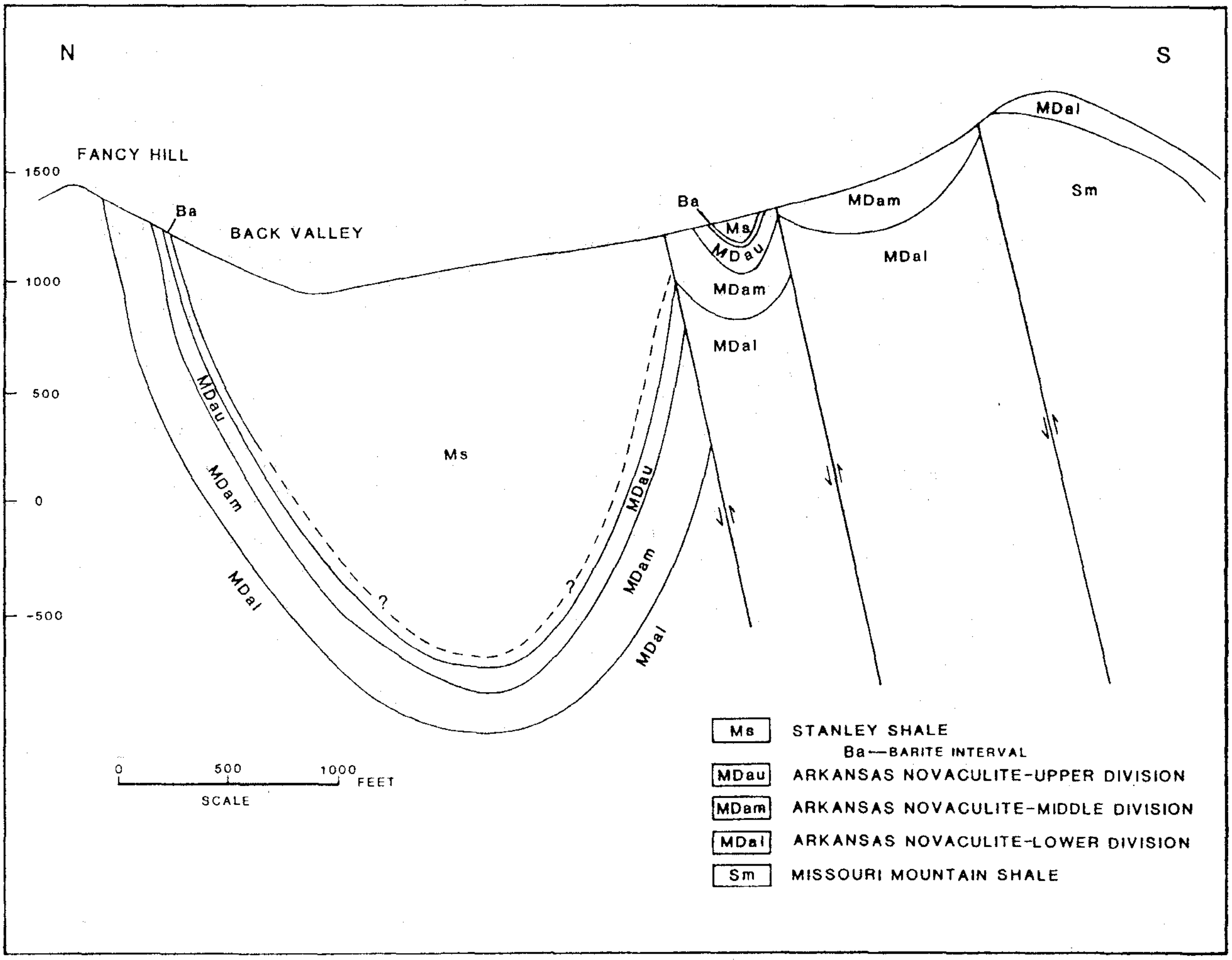

Figure 4. *Section across Back Valley showing the generalized geology of the area (modified from E. F. Lawrence).*

on sandstone. The shales in places are highly carbonaceous and pyritic. Above the barite, 10 to 40 feet of shale are overlain by gray sandstones.

The barite zone averages 20 feet in thickness, but varies from 0 to 40 feet. Three types of barite are common in the ore: (1) massive, finely crystalline gray to black ore of generally high grade (60-80% $BaSO_4$), (2) masses of coalesced nodules which form a solid layer of barite (40-50% $BaSO_4$), and (3) scattered nodules in shale (0-40% $BaSO_4$). Some fractures across the barite also contain crystals of barite up to two inches across.

Along strike the barite pinches and swells to form several distinct lenses of ore. Between the lenses, weak nodular zones can be seen in the shales. Down dip the continuity of the ore has been proven to a depth of at least 600 feet. On the western end the ore consists of two layers separated by interbedded shale and sandstone.

ORIGIN

Based on the structural and stratigraphic features of the barite deposits, it appears that they are very much like the barite deposits of the Selwyn Basin in the Yukon Territory of Canada. In both areas the barite occurs in a sequence of rocks which represent initially a very quiescent depositional environment followed by growth faulting and deposition of sulfides and barite. In the

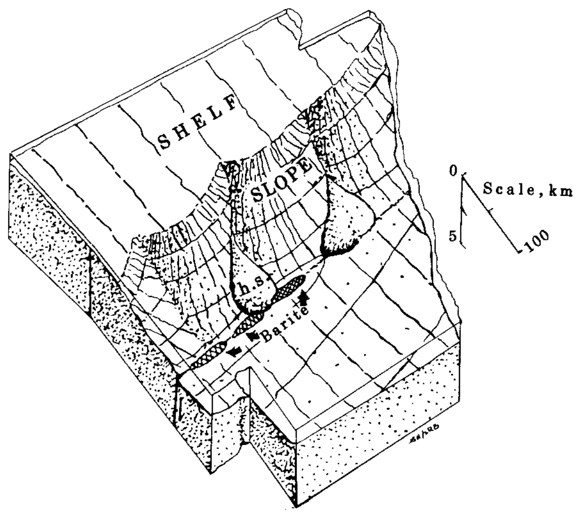

Figure 5. *Conceptual model showing the Hot Springs Sandstone Member (h.s.) and the growth fault along which hydrothermal fluids migrated to form pyrite and barite. Modified from Hanor and Baria (1977).*

Ouachita Mountains the growth faulting caused the brecciated upper surface of the Novaculite and provided the relief to form the chert pebble conglomerate and the Hot Springs Sandstone. It also provided a conduit for the hydrothermal fluids from which the barite precipitated. The barite probably formed in small local depressions in the seafloor that occasionally received influxes of mud and sand. The quality of the ore depended on the balance between barite and sediment influx; high-grade massive barite formed when sediment influx was near zero; as the rate of deposition increased, the quality would decrease and a more nodular ore would result; when shale completely overpowered the barite deposition, or barite influx decreased, then more sparsely nodular material was formed.

Since the Canadian occurrences are also associated with lead-zinc-silver deposits, there has been some interest in examining this area for metals. This basin appears to have some potential for further metal exploration based on the sedimentary exhalative model.

CEMENTED GRAVELS OF THE DIERKS AREA

Barite cements gravels and sands in the Trinity Group and occurs as replacements in the Dierks and DeQueen Limestones. The stratigraphy of the unit is presented in Figure 6. Barite occurs in a belt south of Dierks, Arkansas trending southwest (Figure 7). The barite occurs progressively higher in the section from northeast to southwest. At the Lucky 13 mine on the northeastern end of the trend, the barite cements gravels in the base of the Pike Gravel in the lowermost Trinity Group. The gravel in this area varies from a few inches thick on the eroded northern edge of the outcrop to about 100 feet down dip. At Lucky 13, the gravels are up to about 25 feet thick. This zone is overlain by about 40 feet of fine sand containing some clay and siltstone. Much of the sand contains abundant silt. Occasional clean sand lenses are cemented by barite, probably due to their greater porosity. The Dierks Limestone of the Trinity Group overlies this sand zone. It averages about 40 feet thick and consists of thin-bedded limestone with thin interbeds of green to gray clay. In a few areas immediately south of Dierks, small replacement bodies of barite from 1 to 3 inches thick are found in the limestone along with occasional cross-cutting veinlets of barite. Some of this ore runs over 54% $BaSO_4$. Above the Dierks Limestone is a sand horizon up to 300 feet thick, which is very similar to the horizon below the Dierks Limestone. The more porous clean sand zones have been cemented by barite or iron. The DeQueen Limestone overlies this sand zone and consists of equal or greater amounts of tough green clay and some gypsum and celestite (Miser and Purdue, 1929). Occasional barite replacements of the limestone are found in the base of this unit.

Barite can be found throughout the Trinity Group in the vicinity of Dierks, but the largest occurrences are in the Pike Gravel and the overlying zone. Barite is present along the strike for at least 25 miles and across strike in a band up to seven miles wide.

The gravel ore is a conglomerate with a cement of barite between the individual cobbles and pebbles in layers up to 5 feet thick separated by zones of weakly cemented gravel containing small amounts of barite. The lenses are discontinuous along strike and down dip so that they are isolated pods (McElwaine, unpub. report). In sandstones in the upper part of the Pike Gravel, Scull (1958) observed veins of

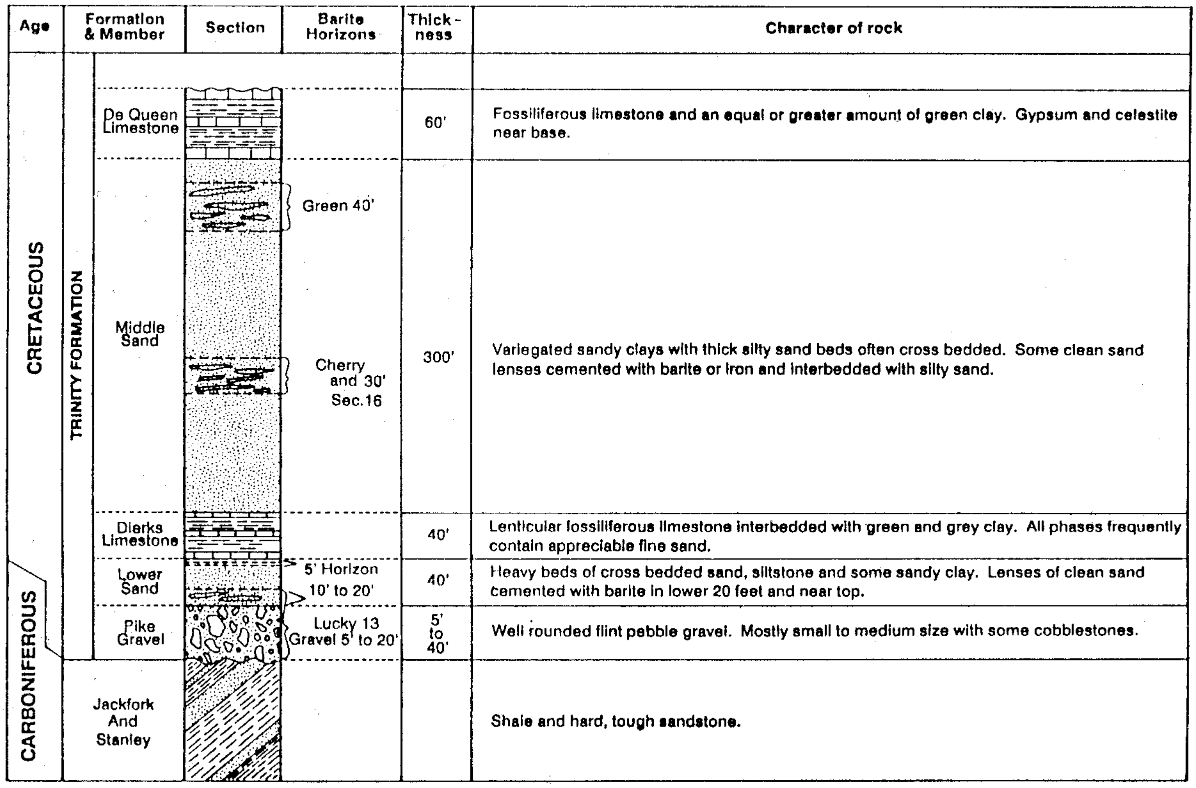

Figure 6. *Generalized columnar section of lower part of the Trinity in the vicinity of the Howard County barite deposits. From an unpublished report by R.B. McElwaine. Ranks of stratigraphic units used by McElwaine do not in all cases conform with those used in the present report.*

barite pinching out downward into the underlying gravels, indicating percolation of barium-rich fluids along the sands and downward into the gravels along fractures. Ore grade in the gravel runs as high as 50% $BaSO_4$, but more commonly it averages at most less than 12 percent. The average mill feed during mining was less than 10% $BaSO_4$.

The sand ores are similar to the gravel ores in that the barite fills pores in the cleaner sands and cements them into a sandstone. Maximum thickness of the overall cemented zones are 18+ feet at Lucky 13, 25 feet at the Cherry Deposit, 30 feet at the Northeast 16 and 8 feet at Northwest 16. These cemented zones are made up of cemented units 1 to 16 inches in thickness (Scull, 1958) separated by layers of uncemented or poorly cemented sand carrying small amounts of barite as scattered crystals. Some cross-cutting veinlets of barite can be found in the sandstone ore (McElwaine, unpub. report). The average grade of firmly cemented sands runs up to 42% $BaSO_4$, but average values run 10-25% (McElwaine, unpub. report).

Scull (1958) cites data to show that the barite probably originated from igneous sources. The diamond-bearing igneous intrusion at Murfreesboro contains veinlets of barite within the igneous mass, and this is less than 20 miles southeast from the barite belt in the Trinity Group. He also cites the work of Ross, Miser, and Stephenson (1929) which concluded that volcanic necks are present in the vicinity of Lockesburg and Nashville, 8 to 15 miles south of the Trinity barite. Cinnabar-bearing veins of hydrothermal origin containing small amounts of barite occur less than 6 miles east and nearly along the same strike as the Trinity occurrences.

It is likely that the barite-cemented gravels and sands represent a complex environment involving perhaps groundwater, seawater, and hydrothermal fluids mixing and

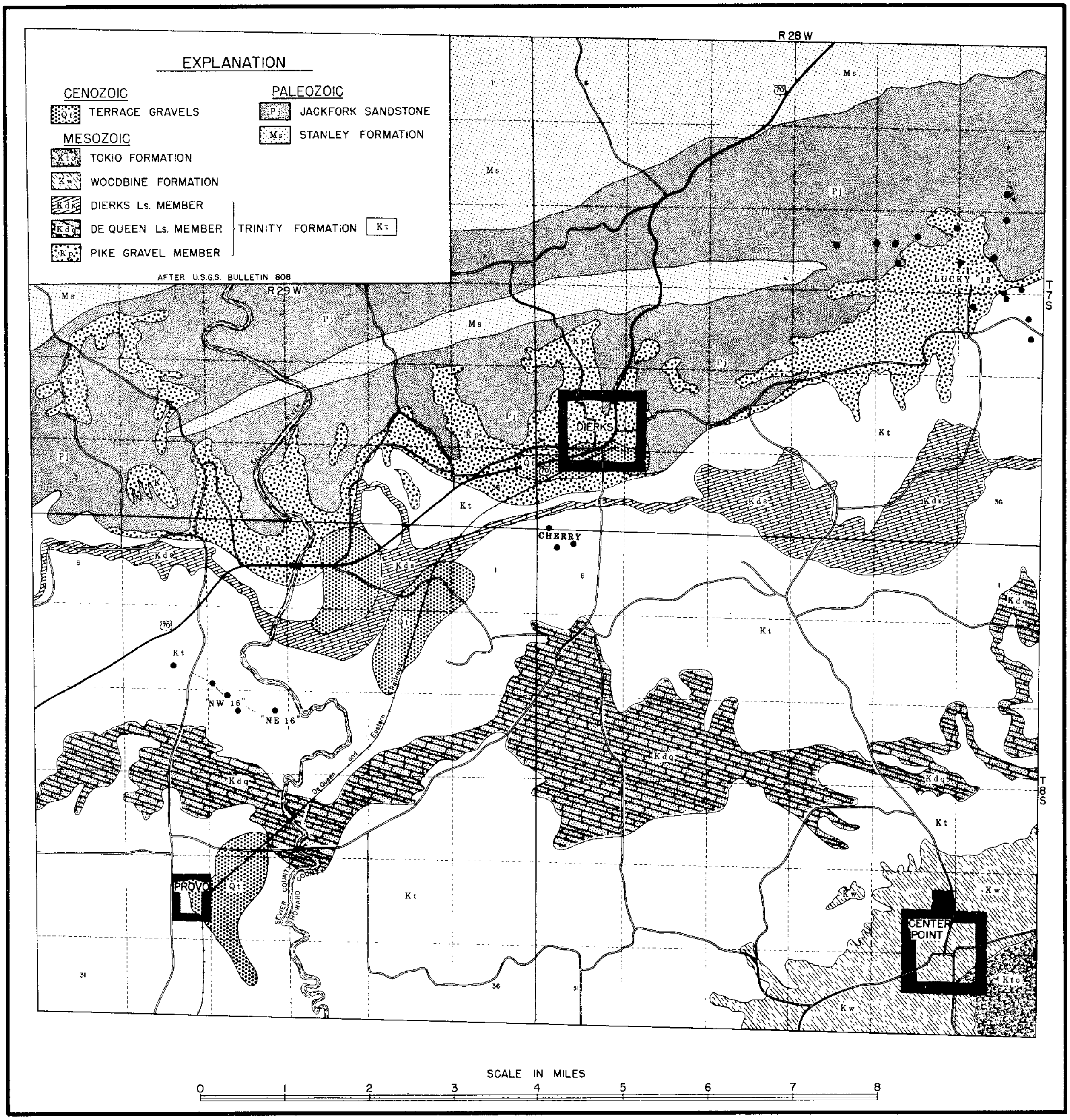

Figure 7. *Geologic map of the Dierks barite district, Arkansas. Known barite localities shown by solid circle. Modified from Scull (1958) and Clardy (1982).*

precipitating barite in the more porous zones where fluid flow could take place.

BARITE VEINS

Barite occurs as rare veinlets in the diamond-bearing igneous intrusive at Murfreesboro. The veinlets, up to 2 inches wide, consist of barite cut by later quartz (Miser and Purdue, 1929). Barite also occurs as a minor constituent in the veins of the western part of the cinnabar district and in numerous cross-cutting veins in various other rocks as noted by Clardy (1982). Neither of these types is considered of any economic importance because of the limited quantities of barite found in them.

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General geology and mineral resources of the Ouachita Mountains, Arkansas

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ABSTRACT

The Ouachita Mountains occupy an area about 250 miles long (east-west) and 75 miles wide (north-south) in west-central Arkansas and southeastern Oklahoma. This area is typified by jagged peaks, hogbacks, and rather broad hummocky basins. The bedrock is mostly sedimentary and composed of shale, sandstone, limestone, chert and novaculite, conglomerate, and tuff. The rocks are mostly of deep-water marine origin and have an aggregate thickness of 50,000± feet. They are all of Paleozoic age, ranging from Late Cambrian to Middle Pennsylvanian. The Ouachita Mountains were formed during late Paleozoic time when the rocks were uplifted by northerly directed compressive forces. The uplift produced prominent east-west folds and large thrust faults. Some rocks were subjected to very low-rank metamorphism and related hydrothermal events. Since the formation of the Ouachita Mountains, there has been minor arching and thousands of feet of rock have been eroded. Many scattered bodies of mid-Cretaceous igneous intrusive rocks are present along or near the eastern boundary.

Mineral resources currently being produced are vanadium, quartz crystals and milky quartz, turquoise, novaculite, tripoli, soapstone, slate, shale, crushed stone, sand and gravel, and spring water. Mineral resources that were previously mined include barite, lead, zinc, copper, mercury, iron, antimony, silver, manganese, titanium, clay, agricultural lime, and fuller's earth. Minerals known to exist, but with no history of production, are nickel, molybdenum, columbium, cobalt, phosphate, rare earths, thorium, and uranium. Limited oil and gas exploration has been conducted in the southern and northern portions of the belt. Large quantities of high-quality surface and ground water are also very important resources. The total estimated value of mineral resources produced in the Arkansas Ouachitas was approximately $21 million in 1975 and $40 million in 1979, but it has declined during the past few years. The Ouachita Mountains will for many years be an area of economic mineral activity and development.

PHYSIOGRAPHY

The principal physiographic subdivisions of the Ouachita Mountains in Arkansas are the Athens Piedmont Plateau; the Trap, Cossatot, Cross, Caddo, Crystal, Zigzag, Northern, and Fourche Mountains; and the Mazarn, Caddo, Ouachita and Saline basins (Fig. 1). The total relief is approximately 2,500 feet, ranging from about 200 feet above sea level locally along the fall line to over 2,700 feet near Mena.

GENERAL GEOLOGY

Essentially all rocks in the area are of sedimentary origin with the exception of numerous scattered mid-Cretaceous igneous bodies. Formations in the Ouachita Mountains of Arkansas range from Late Cambrian to Middle Pennsylvanian in age and exceed 50,000 feet in thickness. They were originally

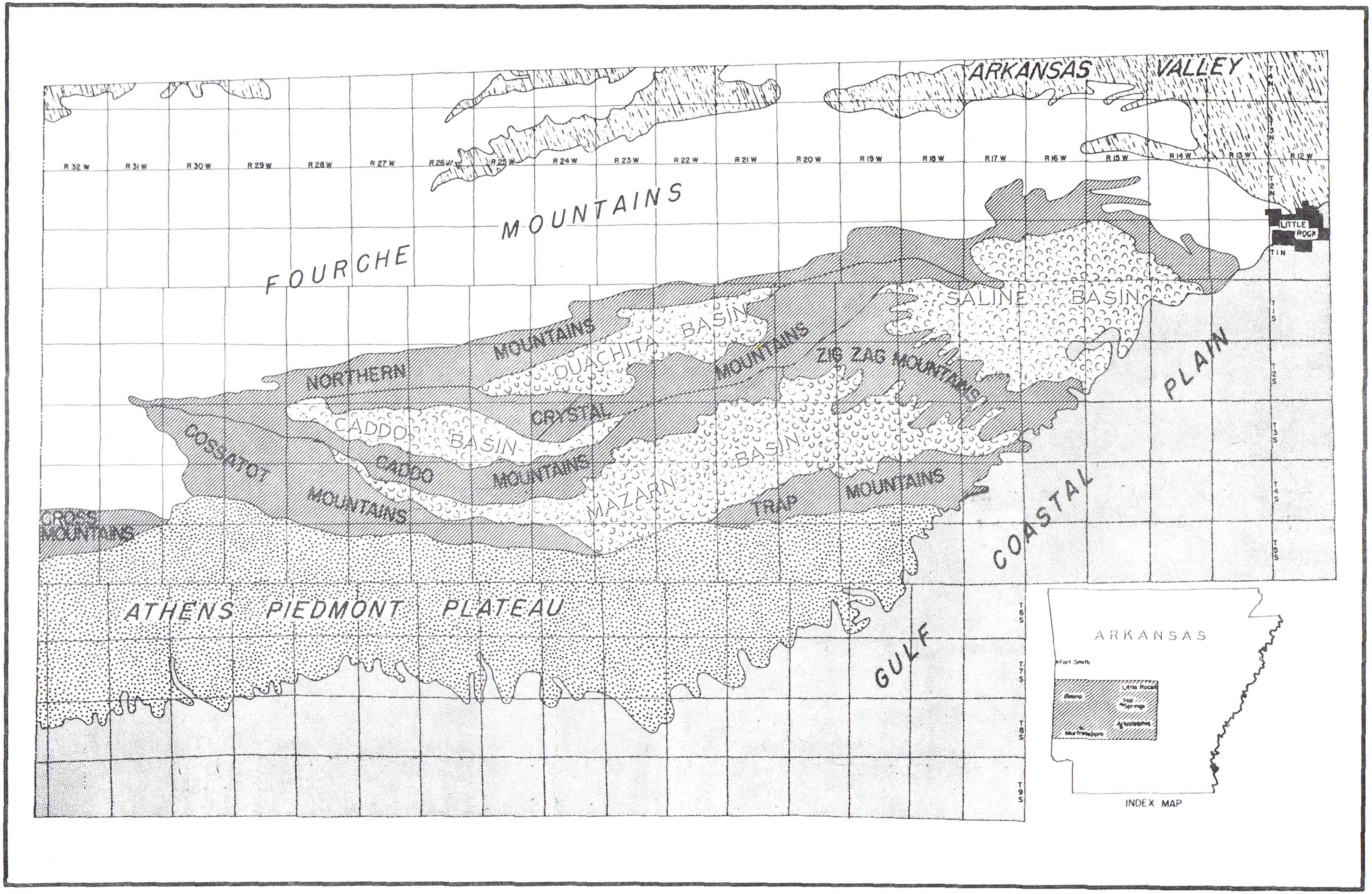

Figure 1. *Map showing major physiographic features in the Ouachita Mountain region of Arkansas. From Scull, 1958.*

deposited as nearly horizontal layers of mud, sand, gravel, marl, lime, volcanic ash, and silica in the marine waters of a deep basin that once occupied the region. With the load and weight of the overlying sediments they were subsequently converted to shale, sandstone, conglomerate, limestone, tuff, chert and novaculite. The rocks were then subjected to intense compressive forces in late Paleozoic time, which transported them towards the north and caused them to bend and fold and, in many places, to rupture and fault (Fig. 2). Ultimately the region was uplifted forming an extensive mountain range. This deformation, the Ouachita orogeny, caused intense pressures and elevated temperatures which slightly metamorphosed the rocks in places, changing some shale to slate and some sandstone to quartzite.

The compression produced prominent generally east-west folds and large thrust faults. The present land forms are essentially a reflection of the underlying bedrock. The softer less resistant shale, limestone, and impure sandstone are more susceptible to erosion and form most of the basins, valley floors, and lower hills. The harder more resistant novaculite, chert, and relatively pure sandstone form the mountains, ridges and peaks.

Subsequent to the Ouachita orogeny, the region has been eroded and dissected and minor arching and extensional faulting have occurred. Some sizable igneous intrusions, notably in mid- Cretaceous time, occur at Little Rock, Bauxite, Magnet Cove and Murfreesboro, and many smaller dike-like masses are present, largely in the eastern part of the Arkansas Ouachitas. In Cretaceous and early Tertiary time, shallow warm seas repeatedly lapped upon the southern and eastern portions of the Ouachita Mountains, leaving thin, gently dipping clay, sand, gravel, marl, chalk, and limestone deposits. Terrace, alluvial, and colluvial deposits are products of extensive Quaternary erosion and deposition.

FORMATION DESCRIPTIONS

Following, is a brief description of the 14 Paleozoic formations recognized in the Ouachita Mountains.

Cambrian and Ordovician Systems

Collier Shale -- Graphitic to "talcose" shale with interbedded, dense to very fine-grained, sandy, sometimes pellatoidal or conglomeratic, bluish-gray limestone. Minor amounts of bluish-black chert, gray calcareous siltstone, fine-grained quartzose sandstone, conglomerate and boulder-bearing breccia are present. At least 1,000 feet of the Collier is present at the surface, but its lower part is hidden in the subsurface. Conodonts and trilobites occur in some of the limestones.

Ordovician System

Crystal Mountain Sandstone -- Massive to thin-bedded quartzose, calcareous, light gray to brown, sometimes conglomeratic, medium-grained sandstones. Interbedded black or gray to buff shales are common in the upper part. Intervals of thin, dense, very fine-grained to sandy, bluish-gray limestone and calcareous gray conglomerate and some layers of breccia containing erratic boulders occur mostly in the lower parts. The formation is about 850 feet thick.

Mazarn Shale -- Black shale with interbedded olive-green shale and silty shale, thinly laminated gray siltstone, brown quartzose sandstone, and dense blue-gray limestone. Worm burrows and other trace fossils occur in the siltstones, and some conodonts and graptolites are found in the limestones and shales. The formation is about 2,500 feet thick.

Blakely Sandstone -- Interbedded thin to fairly massive, fine to medium-grained, sometimes silty or calcareous, quartzose brownish gray sandstones, sometimes conglomeratic and erratic-bearing. Some black to green shales are present. Locally a gray sandy limestone occurs in the upper part and a shale sequence ranging in thickness from 100 to 200 feet is present near the middle. Some of the shales contain graptolite impressions. The formation is about 450 feet thick.

Womble Shale -- Black shale with intervals of dense, bluish-gray limestone and calcareous siltstone with minor amounts of gray chert, fine-grained quartzose sandstone and conglomerate. Graptolite impressions are

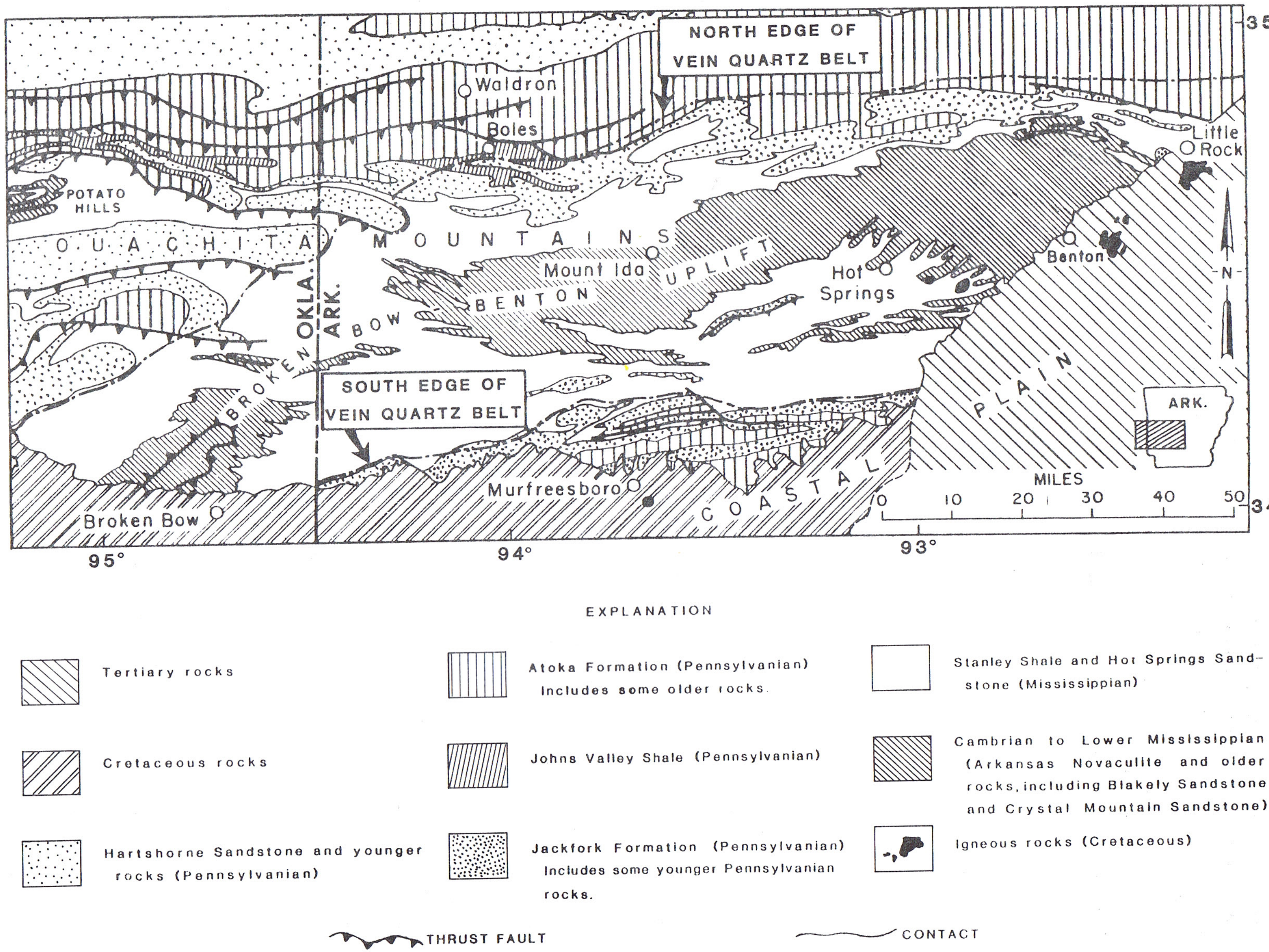

Figure 2. *Highly generalized geologic map of the Ouachita Mountains of Arkansas and nearby part of Oklahoma. Only a selected few of the many thrust faults are shown.*

STRATAGRAPHIC SECTION OF PALEOZOIC ROCKS EXPOSED IN THE OUACHITA MOUNTAINS

	Maximum Thickness
PENNSYLVANIAN SYSTEM	
Atokan Series	
Atoka Formation - shale and sandstone	27,500
Morrowan Series	
Johns Valley Shale - shale, minor sandstone and limestone, and erractic boulders	1,500
Jackfork Sandstone - sandstone and shale	6,000
MISSISSIPPIAN SYSTEM	
Stanley Shale - shale, sandstone, some chert and minor tuff	11,000
DEVONIAN AND MISSISSIPPIAN SYSTEMS	
Arkansas Novaculite - novaculite, shale, and conglomerate	900
SILURIAN SYSTEM	
Missouri Mountain Shale - shale with minor sandstone	200
Blaylock Sandstone - sandstone, siltstone, and shale	1,000
ORDOVICIAN SYSTEM	
Polk Creek Shale - shale	175
Bigfork Chert - chert, limestone, and shale	750
Womble Shale - shale with some thin limestone and sandstone	1,000
Blakely Sandstone - shale, sandstone, and erratic boulders	450
Mazarn Shale - shale with some sandstone and limestone	2,500
Crystal Mountain Sandstone - sandstone, shale, and erratic boulders	850
CAMBRIAN AND ORDOVICIAN SYSTEMS	
Collier Shale - shale and limestone (base incomplete)	$1,000^{+}$

common in the shale and conodonts occur in some limestones. The formation ranges in thickness from 500 feet to 1,000 feet.

Bigfork Chert -- Thin-bedded, highly fractured, gray chert, dense gray limestone, calcareous siltstone and some thin interbedded black shale. Graptolites occur in the shales and conodonts in the limestones. The formation ranges in thickness from 350 feet in the north to 750 feet in the south.

Polk Creek Shale -- Black sooty shale, with some very thin gray chert and a few thin blue-gray limestone intervals. Upper Ordovician graptolite fossils are very common. The thickness ranges from 110 feet to 175 feet.

Silurian System

Blaylock Sandstone -- Alternating thin brownish gray, very fine-grained, silty sandstone and gray shale layers. It is approximately 1,000 feet thick in the Cossatot Mountains and thins to the north to less than 20 feet and locally may be absent.

Missouri Mountain Shale -- Red, green or buff shale or slate with a few layers of novaculite and sandy conglomerate. It is about 50 feet thick in the south, reaches a maximum of 300 feet in the west-central part, and is between 60 and 200 feet in the east-central exposures.

Devonian and Mississippian Systems

Arkansas Novaculite -- White to light gray novaculite with lesser amounts of gray chert, olive-green to black shale, conglomerate and sandstone. It is about 850 to 900 feet thick in the central part, and 200 to 400 feet thick along the northern and northeastern part of the area. Three divisions are generally recognizable: Lower Division -- massive white novaculite, with minor shale and conglomerate; Middle Division -- dark chert and novaculite interbedded with olive-green to black shale and some conglomerate; Upper Division -- white, often tripolitic and calcareous thin-bedded novaculite. Conodonts are present in the shale and novaculite.

Mississippian System

Stanley Shale -- Black to brownish-green shale with lesser quantities of thin to massive, fine-grained, feldspathic gray to brown sandstone. Some thin black siliceous shales and cherts are present. Minor conglomerate and quartzose sandstone (Hot Spring Sandstone Member) and tuff beds (mostly the Hatton Tuff Member) are present in the lower part. Cone-in-cone and other mostly calcareous siltstone concretions typically occur throughout the formation. The maximum thickness is about 11,000 feet.

Pennsylvanian System

Jackfork Sandstone -- Thin to massive, light-brown, fine-grained, quartzitic gray sandstone, blue-black to brown siltstone, and interbedded gray-black shale. Some of the sandstones contain a few thin conglomeratic layers with pebbles consisting of rounded chert and metaquartzite. Many of the siltstones contain coalified plant fragments. The formation has a total thickness of about 6,000 feet.

Johns Valley Shale -- Gray-black clay shale and rather chaotic, silty, thin to massive brownish-gray sandstone. Platform facies erratics occur in the northeastern exposures of the formation. Goniatites are present in some of the concretions. The formation is about 1,500 feet thick.

Atoka Formation -- Shale, sandstone, siltstone and some coal. The lower Atoka is prominently exposed in the Fourche Mountains and in the Athens Plateau. It is composed of thin to rather massive, fine to medium-grained subgraywacke sandstones and interbedded gray-black shales. Locally a few conglomerates and calcareous sandstones contain a mold fauna of transported invertebrates. The Atoka Formation has a thickness of about 27,500 feet in the Fourche Mountains and an incomplete section of about 7,500 feet occurs in the Athens Plateau.

Igneous Rocks

Igneous rocks of mid-Cretaceous age occur at Magnet Cove, Bauxite, Little Rock and south of Murfreesboro (Fig. 2). They include nepheline syenite plutons, volcanic and explosion breccia pipes, a few diamond-bearing lamproite pipes, and numerous small alkalic and lamprophyric dikes and sills. Volcanic tuffs of Mississippian age occur in the lower Stanley Shale and were derived from volcanic sources to the south of the Ouachita trough.

Fragments of igneous and epizonal metamorphic rocks, some as large as boulders, are incorporated in the Collier, Crystal Mountain, Blakely and other formations. Mostly Precambrian in age, these were probably derived by slumping along the walls of submarine scarps flanking the north side of the Ouachita trough.

GENERAL STRUCTURE AND STRUCTURAL HISTORY

At the surface, the intensity of structural deformation is greatest in the central "core area" of the Ouachita Mountains. In the Mississippian Stanley Shale through the Late Cambrian-Early Ordovician Collier Shale they are very tight, often overturned to recumbent folds that are cut by abundant high-angle and near bedding-plane thrust faults. Many miles of displacement have occurred along the thrust faults bounding some major plates. Minor to well developed cleavage and shearing occur in the shales. Milky quartz veins often fill fractures in the rocks. Most of the strata have been affected by low-rank (chlorite grade) regional metamorphism.

In brief, the sequential phases in the structural development of the Ouachita Mountains apparently are as follows: (A) extensional faulting and minor intrusions of magma, (B) major uplift with folding and development of decollements; (C) thrust faulting; (D) folding with further decollement; (E) thrust faulting and related backfolding; (F) cross faulting and folding with arching; and (G) further arching. Step A probably took place during the early to middle Paleozoic, steps B-D during the Middle to Late Pennsylvanian, steps E-F during the Late Pennsylvanian through Permian and possibly into Triassic time, and step G from Triassic to Recent times.

In summary: (1) a northward(?)-dipping fossil Benioff zone was present to the south of the Ouachita Mountain outcrop, probably south of the Sabine uplift in northern Louisiana. (2) the Ouachita Mountains in Arkansas are allochthonous and formed by northward overriding, imbricately faulted thrust plates separated by major sole faults; (3) in the subsurface a few thrust plates possibly involved Precambrian rocks; and (4) the structural deformation probably narrowed the initial width of the Ouachita depositional basin by as much as 200 miles.

MINERAL RESOURCES

Introduction

Significant development of the mineral resources in the Ouachita Mountains of Arkansas started in the middle 1800's and has slowly expanded to the present. The following is a brief summary of the more important mineral resources in the Arkansas Ouachitas.

Metals

Antimony -- The antimony district of southwest Arkansas contains scattered abandoned mines and prospects in a belt 2.5 miles wide and 11 miles long, extending east-northeast across northern Sevier County (Fig. 3). The deposits occur wholly within the Stanley Shale (Late Mississippian), which consists here mostly of shale with minor sandstone. The rocks are tightly folded and steeply dipping and the fissure veins of the deposits tend to follow the bedding.

The orebodies occur as stibnite-bearing milky quartz veins. They are small, lenticular, and subject to pinching and swelling. Mineralization occurred in Permian-Triassic(?) time from hypogene solutions which rose along thrust faults and in subparallel fractures adjacent to fault blocks. Production of antimony ore from the district has been sporadic, generally coinciding with periods of exceptionally high metal prices. Although mining extended over the period 1873-1947, the total estimated production of antimony ore from the district is but 5,400 tons, valued at $230,000. At present, commercial mining of antimony is not feasible.

Columbium (Niobium) -- Columbium-bearing minerals were first reported in the Magnet Cove area, Hot Spring County, in 1890. In 1950, columbium was found associated with syenitic rocks at Potash Sulphur Springs (also known as Wilson Mineral Springs), Garland County. Investigations subsequently confirmed the presence of columbium and titanium minerals associated with syenitic rocks at Magnet Cove, near Bauxite in Saline County, and at Granite (Fourche) Mountain in Pulaski County. While none of the deposits has been mined, some samples contain from 0.1 to 0.9 percent columbium.

Rutile, brookite, perovskite, sphene, and their alteration products are the principal hosts of columbium at Magnet Cove. Columbium-bearing minerals are associated with radioactive rocks and other metallic minerals at the contact between syenite and sedimentary rocks at Potash Sulphur Springs. Reserves of columbium at Magnet Cove, are estimated at 6,000 tons. Reserves of columbium-bearing material at Potash Sulphur Springs are not known but may be significant. To date, the availability of foreign supplies has left the Arkansas deposits in a noncompetitive position.

Copper -- The occurrence of copper minerals in the Ouachita Mountains was briefly described in the earliest geological reports. Archeologists also note that some of the copper-bearing Indian artifacts have been traced to local sources. Sparse quantities of copper minerals commonly are associated with lead, zinc, silver, and antimony ores occupying fissure veins partially filled with quartz. The copper-bearing minerals include turquoise (see section on turquoise), malachite, azurite,

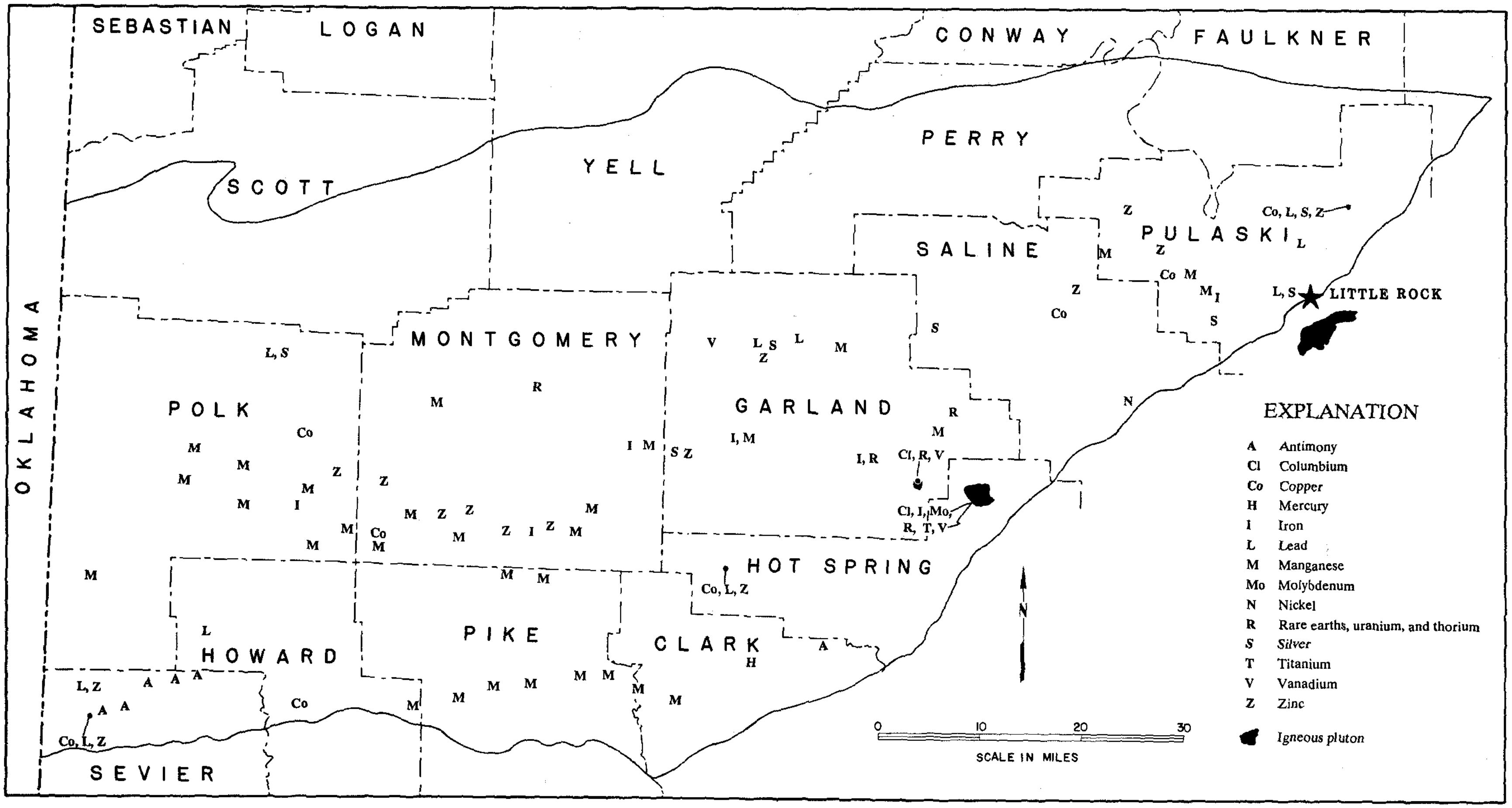

Figure 3. *Metallic mineral occurrences in the Ouachita Mountain region of Arkansas. The igneous complex immediately south of Little Rock, Pulaski County, is discussed in this report as part of the Ouachita Mountain region although, physiographically, it lies within the Mississippi Embayment.*

chrysocolla, chalcocite and native copper.

Some of the more notable mines include: Housely near Point Cedar (Hot Spring County), Kellogg in North Little Rock (Pulaski County), Bellah and Davis near Gillham (Sevier County), and Montezuma at Silver (Montgomery County).

Traces of copper are also reported with many of the manganese occurrences, most of which are in the Arkansas Novaculite. Some copper occurrences are also found in association with wavellite (aluminum phosphate) veins.

All known occurrences of copper minerals in the Ouachita Mountains are small and considered uneconomic, except possibly as a byproduct.

Iron ore -- Magnetite was reported in Arkansas as early as 1835 at Magnet Cove in Hot Spring County. It is associated with igneous rocks composed principally of nepheline syenite. The iron probably was deposited in the syenite in veins, pockets, and lenses, either as a segregation product of the original intrusive magma or as the result of hydrothermal action.

Magnetite from Magnet Cove had an early market for lodestone and later a limited use as iron ore and, reportedly, for heavy aggregate in concrete. Total output was perhaps about 3,400 tons.

Numerous prospects have been made in the small occurrences of limonite, goethite, hematite (iron oxides), and pyrite and marcasite (iron sulfides) present in pockets, seams, and veins in the Arkansas Novaculite and other formations. The two principal districts are located west of Little Rock, and straddling the Polk and Montgomery County boundary line. Iron oxides are also associated with many of the numerous manganese deposits in the novaculite, but they are usually low in iron and too high in silica and phosphorous to be of commercial value.

Other than a small tonnage of magnetite, there has been no reported production of iron ore in the Arkansas Ouachitas.

Manganese -- Deposits of manganese in the Ouachita Mountains have been worked sporadically since 1859. Federal purchases supported the last activity in 1958-59.

Both the Upper and Lower Divisions of the Arkansas Novaculite contain significant manganese deposits occurring as nodules, pockets, and short irregular veins, rarely up to ten feet in thickness. Most of the ore can be found in highly fractured rock at or near the axes of folds and adjacent to faults. Psilomelane, pyrolusite, and manganite make up the largest part of the ore, but lithiophorite, wad, and a few other minerals may be present. The ores may also contain small quantities of copper, nickel, cobalt, and lithium.

More than 100 prospects or mines are known. The largest manganese district includes portions of Polk, Montgomery, Pike, and Howard Counties and has been the principal area of manganese mining and milling in the region. Smaller quantities of manganese have been mined in the Arkansas Novaculite west of Little Rock and near Hot Springs, and in the Crystal Mountain Sandstone at a few sites in Montgomery and Garland Counties. Total production from the Ouachitas has been about 6,000 tons.

Manganese reserves cannot be accurately calculated, but the quantity of manganese ore in any deposit is small (maximum about 50,000 tons) and additional suppliers would be necessary to support milling operations. In times of dire need, the reserves could measurably augment the United States supply.

Molybdenum -- In 1939, molybdenite (molybdenum sulfide) was recognized in Magnet Cove, Hot Spring County, where it is associated with an undeveloped pyrite prospect. The molybdenite and pyrite are related to jacurpirangite (pyroxenite) intrusions. Neither mineral has been produced from the deposit.

Traces of molybdenite associated with

rutile and calcite deposits were found elsewhere at Magnet Cove. About 3 miles southeast of Benton, Saline County, traces of molybdenite in carbonate veins cutting pyroxenite were observed in cores from drill holes. Trenching and pitting in the northern part of Magnet Cove revealed feldspar-pyrite-molybdenite veins to 5 feet wide in a zone that cuts through jacupirangite for a distance of approximately 400 feet. The larger surface veins have an average of approximately 1.07 percent MOS_2.

The larger veins at Magnet Cove are relatively high-grade, but their extent and volume are suspect.

Nickel -- Nickel is present in interesting quantities in the talc-soapstone deposits of northeastern Saline County. The nickeliferous sulfides and oxides occur in soapstone-serpentine rock that forms six small discontinuous sill-like masses in a 4-mile long belt trending east-west. Nickel content ranges from a trace to 15 percent, but averages less than 1 percent. Nickel-bearing millerite has also been reported in quartz veins cutting the Womble Shale north of Benton in central Saline County.

It is reported that about 2,000 pounds of nickel-bearing sulfides containing 1.46 percent nickel and some cobalt were mined in 1887 at the Rabbit Foot mine north of Benton in central Saline County. There is little evidence of large quantities of sulfide ore at this locality.

Some nickel-rich sulfides may, in the future, be profitably extracted as by-products of other mining operations.

Rare-earth elements, thorium and uranium -- Until recently the rare earths were scientific curiosities, but new applications have made them commercially valuable. Rare-earth elements were found in association with uranium and thorium in metal-bearing, altered syenite at Potash Sulphur Springs, Garland County, and Magnet Cove, Hot Spring County. Exploration has not yet disclosed significant concentrations of rare earths. However, other associated metallic minerals, especially vanadium (which is being mined), but also columbium, and titanium are present. Up to 4.3 percent combined rare earths occur in rocks at Magnet Cove.

The radioactivity of vein deposits associated with nepheline syenite and related rocks at Magnet Cove is attributed to thorium in an unknown mineral. Thorium content of the igneous rocks ranges from 2.8 to 33.9 grams per ton. The highest concentrations are in nepheline-bearing pyroxenite (jacupirangite).

Thorium and uranium occur in exotic granitic boulders in the Blakely Sandstone in northeastern Saline County. A selected sample of the rock analyzed 1.5 percent thorium and 0.019 percent uranium.

Uraniferous rocks were first discovered in 1950 at Potash Sulphur Springs (Wilson Springs prospect), Garland County. This deposit is associated with nepheline syenite and hydrothermally altered country rock. Studies indicate that the uranium-bearing mineral is pyrochlore. Soil samples assayed up to 0.4 percent uranium. At the Runyan prospect at Magnet Cove, uranium minerals occur with small brookite-quartz veins cutting the Arkansas Novaculite. At the Chandler prospect in eastern Garland County, uranium occurs in a rare mineral (gorceixite) that forms veinlets in narrow fractures in chert. Small quantities of uranium (0.1 percent or greater uranium oxide) have been reported in the Paleozoic rocks elsewhere in the Ouachita Mountains region.

Rare earths, uranium, and thorium may eventually be found in small deposits of economic importance, or they might be produced as by-products from other mining operations.

Titanium -- The occurrence of titanium minerals in the Magnet Cove area, Hot Spring County, was first noted in 1890. Mining and milling operations began in 1930 and ceased in 1944.

Other possible sources of titanium minerals are associated with syenitic rocks at Potash Sulphur Springs (Garland County), in the vicinity of Bauxite (Saline County), and at Granite or Fourche Mountain (Pulaski County).

Conspicuous quantities of rutile are associated with feldspar-carbonate veins that cut aegirine phonolite porphyry at Magnet Cove. Rutile is of primary economic interest, but significant amounts of columbium and pyrite are also present. The deposit was mined to a depth of 30 feet.

Concentrations of brookite were investigated in several other areas in the Magnet Cove district. Brookite crystals are present in quartz veins and in vuggy and porous zones in recrystallized novaculite and in otherwise relatively barren layers of clay. Although the extent of the rutile deposits has not been fully delineated, inferred ore reserves are 8 million tons having a TiO_2 content of 4 to 8 percent.

Additional and improved metallurgical procedures are needed to enhance recovery of titania concentrates. If a greater demand for metal develops, perhaps present mineral dressing techniques would again produce salable ore. Titania may prove a valuable by-product from other mining operations.

Zinc, lead, and silver -- Zinc-lead-silver deposits are typically small and occur in telethermal quartz veins emplaced in fractured rocks ranging from the Collier Shale to the Jackfork Sandstone. At several localities in the central and southern Ouachita Mountains.

Lead was first mined in Sevier and Pulaski Counties about 1840. A few zinc and lead mines were operated through shafts west of Gillham, Sevier County, and sparingly elsewhere in the region by the Confederate States Government in the early 1860's. About 1,000 to 1,500 tons of ore were mined and smelted. From 1875 to the end of World War I, lead and zinc ores were mined and smelted intermittently in Sevier and Pulaski Counties. In 1901-02, ore production in Sevier County amounted to 1,140 tons.

The Kellogg mine in northeastern Pulaski County near the outskirts of North Little Rock was worked intermittently from about 1840 until 1930. The deposit was worked through a shaft to a depth of about 1,125 feet. Available records indicate an output of 70 short tons of lead-silver concentrates and 40 short tons of zinc concentrates. Production of 3,118 troy ounces of silver, valued at $2,164, was recorded in 1925.

Prior to World War I, a zinc-lead-copper deposit in western Hot Spring County near Point Cedar was developed by surface workings, and production reportedly consisted of 16 railroad cars of lead ore.

Significant quantities of silver-bearing galena, sphalerite, and other minerals have also been mined near Silver, Montgomery County. Small quantities of silver and traces of gold are associated with nepheline syenite rocks at the "V" intrusive adjoining Lake Catherine. Recently several companies have conducted stream sediment sampling and exploratory drilling programs on sites in the Ordovician strata in southwestern Montgomery County. These investigations were in search of zinc and other elements formed by sedimentary exhalative emanations on the seafloor during deposition of the rocks. Exploration may continue for these minerals if market values should increase.

Vanadium -- A significant occurrence of vanadium was found in Arkansas in 1950 at Potash Sulphur Springs (Wilson Springs) in Garland County. In 1962, Union Carbide Corporation began systematic exploration at Potash Sulphur Springs and Magnet Cove. Mining started at Potash Sulphur Springs in 1966, and mill construction was completed in 1967. Mining at the Christy deposit in Magnet Cove began in 1983. However mining operations have been virtually idle at both sites since 1985, although currently Stratcor is processing previously mined ores for vanadium oxides.

The deposits are closely associated with hydrothermally altered intrusions of syenite, and associated dike and sedimentary rocks at both sites. The mineral suites are complex, and some concentrations of titanium and columbium minerals occur in close association. Lesser quantities of tantalum, uranium, complex rare-earth oxides, and fluorine also are present.

The ores at Potash Sulphur Springs contain about one percent V_2O_5 as discrete clay-sized vanadium minerals. The Christy vanadium ore consists of geothite-rich clay and brookite and averages slightly less than 1% V_2O_5.

Vanadium production in the State is assured if the worldwide market remains stable.

Nonmetallic Minerals

Barite -- Barite ($BaSO_4$), a heavy nonmetallic mineral containing 65.7 percent BaO and used primarily as a weighting agent in drilling for oil and gas, occurs at several localities (Fig. 4) in the central Ouachita Mountains. Barite was first discovered in Arkansas in 1888 in Montgomery County and in 1900 in Hot Spring County just east of Magnet Cove. The barite occurs in beds, nodules, or rarely veins near the base of the Stanley Shale and, to a much lesser degree, in the Middle Division of the Arkansas Novaculite.

The largest deposit, Chamberlain Creek in Hot Spring County, is located near Magnet Cove. Production from the Chamberlain Creek deposit began in 1939 and from 1944 to 1966 the mine yielded sufficient barite that Arkansas led the nation in its production. From 1957 to 1982 there was small-scale mining of barite in Montgomery County. Barite was also mined west of Hopper in the Fancy Hill district, near Pigeon Roost Mountain northeast of Glenwood, and in the vicinity of Dierks. Most of the barite has been processed at flotation mills that utilized ore containing about 50% $BaSO_4$. The product was a concentrate of 92-94 percent $BaSO_4$.

In 1981-82, when the cost of extracting and processing the ore exceeded its value, mining operations were abandoned. Reserves of barite in the Ouachita Mountains are estimated at several million tons. Further barite mining ventures are dependent upon more favorable marketing conditions.

Clay and Shale -- Shale formations contain abundant and varied clay mineral suites, many of which are suitable for refractories, heavy clay products, pottery, and filtering and clarifying. Clay deposits of limited size also occur in some of the weathered shales, slates, or igneous rocks.

Clay has been produced near Mena in Polk County for making bricks. The Malvern Brick Company formerly mined gray-black shale from a deposit in the Stanley Shale in Hot Spring County for making red-colored brick and tile.

From 1901-1922 fuller's earth was mined from small weathered basaltic igneous dikes at a locality west of Benton in Saline County. Production was estimated at 20,000 short tons valued at about $200,000. While the fuller's earth is of high quality, the quantities are limited.

Carbonaceous black shale from the Middle Division of the Arkansas Novaculite is mined northeast of Morning Star, Garland County, by the Malvern Minerals Company. It is marketed under the name Ebony as an extender pigment and for other purposes.

Several of the Paleozoic formations (Atoka, Johns Valley, Jackfork, Stanley, Missouri Mountain, and Polk Creek) afford an inexhaustible quantity of shale suitable for the manufacture of mostly red building brick and tile. Some of the shale can be used for making stoneware and ovenware. To meet plasticity requirements for these uses, some mixing with other clays or shales is probably necessary.

Crushed Stone -- Vast reserves of rock aggregate and road material are available from the nepheline syenite, sandstone, novaculite, and chert deposits in the Ouachita Mountains. There are several operating quarries in each of these rock types.

Nepheline syenite is a quartz-free, crystalline igneous rock containing nepheline, feldspars, and ferromagnesium minerals. It is fine to coarse grained and resembles granite. In Arkansas, the rock may be bluish gray or light gray and, locally, may have pink, brown, or green tints. Although syenite has been quarried in both Hot Spring and Pulaski Counties, all production in the past decade has been from Pulaski County. The syenite from Hot Spring County was used primarily as monumental and building stone.

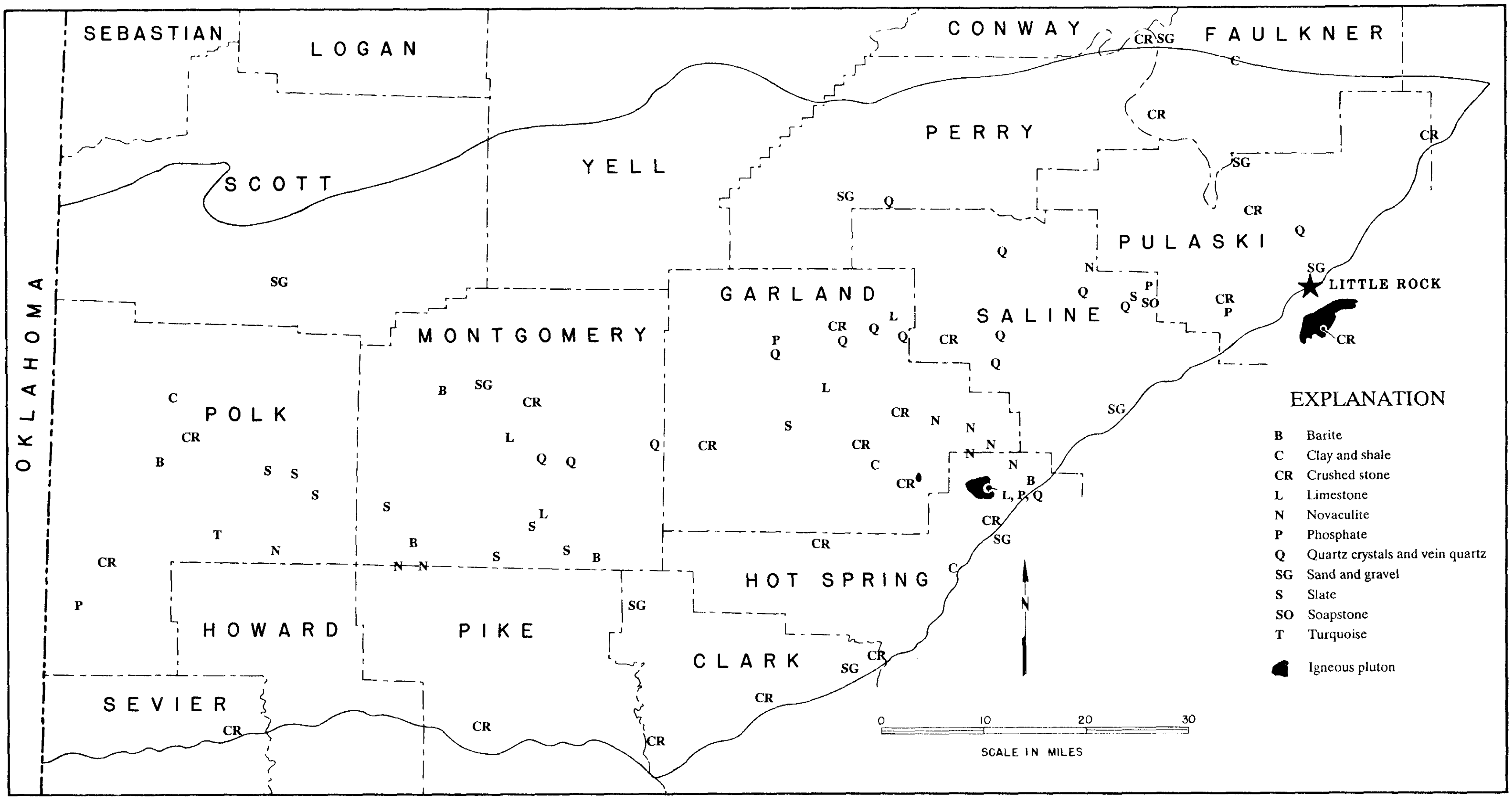

Figure 4. *Nonmetallic mineral occurrences in the Ouachita Mountain region of Arkansas. The igneous complex immediately south of Little Rock, Pulaski County, is discussed in this report as part of the Ouachita Mountain region although, physiographically, it lies within the Mississippi Embayment.*

Currently, syenite in Arkansas is used in the manufacture of roofing granules and for concrete aggregate, railroad ballast, roadstone, riprap, and jetty rock. Some of the rock may be suitable for use in the ceramic industry, or for the manufacture of abrasives, and refractory cement. Syenite also is a potential source of alumina. Additional research is needed to stimulate the development of new or extended applications

The Granite Mountain Quarries, Inc. operates two large quarries on the southern portions of Granite Mountain, Pulaski County, for a variety of aggregates. The Big Rock Stone and Material Company also operates a large quarry on the northwestern portion of Granite Mountain to produce roofing granules consumed by the Minnesota Mining and Manufacturing Company.

Relatively low-cost barge transportation on the Arkansas River has expanded the many markets for syenite. Minable reserves of nepheline syenite in the Pulaski County area exceed 100 million tons. There are several billion tons of additional undeveloped reserves at the various syenite exposures.

Sandstone is a widely used stone and is marketed in a number of forms. Crushed sandstone is consumed in road construction projects, as railroad ballast, and as concrete aggregate. Rough sandstone in large blocks is used as riprap and rubble for facing and as fill. Dimension sandstone is used as a residential and commercial buiding stone.

Large areas of sandstone and quartzitic sandstone are found in the Ouachita Mountains. Fairly thick sandstone sequences meeting commercial specifications occur in the Jackfork Sandstone, Hot Spring Sandstone, some intervals of the Stanley Shale, and less commonly in the Blakely and Crystal Mountain Sandstones and the Atoka Formations.

The major part of the sandstone output in the Ouachita Mountains is used in the construction industry. Sandstone for this market is quarried principally from the Jackfork Sandstone and Atoka Formation. Sandstone for dimension stone is obtained from the Jackfork Sandstone and Hot Springs Sandstone. Rough field stone has in recent years been increasingly in demand for agricultural purposes, and large quanities of this ornamental stone are obtained from talus deposits throughout most of the region.

Some of the larger producers of crushed sandstone are: Freshour Construction Company near Cabot in Lonoke and Pulaski Counties; M and M Rock Company west of Conway in Perry County; E. C. Rowlett Construction Company northwest of North Little Rock in Pulaski County; Little Rock Quarry Company, Inc. near Friendship in Clark County; the Pine Bluff Sand and Gravel Company north of Hollywood in Clark County; Souter Construction Company, north of Murfreesboro in Pike County; HMB Construction Company east of DeQueen in Sevier County.

Reserves of sandstone in the Ouachita Mountains are virtually inexhaustible. It is anticipated that the demand for sandstone will continue to expand.

Broken and crushed novaculite is used for fill, roadstone, railroad ballast, concrete aggregate, and some crushed novaculite is used in the manufacture of refractory bricks. As previously mentioned, a very modest tonnage of novaculite is used for whetstones and oilstones.

The Mid-State Construction and Materials Company is the main producer of crushed novaculite with quarries and plants west of Little Rock in Pulaski County, north of Malvern in Hot Spring County, and both east and south of Hot Springs in Garland County. The Herzog Contracting Corporation produces crushed novaculite from a quarry at Hatton in southern Polk County.

Intervals of thin-bedded chert are present in the Bigfork Chert. These have been quarried extensively for aggregate, for local uses. Shale is used locally for rock aggregate on rural roads and other purposes.

There are nearly inexhaustible supplies of all rock types suitable for crushed stone in the Ouachita Mountains of Arkansas.

Limestone -- Thin to rather thick beds and intervals of dense, grayish-blue limestone are found in most of the Ordovician rocks. Limestones are especially abundant in the Collier Shale, some portions of the Mazarn Shale, and in the upper Womble Shale. Limestone from the Collier was used locally for road material and agricultural purposes. There also has been some use of limestones near Black Springs, Montgomery County, and elsewhere for agricultural limestone, lime, and as a decorative marble building stone. Analysis indicates that the limestone contains 75 to 90 percent $CaCO_3$. Limestone also occurs in the carbonatite masses at Magnet Cove where it was previously mined for agricultural uses.

Limestone is not being produced at this time. Further exploration will be necessary to evaluate the apparently significant reserves.

Novaculite and tripoli -- As its name implies, the Arkansas Novaculite is composed principally of a highly siliceous rock known as novaculite. Typically novaculite is white or light colored, transluscent or thin edges, has a dull or waxy luster, a conchoidal fracture, and is composed almost entirely of cryptocrystalline quartz. Some beds in the lower and upper divisions of the formation have a silica content of more than 99 percent.

Novaculite is presently quarried at several places and is used extensively as highway aggregate, railroad ballast, and for making high silica refractory materials. However, it is best known for its widespread use as whetstones and oilstones, its unique properties making it highly valued for sharpening surgical instruments, knives, and fine tools.

The earliest record of production for whetstones goes back to 1885 and it is still quarried as an abrasive material, mostly in Garland and Hot Spring Counties. In spite of competition from artificial abrasives, the demand for natural stone has increased in recent years. In addition to the uses listed above, there is also a potential for future use of high-grade novaculite in ferro-silicon materials, for fire brick, and in compound interlayered materials combined with plastics.

Tripoli is a finely granular, porous, cryptocrystalline silica. It is used principally for an abrasive polishing agent and as a filler or additive. The high silica tripoli occurs in the Upper Division of the Arkansas Novaculite.

Several thousand tons of the rock are mined yearly in southeastern Garland County by the Malvern Minerals Company using open-pit methods. The tripoli is ground, dried, and air separated into sized products in the company's plant at Hot Springs.

Phosphate -- Phosphates occur in minor quantities in a number of sedimentary rocks and also in some igneous rocks. Ordovician conglomerates in northern Garland County contain from 5 to 18% P_2O_5 and from 1 to 5% P_2O_5 in Pulaski County west of Little Rock. Widely separated thin layers, lenses, and nodules of black phosphate-rich rock occur at several places in the basal Stanley Shale.

Phosphate also occurs, primarily in the mineral apatite, in the carbonatites, calcite-pyrite and related veins, and in weathered saprolite products at Magnet Cove and probably also at Potash Sulphur Springs. The phosphate content ranges from less than 20 to more than 40 percent. Wavellite and variscite occur at numerous places mostly in the Ordovician Bigfork Chert. Some other rather uncommon phosphate minerals (rockbridgeite, dufrenite, strengite, cacoxenite, etc.) occur in association with manganese deposits in Montgomery and Polk Counties.

None of the above occurrences are considered to be of commercial quantity or grade, but the associated values of rare earths, uranium, thorium, vanadium, and other elements at some sites make them of economic interest.

Quartz -- Crystal quartz and vein quartz are abundant in the Ouachita Mountains of Arkansas and their exploitation, especially that of the former, has played a significant role in the economy of the State. Rather than repeat material presented elsewhere in this volume, the reader is referred to the paper by Howard and Stone (p. 63-71), where quartz is discussed in considerable detail.

Sand and Gravel -- Sand and gravel are widely distributed throughout the Ouachita Mountains. The beds and terraces of the Arkansas, Fourche LaFave, Ouachita, Saline, Cossatot, and other rivers are the main sites for the commercial sand and gravel operations. Local supplies are also obtained from talus slopes, and smaller streams.

The principal uses of Arkansas sand and gravel are as aggregate in concrete, as road surfacing material, in railroad ballast, and in bridge, dam, and other construction. Selected pebbles from some novaculite gravel deposits are suitable for use as a grinding agent in pebble mills. Sands from a few locations are suitable for special application such as molding, glass, abrasive, and filter sands. Ground silica sand is widely used as a filler in paint, asphalt, tile, plastic, rubber, and ceramics.

Mining operations vary from a simple roadside pit to very large quarries and large plants where thousands of yards of sand and gravel are excavated, washed, and sized each day. Sand and gravel are also obtained from river beds by dredging. Washing and sizing plants are necessary since much of the material is used in concrete aggregate. This aggregate must be clean, and stringent size specifications must be met. In a few instances, railroad spur lines connect the plant facilities to main tranportation routes.

There are immense quantities of sand and gravel in the Ouachita Mountains. Not all deposits will meet specifications in certain construction projects; however, the amount of material suitable for most construction use is on the order of many millions of tons.

Slate -- Slate is a metamorphosed shale with well-developed cleavage. Common colors are black, gray, red, or green. It is used chiefly for roofing granules and as filler in asphalt compounds, paint, roofing mastic, and in the manufacture of linoleum. Other uses include rough and cut blocks of slate for roofing, flooring, patio flagging, and for table tops.

The highest quality slate occurs in portions of Polk, Montgomery, Garland, Pulaski, and Saline Counties, where it can be obtained from the Stanley Shale, Missouri Mountain Shale, Polk Creek Shale, and the Womble Shale. The slaty units are 50 to 300 feet thick. There are wide variations in cleavage, texture, and hardness, and in the frequency or spacing of joints. Slates from the Stanley apparently have the best physical qualities for most purposes.

Slate in the Missouri Mountain shale was formerly produced in Polk County for electric switchboards and for roofing granules. Slates in the Polk Creek Shale were also used at one time. Slates in the Womble Shale are being mined to some extent today. Most of the recent production however, has come from the Stanley Shale in southern Montgomery County. Presently slate is being quarried from roofing granules by the Genstar Roofing Products Company from a large pit in the Stanley north of Glenwood in Montgomery County. Slaty shale from the Womble Shale to be used as a filler or additive is mined by open-pit methods by The Milwhite Company, in northern Saline County.

Slate reserves in Arkansas are enormous. Markets for slate products are limited by competition from substitute materials and by other factors.

Soapstone -- The soapstone of Arkansas, is an impure variety of talc, commonly containing 50 to 80 percent talc mixed in varying proportions with chlorite, serpentine, pyrite, quartz, calcite, magnesite and other minerals. It is associated with tabular deposits of altered serpentine rock. The serpentine occurs as lenses or masses in shale and chert units. Zones of magnesite, soapstone, talc, milky quartz veins, chlorite, and talcose shale or metamorphosed chert are arranged concentrically around the serpentine.

The Milwhite Company, Inc., of Houston, Texas, operates two small talc (soapstone) mines along a narrow 4-mile long belt in northeastern Saline County. At the mill in Bryant, the soapstone is crushed, dried, ground as fine as 325 or 650 mesh, passed through a cyclone separator, and bagged. The product is used principally as an inert filler in rubber and in roofing products, and as a carrier for insecticides.

The six known deposits are estimated to contain more than 500,000 tons of soapstone. Some 150,000 short tons of soapstone have been processed since operations began in 1953. The supply of soapstone in Arkansas is apparently sufficient to maintain the current rate of mining for many more years.

Turquoise -- Turquoise mineralization occurs in fractures in the Arkansas Novaculite and consists of iron oxides (goethite and limonite), quartz, turquoise, and a small amount of manganese. Soft to hard gem-quality turquoise and clay minerals occur in fractures and pockets 4 to 5 inches thick. Gem-quality material is rather scarce.

The mineral has been mined since 1974 on Porter Mountain east of Vandervoort in southern Polk County. A few tons of soft to some top grade gem quality bluish-green turquoise have been mined, cleaned, treated, and polished from this locality. It has been marketed primarily at Santa Fe, New Mexico under the trade name of "Mona Lisa".

Reserves are not known.

Oil, Gas, and Asphalt

Exploratory drilling in the western Ouachita Mountains of Oklahoma has resulted in the discovery of a few new oil and gas fields. The hydrocarbons occur mostly in highly fractured reservoirs in cherts and novaculites of the Bigfork Chert, Arkansas Novaculite, or in sub-thrust sequences containing Arbuckle or other foreland facies. These fields and scattered occurrences of asphaltite in Arkansas have kindled interest in the Arkansas portion of the Ouachita Mountains.

Some of the surface rocks in the central core of the Ouachita Mountain are slightly metamorphosed, but the degree of metamorphism decreases both to the north and south. The rocks and their thermal histories are mostly unknown at depth. However, a COCORP deep seismic reflection profile across the Ouachitas in western Arkansas has afforded new insights into the deep structure and in the oil and gas potential, and may lead to further exploration.

Asphaltites are reported in rather large occurrences in the Jackfork Sandstone and other formations at a number of sites in the frontal and central Ouachita Mountains of Oklahoma. Until recently only a single occurrence was known in Arkansas, -- near Eagle Gap north of Mena. Recently numerous veinlets of asphaltite have been noted in the upper Womble Shale and Bigfork Chert of Ordovician age and other formations in Montgomery County and elsewhere.

Some asphalt is present in the Jackfork Sandstone and the overlying Lower Cretaceous rocks near Murfreesboro in Pike County, and Dierks, Sevier County.

Water Resources

Water for domestic and nonirrigation farm use usually can be obtained from wells in the Ouachita Mountains. Locally, ground-water supplies as large as 50,000 gpd (gallons per day) can be developed. Treatment for the removal of iron, calcium, and magnesium hardness may be required.

Numerous high quality cold water springs are present in the Ouachita Mountains. The quality of the water of most cold springs is considered to be good to excellent. A few springs contain dissolved mineral constituents and are classified as mineral waters. The hot springs of Hot Springs National Park are among the major flowing springs in the Ouachita Mountains and are of excellent quality.

Streams are the best potential sources of water for municipal growth and economic development in the area. Although most streams occasionally have very little or no flow during part of the year, they can provide 50,000 gpd or more if adequate storage facilities are constructed. The stream water is of excellent quality and is suitable for nearly all uses.

Ground Water -- Most ground water in the Ouachita Mountains occurs principally in secondary openings such as joints, fractures, and bedding-plane separations and limited supplies are available at most places. The Bigfork Chert of Ordovician age, which is brittle and highly fractured, is the most reliable aquifer.

Most wells are less than 100 feet deep, but some larger yield wells range from 100 to 627 feet in depth. The static water level generally is less than 20 feet below land surface, but some flowing artesian wells have been reported. Seasonal water-level fluctuations in the wells generally are less than 10 feet. Wells that yield more than 10 gpm continuously for a week are not common.

In general, ground-water supplies are not adequate for large municipalities nor for industries dependent upon large quantities of water.

Cold Springs -- Cold springs are very numerous in the Ouachita Mountains, especially in the central mountainous areas. Most are rather small in volume. The quality of the water from most springs is considered to be good to excellent and is suitable for all uses. A few, however, contain dissolved mineral constituents such as H_2S, Na_2SO_4, $MgSO_4$, NaCl, and iron compounds are classified as mineral water springs. The formations which contain the largest quantities of spring water are the Crystal Mountain Sandstone, the Bigfork Chert and the Arkansas Novaculite. Of these the Bigfork Chert contains the greatest number of springs with the largest volumes because of its uniformly shattered condition, its considerable thickness, and its comparatively large area of outcrop.

The daily flow from individual springs varies from a trickle to many thousands of gallons. Springs provide water for some household needs and locally some springs provide large supplies of bottled water that is marketed under various names. Several springs have been utilized, mostly in earlier years, for medical purposes.

Warm and hot springs -- The hot springs of Hot Springs National Park, Arkansas, issue from the Hot Springs Sandstone Member of the Stanley Shale (Mississippian) at the crest of a plunging overturned anticline, along the southern margin of the Ouachita anticlinorium. The combined flow of the 47 hot springs ranges form 750,000 to 950,000 gallons per day (.033 to .042 cubic meters per second). The temperature of the combined hot-springs water is about 143°F (62°C). Tritium and carbon -14 analyses of the water indicate that most of it is about 4,400 years old.

The average composition (adapted from Bedinger, et al., 1979) of 9 samples of Hot Springs waters is as follows.

Constituent	Parts per million
Aluminum (Al)	0
Bicarbonate (HCO_3)	162
Calcium (Ca)	45
Chlorine (Cl)	1.9
Fluoride (F)	.2
Iron, total (Fe)	.05
Magnesium (Mg)	4.7
Manganese (Mn)	.17
Nitrate (NO_3)	0
Potassium (K)	1.5
Silica (SiO_2)	42
Sodium (Na)	4.0
Strontium (S_2)	.11
Sulphate (SO_4)	8.3
Zinc (Zn)	.05
Total dissolved solids	191

(Adapted from Bedinger, et al., 1979)

Bedinger, et al., (1979) also state that radium and radon gas are present in the hot spring waters. The radium concentration is 2.1 picocuries (10^{-12} curies) per liter and radon ranges from 0.14 to 30.5 nanocuries (10^{-9} curies) per liter.

There are also several warm springs in the west central Ouachita Mountains of Arkansas.

Surface Water -- The streams of the Ouachita Mountains are the best source of water for municipal growth and economic development, and are utilized by nine of the ten largest communities in the mountains. The mountain area receives between 50 and 55 inches of precipitation in the normal year, and

16 to 24 inches of this total enters the streams as surface runoff. Several reservoirs have been constructed for water supply, conservation, flood control, recreation, power production, or for various combinations of these purposes. Analyses indicate that water in the streams generally is of excellent quality and chemically is suitable for nearly all uses. The concentrations of most mineral constituents in the surface waters are low, even during periods of little streamflow.

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The marbles of Nepal: A preliminary report on the Godavari marble deposit, southwestern Kathmandu Valley, Nepal

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ABSTRACT

A relatively short distance from the city of Kathmandu, Nepal, there is a large outcrop of marble that has seen some limited development. The authors believe that this deposit has the potential to become an important source of revenue for a developing country by creating a new and economically viable industry. The purpose of this paper is to present the data on this deposit so that workers in the western world can be more familiar with its potential.

Some limited studies have been done on this deposit by other workers. The authors will present a review of these data, plus a generalized review of the regional geology of Nepal, and more specifically, the western edge of the Kathmandu Valley. An economic analysis of the quality of the marble will also be included, as well as an appraisal of further studies needed to completely evaluate the potential of this deposit.

INTRODUCTION

The topic of this presentation is more a discussion of the potential of an area than it is a detailed geological study. Only a limited number of geological analyses on the Godavari marble have been done, and these studies have concentrated more on theoretical geological studies than they have on the economical and developmental problems associated with the development of a deposit of this type. The authors have begun a preliminary evaluation of these deposits from an independent explorationist's perspective with an ultimate goal of answering questions on the economic feasibility of developing the Godavari deposit.

The Kingdom of Nepal is located between India and the People's Republic of China (Figure 1). Greater than 90 percent of the country is within the thrust ranges of the Himalayas; this makes the geological evaluation of the mineral potential of Nepal more difficult. Because of this difficulty, Nepal has been considered to be resource poor, and has consequently been grouped with those countries known as "Third World" or "developing nations". The authors are not convinced that this classification is accurate, as no detailed study, particularly from theindependent's perspective, has been done. The senior author of this paper has spent some time evaluating the Godavari deposit in the field. On the basis of this analysis, the authors suggest that the potential exists for a large commercial deposit to be present in the Kathmandu Valley region.

Definition of Terms

The term "marble" has come to represent many types of building stone and ornamental materials: these include both naturally formed and chemically altered varieties. In this paper, the authors define marble as a carbonate rock which has been altered by regional metamorphic processes (i.e., recrystallization resulting from the increase in temperature and pressure associated with mountain building tectonics). The metamorphic activity causes a alteration of all internal structures and often causes the coarsening of texture and a change in coloration from the

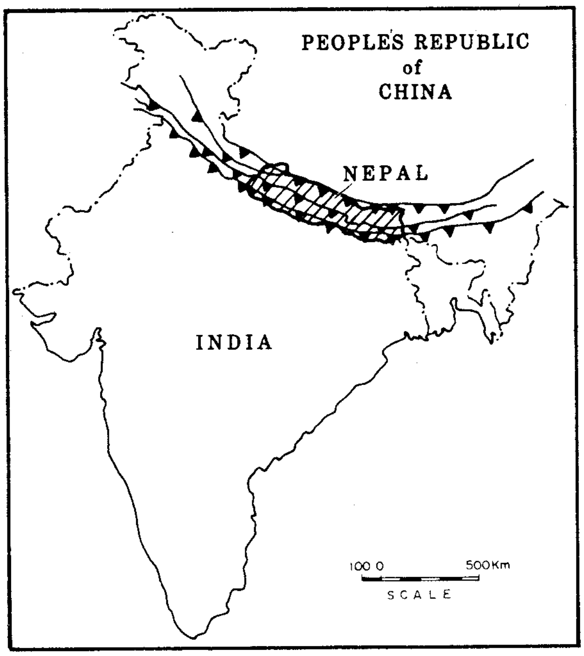

Figure 1. *Location map, Kingdom of Nepal (cross hatched)*

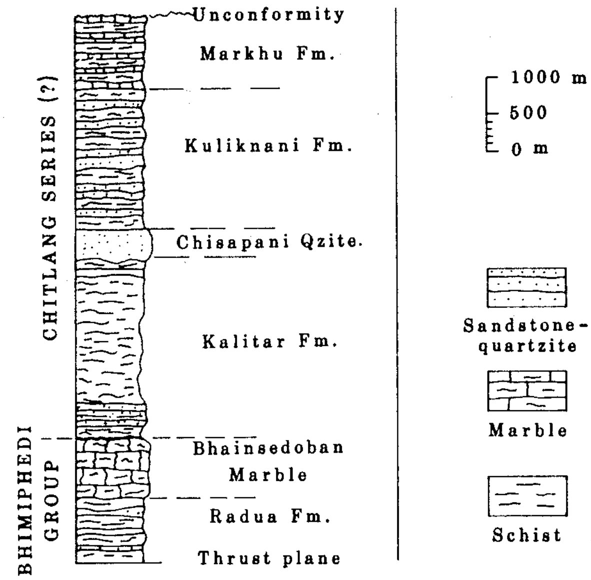

Figure 2. *Stratigraphic sequence of the Precambrian/Eocambrian Series, Kathmandu Valley, Nepal*

original rock. Marbles range in color from black to white with many shades in between. The variation in color is associated with one or more impurities in the carbonate depositional system or by flushing of metamorphic waters during metamorphism.

Technically, marble can be categorized in the following grades:

A. Statuary grade -- pure white,heterogeneous
B. Architectural grade -- uniform coloration
C. Ornamental grade -- variegated coloration

As a generalization, coloration and coarseness of grain are the main factors determining the quality of a marble. Of secondary importance are the types and number of fractures and joints in the in situ deposit. This factor is of the most importance in determining the quarrying potential and the sizing ability of the raw marble.

GEOLOGY

The Godavari marble deposit is located to the southwest of the Kathmandu Valley, one of several intermontane valleys of Quaternary age found in the country of Nepal. There are two deposits in the area which are currently referred to as "marble". The first, and of greater interest to the authors, is a marble which was originally a limestone member of a Precambrian/Eocambrian sedimentary sequence (Figure 2). The sequence was subsequently metamorphosed during the compressional tectonic activity which formed the Himalayas during Tertiary times, and was then exposed during post-compressional tectonic activity. A second source of "marble" in the area is a limestone bed of possible Ordovician age; this deposit has been test quarried with good results.

Current geological thinking suggests that the metasedimentary sequence which hosts the marble is of Precambrian or Eocambrian age. The sequence, now identified as the Bhimiphedi Group, includes several low- to medium-grade metamorphic sequences (i.e. schists, etc.) along with the prominent Bhainsedoban marble (Figure 3). The sequence is the lower member of a large thrust wedge (Figure 4) identified as the Kathmandu Nappe, and is mapped on the surface as a syncline known as the Mahabharat synclinorium (Figure 5).

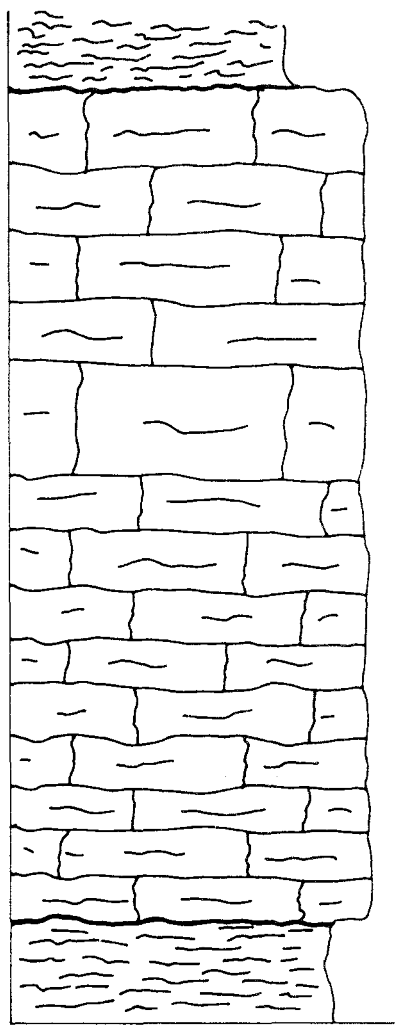

Figure 3. *Section of the Bhainsedoban Marble, (about 1,500m thick), Bhimiphedi Group, Kathmandu Valley, Nepal*

The middle member of the Kathmandu Nappe thrust is the Chitlang Series; this name is questionable in light of the current stratigraphic nomenclature used. The Chitlang is a unit in which the phyllites are interbedded with quartzose sandstones and minor amounts of white limestone. The Chitlang lies unconformably between the Bhimiphedi and the overlying Chandragiri-Godavari series. Very few additional data are available on this sequence.

A second source of marble in the area, and one which has been developed, is found in the Chandragiri-Godavari Series of Paleozoic age (Figure 6). This series is the upper member of the Kathmandu Nappe thrust wedge, and apparently has a restricted distribution in the area of the Phulchauki-Chandragiri range. The Chandragiri-Godavari series consists of interbedded siltstones and shales, quartzose sandstones, and limestones ("marbles"). Paleontological evidence suggests that the limestones are of Ordovician age. They occupy the upper beds of the series and are generally easily accessible.

ECONOMIC ANALYSIS

The Nepalese government has developed a test facility for the extraction and processing of its marble resource. Funding for this prospect was obtained from World Bank sources. Three separate quarries supply the processing plant with approximately 200 cubic feet of block marble and 1,000 cubic feet of

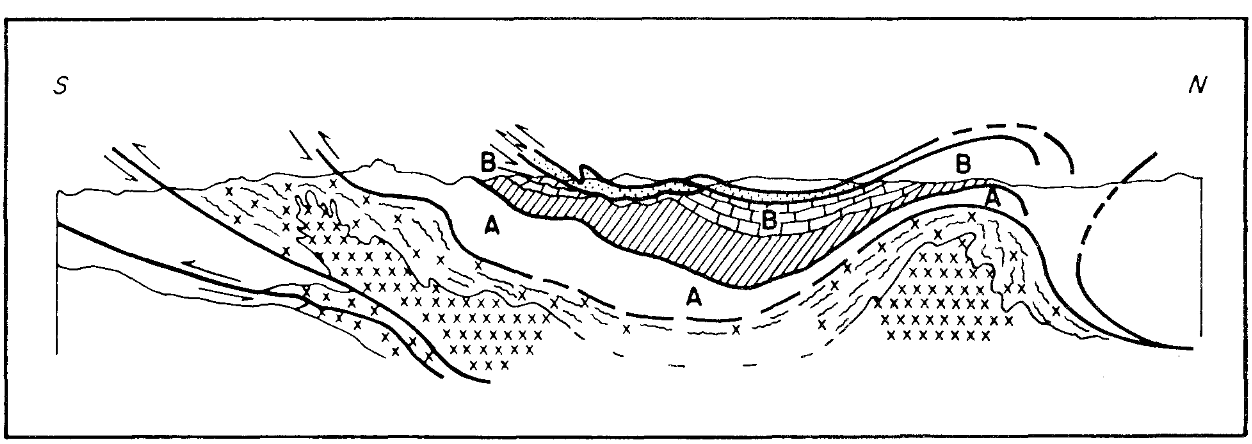

Figure 4. *Schematic diagram, Kathmandu Nappe, Kathmandu Valley, Nepal. A -- Bhainsedoban Marble, B -- Godavari Limestone*

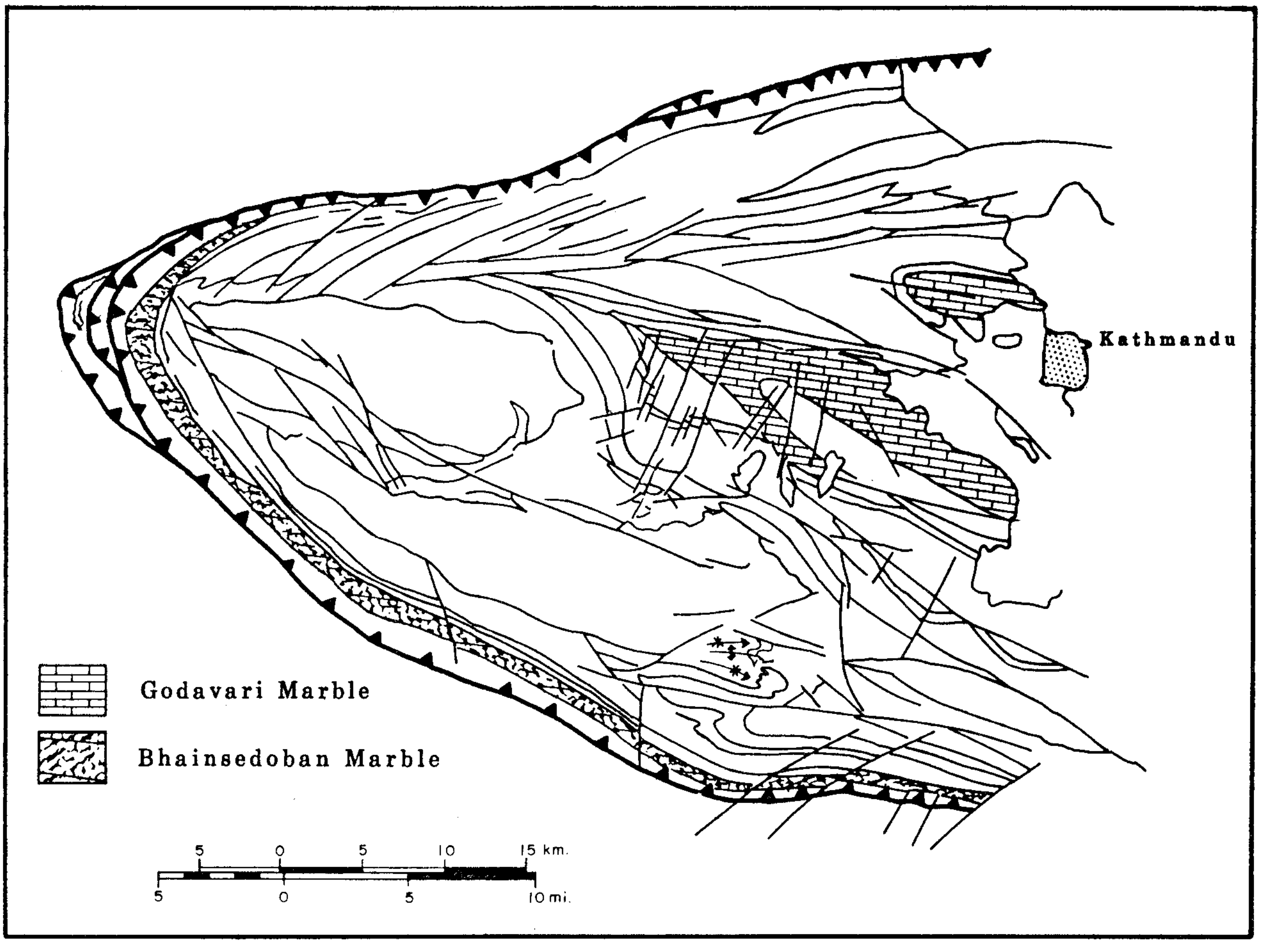

Figure 5. *Generalized geologic map of the Mahabharat synclinorium, Kathmandu Valley, Nepal*

large boulders per day. The remaining rubble is processed for road metal or decorative marble chips. The marble is worked in benches that are nine meters by nine meters in size. Selective drilling and blasting are used to quarry the blocks of marble; blocks with excessive fractures are discarded or at least not processed further. More competant material is sent to the processing facility. Here it is slabbed, trimmed, sorted, and polished. The processed material is then packed and readied for shipment.

Dependent on the given marble bed, the reserves of the Godavari deposit vary from 1.5 million to 2.5 billion pounds. No precise determination of total reserves has been attempted, nor has a detailed geological mapping project accompanied by a test core program been done. A program of this type is necessary to make a good estimate of reserves so that an economic feasibility study can be done to attract private investment capital.

Marketing and transportation are additional problems to be addressed by any potential developer. Currently, the processed material is trucked to Calcutta, India, for further distribution. Transportation from the processing plant to the port might be the most expensive cost associated with any large scale operation. These costs could be offset somewhat by lower labor costs and the general availability of water for processing.

SUMMARY

The Godavari deposit has the geological potential to become a significant resource for the Kingdom of Nepal. With the

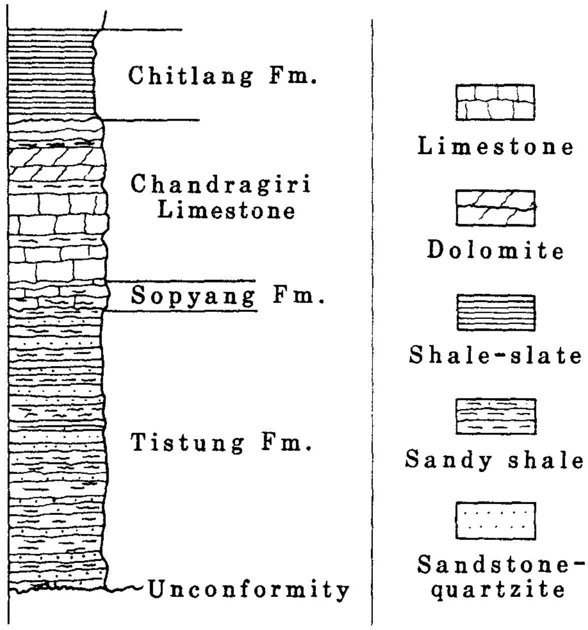

Figure 6. *Stratigraphic section of Lower Paleozoic rocks, Kathmandu Valley*

proper development, this resource could become a major industry for the country, creating wealth and supplying jobs for Nepalese nationals. The operating record of the test facility suggests that the marble can be quarried and processed. Further geological studies, along with additional economical studies (particularly on marketing and transportation issues) need to be done prior to attracting private investment capitol.

ACKNOWLEDGEMENTS

The authors wish to thank the staff members of the Department of Mines and Geology, especially Mr. G.S. Tharpa, for their hospitality and assistance in obtaining information of the Godavari deposit. We also thank Mr. Ravidra Kumar, of the Center of Advanced Study in Geology, Panjab University, for his help in understanding the regional stratigraphy of this area. Finally, we would like to thank the Arkansas Geological Commission, especially Mr. Bill Bush, for allowing us the opportunity to present this data.

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Abstracts

INDUSTRIAL SAND

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Silica Products Company, Inc., founded in 1921, produces industrial sand from the St. Peter Sandstone, a Middle Ordovician sand which outcrops extensively from northwest Arkansas eastward to the Mississippi Valley alluvial plains. The purity, high silica content, and grain characteristics of the St. Peter sand make it highly suitable for the manufacture of glass and for molding purposes in the foundry industry. Other uses include roofing, blasting, and chemical manufacturing.

At Guion, the sandstone is mined by both open pit and underground methods. The sand is crushed, washed, and screened to produce several gradations which are blended to meet stringent specifications for grain distribution. The sand is shipped by rail and truck, bulk and bagged, to industrial consumers in twelve states throughout the Southeast and Southwest.

GETTING INTO INDUSTRIAL MINERALS: FACING THE REALITIES

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The popular business trend of "getting into industrial minerals" is much more complicated and requires more preparation than most would-be entrants realize. The industrial minerals industry covers 70 separate minerals and is fragmented into many more distinct markets. Success as a new producer requires an early understanding of the generally complex mix of geology, processing, specifications, pricing, and competitive marketing. Strategies and specific suggestions for new entries are presented with case histories of successful efforts.

NATURAL ZEOLITES AS A COMMODITY: HAVE THEY ARRIVED YET?

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Over the past thirty years natural zeolites have become established as reliable commercial mineral commodities in Japan and Eastern Europe. Despite two major marketing drives during this time within the United States, they have failed to gain major commodity status domestically through failure to gain quick acceptance and the lingering suspicion that natural zeolith deposits could not yield competitive commercial products or maintain consistent specifications. High-quality products have in fact been produced by Union Carbide, Occidental Minerals, Anaconda Minerals, and others and consistency in product quality has been well established. Sound geologic control and careful mining and processing practices are the keys to natural zeolite quality control. Case histories of successful zeolite production are presented. Smaller producers, including Teague Mineral Products, East-West Minerals, Tenneco Specialty Minerals, and others are rebuilding the natural zeolite industry in the U. S. on a more practical level and hopefully with a sharper eye on product quality. Perhaps this time natural zeolites will emerge as a respectable major commodity.

CARBONATITE AND ALNOITE OF NORTH-CENTRAL ARKANSAS: DIAMONDS IN POPE COUNTY?

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Carbonatites, alnoite, and related rocks are found substantially north of the principal trend of the Arkansas alkalic province. These rocks are also Cretaceous in age, and contemporaneous with rocks of the main trend. However, their mineralogical and trace element compositions are more kimberlitic than main-trend rocks, and suggest that they evolved from one or more distinctly different mantle source(s).

Carbonatite dikes occur near Perryville (Perry County) and Morrilton (Conway County). The bodies are small, averaging 3 m in width, and contain a variety of crustal and lower crustal xenoliths. K-Ar dates on phlogopite separates yield a mean age of 96.1 ma. Compositions of phlogopite and diopside megacrysts are more closely related to kimberlitic compositions than to the lamproitic trends of Prairie Creek, Pike County, Arkansas. Trends of REE and other trace elements are compatible with a kimberlitic source.

Alnoite occurs in a single, poorly exposed pipe at Dare Mine Knob, 39 km north of Russellville. The rock has been dated at 83 ma based on K-Ar of phlogopite separates (Dennison). Again, compositions of phlogopite and perovskite indicate a high-pressure, mantle source distinct from the main trend. The rock is extremely enriched in LREE (100 x Chondrite), and has high Ni (500 ppm). These and other trace elements unequivocally indicate an enriched, "kimberlitic" mantle source.

The continuum from carbonatite through alnoite to kimberlite suggests that true kimberlite may be present in small, as yet undetected pipes in the Ozark Plateau of north-central Arkansas. Diligent prospecting using geophysical methods such as magnetics could reveal diamondiferous rocks in this northern province.

METAGABBROS OF THE OUACHITA CORE, ARKANSAS AND OKLAHOMA

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Two occurrences of deformed, greenschist facies metagabbro have been documented in the core of the Ouachita Mountains, one at Hominy Hill in the Benton uplift near Alexander, Arkansas, and the other, previously reported by Honess, (1923) near Broken Bow, Oklahoma. Their structural and stratigraphic setting is similar to metamorphosed ultramafics ("soapstones") a few kilometers west of the Hominy Hill locality , and these rocks may all be related to a similar source. The age obtained by K-Ar whole-rock methods on the Hominy Hill metagabbro is 1025 + 48 Ma (Precambrian).

The Hominy Hill metagabbro extends as boudins or 25 m-wide (82 feet) en echelon pods approximately 2 km (1.2 mi) along a NW-SE trend. Contacts with the host Womble Shale appear sheared. The Hominy Hill metagabbro contains titanaugite with an average of 2.3 wt% TiO_2 and high Al_2O_3, indicating a mildly alkaline nature. Rare earth elements (REE) are 30 x chondrite, and have a flat pattern. These and other low-mobility geochemical discriminants (TiO_2, Zr, P_2O_5, Y) indicate a slightly lithophile (LIL)-enriched oceanic character, similar to enriched mid-ocean ridge basalt (EMORB). Possible settings for the origin of this rock include back-arc basin or transform fault.

The Honess gabbro from the Broken Bow uplift is an extremely sheared rock which occurs in separated pods 3 to 10 m (10-33 feet) in width along a 1 km (0.6 mi) NE-SW trend in the southernmost Ouachita core. The host Womble is a coarser-grained rock than at Hominy Hill and is metamorphosed to lowermost greenschist facies. Limestone pods occur in the Womble adjacent to the Honess gabbro. Major-element abundances of the Honess gabbro may not accurately reflect its original nature due to the extreme deformation and alteration, but suggest that it is (was) a slightly more silicic rock than that of Hominy Hill.

The metagabbros of the Ouachita core may define an economically significant trend which may be related to early rifting or transform motion in the Ouachita trough. Deposits of serpentinized ultramafic rocks which are tectonically and petrologically related to these gabbros have been mined for use as additives, and contain small amounts of nickel. Sedimentary exhalative (SEDEX) deposits in both the pre-Novaculite shales and in the Stanley Group are found along the trend connecting the metagabbro occurrences. Because rifts and other oceanic fault systems are common sites of mineralization, further exploration of this trend is recommended.

PETROLOGY AND GEOCHEMISTRY OF GRANITE MOUNTAIN SYENITES: Multi-stage evolution of a mantle-derived system

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Mineralogic, geochemical, and isotopic data indicate that the syenites of Granite Mountain are mantle-derived magmas which have undergone little fractionation and crustal contamination. The syenites are of two distinctly different generations which have separate mantle sources.

The earliest syenites are olivine and plagioclase-bearing rocks with an age of 108-100 Ma determined by fission-track methods on apatite separates. These rocks are dark blue-grey on fresh surfaces, and are virtually indistinguishable in hand specimen from later dark-grey syenites. Olivine is Fo70, and shows little reaction-relation with the host magma except for a rim of small biotites. Plagioclase is An 30-40, with very high (1-2 wt %) BaO, and is rimmed and di-gested by anorthoclase (Or40 Ab50 An10). Diopside and calcic diopside form euhedral phenocrysts; groundmass py-roxenes are salite. Biotite is relatively rich in Mg and Al in the olivine syenites. Sphene is absent in these rocks, but apatite is large, abundant, and commonly associated with the olivine. Whole-rock geochemistry shows extreme enrichment in Ba (4000 to 4500 ppm), and moderate enrichment in rare earth elements (REE) and light rare earth elements (LREE). These rocks are olivine-nepheline normative, have Na20:K20 = 3:2, Fe/Fe+Mg = 0.26, and Rb/Sr = 0.05. Their 87/86 Sr is 0.70393, indicating direct mantle derivation.

In the second generation of syenite, both olivine and plagioclase are absent and sphene becomes an abundant accessory. This second generation shows three distinct stages of evolution. Stage I is a dark grey rock which contains diopside, salite, biotite, and locally kaersutite as mafic phases. Feldspars are anorthoclase of variable composition, usually containing about 10% CaO. Fission track ages of apatite and sphene are both 87-86 Ma. Major element compositions of Stage I rocks are similar to olivine syenite, but trace elements are significantly different. BaO is 1500-1000 ppm. LREE are nearly identical to olivine syenite, but heavy rare earth elements (HREE) are more enriched in Stage I rocks. For stage 1 87/86 Sr is 0.70657, suggesting some crustal assimilation.

White syenites (Stage II) which mottle and in some places intrude the Stage I rocks are more sodic. Aegerine mantles salite, CaO is absent from the sodic anorthoclase feldspar, and sphene is large and enriched in U. These rocks have a fission-track age of 86-85 Ma, and feldspar separates yield an 87/86 Sr of 0.70452, indicating less involvement of crust. Pink syenite dikes (Stage III) (85-78 Ma) are more sodic and extremely undersaturated, with hypersolvus micro-perthite feldspars and abundant miariolitic cavities.

Trace element data constrain the 100 Ma olivine syenite to a metasomatized spinel lherzolite source, and the 87 Ma syenites to a deeper garnet lherzolite source. The 87 Ma event generated the great volume of syenite magma which flooded and assimilated the olivine syenite.

The early (108-100 Ma) olivine syenites may be related to a lamproitic mantle source similar to that of Prairie Creek (Crater of Diamonds). The abundance of sulfide-rich ultramafic xenoliths in olivine syenites and Stage I syenite suggests that lamproite may be present at depth. Late pegmatites (Stage III syenite) may contain economic abundances of Nb, Zr, and some zeolites. The principal use of Granite Mountain syenites will probably remain as aggregate, road metal, and other applications requiring abrasion-resistant rock. Stage II and Stage III syenites should be restricted from such use because their hydrous feldspars weather to clays rapidly and are not suitable for high-abrasion applications.

WEYERHAEUSER GYPSUM OPERATION--BRIAR PLANT AND MINE

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The Weyerhaeuser Company's gypsum operation is located near Briar in eastern Howard County, Arkansas. The mine is the sixth largest gypsum mine in the United States and the manufacturing facility is the fourth largest wallboard plant in the world. Wallboard is the sole product, constituting nearly 3 percent of the nation's annual wallboard production. In other terms this is equivalent to the wallboard used in the interior walls and ceilings of about 80,000 average homes. The hourly production rate is sufficient for about 7 1/2 homes. At the present rate of production, reserves on the present Weyerhaeuser land holdings should last well in excess of 100 years.

The gypsum deposits were discovered in 1956 during excavation of a railroad cut for the DeQueen and Eastern Railroad (now the Missouri Pacific Railroad) near Briar. This is the most southeasterly known outcrop of commercial grade gypsum in the United States. The gypsum occurs in the lower part of the DeQueen Limestone Member of the Trinity Formation of Early Cretaceous age. The DeQueen has been traced in outcrop from a point about 11 miles east of Briar westward into Oklahoma; it dips southward into the sub-surface at about 1 1/2 degrees.

Open pit methods are used to mine three beds of gypsum of variable grade and thickness. The average aggregate thickness of the three beds is approximately 19 feet and the interval of predominantly non-gypsiferous rock between them is about 17 feet.

THE HARD AND SOFT OF IT: USES OF ARKANSAS NOVACULITE

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Indians were the first to use novaculite. They made their various tools and hunting implements from the weathered broken rock until they learned quarrying techniques. The first white men in the area recognized the value of novaculite for sharpening tools and knives; previously whetstones were obtained in small quantities from Europe. To this day whetstone is quarried mostly in areas where the Indians and possibly the Spanish had previously worked. Some of the current mining practices have changed very little from those of the early quarryman.

In areas where the novaculite of the Upper Division is poorly cemented, this friable tripolitic material has found applications in such uses as an abrasive, as a filler or extender in paints and plastics and for other purposes. Some of the dense novaculite is suitable as a filler in fire bricks and also in plastics. Because some of it has a tendency to decrepitate when heated, not all novaculite can be used for the above applications.

Several quarry operators are crushing novaculite for road, concrete, and other aggregate. This use was formerly rather limited due to the abrasiveness of the novaculite on crushing and screening equipment. Further potential uses of novaculite are speculative, but include application as high purity silica in the production of silicon metal for solar cells, seed or "growing" quartz, and as fusing quartz for electronics.

ARKANSAS PRODUCTION OF MINERAL RESOURCES WITH EMPHASIS ON INDUSTRIAL MINERALS AND ROCKS

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Arkansas' greatly diversified mineral output each year is highlighted by the production of mineral fuels, metals, and industrial minerals and rocks. Minerals production in the State is one of the most consistent business enterprises conducted, and has a profound economic impact on the economy. Value of crude minerals production in 1976 was placed at $535.4 million, whereas the value level was in excess of $1.1 billion in 1985. Most of the value increase in the ten-year span is attributed to price increases assigned to mineral fuels output. Although Arkansas is thought of by many people as an agricultural State, truly, value of mineral production usually exceeds the cash value of all agricultural products every year with few exceptions. With exclusion of iron ore, barite, and phosphate rock, the list of minerals produced in 1985 was the same as in 1976.

Arkansas continued to be among the national leaders particularly with regard to production of abrasives, bauxite, and bromine in 1985, and is expected to remain in the forefront in output in the forseeable future.

Twelve very important industrial minerals and rocks were produced in 1985 and by-product output of elemental sulfur can be added. Obviously some mineral products from refining of petroleum would augment the list.

Total value of Arkansas minerals in crude form used in industrial applications exceeded an estimated $270 million in 1985. These minerals in manufactured mineral product form have a value of more than $2 billion. According to employment data provided by the Arkansas Labor Department, about 1200 people received about $21 million in weekly earnings in 1985 as miners of industrial minerals and rocks. Nearly 7700 people were engaged in manufacture of industrial mineral products in Arkansas in 1985. Their aggregate weekly wages exceeded an estimated $182 million. These data fortify the economic importance of minerals in Arkansas and are representative of the economic impact that the mineral industry has across the Nation.

INDUSTRIAL GARNET PRODUCTION FROM NORTH IDAHO PLACERS

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The United States is the world's largest consumer of industrial garnet. More than one-half of domestic production comes from an integrated facility in north Idaho. This operation is Idaho's largest placer mine, with garnet-bearing gravel extracted from five sources on both private and public lands. The author reviews the geology, mining and milling methods, product processing, and contemporary uses of the refined product. Special note is made of operating efficiencies, including the recent transition from draglines to a hydraulic backhoe as the primary excavator, and successful compliance with environmental standards.