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GEOLOGY, GEOCHEMISTRY, AND RESOURCE POTENTIAL OF CARBONATE ROCKS IN THE SAN BERNARDINO NATIONAL FOREST, CALIFORNIA

SUMMARY PAMPHLET TO ACCOMPANY GEOLOGIC MAPS

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ABSTRACT

Outcrops of limestone and(or) dolomite marble are present throughout the San Bernardino National Forest, California. Where possible, these Precambrian to Late Paleozoic carbonate rocks are divided into the Bonanza King Formation, the Nopah Formation, the Sultan Limestone, the Monte Cristo Limestone, and the Bird Spring Formation. Other carbonate rocks are mapped as the Furnace Limestone or as members of the Desert Divide Group and the Palm Canyon Complex where existing geologic data does not differentiate between the various limestone and dolomite units. Past mining in the national forest, combined with new geologic and geochemical data, indicate that all of the carbonate rocks within the San Bernardino National Forest have high resource potential for construction-grade carbonate rocks. These rocks have been quarried for roofing materials, construction stone, and industrial uses for more than 100 years; demand for these materials is expected to increase at an annual growth rate of 2-4 percent to the year 2000. White marble in the Bonanza King and the Nopah formations, the lower and middle members of the Bird Springs Formation, and marble in the Desert Divide Group have high resource potential for cement-grade carbonate rocks. The Crystal Pass Member of the Sultan Limestone and the middle member of the Monte Cristo Limestone have high resource potential for chemical-grade carbonate rocks. These high grade (high CaO, high brightness) marbles are used as fillers and extenders in the paper, paint, and plastics industries and yield the greatest per unit value of any of the carbonate rocks in the San Bernardino National Forest.

INTRODUCTION

Carbonate rocks, consisting of limestone ($CaCO_3$) or dolomite ($CaMg\{CO_3\}_2$) marble, are present in the eastern San Gabriel, San Bernardino, and San Jacinto Mountains of the San Bernardino National Forest, California (fig. 1). These rocks have been quarried from the 1880s to the present day and produce several million tons of limestone-based products per year for the construction, cement, chemical, and pharmaceutical industries. Part of this national forest is adjacent to the Lucerne Valley Limestone Mining District, one of the largest limestone producing districts in the United States (fig. 1); gross sales from this district alone are $180-220 million per year (Fife, 1988). This report describes the geology and geochemistry of the carbonate rocks as well as carbonate-rock quarries, mines, and prospects in the San Bernardino

National Forest; these data are used to assess the resource potential of carbonate rocks in the national forest.

GEOLOGY AND GEOCHEMISTRY

EASTERN SAN GABRIEL MOUNTAINS

Geologic Setting

The eastern San Gabriel Mountains are divided into two distinctive geologic terranes by the Icehouse Canyon Fault (Plate 1). Rocks north of this fault include the Mesozoic Pelona Schist and a mylonitic and gneissic granite complex. The Pelona Schist consists of well-foliated blue-gray mica schist and green-gray chlorite schist; discontinuous layers of metachert, siliceous schist, interbedded marble and quartzite, and greenstone also occur within this unit. All of these rocks are folded and metamorphosed to upper greenschist or lower amphibolite grade and are structurally overlain by the mylonitic and gneissic complex. This metamorphic complex consists of hard platy black mylonite grading upward into gray foliated cataclastic rocks. The Pelona Schist and the overlying metamorphic complex are intruded by the 14- to 16-Ma Lytle Creek pluton (Morton and Matti, written commun., 1993).

Rocks south of the Icehouse Canyon Fault include the Paleozoic(?) Placerita metasedimentary suite and retrograde metamorphosed and mylonitized granulite; all of these rocks are intruded by late Mesozoic granitic rocks that include massive to gneissic gray quartz diorite and massive gray to white granodiorite and quartz monzonite. The metasedimentary suite consists of approximately 7,000 ft of tan quartzite, gray to white marble, and amphibolite-grade biotite schist. The mylonitized granulite consists of Precambrian(?) cataclastic gneiss and discontinuous lenses of marble; pods, up to 1.2 mi long, of light-gray 70-Ma charnockitic rocks occur locally in the gneiss (Dibblee, 1982; Morton and others, 1983; Morton and Matti, written commun., 1993).

The pre-Tertiary crystalline rocks are overlain by sedimentary deposits in Cajon Valley (Plate 1). The sedimentary deposits include the Cretaceous or Paleocene San Francisquito(?) Formation, the lower Miocene Vaqueros(?) Formation, the middle and upper Miocene rocks of Cajon Valley, the lower to upper Miocene Crowder Formation, and the upper Miocene to Pliocene rocks of Phelan Peak; small outcrops of folded Tertiary sandstone and conglomerate are also located near the mouth of Lytle Creek (Plate 1). The rocks of Cajon Valley, the Crowder Formation, and the rocks of Phelan Peak are unconformably overlain by the Pleistocene Harold Formation; this unit grades upward into the Pleistocene Shoemaker Gravel which is unconformably overlain by Pleistocene and Holocene alluvial deposits (Dibblee, 1982; Morton and Matti, written commun., 1993).

Carbonate Rocks

Carbonate rocks in the eastern San Gabriel Mountains are present south of the Icehouse Canyon Fault and along the San Andreas Fault near Wrightwood (Plate 1). Gray to white marble south of the Icehouse Canyon Fault near Lytle Creek is present as pendants or septa in plutonic rocks and is interbedded with hornfels, slate, and micaceous quartzite; the marble beds thicken to the west and occur with quartzite, schist, and graphitic schist in San Antonio Canyon (Morton and others, 1983). White dolomitic marble along San Antonio Canyon was mined as filler from 1958 to 1963; similar rocks have been quarried for roofing granules in the western part of the range (Gray, 1982; Dibblee, 1982).

Carbonate rocks north of the Icehouse Canyon Fault occur in a narrow east-west-trending belt, approximately 4 mi long, north of Wrightwood, and as discontinuous pods and lenses along the San Andreas Fault south of Wrightwood (Plate 1). The Big Pine and the Sheep Creek Mines are located within the belt of carbonate rocks north of Wrightwood. White dolomitic(?) marble occurs as lenses and pendants in granite and gneiss at the Big Pine Mine (Table 1, no. 1). This marble contains too much magnesium for use in cement, but is excellent for roofing rock, sand (fines), and aggregate material (Dibblee, 1982; Gray, 1982).

Cloudy white coarse-crystalline marble at the Sheep Creek Mine (Table 1, no. 2) occurs in northwest-trending lenses in granite; the lenses are approximately 1000 ft long and at least 100 ft wide and are cut by numerous granitic dikes. Chemical analyses indicate that the marble contains 50.5-53.4 percent CaO and 0.7-1.1 percent MgO (weight percent oxides in this report are recalculated from whole-rock chemical analyses with volatiles removed). These data indicate that marble at Sheep Creek Mine is suitable for portland cement; selected beds are chemically pure enough for special uses (Logan, 1947).

Marble at the Cajon Mine (Table 1, no. 3) occurs as discontinuous northwest-trending lenses in gneiss and schist along the San Andreas Fault south of Wrightwood. These rocks have been mined sporadically since the mid-1920's and are quarried for agricultural and industrial uses (Logan, 1947).

SAN BERNARDINO MOUNTAINS

Geologic Setting

The oldest rocks in the San Bernardino Mountains are located east of Big Bear Lake and were named the Baldwin Gneiss by Guillou (1953). Cameron (1982) divided the Baldwin Gneiss into an older sequence of well-foliated and compositionally-layered paragneiss, schist, and quartzite, and a younger sequence of 1750±15-Ma (Silver, 1971) orthogneiss and pegmatite dikes.

Metasedimentary rocks unconformably overlie the Baldwin Gneiss north, east, and south of Big Bear Lake and are divided into a quartzite sequence and a carbonate sequence. The quartzite sequence consists of the Big Bear Group (?), the Johnnie(?) Formation, the Stirling Quartzite, the Wood Canyon Formation, and the Zabriskie Quartzite and ranges in age from Late Proterozoic into Early Cambrian (fig. 2). The carbonate sequence is divided into a dolomite-dominated unit unconformably overlain by a limestone-dominated unit. The dolomite-dominated unit consists of the Carrara Formation, the Bonanza King Formation, and the Nopah Formation; all of these rocks are Cambrian in age. The limestone-dominated unit consists of the Devonian Sultan Limestone, the Mississippian Monte Cristo Limestone, and the Pennsylvanian and Permian Bird Spring Formation. Ordovician and Silurian rocks have not been recognized in the San Bernardino Mountains (Tyler 1979; Brown, 1991; Morton and Matti, written commun., 1993).

The Baldwin Gneiss and younger metasedimentary rocks are intruded by a variety of late Paleozoic and Mesozoic plutonic rocks in the San Bernardino Mountains. The oldest plutonic rocks are Permian and Triassic (214±2.9 Ma; Miller and Cameron, 1982) alkalic hornblende monzonites that intrude deformed marble north of Big Bear Lake; Jurassic (156-158 Ma) diorite, quartz diorite, and tonalite are also present in this area. Shallow-level Jurassic(?) quartz latite porphyry plutons and dikes at the base of the mountains have been correlated with the Sidewinder Volcanic Series of Bowen (1954) in the Victorville area (Smith, 1982). All of these rocks are engulfed by several Late Cretaceous (70-80 Ma; Miller and Morton, 1980) biotite quartz monzonite batholiths that are exposed over several hundred square miles in and north of the San Bernardino Mountains. The youngest plutonic rocks are steeply-dipping light-gray felsite dikes characterized by folded flow foliation and spherulitic chilled border zones. The dikes clearly cut all other plutonic rocks in the San Bernardino Mountains and may be Tertiary in age (Brown, 1991).

Tertiary sedimentary rocks are exposed in two areas in the San Bernardino Mountains. The Miocene Santa Ana Sandstone of Vaughan (1922) unconformably overlies Mesozoic granitic rocks and Precambrian gneiss along the Santa Ana River; scattered exposures of the Pliocene Old Woman Sandstone unconformably overlie the granitic and metasedimentary rocks along the northern front of the mountains. These Tertiary sedimentary rocks may represent the remnants of a sedimentary blanket that covered the San Bernardino Mountains (Morton and Matti, written commun., 1993).

Carbonate Rocks

A relatively complete section of the metasedimentary carbonate sequence is well exposed along the northern front of the north-central San Bernardino Mountains just south of the Lucerne Valley Limestone Mining District; pendants and fault slivers of these carbonate rocks are also exposed in the Sugarloaf Mountain-Onyx Peak area and along the San Andreas Fault, respectively (Plate 1). All of these rocks have been metamorphosed to marble during Mesozoic intrusive events (Brown, 1991).

The Carrara Formation, the oldest formation within the carbonate sequence, consists of phyllite, schist, and thin beds of limestone marble (fig. 2). The marble beds are relatively rare and, save for the Coon Creek Jumpoff prospect (Table 1, no. 36), have not been exploited for carbonate resources.

The Bonanza King Formation is well exposed from the crest of White Mountain to Bertha Ridge and in a narrow continuous belt beneath the Doble Thrust from the north end of Lone Valley to Onyx Peak; isolated pendants of this formation are present south and east of Onyx Peak (Plate 1). It consists of thin-bedded to massive, light- to dark-gray, slightly dolomitic marble and tan, gray, and white, banded dolomite (fig. 2). The dolomitic marble contains 50.5-57.4 percent CaO and 3.7-5.3 percent MgO (Table 2); these rocks are generally iron stained and contain pyrite. The banded dolomite is characterized by a mottled texture and locally includes cherty and(or) siliceous beds; these rocks contain 37.0-39.0 percent CaO, ≈20.5-25.0 percent MgO, and ≈1.0-8.0 percent SiO_2 (Table 2). Bowen (1973) and Fife and Brown (1982) reported that the White Mountain #2 prospect (Table 1, no. 14) contains $>20 \times 10^6$ tons of white dolomitic marble with 50-55 percent CaO and less than 3.5 percent MgO; Matti and others (1993) mapped these rocks as part of the Bonanza King Formation.

The Nopah Formation includes the Dunderberg Shale Member overlain by a thick dolomite member. The Dunderberg Shale Member crops out in Furnace Canyon (Plate 1) and consists of brown and gray shale, siltstone, and hornfels interbedded with brown and gray sandy dolomite and limestone. The dolomite member occurs in large outcrops from Furnace Canyon to Holcomb Valley (Plate 1) and consists of medium-bedded to massive white to gray fine-crystalline to sugary dolomite with a few cherty or siliceous beds. The dolomite contains 36-39 percent CaO and 18-20 percent MgO (Table 2); white limestone marble at the Lucerne Valley deposit, however, contains as much as 55 percent CaO and as little as 0.4 percent MgO (Table 1, no. 19). This relatively high-grade marble is mapped as part of the Nopah Formation and occurs near intrusive contacts with granitic rocks (Matti and others, 1993).

The Sultan Limestone crops out between Furnace Canyon and Cushenbury Canyon (Plate 1) and is divided into the Ironside, Valentine, and Crystal Pass Members. The Ironside Member consists of medium-bedded to massive gray dolomite with white calcite veinlets that resemble worm tubes. The dolomite contains approximately 36-37 percent CaO, about 23 percent MgO (Table 3), and has been quarried for roofing granules (Brown, 1987). The Valentine Member consists of thin-bedded to massive, gray, yellowish-brown, and white, fine-crystalline dolomite with rare cherty or siliceous beds; stromatoporoids are present but not common. The Crystal Pass Member consists of medium- to thick-bedded platy white limestone marble with thin dark-gray limestone and dolomite layers; the number of limestone and dolomite layers decreases upsection. The white marble contains 50.2-55.7 percent CaO, less than 1 percent MgO (Table 3), and is often iron stained.

The Monte Cristo Limestone is exposed in discontinuous outcrops from White Mountain through Furnace Canyon to Cushenbury Canyon (Plate 1) and is divided into lower, middle, and upper members. The lower member is laterally equivalent to the Dawn and Anchor Limestone Members of the Monte Cristo Formation in the southern Great Basin and consists of thin- to medium-bedded gray limestone and cherty limestone with dark-gray chert nodules and discontinuous chert layers; the number of chert nodules and chert layers becomes more common upsection. The middle member is laterally equivalent to the Bullion Dolomite Member of the Monte Cristo Formation in the southern Great Basin and consists of light-gray to white limestone marble characterized by abundant pelmatozoan debris and crinoid fragments. The marble contains 54.7-55.9 percent CaO, less than 1 percent MgO (Table 4), and has been extensively quarried for pure limestone-based products (Brown, 1987); white, high-grade limestone marble from the White Mountain prospect (Table 1, no. 13) is obtained from this member. The upper member consists of gray limestone marble with a few dolomite or siliceous marble layers. This member contains pelmatozoan debris, corals, and crinoids and is laterally equivalent to the Yellowpine Limestone Member of the Monte Cristo Formation in the southern Great Basin.

The Bird Spring Formation is divided into lower, middle, and upper members that are exposed along the northern front of the San Bernardino Mountains from White Mountain to Blackhawk Mountain then southward to Tip Top Mountain (Plate 1). The lower member consists of a basal clastic interval overlain by a carbonate interval. The clastic interval consists of quartzite, metasiltstone, and chert locally interbedded with limestone. The carbonate interval consists of gray to white limestone marble interbedded with brown-weathering dolomite and(or) siliceous layers as well as a dark-gray limestone layer. The geochemistry of the carbonate rocks varies within this unit. For example, cement-grade marble from Mitsubishi Cement Corporation's Cushenberry Canyon Quarry (Table 1, no. 17) contains 52-53 percent CaO, less than 1 percent MgO, and 3.4-4.8 percent SiO_2 (Table 5); these same rocks were mined in the 1950s as flux for Kaiser Steel mills in the Los Angeles area (Fife, 1988). Gray marble at the Smart Ranch deposit (Table 1, no. 28) contains 53-55.6 percent CaO, 0.6-2.2 percent MgO, and was quarried for roofing granules until 1975 (Brown, 1982); marble at the Terrace Spring deposit (Table 1, no. 27) was quarried for swimming pool sand and for pigment used in white stucco (Fife, 1982).

The middle member of the Bird Spring Formation consists of gray silty and(or) cherty limestone marble with lenses and layers of sandstone and siltstone. Marble in this member is geochemically similar to marble in the lower member and is mined at the Cushenberry Canyon Quarry (Table 1, no. 17) and the Carriere Limestone prospect (Table 1, no. 20) The upper member consists of light-colored limestone marble with layers of white to gray mottled marble and dirty siliceous marble. The limestone marble contains 35.6-40 percent CaO and 1.5-2 percent MgO; the siliceous marble contains 28^+ percent SiO_2 (Table 5).

Carbonate rocks along the San Andreas Fault in the western San Bernardino Mountains and in the Ord Mountains are collectively mapped as the Paleozoic Furnace Limestone (Plate 1). These rocks are lithologically similar to rocks in the north-central San Bernardino Mountains, but time constraints precluded mapping out the various dolomite and limestone units. Tucker and Sampson (1943) reported that white limestone at the Devil Canyon and other prospects along the San Andreas Fault (Table 1, nos. 4-9, 37,38) have been extensively mined and(or) quarried for roofing granules. Dolomite from the Hesperia Mine (Table 1, no. 10) contains 32 percent CaO, 21-22 percent MgO, and less than 0.5 percent SiO_2 (Logan, 1947).

SAN JACINTO MOUNTAINS

Geologic Setting

The oldest rocks in the San Jacinto Mountains are the Desert Divide Group of Brown (1980, 1981) and the Palm Canyon Complex of Miller (1944). The Desert Divide Group occurs in the lower plate of the Palm Canyon Fault (Plate 2) and consists of about 8,000 ft of quartz- and carbonate-rich metasedimentary rocks that are divided into the Bull Canyon Formation and the Ken Quartzite (Brown, 1980, 1981). The Bull Canyon Formation consists of well-foliated quartz-feldspar-biotite gneiss, biotite schist, quartzite, and marble (fig. 2). The gneiss and the schist contain garnet and silimanite and were probably derived from a clastic marine protolith; the marble may correlate with carbonate rocks south of the national forest that contain Ordovician conodonts (Dockum and Miller, 1982). The Ken Quartzite consists of 95 to 98 percent quartzite with minor lenses of marble, schist, and gneiss (fig. 2). Metamorphic mineral assemblages within the Bull Canyon Formation indicate that the Desert Divide Group was regionally metamorphosed to the garnet-amphibolite facies, probably during intrusion of the Mesozoic Peninsular Ranges batholith.

The Palm Canyon Complex occurs in the upper plate of the Palm Canyon Fault (Plate 2) and consists of pelitic schist, gneiss, marble, and metasedimentary rocks; the metasedimentary rocks include amphibole and calc-silicate hornfels probably derived from a lower Paleozoic or upper Precambrian miogeoclinal protoliths (Miller, 1944; Erskine, 1985). The metasedimentary rocks in the Palm Canyon Complex include less quartzite and are deformed and metamorphosed to a slightly higher grade than metasedimentary rocks in the Desert Divide Group.

The Desert Divide Group and the Palm Canyon Complex are intruded by plutonic rocks of the mid-Cretaceous (93-99 Ma) Peninsular Ranges batholith. Hill (1984) divided this batholith into early and later intrusive rocks. The early intrusive rocks form relatively small stocks and plugs of medium- to coarse-grained quartz monzonite intruded by hornblende gabbro. The quartz monzonite is also cut by northeast-trending aplite and pegmatite dikes and a few quartz veins. The gabbro forms sharp, steeply-dipping contacts with the quartz monzonite and is deeply weathered.

The later intrusive rocks include tonalite, monzogranite, and granodiorite. These intrusive rocks grade eastward into strongly deformed mylonitic rocks, characterized by a well-developed east-dipping foliation and a northeast-trending lineation, associated with the Palm Canyon Fault. Granitic rocks in the upper plate of the Palm Canyon Fault include coarse-grained, foliated hornblende quartz diorite, medium- to coarse-grained hornblende granodiorite, and biotite hornblende tonalite.

The Pleistocene Bautista Formation of Axlerod (1966) unconformably overlies the Peninsular Ranges batholith and the Santa Rosa mylonite zone. The Bautista Formation consists of poorly indurated fanglomerate deposits that were shed southwestward during uplift of the Santa Rosa Mountains (Morton and Matti, written commun., 1993).

Carbonate Rocks

Gray to white marble, characterized by dark layers of calcite containing a trace of magnetite, occurs as layers or large boudins separated by schist or gneiss in the Bull Canyon Formation; streaks, lenses, and blebs of fine-crystalline calc-silicate hornfels are scattered throughout the carbonate rocks. The marble contains 54.4 percent CaO (Table 6) and has been mined for Portland cement, roofing granules, decorative stone, road base, rip rap, and building stone (Brown, 1980). Brown concluded that more than 140x10^6 tons of marble may be mined from the Desert Divide Group by surface mining techniques without removing overburden.

Table 6. Chemical analyses of carbonate rocks in the Desert Divide Group (from Brown, 1980).

SiO_2	3.49	5.98	3.31
Al_2O_3	0.42	0.34	0.26
Fe_2O_3 (a)	0.46	0.72	0.48
CaO	53.37	51.89	53.56
MgO	0.28	0.42	0.25
Total alkalis (b)	0.02	0.09	trace
Total	58.04	59.44	57.86
LOI (c)	41.97	40.62	42.16

(a) Total iron as Fe_2O_3

(b) Total alkalis = Na_2O+K_2O

(c) Loss on ignition

The Palm Canyon Complex contains strongly foliated and lineated marble and calc-silicate rocks that contain finely comminuted calcite; impurities such as calc-silicate minerals, chert, and siderite are locally abundant. White to light-gray limestone marble occurs in large monolithologic outcrops that are laterally continuous for several 10s to 100s of feet; smaller lenses and bodies of brown dolomitic marble are complexly interbedded with gneiss and schist. Marble from the Dolomite Mine (Table 1, no. 41) was mined for roofing granules and decorative stone (Matti and others, 1983). This mine, as well as the Harris Limestone Claims and the Nightingale Limestone Claims (Table 1, nos. 39 and 40), were inactive in 1987 (Calzia and others, 1988).

RESOURCE POTENTIAL

Carbonate rocks are an important commodity for the construction, cement, and chemical industries. For example, the cement industry in California consumes approximately 9x10^6 tons of carbonate rocks each year; an additional 4.5x10^6 tons are consumed annually by the construction, chemical, and pharmaceutical industries (Carrillo and others, 1990; Bowen, 1973; Joseph, 1982). The classification and resource potential of carbonate rocks are primarily a function of color, the amount of lime, magnesia, silica, and other impurities in the rock, and the proximity to markets. Generally, construction-grade carbonate rocks are darker, contain more impurities, and have a lower unit value than do cement-grade carbonate rocks; chemical-grade carbonate rocks are white, bright, and contain less than 2 percent impurities. These high-grade carbonate rocks can be transported relatively long distances to market because of their relatively high unit value. This section describes the uses and grades of carbonate rocks; these data are combined with the geologic and geochemical data to assess the resource potential of carbonate rocks in the San Bernardino National Forest.

Mineral resource potential is defined as the likelihood of the presence of mineral resources in a defined area; it is not a measure of the amount of resources or their profitability. Based on available geologic, geochemical, and geophysical data, these defined areas may be assigned low, moderate, or high mineral resource potential. Low mineral resource potential is assigned to areas where the geologic, geochemical, and geophysical data indicate that the existence of resources is unlikely. This level of potential covers areas of widely dispersed mineralized rock and(or) areas with few (if any) areas of known mineralization.

Moderate mineral resource potential is assigned to areas where the geologic, geochemical, and geophysical data suggest a geologic environment favorable for mineralization. This classification does not require known and(or) exploited mineral deposits, but the geologic environment must be compatible with genetic mineral resource models.

High mineral resource potential is assigned to areas where the geologic, geochemical, and geophysical data as well as the mining records are indicative of a geologic environment favorable for mineralization. These areas are compatible with genetic mineral resource models and are often used to refine or modify these models.

USES AND GRADES

Construction Grade

The most common use of carbonate rocks in the construction industry is a crushed aggregate in road base. The crushed particles vary in size from 50 to 0.6 mm (depending upon application as road base or base coarse material) and should be as cubic as possible with no laminations or cracks. Particle shape is important because cubic particles interlock and press firmly into the asphalt binder; flat elongate particles do not interlock and develop voids that lead to premature breakup of the road surface (Power, 1985; Tepordei, 1985; Danner, 1966).

Crushed carbonate rocks are also used as roofing materials and as swimming pool sand because these materials wear well, yield high reflectivity due to their color and rhombohedral crystal structure, and have low porosity that resists water absorption. Crushed particles vary in size from 19.2 to 2.4 mm and should be as white as possible to reflect heat (Power, 1985; Danner, 1966).

Cement Grade

Raw materials necessary for the manufacture of Portland cement are lime, silica, alumina, and iron; magnesium is not required but is permitted and often beneficial at low concentrations (2-3 percent MgO). Lime in cement comes from calcite in limestone, marble, or marl that contains 61.0-68.2 percent $CaCO_3$; limestone with as little as 53.9 percent $CaCO_3$ has been used but results in an inferior product. Although specifications vary, most grades of Portland cement contain 12 to 15 percent SiO_2 obtained from chert and quartz sand impurities in the raw materials; higher concentrations increase mining and processing costs by excessive wear on drill bits as well as crushing and grinding equipment. Alumina and iron are provided by clay or shale impurities in limestone; most grades of cement contain <3.7 percent Al_2O_3 and <6.0 percent total iron. Experience has shown that the ideal mixture of limestone to clay and shale impurities is approximately 4:1; the ratio of silica to alumina plus iron (collectively denoted as R_2O_3) varies from 1.5 to 3.5 and must be closely monitored to control cost and produce a useful product. Finally, cement requires sulfur to control setting times of the concrete. The sulfur is obtained from gypsum and(or) anhydrite and is added in the final stages of the manufacturing process (Ames and Cutcliffe, 1983; Danner, 1966; Power, 1985).

The raw materials are ground, blended, and roasted to produce five types of Portland cement (Ames and Cutcliffe, 1983). Since the specifications for each of these types varies (Table 7), it is not possible to have the proper proportions of lime, silica, alumina, and iron in a naturally-occurring impure or cement-grade limestone to meet all needs; in fact, fine grinding, blending of various grades of limestone, and close control of the mixture are the norm in the manufacture of Portland cement (Ames and Cutcliffe, 1983; Danner, 1966).

Chemical grade

Most of the chemical-grade carbonate rocks produced in the Lucerne Valley Limestone Mining District are used as fillers and extenders in the paper, paint, and plastic industries. These products are commonly known as whitenings and are classified by particle size, chemical purity, brightness, and yellowness. Although variable between industries, specifications for finely-ground carbonate whitenings require that at least 97 percent of the crushed particles, containing 68-71 percent $CaCO_3$, will pass through a 45 micron (0.045 mm) sieve. Brightness and yellowness are synonymous with whiteness and color. Brightness is defined as the ratio (expressed as a percentage) of the radiation reflected from a sample to that reflected from a perfectly reflecting diffuser at $\lambda=457 \times 10^{-9}$ m (nm) with Elrepho; yellowness is defined as the difference between the brightness ratio at $\lambda=570$ nm and the brightness ratio at $\lambda=457$ nm. These finely-ground high purity carbonate whitenings have a specialized market and command a premium price. The unit price of limestone whitening in 1979 was about $27 per ton as compared to $2-3 per ton for limestone used in the construction industry (Power, 1985; H.J. Brown, written commun., 1990).

Specifications for the paper industry

Paper has been made from wood pulp fiber since the Industrial Revolution. The pulp is cooked, bleached, and chemically processed to remove impurities. Unfortunately, the chemical used for sizing (alum rosin) causes the paper to become increasingly acid with time. This progressive decrease in pH causes the paper to become discolored and more brittle. Since the 1970s, books have been printed on paper with alkaline sizing to increase longevity, reduce costs, and improve paper quality (Power, 1985).

In addition to increased longevity, alkaline sizing also allows the use of $CaCO_3$ fillers as a partial replacement for the relatively expensive wood pulp and kaolin. Limestone and marble are used as paper fillers in conjunction with adhesives (such as starch and resin) to fill interstices between the wood pulp fibers, and as paper coatings using a finer material with high brightness. Although specifications vary, the paper industry requires that 30 to 40 percent of the carbonate particles used as filler in paper pass through a 2 micron sieve and yield 85.5 percent brightness; 80 to 90 percent of the particles for paper coatings must pass through a 2 micron sieve and yield 89-96 percent brightness (Power, 1985; H.J. Brown, written commun., 1990). This finely-ground material contains 68.2 to 70.7 percent $CaCO_3$ and <5 percent impurities (Table 7).

Specifications for the paint industry

Limestone is used as a pigment, filler, or extender in paint. It is the primary pigment in white ceiling paint and is used as a partial substitute for pigment in industrial, marine, anti-corrosive, and road making paints. The particle size of limestone fillers and extenders in paint is generally less than 75 microns with 30 to 40 percent of the particles passing through a 2 micron sieve (Power, 1985; H.J. Brown, written commun., 1990). This finely-ground material yields 85.5 percent brightness and contains 68.9 to 70.4 percent $CaCO_3$ (Table 7).

Specifications for the plastics industry

In 1989, about 9,000 short tons of fine and ultra fine ground carbonate fillers were used in plastics in North America; the largest markets were thermoplastics for the automotive industry, plastic resins, and PVC products. Typically, the carbonate raw material yields a minimum brightness of 84 percent and contains at least 70.7 percent $CaCO_3$ and no more than 0.14 percent total alkalis (Table 7). The particle size of limestone fillers in thermoplastics vary from 5 to 10 microns; fillers in PVC products varies from 0.5 to 3 microns. Limestone fillers in resins vary in particle size from 1 to 3 microns and constitute 20-40 percent of the product (Power, 1985; H.J. Brown, written commun., 1990).

Metallurgical Grade

Limestone is used as a flux material in the iron and steel industries; the grade of limestone used is dependent on the smelting technique. The ideal limestone flux used in blast furnaces contains $\leq$3-5 percent SiO_2 and minor amounts of Al_2O_3, SO_3, and P_2O_4; the MgO content is not critical (Table 7). The lime content is variable but generally the greater the CaO content, the better. Limestone used as fluxing agents in the open-hearth process contains $\leq$2 percent SiO_2, <5 percent MgO, $\approx$0.01 percent P_2O_4, and 0.5 percent SO_3. Grain size of the limestone flux is not critical because the limestone is roasted and amalgamated with iron ore and coke to produce a sinter; this sinter is pelletized and used in either the blast furnace or the open hearth process (Power, 1985; Danner, 1966).

Pharmaceutical Grade

Ultra fine ground carbonate rocks are used in the pharmaceutical and food industries as fillers in cosmetics and medicines. Although variable, the specifications for these products are more strict than those described in the preceding sections. Briefly, the mean particle size of carbonate fillers in the pharmaceutical and food industries is 2.4 microns; these fillers yield 95.0 percent brightness and contain more than 71 percent $CaCO_3$ and less than 1 percent trace metals including iron and total alkalis (Table 7). It is rare to discover and difficult to process a filler this pure in naturally-occurring carbonate rocks so most pharmaceutical fillers are obtained from precipitated $CaCO_3$ (Power, 1985; H.J. Brown, written commun., 1990).

RESOURCE POTENTIAL

Geologic and mining data indicate that all of the carbonate rocks within the San Bernardino National Forest have high resource potential for construction-grade carbonate rocks. Many of these rocks, including the Furnace Limestone in the eastern San Gabriel and the San Bernardino Mountains, the Nopah Formation and the lower member of the Sultan Limestone in the San Bernardino Mountains, and marble in the Desert Divide Group in the San Jacinto Mountains, have been quarried for roofing granules or other construction stone for many years.

Geochemical data, combined with geologic and mining data, indicate that marble in the Desert Divide Group as well as the lower and the middle members of the Bird Spring Formation have high resource potential for cement-grade carbonate rocks (fig. 3). The upper member of the Bird Spring Formation generally contains too much SiO_2 for cement-grade rocks; however, Brown (1987) reported that Pfizer Inc. and Pleuss-Staufer have quarried white limestone marble from this member for many years. In addition, chemical data indicate that the Bonanza King and the Nopah Formations generally contain too much MgO for cement-grade rocks; however, selected samples of white marble from the Bonanza King Formation meet the specifications of cement-grade carbonate rocks (Fig. 3). Richmond (1960) reported that metamorphism of the Nopah Formation along the contacts with the granitic batholiths locally results in cement-grade carbonate rocks. These data indicate that white marble in the Bonanza King Formation and marble near intrusive contacts in the Nopah Formation also have high resource potential for use as cement-grade carbonate rocks.

Geologic and geochemical data indicate that the Crystal Pass Member of the Sultan Limestone and the middle member of the Monte Cristo Limestone have high resource potential for chemical-grade carbonate rocks. The lower member of the Monte Cristo Limestone meets the chemical specifications of cement- and chemical-grade carbonate rocks (fig. 3); however, this member consists of gray and black cherty limestone with many chert lenses, layers, and nodules. The abundance of SiO_2 precludes mining the lower member of the Monte Cristo Limestone for cement- or chemical-grade rocks.

CONCLUSIONS

Geologic, geochemical, and mining data suggest that the San Bernardino National Forest contains more than 1 billion tons of construction-grade carbonate rocks and at least 140 million tons of cement- and chemical-grade carbonate rocks (Table 8). The demand for construction-, cement-, and chemical-grade carbonate rocks is projected to increase at a moderate rate of 2 to 4 percent per year through the year 2000 (Tepordei, 1985; Carr and Rooney, 1983; Johnson, 1985); the greatest growth is expected for carbonate-based whitenings in the paper, paint, and plastic industries. The use of alkaline sizing in paper increased from 58 percent of the market in 1988 to 86 percent in 1990; the amount of carbonate filler in the American paper industry ranges from 7 to 12 percent in the mid-1980s and is projected to increase to 30 percent by the year 2000 (Power, 1985). The large reserves of cement- and chemical-grade carbonate rocks within the Lucerne Valley Mining District and the San Bernardino National Forest are projected to meet local demand for these commodities beyond the year 2000 (Mitsubishi Cement Corp., written communication, 1993).

Table 8. Estimate of carbonate rock resources (in millions of tons) within the San Bernardino National Forest (from Table 1)

Construction Grade	1,015
Cement Grade	80
Chemical Grade	60
Total	1,155

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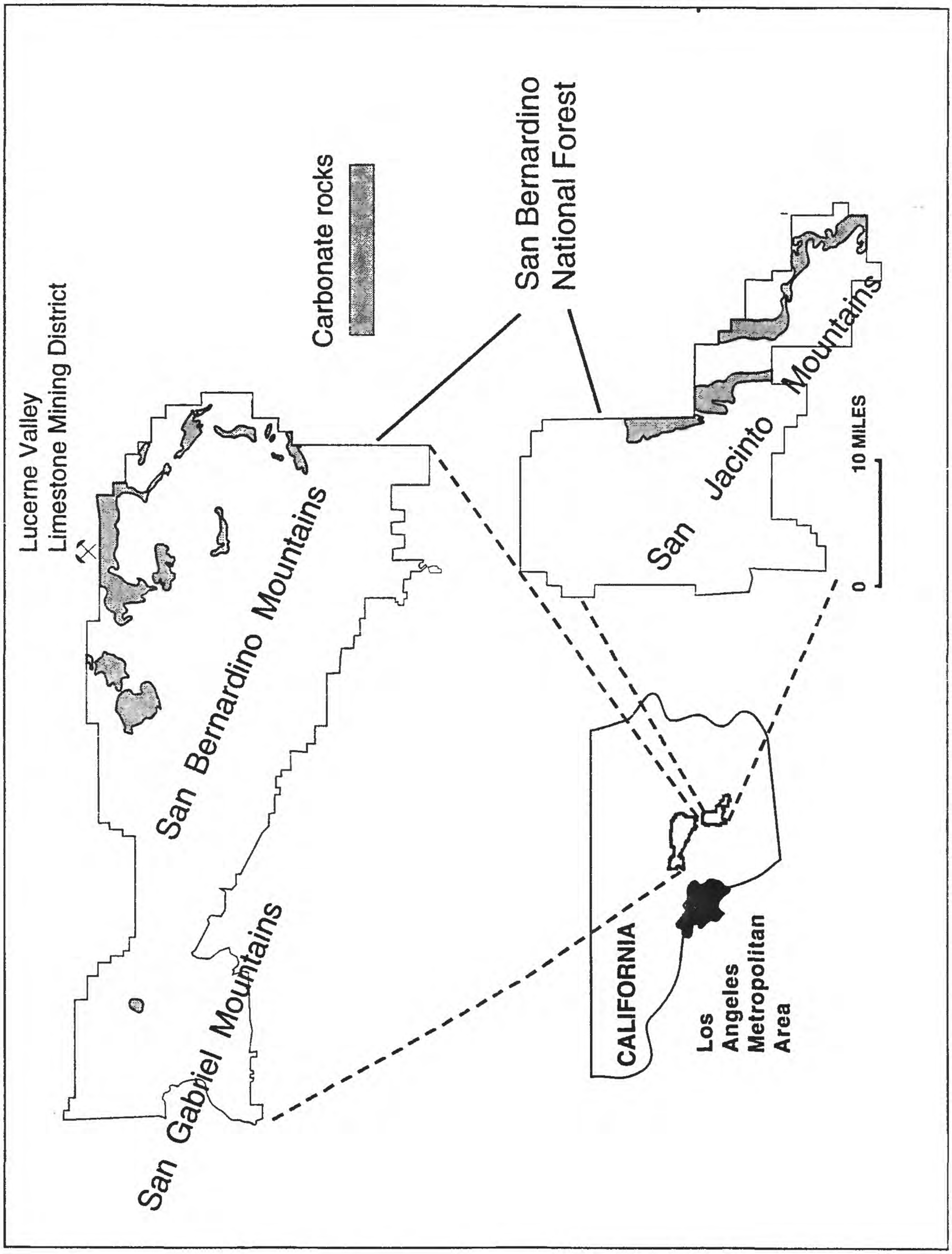

Figure 1. Index map of carbonate rocks in the San Bernardino National Forest, California

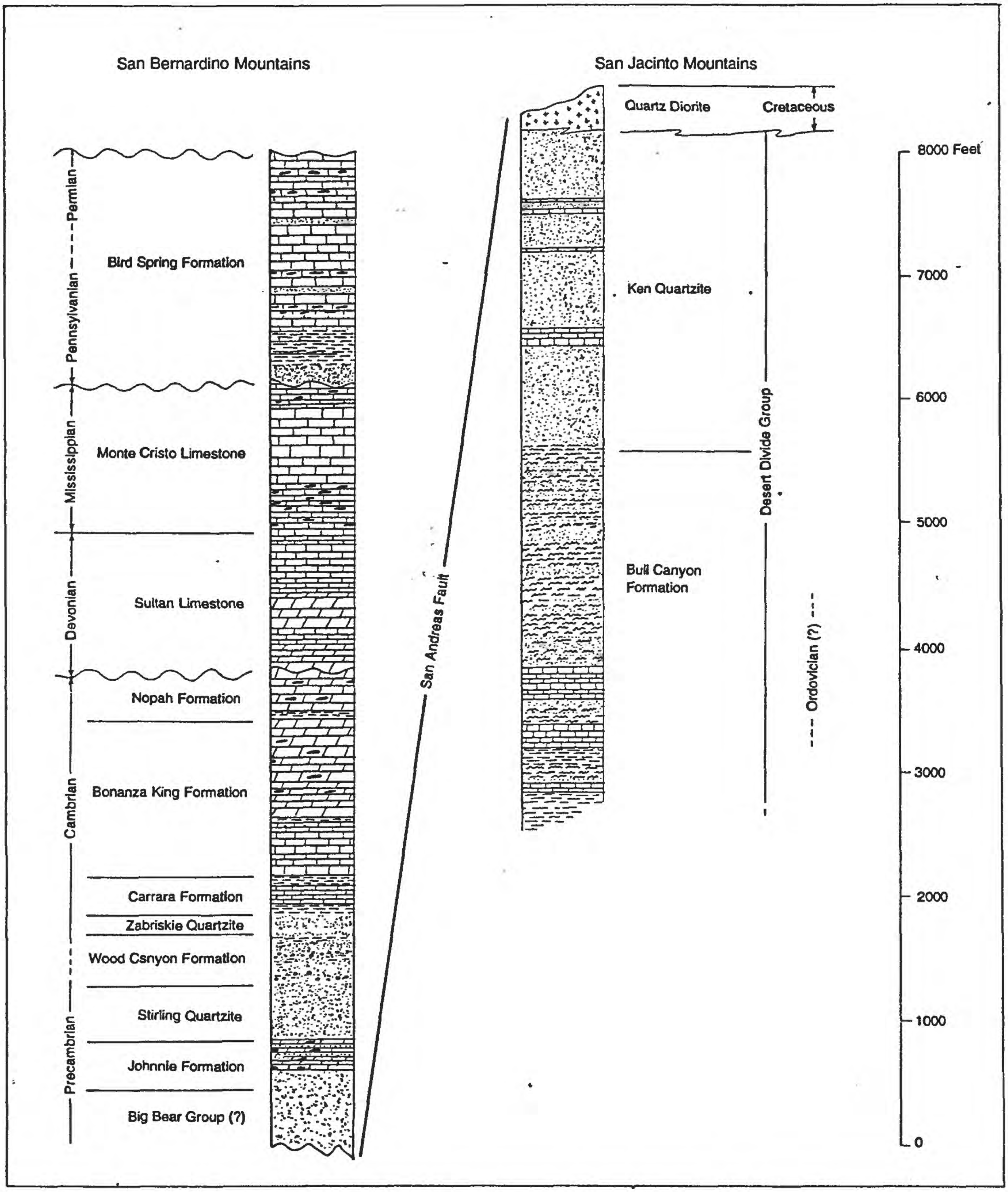

Figure 2. Generalized stratigraphic columns of metasedimentary rocks in the San Bernardino and the San Jacinto Mountains.

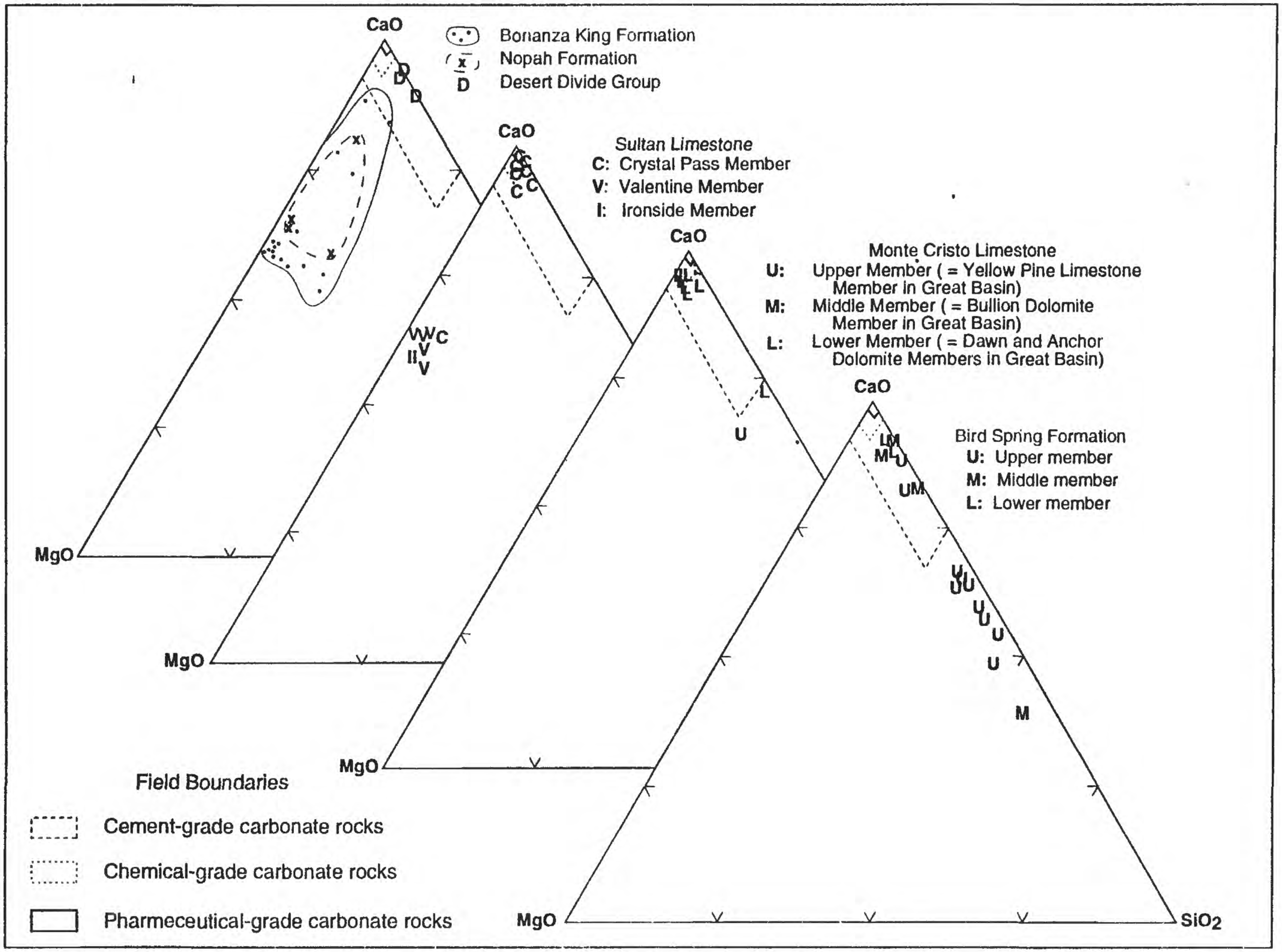

Figure 3. Geochemical classification of carbonate rocks in the San Bernardino National Forest. Geochemical data normalized to 100 percent.

TABLE 1. CARBONATE-ROCK MINES, QUARRIES, AND PROSPECTS IN THE SAN BERNARDINO NATIONAL FOREST CALIFORNIA

Msp No.	Name	Geology	Development	Production snd Resources	References
			SAN GABRIEL MOUNTAINS		
1.	Big Pine	White marble lenses, ≈6000 ft long and 200-400 ft thick, in granite; marble strikes ≈EW, dips 45°SW, and contains 85-95% $CaCO_3$.	Several prospect pits and shallow cuts on three 160-acre placer claims.	Resources estimated at $>20x10^6$ tons.	Logan (1947); Tucker and Sampson (1943); Richmon (1960).
2.	Sheep Creek	Translucent cloudy white coarse-crystalline marble in NW-trending pendants in granite cut by granitic dikes. Numerous analyses indicate that the marble contains 1.7-6.0% SiO_2, 0.54-1.42% Al_2O_3, 0.26-0.38% Fe_2O_3(total), 0.73-1.07% MgO, 53.4-50.5% CaO, and 42.6-40.6% volatiles.	Discovered and in continuous operation since mid-1950s.	Marble is suitable for cement and as roofing materials; beds with high percentage of CaO suitable for special applications. Resources estimated at 46-$50x10^6$ tons.	Logan (1947).
3.	Cajon	En echelon NW-trending limestone lenses in gneiss and schist; lenses ≈1 mi long and several hundred feet wide.	Three quarries and rotary lime kiln with 125 tons/day capacity.	Opened in mid-1920's; sporadic production to 1927. Reopened in mid-1940's to produce limestone for agriculture (poultry) and industrial uses. Resources estimated at $<20x10^6$ tons.	Logan (1947); Bowen (1973).
			SAN BERNARDINO MOUNTAINS		
4.	Lawton Mine	Pendants of white dolomitic(?) marble with minor calc-silicate rocks and quartzite along the San Andreas Fault Zone. Marble pendants typically surrounded by garnet dropside skarns and cut by quartz-rich dikes and veins.		Resources estimated at $<20x10^6$ tons.	Wright and others (1953); Bowen (1973); Weldon and others (1981).
5.	Merit Grove	No data, but probably similar to the Lawton Mine (no. 4).		Resources estimated at $<20x10^6$ tons.	Bowen (1973).
6.	Marble Heart	No data, but probably similar to the Lawton Mine (no. 4).		Resources estimated at $<20x10^6$ tons.	Bowen (1973).
7.	Cook	No data, but probably similar to the Lawton Mine (no. 4).		Resources estimated at $<20x10^6$ tons.	Bowen (1973).
8.	Devil Canyon	White crystalline limestone.	Quarry with 40 tons/day crushing and screening plant.	Operating in 1942; crushed and screened product was used in defense housing projects. Resources estimated at $<20x10^6$ tons.	Logan (1947); Bowen (1973).
9.	Waterman Canyon	No data, but probably similar to Devil Canyon deposit (no. 8).	Quarry shown on topographic map.	Active since 1965; resources estimated at $<20 \times 10^6$ tons.	Bowen (1973).
10.	Hesperia Prospect	White and brown dolomite pendants, 1.5 mi long x 10.5 mile wide x 700 ft thick, in granitic rocks. Dolomite contains 0.4% SiO_2, 0.4% Fe_2O_3, 32.1% CaO, and 21.7% MgO. Carbonate rocks are mapped as part of the White Mountain Complex by MacColl (1964) and are lithologically similar to fossiliferous marble in the Furnace Limestone. Brown (1991) mapped the carbonate rocks as dolomite in the Bonanza King and the Nopah Formations, as well as the lower member of the Sultan Limestone.	Mine shown on topographic map.	Inactive since 1965; resources estimated at $80x10^6$ tons.	Logan (1947); Bowen (1973).
11.	Twin Row	No data, but probably similar to Hesperia deposit (no. 10).		Active since 1965; resources estimated at $<20 \times 10^6$ tons.	Bowen (1973).
12.	Bowen Ranch	No data, but probably similar to Hesperia deposit (no. 10).	Quarry shown on topographic map.	Resources estimated at $<20x10^6$ tons.	Bowen (1973).

TABLE 1. CARBONATE-ROCK MINES, QUARRIES, AND PROSPECTS IN THE SAN BERNARDINO NATIONAL FOREST CALIFORNIA

Msp No.	Name	Geology	Development	Production and Resources	References
13.	White Mountain	White coarse-crystalline limestone, locally more than 100 ft thick, that contains 54.5-55.2% CaO, 0.1-0.2% MgO, and 0.4-1.0% SiO_2 These rocks, as well as lower grade limestone and dolomite, are mapped as part of the middle member of the Mississippian Monte Cristo Limestone and the lower and middle members of the Pennsylvanian and Permian Bird Spring Formation by Matti and others (1993).	Area divided into the Gullixon, White Ridge, White Knob, and White Mountain deposits; most of these deposits are developed by quarries.	Resources estimated at several million tons of high grade limestone.	Fife and Brown (1982).
14.	White Mountain #2	Complexly folded dolomite and white marble mapped as the Cambrian Bonanza King Formation by Matti and others (1993). The rocks are divided into high-grade white, medium-crystalline limestone and lower grade medium- to fine-crystalline limestone with flakes of graphite. The high-grade limestone contains 50.8-55.4% CaO, 0.2-3.5% MgO, and 0.3-2.4% SiO_2; the lower grade limestone contains 49.3-51.3% CaO, 3.7-5.2% MgO, and 0.6-3.2% SiO_2. Dolomite skarns near intrusive contents contain (on average) 3.1.9% CaO, 22.7% MgO, and 2.4% SiO_2.		Resources estimated at >20 x 10^6 tons.	Bowen (1973); Fife and Brown (1982).
15.	Pluess-Staufer (CA)	Massive white medium- to coarse-crystalline limestone and dolomite from the Crystal Pass Member of the Devonian Sultan Limestone, the middle member of the Mississippian Monte Cristo Limestone, and the upper member of the Pennsylvanian and Permian Bird Spring Formation.	Took over Sentinal Dolomite Quarry and plant in 1977, and began intensive quarry development. Began construction of new plant in 1978.	Blend limestone and dolomite from three ore bodies to produce (1) chemical-grade carbonate products for fillers and extenders in paint, plastics, PVC pipe, putty, and paper; (2) metallurgical-grade carbonate rocks for flux in the steel industry; and (3) pharmaceutical-grade carbonate products for fillers in chewing gum, food preservatives, and leavening agent in bread.	Brown (1987); Gray (1982); Joseph (1982).
16	Chas. Pfizer and Company	High-calcium, high-brightness marble from the Devonian Sultan Limestone and the Mississippian Monte *Cristo Limestone.*	Several quarries on Bonnicamp Group, White Mountain, and Gullixon deposits; *processing plant in Lucerne Valley.*	>20x10^6 tons of limestone and dolomite reserves on Bonnicamp *Group worth >\$1M; primary* product is carbonate whiting. Also produce high-brightness agriculture-, metallurgical-, and pharmaceutical-grade carbonate products.	Bowen (1973); Miller and Morton (1982).
17.	Mitsubishi *Cement* Corp. (Kaiser)	Gray and white laminated marble from the lower and *the middle members of the Pennsylvanian and Permian* Bird Spring Formation.	Placer claims and a quarry in Cushenberry Canyon, developed in the 1940s, were purchased by Kaiser in the early 1950s. Kaiser built a railroad and opened a processing plant in 1957. Plant was modernized in 1982 and purchased by Mitsubishi Cement Corp in 1988.	Quarry produces 32x10^6 tons/yr *of ore; plant produces* 1.6x10^6 tons/yr of carbonate (primarily cement) products.	Logan (1947); Mitsubishi *Cement Corp (written* commun., 1991), Brown (1987); Fife (1988); Rzonca and Clark (1982).

TABLE 1. CARBONATE-ROCK MINES, QUARRIES, AND PROSPECTS IN THE SAN BERNARDINO NATIONAL FOREST CALIFORNIA

Map No.	Name	Geology	Development	Production and Resources	References
18.	Sentinal Dolomite	Large pendants of white limestone and dolomitic marble in Mesozoic granite rocks. Limestone reported to contain rare scheelite and lead ore minerals; dolomite locally contains clots and seams of white tremolite. Granitic rocks contain radioactive minerals. Marble contains 0.2-14.6% SiO_2, 0.5-2.1% Al_2O_3, 0.35-0.43% Fe_2O_3 (total), 30.0-30.9% CaO, and 21.2-13.7% MgO, and is mapped as the Cambrian Nopah Formation by Matti and others (1993).	Area prospected for metallic minerals for many years. Carbonate-rock quarry developed ca. 1958.	Resources estimated at >20x10^6 tons.	Richmond (1960); Bowen (1973).
19.	Lucerne Valley	White medium-crystalline limestone and dolomitic marble locally intruded by Mesozoic granite rocks. Marble contains 30.1-55.5% CaO, 0.4-21.3% MgO, and 0.3-0.8% SiO_2, and is mapped as the Cambrian Nopah Formation by Matti and others (1993).	Numbous placer claims located in 1956; claims explored and developed from 1956 to 1958; mill under construction in 1958.		Richmond (1960).
20.	Carriere Limestone	Limestone and dolomitic marble intruded by Mesozoic granite rocks. Marble contains 52.4-54.6% CaO, 0.4-1.1% MgO, and 1.0-3.6% SiO_2 and is mapped as middle member of the Pennsylvanian and Permian Bird Spring Formation by Matti and others (1993).	23 placer claims located in 1957.	Resources estimated at >20x10^6 tons.	Richmond (1960); Bowen (1973).
21.	Old Glory #4	Pendants of white fine-crystalline limestone and dolomitic marble in granite. Carbonate rocks mapped as the Cambrian Bonanza King Formation by Matti and others (1993).		Resources estimated at >20x10^6 tons.	Richmond (1960); Bowen (1973).
22.	Poligue Canyon	Pendants of dolomitic marble in Mesozoic granitic rocke. Marble mapped as the Cambrian Bonanza King Formation by Matti and others (1993)		Resources estimated at >20x10^6 tons.	Richmond (1960); Bowen (1973).
23.	Van Dusen Canyon	Limestone and dolomite mapped as the Cambrian Bonanza King Formation by Matti and others (1993)		Resources estimated at >20x10^6 tons.	Bowen (1973).
24.	Arlington and Blackhawk Groups.	Brecciated fine- to coarse-crystalline limestone and dolomitic marble characterized by gray, white, and red bands. Marble contains 38.5-53.4% CaO, 0.9-4.8% MgO, and 2.2-21.8% residue, and is mapped as the Pennsylvanian and Permian Bird Spring Formation by Matti and others (1993).	Multiple claims located for gold within the Blackhawk landslide; these claims were not developed for carbonate rocks.	Resources estimated at 400-500x10^6 tons.	Logan (1947); Fife (1982); Woodford and Harriss (1928).
25.	Blackhawk Mountain	Marble mapped as the lower member of the Pennsylvanian and Permian Bird Spring Formation by Matti and others (1993).	Crushing plant	Resources estimated at >20x10^6 tons.	Bowen (1973).
26.	Grapevine Creek	Marble mapped as the lower member of the Pennsylvanian and Permian Bird Spring Formation by Matti and others (1993).		Resources estimated at <20x10^6 tons.	Bowen (1973).
27.	Terrace Spring	Marble mapped as the lower member of the Pennsylvanian and Permian Bird Spring Formation by Matti and others (1993).	Small quarry and crushing plant that began development in mid 1960s.	Partins Limestone Products Inc. produces "Cal White", a white limestone pigment used in stucco and swimming pools. Resources estimated at >20x10^6 tons.	Fife (1982); Bowen (1973)

TABLE 1. CARBONATE-ROCK MINES, QUARRIES, AND PROSPECTS IN THE SAN BERNARDINO NATIONAL FOREST CALIFORNIA

Map No.	Name	Geology	Development	Production snd Resources	References
28.	Smart Ranch	Gray marble pendants in Mesozoic granite rocks. Pendants locally include lenses and layers of white medium- to coarse-crystalline limestone marble that contains 53.0-55.6% CaO, 0.6-2.2% MgO, and 0.2-0.4% SiO_2. Gray marble near Moranga Wash contains 55.7% CaO, 0.7% MgO, and 0.1% SiO_2. These carbonate rocks are mapped as the lower member of the Pennsylvanian and Permian Bird Spring Formation by Matti and others (1993).	Quarry and crushing plant at the NW end of this deposit, originally named the White Rock Limestone deposit, operated intermittently from 1949-1951; Moronga Wash White Limestone Quarry at the S end of this deposit in operation from 1953 to 1975.	About 10,000 tons of high quality white limestone for roofing granules wss produced at the White Rock Quarry; as much as 100 tons of white construction-grade limestone was produced from the Moronga Wash Quarry	Brown (1982).
29.	Tip Top Mountain	Faulted pendants of the lower member of the Pennsylvanian and Permian Bird Spring Formation in Mesozoic granitic rocks.	Quarry shown on topographic map.	Resources estimated at <20x10^6 tons.	Bowen (1973).
30.	Rose Mine	Steeply-dipping pendants of white coarse-crystalline marble in Mesozoic granitic rocks. Pendants ere cut by granite dikes and are mapped as the lower member of the Pennsylvanian and Permian Bird Spring Formation by Matti and other (1993).	Claims originally located for gold; not developed for carbonate rocks.	Resources estimated at <20x10^6 tons.	Bowen (1973).
31.	Marmo Diamante	Marble along faulted contact between the Cambrian Carrara Formation and the lower member of the Pennsylvanian and Permian Bird Spring Formation.	Prospect shown on topographic map.	Resources estimated at <20x10^6 tons.	Bowen (1973).
32.	Rattlesnake Gulch	Massive white coarse-crystalline marble several hundred feet thick that strikes N30-40°W and dips 35°NE.	Quarry and mill developed in 1951.	Produced 40 tons of crushed carbonate rocks used for roofing materials; resources estimatsd at >20x10^6 tons.	Bowen (1973).
33.	Green Canyon	Massive white medium-crystalline dolomitic marble that contains 36% CaO, 11% MgO, 4% SiO_2, 1.5% Fe_2O_3, and <1% Al_2O_3+K_2O+P_2O_5. Marble along the north slope of Sugarloaf Mountain, mapped as Paleozoic carbonate rocks by Powalt and others (1983) and the Green Spot Formation by Cameron (1982), may be in part equivalent to the Cambrian Bonanza King Formation.	Quarry with 2 benches.	Bowen (1973) estimated >20x10^6 tons of limestone resources; Powell and others (1983) reported 2.2x10^9 tons of marble resources along the north slope of Sugarloaf Mountain. Small tonnage produced in early 1960's, presumably for roofing materials.	Dibblee (1964a, 1964b).
34.	Sugarloaf Mountain Prospect	Small pendants of massive Paleozoic marble in Mesozoic quartz diorite. Marble contains 28% CaO, 14% MgO, 15% SiO_2, 2% Fe_2O_3, and <1% Al_2O_3+K_2O+P_2O_5. May be equivalent to Sugar Loaf deposit originally described by Tucker and Sampson (1943).	Small discovery pit on NW side.	Resources estimated at 30x10^6 tons.	Bowen (1973); Powell and others (1983).
35.	Morango Onyx Quarry	Marble pendant in Mesozoic granitic rocks. Marble may be equivalent to Cambrian Bonanza King Formation or carbonate rocks in the Cambrian Carrera Formation.	Quarry shown on topographic map.	Resources estimated at <20x10^6 tons.	Bowen (1973).
36.	Coon Creek Jumpoff	Pendants of carbonate rocks in Mesozoic granitic rocks. The carbonate pendants are mapped as the Paleozoic Furnace Limestone by Sadler (1982) and may be equivalent to the Cambrian Carrara Formation or Bonanza King Formation.		Resources estimated at >20x10^6 tons.	Bowen (1973).
37.	Mill Creek	Faulted slivers of white medium- to coarse-crystalline limestone and dolomitic marble in gneiss along the San Andreas Fault Zone. Marble is poorly bedded, locally iron stained, and occurs in lenses 60-70 ft thick and up to 300 ft long.	Quarry and crushing plant developed and operated in 1942 and 1943.	Resources estimated at <20x10^6 tons.	Bowen (1973); Logan (1947).

TABLE 1. CARBONATE-ROCK MINES, QUARRIES, AND PROSPECTS IN THE SAN BERNARDINO NATIONAL FOREST CALIFORNIA

Map No.	Name	Geology	Development	Production and Resources	References
38.	Lucky Strike	Faulted white to gray limestone marble in road cut along State Highway 18 between San Bernardino and Lake Arrowhead. Outcrop is 150-200 ft thick, 1000 ft long, and occurs at an elevation of 4,500 ft.			Tucker and Sampson (1931).
			SAN JACINTO MOUNTAINS		
39	Harris Limestone Claims				Matti and others (1983).
40	Nightingale Limestone Claims				Matti and others (1983).
41	Dolomite Mine	White coarse-crystalline limestone and dolomitic marble more than 50 ft thick; weathers tan and is friable.	200 x 60 ft quarry; 80 ft highwall.		Matti and others (1983).

Table 2. Chemical analyses of carbonate rocks in the Bonanza King and the Nopah Formations. Samples collected by J.C. Matti, C.T. Wrucke, and J.P. Calzia and analyzed by Mitsubishi Cement Corp., Lucerne Valley, California under the supervision of Michael Gantenbein, Mine Superintendent.

Bonanza King Formation

Spl. no	JF-120-1A	JF-120-1B	JF-120-2	JF-121-1	JF-121-2	JF-121-3	JF-121-4A	JF-121-4B	JF-122-4	123
SiO_2	5.30	8.48	2.08	1.30	4.36	8.03	2.41	4.99	0.13	0.16
Al_2O_3	0.08	1.21	0.48	0.33	1.03	0.59	0.27	0.58	0.07	0.06
Fe_2O_3 (a)	0.31	0.79	0.18	0.21	0.51	0.53	0.34	0.20	0.20	0.13
CaO	35.72	33.35	57.39	50.55	43.82	35.04	38.85	50.00	37.34	38.25
MgO	22.46	22.69	3.68	5.26	10.98	21.61	20.41	4.06	24.63	23.67
SO_3	0.02	0.01	0.05	0.03	0.04	0.05	0.05	0.04	0.04	0.05
Na_2O	0.10	0.15	0.04	0.03	0.06	0.11	0.09	0.04	0.10	0.10
K_2O	0.03	0.30	0.34	0.22	0.24	0.08	0.23	0.06	0.05	0.04
TiO_2	0.01	0.11	0.02	0.03	0.10	0.05	0.03	0.04	0.01	0.01
P_2O_5	0.00	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.01
Mn_2O_3	0.08	0.04	0.02	0.02	0.04	0.05	0.04	0.03	0.08	0.06
Total	35.95	32.88	41.66	42.09	38.91	33.98	37.41	40.07	37.46	37.60
LOI (b)	100.06	100.03	105.92	100.08	100.09	100.12	100.12	100.11	100.12	100.14
C_3S (c)	162.40	91.20	326.40	333.60	224.10	115.90	219.50	288.90	240.20	246.60

Spl. no	JF-124-2	JF-133-3	JF-134-1	JF-135-1	JF-141-2	JF-144-3	JF-144-5	JF-146-1	JF-146-2	JF-141-3	JDF-141-5
SiO_2	0.06	2.55	0.96	1.02	0.85	2.03	1.59	2.70	1.14	3.59	1.18
Al_2O_3	0.05	0.28	0.04	0.07	0.01	0.26	0.31	0.20	0.08	0.12	0.12
Fe_2O_3 (a)	0.28	0.33	0.16	0.13	0.19	0.28	0.38	0.41	0.25	0.61	0.25
CaO	37.30	38.19	37.12	36.64	36.63	45.94	36.18	35.96	37.94	35.85	37.29
MgO	24.82	20.95	23.50	24.33	24.34	11.17	24.16	24.50	23.43	23.63	24.03
SO_3	0.04	0.08	0.09	0.03	0.07	0.08	0.08	0.08	0.08	0.08	0.08
Na_2O	0.10	0.11	0.12	0.12	0.12	0.10	0.12	0.12	0.12	0.12	0.12
K_2O	0.03	0.13	0.08	0.08	0.07	0.15	0.12	0.10	0.09	0.08	0.09
TiO_2	0.01	0.03	0.01	0.01	0.01	0.04	0.04	0.03	0.03	0.03	0.03
P_2O_5	0.00	0.01	0.02	0.00	0.02	0.01	0.02	0.01	0.02	0.02	0.02
Mn_2O_3	0.09	0.06	0.16	0.14	0.09	0.02	0.05	0.04	0.06	0.06	0.04
Total	37.33	37.40	37.84	37.41	37.73	40.03	37.08	35.97	36.88	35.94	36.89
LOI (b)	100.10	100.12	100.11	99.99	100.12	100.11	100.14	100.12	100.12	100.14	100.13
C_3S (c)	240.30	213.50	230.20	224.70	228.90	282.20	210.40	193.50	229.40	182.60	224.40

Nopah Formation

Spl. no	JF-130-1	JF-130-2	163-2	JF-144-2
SiO_2	7.59	1.05	1.26	2.44
Al_2O_3	0.45	0.04	0.07	0.43
Fe_2O_3 (a)	0.64	0.16	0.23	0.36
CaO	36.58	39.35	39.64	48.87
MgO	18.71	20.85	19.96	8.38
SO_3	0.08	0.07	0.08	0.08
Na_2O	0.11	0.12	0.11	0.09
K_2O	0.22	0.09	0.10	0.15
TiO_2	0.05	0.01	0.01	0.05
P_2O_5	0.26	0.02	0.06	0.01
Mn_2O_3	0.22	0.05	0.06	0.04
Total	35.18	38.28	38.50	39.20
LOI (b)	100.08	100.09	100.10	100.11
C_3S (c)	131.50	245.50	244.40	290.60

(a) Total iron as Fe_2O_3

(b) Loss on ignition, including H_2O and CO_2

(c) Tricalcium silicate = CaO (4.071) - SiO_2 (7.6) - (Al_2O_3+K_2O+TiO_2) (6.718) - Fe_2O_3 (1.43) - SO_3 (2.852)

Table 3. Chemical analyses of carbonate rocks in the Sultan Limestone

Samples collected by J.C. Matti, C.T. Wrucke, and J.P. Calzia and analyzed by Mitsubishi Cement Corp., Lucerne Valley, California under the supervision of Michael Ganterbein, Mine Superintendent.

Crystal Pass Member

Spl. no	150-4	163-3	166-5	167-4	JF-126-1	JF-126-4	JF-128-5	JF-126-6	JF-133-6
SiO_2	3.69	1.64	2.25	3.75	1.56	0.83	1.48	1.56	4.05
Al_2O_3	0.37	0.16	0.09	0.34	0.12	0.01	0.30	0.29	0.66
Fe_2O_3 (a)	0.28	0.16	0.15	0.59	0.09	0.12	0.13	0.16	0.32
CaO	52.68	54.67	52.68	38.36	55.33	55.68	54.66	54.31	50.18
MgO	0.83	0.76	2.85	19.09	0.40	0.46	0.59	1.06	3.24
SO_3	0.07	0.07	0.08	0.06	0.01	0.07	0.07	0.06	0.07
Na_2O	0.08	0.08	0.08	0.11	0.06	0.07	0.07	0.07	0.08
K_2O	0.18	0.13	0.10	0.19	0.09	0.09	0.17	0.12	0.25
TiO_2	0.02	0.02	0.02	0.04	0.01	0.00	0.02	0.02	0.04
P_2O_5	0.01	0.01	0.01	0.01	0.06	0.02	0.02	0.00	0.01
Mn_2O_3	0.04	0.03	0.03	0.08	0.02	0.02	0.02	0.02	0.03
LOI (b)	41.85	42.19	41.74	37.47	42.18	42.75	42.58	42.36	41.14
Total	100.10	100.10	100.09	100.10	99.94	100.13	100.11	100.05	100.08
C_3S (c)	315.50	356.50	337.00	196.80	366.70	384.60	364.10	356.60	285.90

Valentine Member

Spl. no	JF-124-1	JF-133-2A	JF-133-2B	JF-134-2	JF-134-3
SiO_2	3.28	2.11	1.14	1.64	2.46
Al_2O_3	0.61	0.06	0.09	0.06	0.20
Fe_2O_3 (a)	0.54	0.19	0.20	0.15	0.64
CaO	35.95	39.05	36.96	39.17	37.46
MgO	23.30	19.92	21.34	20.86	22.01
SO_3	0.05	0.08	0.06	0.08	0.01
Na_2O	0.10	0.11	0.11	0.11	0.11
K_2O	0.28	0.09	0.10	0.09	0.15
TiO_2	0.06	0.01	0.01	0.01	0.02
P_2O_5	0.27	0.03	0.04	0.04	0.12
Mn_2O_3	0.32	0.06	0.05	0.04	0.16
LOI (b)	35.34	38.39	37.94	37.83	36.60
Total	100.1099	100.10	100.10	100.10	99.94
C_3S (c)	176.80	230.50	239.70	234.80	206.00

Ironsides Member

Spl. no	JF-127-3A	JF-127-3B
SiO_2	1.93	2.11
Al_2O_3	0.06	0.17
Fe-O_3 (a)	0.33	0.42
CaO	36.75	36.79
MgO	23.35	23.34
SO_3	0.07	0.06
Na_2O	0.12	0.12
K_2O	0.09	0.10
TiO_2	0.01	0.03
P_2O_5	0.02	0.01
Mn_2O_3	0.04	0.05
LOI (b)	37.34	36.91
Total	100.11	100.12
C_3S (c)	214.00	209.10

(a) Total iron as Fe_2O_3

(b) Loss on ignition, including H_2O and CO_2

(c) Tricalcium silicate = CaO (4.071) - SiO_2 (7.6) - (Al_2O_3+K_2O+TiO_2) (6.718) - Fe_2O_3 (1.43) - SO_3 (2.852)

Table 4. Chemical analyses of carbonate rocks in tha Monte Cristo Limestona

Samples collected by J.C. Matti, C.T. Wrucke, and J.P. Calzia and analyzed by Mitsubishi Cement Corp., Lucerne Valley, California under the supervision of Michael Gantenbein, Mine Superintendent.

Yellowpine Member

Spl. no	159-2A	159-2B
SiO_2	16.66	2.33
Al_2O_3	1.51	0.10
Fe_2O_3 (a)	0.89	0.13
CaO	40.33	54.71
MgO	5.74	0.83
SO_3	0.23	0.06
Na_2O	0.10	0.08
K_2O	0.42	0.10
TiO_2	0.10	0.01
P_2O_5	0.27	0.02
Mn_2O_3	0.03	0.02
LOI (b)	33.66	41.65
Total	99.93	100.05
C_3S (c)	35.70	349.50

Bullion Mamber

Spl. no	JF-132-5	160-1B	160-3	161-2	167-2	JF-131-2	JF-132-1
SiO_2	0.69	1.56	1.90	1.25	0.89	2.04	1.75
Al_2O_3	0.02	0.07	0.09	0.02	0.02	0.14	0.16
Fe_2O_3 (a)	0.03	0.13	0.14	0.11	0.09	0.18	0.41
CaO	55.92	54.70	54.61	55.54	55.92	54.82	54.40
MgO	0.42	0.83	0.69	0.24	0.25	0.42	0.52
SO_3	0.07	0.07	0.06	0.07	0.08	0.01	0.06
Na_2O	0.07	0.07	0.07	0.07	0.07	0.08	0.07
K_2O	0.07	0.10	0.10	0.09	0.09	0.10	0.11
TiO_2	0.00	0.01	0.01	0.01	0.01	0.01	0.01
P_2O_5	0.00	0.01	0.03	0.02	0.00	0.01	0.02
Mn_2O_3	0.02	0.03	0.03	0.05	0.03	0.03	0.05
LOI (b)	42.80	42.49	42.32	42.62	42.64	42.12	42.52
Total	100.12	100.09	100.06	100.10	100.10	99.97	100.10
C_3S (c)	389.00	365.20	358.50	376.60	384.60	356.70	359.30

Anchor Member

Spl. no	160-1A	164-1
SiO_2	2.99	16.52
Al_2O_3	0.18	0.43
Fe_2O_3 (a)	0.17	0.90
CaO	52.95	44.52
MgO	1.33	0.69
SO_3	0.08	0.08
Na_2O	0.08	0.08
K_2O	0.15	0.14
TiO_2	0.02	0.04
P_2O_5	0.12	0.07
Mn_2O_3	0.02	0.17
LOI (b)	41.99	36.46
Total	100.09	100.08
C_3S (c)	328.30	79.90

Dawn Mamber

Spl. no	JF-128-3A	JF-128-3B	JF-128-3C	JF-131-1	JF-133-5	164-6
SiO_2	1.03	0.93	0.93	1.53	2.16	1.45
Al_2O_3	0.05	0.03	0.01	0.04	0.24	0.13
Fe_2O_3 (a)	0.08	0.08	0.07	0.16	0.17	0.21
CaO	55.33	54.01	54.22	54.96	53.36	53.56
MgO	1.92	2.50	2.41	1.76	2.70	2.33
SO_3	0.08	0.08	0.08	0.08	0.08	0.08
Na_2O	0.08	0.08	0.08	0.08	0.08	0.08
K_2O	0.10	0.09	0.08	0.08	0.17	0.09
TiO_2	0.01	0.01	0.01	0.01	0.02	0.01
P_2O_5	0.01	0.02	0.01	0.01	0.01	0.01
Mn_2O_3	0.02	0.02	0.02	0.03	0.02	0.06
LOI (b)	41.42	42.30	42.19	41.37	41.11	42.08
Total	100.11	100.13	100.11	100.09	100.12	100.09
C_3S (c)	370.50	368.40	369.30	360.90	337.80	355.30

(a) Total iron as Fe_2O_3

(b) Loss on ignition, including H_2O and CO_2

(c) Tricalcium silicate = CaO (4.071) - SiO_2 (7.6) - (Al_2O_3+K_2O+TiO_2) (6.718) - Fe_2O_3 (1.43) - SO_3 (2.852)

Table 5. Chemical analyses of carbonate rocks in the Bird Spring Formation

Samples collected by J.C. Matti, C.T. Wrucke, and J.P. Calzia and analyzed by Mitsubishi Cement Corp., Lucerne Valley, California under the supervision of Michael Gantenbein, Mine Superintendent.

Upper Member

Spl. no	153-1A	153-1B	154-2	154-4	155-3A	155-3B	156-2	157-1A	157-1B	157-2
SiO_2	8.37	6.03	20.05	25.08	28.64	19.66	18.86	19.79	28.73	24.06
Al_2O_3	1.27	0.69	2.66	3.05	2.39	2.24	1.45	2.67	3.78	1.60
Fe_2O_3 (a)	0.72	0.46	1.48	1.46	1.57	1.45	1.17	1.47	2.22	1.28
CaO	47.57	50.84	39.37	35.99	35.62	39.82	41.46	39.29	30.51	38.09
MgO	1.96	0.63	1.79	1.93	1.46	1.80	1.72	2.05	3.33	1.44
SO_3	0.07	0.08	0.15	0.03	0.07	0.34	0.00	0.03	0.01	0.20
Na_2O	0.08	0.08	0.10	0.11	0.09	0.10	0.09	0.10	0.12	0.09
K_2O	0.43	0.29	0.44	0.51	0.30	0.40	0.35	0.47	0.55	0.32
TiO_2	0.08	0.05	0.18	0.20	0.19	0.15	0.10	0.17	0.26	0.11
P_2O_5	0.12	0.00	0.05	0.10	0.07	0.09	0.17	0.11	0.08	0.07
Mn_2O_3	0.05	0.05	0.05	0.05	0.04	0.04	0.03	0.04	0.04	0.05
LOI (b)	39.33	40.89	33.60	31.43	29.64	33.85	34.53	33.81	30.34	32.61
Total	100.06	100.08	99.92	99.94	100.07	99.93	99.93	99.99	99.97	99.95
C_3S (c)	196.20	263.10	-20.60	-100.20	-131.60	-9.10	18.70	-18.60	-179.30	-61.80

Middle Member

Spl. no	157-3A	157-3B	158-1	158-2
SiO_2	4.22	37.45	9.18	4.77
Al_2O_3	0.40	5.14	1.07	0.22
Fe_2O_3 (a)	0.28	3.04	0.53	0.24
CaO	51.74	26.41	49.07	52.88
MgO	2.42	3.55	0.89	0.32
SO_3	0.03	0.68	0.01	0.06
Na_2O	0.08	0.12	0.09	0.08
K_2O	0.14	0.74	0.20	0.12
TiO_2	0.03	0.33	0.08	0.02
P_2O_5	0.00	0.12	0.01	0.01
Mn_2O_3	0.02	0.05	0.03	0.03
LOI (b)	40.63	22.31	38.79	41.32
Total	100.00	99.94	99.94	100.06
C_3S (c)	295.40	-281.70	198.50	301.80

Lower Member

Spl. no	159-1A	159-1B
SiO_2	3.35	4.82
Al_2O_3	0.26	0.48
Fe_2O_3 (a)	0.20	0.35
CaO	53.17	52.10
MgO	1.04	0.72
SO_3	0.06	0.02
Na_2O	0.08	0.08
K_2O	0.18	0.18
TiO_2	0.02	0.04
P_2O_5	0.10	0.02
Mn_2O_3	0.02	0.06
LOI (b)	41.58	41.12
Total	100.06	99.99
C_3S (c)	322.10	291.10

Undivided

Spl. no	148-2A	149-1	149-3	149-5	148-2B	148-3
SiO_2	11.74	2.83	5.29	2.92	10.45	6.49
Al_2O_3	1.64	0.28	0.68	0.29	1.01	0.73
Fe_2O_3 (a)	0.88	0.21	0.39	0.25	0.69	0.50
CaO	45.66	53.19	51.42	53.48	47.23	50.04
MgO	1.21	1.16	0.98	0.48	0.98	0.93
SO_3	0.05	0.02	0.06	0.07	0.00	0.00
Na_2O	0.09	0.08	0.08	0.08	0.08	0.08
K_2O	0.39	0.16	0.28	0.18	0.26	0.20
TiO_2	0.11	0.02	0.05	0.03	0.07	0.05
P_2O_5	0.02	0.09	0.04	0.01	0.02	0.01
Mn_2O_3	0.03	0.02	0.03	0.03	0.03	0.02
LOI (b)	38.23	41.91	40.76	42.26	39.19	40.87
Total	100.04	99.98	100.05	100.09	100.01	99.91
C_3S (c)	135.40	330.70	275.90	334.30	173.73	251.64

(a) Total iron as Fe_2O_3

(b) Loss on ignition, including H_2O and CO_2

(c) Tricalcium silicate = CaO (4.071) - SiO_2 (7.6) - (Al_2O_3+K_2O+TiO_2) (6.718) - Fe_2O_3 (1.43) - SO_3 (2.852)

Table 7. Chemical specifications of carbonate rocks

Use	CaO (a)	MgO	SiO_2	Al_2O_3	Fe_2O_3 (b)	Na_2O+K_2O	SO_3	LOI	Residue	References
						Cement Grade				
Raw Material	54.4	4.0	14.1	5.0	1.0-2.0	0.8	2.5-3	3.0-4.0	1.5	Power, 1985
Type I		6.0					3.0-3.5	3.0	0.8	Ames and Cutcliffe, 1983
Type II	55.0 (c)	6.0	20.0	6.0	6.0		3.0	3.0	0.8	do
Type III		6.0					3.0-4.5	3.5	0.8	do
Type IV	35.0	6.0			6.5		3.5	2.5	0.8	do
Type V		6.0					3.5	3.0	0.8	do
	$CaCO_3$					Chemicel Grade				
Paper	68.2-70.7	3.0	0.1-1.5	0.5 (d)		0.13-0.14				Power, 1985; H.J. Brown, written commun., 1990
Paint	68.9-70.4					0.1		0.2		Power, 1985
Plastic pipe	70.7					0.1		1.0		do
Metallurgical flux	69.7		2.0				1.2			Carr and Rooney, 1983
						Pharmaceutical Grade				
	71.0	1.0						2.0	0.2	H.J. Brown, written commun., 1990

(a) Minimum content; all other oxides are maximum content

(b) Total iron as Fe_2O_3

(c) CaO as $C_3S = 3CaO \times SiO_2$

(d) $Al_2O_3 + Fe_2O_3 = R_2O_3$