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**Yucca Mountain Site
Characterization Project**

**Assessment of Industrial Minerals
and Rocks
in the Controlled Area**

*original
large maps
report prepared
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OSTI

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Appendices

Appendix 1	Location of industrial mineral occurrences shown in Plate 1, numerically listed.
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1. INTRODUCTION

Yucca Mountain in Nye County, Nevada, is a potential site for a permanent repository for high-level nuclear waste in Miocene ash flow tuff. The Yucca Mountain controlled area occupies approximately 98 km² that includes the potential repository site. It is shown in Plate 1.

The Yucca Mountain controlled area is located within the southwestern Nevada volcanic field, a large area of Miocene volcanism that includes at least four major calderas or cauldrons. It is sited on a remnant of a Neogene volcanic plateau that was centered around the Timber Mountain caldera complex (Christiansen et al., 1977).

The Yucca Mountain region contains many occurrences of valuable or potentially valuable industrial minerals, including deposits with past or current production of construction aggregate, borate minerals, clay, building stone, fluorspar, silicate, and zeolites (Plate 1). The existence of these deposits in the region and the occurrence of certain mineral materials at Yucca Mountain, indicate that the controlled area may have potential for industrial mineral and rock deposits. Consideration of the industrial mineral potential within the Yucca Mountain controlled area is mainly based on petrographic and lithologic studies of samples from drill holes in Yucca Mountain. Clay minerals, zeolites, fluorite, and barite, as minerals that are produced economically in Nevada, have been identified in samples from drill holes in Yucca Mountain (e.g. Caporuscio et al., 1982; Scott and Castellanos, 1984; Bish, 1989; Broxton et al., 1987).

In 1995 the authors were awarded a contract funded by the U.S. Department of Energy through the University of Nevada, Las Vegas, for an assessment of industrial mineral resources of the Yucca Mountain controlled area. In the following pages the data collected from the literature that pertains to the potential for economic industrial mineral deposits at Yucca Mountain are compiled and discussed. It is the intent of this report to present the potential for economic development of industrial minerals in the controlled area by comparing available geologic information on potential mineral occurrences in the rocks of Yucca Mountain with available information on industrial mineral deposits in the surrounding region and elsewhere.

2. LOCATION

The potential Yucca Mountain repository site is centered midway along the 30 km length of the range of hills known as Yucca Mountain. The range, which has a maximum elevation of

about 1,800 m, arcs from a northwesterly orientation to the north of the potential repository site to a north-south orientation south of the site. Geographically the range is bounded to the north by Beatty Wash, and extends towards US Highway 95 further to the south. For most of its length, Yucca Mountain is bounded by Crater Flat on the west and the Forty-mile and Yucca Wash drainages to the east.

The small community of Amargosa Valley is the closest settlement to the repository site, located approximately 20 km south of Yucca Mountain. The town of Beatty is located 25 km west of the repository site. It has been the historic center for a variety of mining and mineral activities in the Bullfrog mining district to the west of town and the Bare Mountain mining district which is centered on the Bare Mountain range immediately to the east of the town, and 15 km to the west of the Yucca Mountain controlled area. The nearest population center of any size is the city of Las Vegas about 150 km to the southeast, which is the largest city in Nevada with a population of about 900,000.

The potential nuclear waste repository site is located on land administered by three federal agencies. The northwestern portion overlaps onto the Nellis Air Force Range administered by the Department of Defense; the eastern portion of the site is located on the National Test Site, administered by the Department of Energy; and the southwestern portion is administered by the U.S. Bureau of Land Management. The U.S. government settlement of Mercury is located in the National Test Site, about 40 km southeast of the controlled area and just outside the area of Plate 1.

Since 1979, The Yucca Mountain controlled area has been the site of extensive drilling and trenching as a result of the U.S. Department of Energy site characterization effort. In this report, drill hole numbers may be shortened in the interest of brevity. The USW prefix may be dropped from holes such as USW G-1, USW H-6, and USW SD-9 to give G-1, H-6, and SD-9, respectively; and drill holes UE 25b 1H, and UE 25p 1 may be referred to as 25b and 25p, respectively. The locations of drill holes cited in this report are shown on Figure 1.

3. METHODS OF STUDY

This report is a compilation of published information on industrial minerals in the Yucca Mountain area. A literature search by area and commodity was performed using materials available in the University of Nevada, Reno, Mines Library. A 1:250,000 scale map (Plate 1) was prepared

using published data as well as unpublished material from the Nevada Bureau of Mines and Geology files. No field work was carried out for this study.

4. HISTORIC MINERAL PRODUCTION

Most of the industrial mineral production in the region surrounding the potential Yucca Mountain repository has come from four mining districts - the Bare Mountain, Bullfrog, Ash Meadows and Death Valley mining districts. Gold was mined in the Bare Mountain (Fluorine) district as early as 1861, and fluorspar (fluorite) deposits were discovered there in 1918. The district has produced more fluorspar than any other district in Nevada, and most of this came from the Daisy mine which operated continuously between 1928 and 1989 (Castor, 1988; Castor, 1990). The Daisy mine was the last remaining producer of fluorspar in the western United States when mining ceased. Other industrial mineral commodities listed for the district are marble, kaolin, montmorillonite, silica, perlite, and volcanic cinder (Tingley, 1994), but production of these commodities has been minor with the exception of volcanic cinder which is mined from a deposit near Lathrop Wells. The Bullfrog district, where gold was discovered in 1904, has had minor clay production since the 1950s (Cornwall, 1972).

In contrast to the Bare Mountain and Bullfrog districts, which have primarily been sites of gold and silver production, the Ash Meadows and Death Valley districts are true industrial mineral districts. The Ash Meadows district covers a large sink and meadow area in the Amargosa Desert in Nevada and California. Clay was discovered in the district in 1917, and has been mined there fairly steadily since 1918 (Hosterman and Patterson, 1992). Large-scale clay mining in Ash Meadows took place in the late 1920s and early 1930s, and was revived in the 1970s. The clay is mined from deposits in both California and Nevada, and processed in Nevada, and the district is now the site of most of Nevada's clay production. In addition, small amounts of zeolite are mined from the California side of the Ash Meadows district and processed in Nevada.

The Death Valley district, which is wholly within California, is one of the best known sources of borate minerals in the world and has also been important as a source of talc. Production of borates from Death Valley began in 1881-1882 when the Eagle Borax Works and Harmony Borax Works were built, and all but ceased during the period 1928-1956 (Evans et al., 1976). Modern production began in the 1970s when Death Valley deposits became a major source of calcium borate, and continues to the present at the Billie mine. Mining of talc deposits in the Death Valley area began about 1910, but production of significant amounts of the mineral

from Death Valley did not take place until the 1940s (Evans et al., 1976). With the exception of the Omega mine which is located south of the boundary of Plate 1, talc mines in the Death Valley district are inactive (Piniaskiewicz et al, 1994).

5. GEOLOGIC SETTING

5.1. Regional setting

5.1.1. Lithology

The geology of the area around the Yucca Mountain Addition is dominated by the rocks of the southwestern Nevada volcanic field (SWNVF) as defined by Byers et al. (1976). Ash-flow tuff and related rocks from at least four major Miocene calderas comprise this volcanic field, which once covered an area of more than 10,000 km² (Byers et al., 1989). The Tertiary rocks overlie variably metamorphosed and deformed sedimentary rocks of Precambrian to Permian age.

Precambrian rocks are exposed on Bare Mountain to the west of the controlled area, where they consist of mildly metamorphosed quartzite, siltstone, and shale. Further to the west in the Death Valley area, Precambrian rocks include high-grade schists and gneisses.

Paleozoic rocks in the Yucca Mountain region are part of a miogeoclinal sequence that is dominated by carbonate rocks, but includes minor quartzite, siltstone and shale. They occur in structural blocks to the west, south, and east of the controlled area. The nearest Paleozoic exposures to Yucca Mountain controlled area are Cambrian to Mississippian rocks of Bare Mountain and Devonian to Mississippian rocks of the Calico Hills.

Volcanic activity of the SWNVF was of middle to late Miocene age, about 15 to 7 Ma. Volcanic rocks of the SWNVF overlap Oligocene to early Miocene volcanic rocks to the north, such as volcanic rocks of the Goldfield mining district. Many of the units that make up the volcanic stratigraphy of the SWNVF have been dated by K/Ar and Ar/Ar methods, and this data supports episodic activity that can be divided into four main stages. The earliest stage includes the 15 Ma calc-alkaline Redrock Valley and tuff of Yucca Flat (Sawyer et al., 1994) whose source area is not known, and the 14.9 Ma peralkaline Tub Spring Tuff (Sawyer et al., 1990) which probably came from the proposed Sleeping Butte caldera about 35 km northwest of the Yucca Mountain Addition (Christiansen et al., 1977). The second stage of volcanic activity, which together with the above

mentioned tuffs has been referred to as the "main magmatic stage" by Noble et al. (1991) consists of ash flow sheets and lavas that range between about 14 Ma and 12.5 Ma (Sawyer et al., 1990). A hiatus in SWNVF volcanic activity of about 0.8 million year is indicated between the first and second stages, but older tuffs and lava flows intersected by drill holes at Yucca Mountain (Table 1) may have been erupted during this period.

The second stage of SWNVF activity includes ash flows of the Lithic Ridge Tuff and Crater Flat Group (14.0 to 13.1 Ma) that are considered by Carr et al. (1986) to be from the Crater Flat - Prospector Pass Caldera complex, whose eastern wall is thought to lie beneath the west flank of Yucca Mountain. However, the existence of this complex has been contested (Scott, 1986; Sawyer et al., 1994), and Byers et al. (1976) speculated that parts of the Crater Flat Tuff were erupted from the proposed Sleeping Butte caldera.

At Wahmonie, about 30 km east of Yucca Mountain, flows and tuffs with associated intrusives now Assigned to the Wahmonie Formation were deposited at about 13.0 Ma (Sawyer et al., 1994). These rocks, which are of andesitic to rhyodacitic composition (Ekren and Sargent, 1965), differ from most other rocks of the SWNVF, which are predominantly rhyolitic to latitic. At about 12.9 Ma (Sawyer et al., 1990), lavas and tuffs of the Calico Hills Formation were deposited in the Calico Hills, 10 km northeast of the Yucca Mountain Addition, and thick sections of the Calico Hills Formation were intersected by drill holes at Yucca Mountain (Table 1).

The Paintbrush Group, a 1300+ km³ unit consisting of four ash-flow formations and associated bedded tuff units, was erupted between 12.8 and 12.7 Ma (Sawyer et al., 1990). Byers et al. (1976 and 1989) suggested that these tuffs erupted from the Claim Canyon caldera about 5 km north of the Yucca Mountain site, but the upper parts of the Paintbrush Group may have originated from the Oasis Valley caldera segment further to the northwest (Christiansen et al., 1977). Following Paintbrush Group eruptions, rhyolitic lavas were extruded between 12.7 and 12.45 Ma at several places in the SWNVF. The main magmatic stage was followed by a 0.8 million year hiatus in volcanic activity (Fleck et al., 1991); although Noble et al. (1991) noted that some volumetrically minor lavas with petrographic characteristics intermediate between those of the Paintbrush Group and subsequent Timber Mountain magmatic stage ash-flow tuffs may have been erupted during this period.

A 11.7-Ma rhyolite flow was the earliest extrusion in the Timber Mountain magmatic stage (Fleck et al., 1991). It was followed by eruption of the Timber Mountain Group, the most significant ash-flow sequence in the SWNVF in terms of total volume (2000+ km³), between 11.6

and 11.45 Ma (Sawyer et al., 1990). Eruption of this unit, which consists of two major members, produced the Timber Mountain caldera (Byers et al., 1976), a large, well-preserved feature centered about 25 km north of the Yucca Mountain site. Post-collapse volcanic activity in the Timber Mountain caldera, mainly as rhyolitic flows, is thought to have continued until about 10.4 Ma (Fleck et al., 1991). Rhyolitic tuffs and lavas of the Bullfrog Hills about 30 km west of Yucca Mountain have yielded K/Ar ages as young as 10.1 ± 0.3 Ma (Noble et al., 1991).

The late magmatic stage of Noble et al. (1991) includes the 9.4-Ma Thirsty Canyon Group tuffs, 9.2-Ma basalts (Fleck et al., 1991), and the 7.5-Ma Stonewall Flat Tuff (Sawyer et al., 1990). These units completed the history of major ash-flow deposition in the SWNVF, but Miocene basalt flows as young as 7.0 Ma were subsequently erupted (Fleck et al., 1991).

A hiatus in volcanic activity of about 3 million years followed the Miocene late magmatic stage. Pliocene basalt yielding a 4-Ma date has been drilled beneath Crater Flat 5 to 10 km west of the Yucca Mountain site (Carr, 1988a). Fleck et al. (1991) reported dates of 3.8-2.8 Ma for Pliocene basalts and 1.2-0.13 Ma for Quaternary basalts in the SWNVF. Basalt flows and cinder cones erupted about 1 Ma occur at the surface on Crater Flat (Carr, 1988a). Lava flows at the Lathrop Wells volcanic center 13 km south of the Yucca Mountain site are thought to be less than 100 Ka, and cinder cone deposition at the same site is estimated at less than 15 Ka (Crowe et al., 1988).

Tertiary sedimentary rocks in the Yucca Mountain region include volcanogenic sedimentary sequences that occur at low levels in the SWNVF sequence. Such rocks have been mapped in the Bare Mountain area (Monsen et al., 1992) and in the Bullfrog Hills (Maldonado and Hausback, 1990). In the Death Valley area of California, sedimentary rocks dominate the Tertiary strata. The Oligocene to Pliocene Artist Drive Formation is partly contemporaneous with the volcanic rocks of the SWNVF, but contains sedimentary rocks that range from mudstones to conglomerates, along with pyroclastic and volcanic flow sequences (McAllister, 1970). In the Ash Meadows area, about 25 km south of Yucca Mountain, contains a Pliocene sequence of fluvial to lacustrine sedimentary rocks with tuffaceous beds that have been dated at about 3 Ma (Hay et al., 1986). In basinal areas between the mountain ranges, the Yucca Mountain region contains Quaternary fanglomerate deposits along with modern playa, eolian, and fluvial deposits.

5.1.2. Structure

Structures affecting the rocks of the SWNVF are mostly considered to have resulted from

two interactive tectonic processes that took place about 17-8 Ma: extension of the southern Basin and Range province; and caldera formation. As noted by Sawyer et al. (1994), volcanism and extensional tectonism were broadly concurrent in the area, but in detail were episodic in time and not coincident in space. Large-scale Paleozoic and Mesozoic structures in the region, which were strongly modified during the Cenozoic, have been used in attempts to determine the direction and intensity of regional Cenozoic extension (e.g., Guth, 1981; Wernicke et al, 1988). Miocene extension was accommodated by west-dipping normal faults that are thought to bottom in low-angle detachment surfaces and by right-lateral shear along the Walker Lane, a major 100-km-wide northwesterly zone in western Nevada that includes the SWNVF. Fault patterns related to caldera subsidence and resurgent doming add to the structural complexity.

Steeply westward-dipping normal faults are abundant in the Yucca Mountain area (Scott and Bonk, 1984), and may represent the breakaway zone for detachment faulting that bounds Bare Mountain about 10 km east of Yucca Mountain. According to Hamilton (1988), normal faults at Yucca Mountain were active above an 11 Ma hinge line between more-or-less flat-lying detachment to the east and moderately westward dipping detachment to the west. Hamilton believes that this detachment surface, which separates Tertiary volcanics from pre-Tertiary rocks, now extends from east of Yucca Mountain in the subsurface, through surface exposures on Bare Mountain and the Funeral Mountains, into Death Valley. Range-bounding faults around Bare Mountain are considered by Hamilton to be part of a low to moderately dipping detachment surface, whereas Carr (1988a) proposed that the fault bounding the east side of Bare Mountain is a steeply dipping feature related mainly to subsidence of the proposed 14-Ma Crater Flat-Prospector Pass caldera and that Yucca Mountain normal faulting was caused by reactivation along subsidence-bounding fractures of the same caldera. Carr (1988b) proposed that the southwestern Nevada volcanic field calderas were emplaced along a north-south rift in the Walker Lane structural zone that separated detachment faulting to the west from gravitational extensional faulting to the east.

Geophysical data suggest that the faults bounding the Bare Mountain Precambrian and Paleozoic block dip at 30° or less (Ackermann et al., 1988). The Fluorspar Canyon fault, which forms the northern boundary of Paleozoic rocks in the Bare Mountain area is thought to be an extension of the nearly flat-lying Bullfrog detachment fault between Tertiary and pre-Tertiary rocks at the Original Bullfrog mine 30 km west of the Yucca Mountain Addition. Although surface outcrops along the Fluorspar Canyon fault suggest northerly dips of 60° or more, drilling at the Mother Lode gold deposit near the east end of the fault indicated a northerly dip of about 30°.

Table 1. Generalized stratigraphy, Yucca Mountain

Compiled from Spengler et al. (1979), Spengler et al. (1981), Maldonado and Koether (1983), Carr et al (1986a), Carr et al. (1986b), Scott and Bonk (1984), Byers et al. (1976), Sawyer et al. (1990), Scott and Castellanos (1984), Caporuscio et al (1982), Broxton et al. (1989), and Sawyer et al. (1994).

Stippled pattern = bedded tuff sequence; striped pattern = volcanic flow unit.

Unit	Subunit	Thickness in feet (meters)	Age (Ma)	General Description	Remarks
Timber Mountain Tuff	Rainier Mesa Member	525+ (160+)	11.6	Crystal-rich, partly vitric, gray to pink densely welded, ash-flow tuff with rare lithics.	Abundant quartz phenocrysts; surface only
		20+ (6+)		Air-fall tuff	Surface only
Paintbrush Tuff	Tiva Canyon Member	75-375 (23-114)	12.7	Mostly crystal-poor densely welded rhyolitic ash-flow tuff with thin crystal-rich quartz latite cap; partly vitric; locally abundant lithophysal cavities; rare lithics.	Very sparse quartz phenocrysts; thickens northward
		1-50 (<1-15)		Air-fall tuff, some ash-flow and reworked tuff	Thickens northward
		0-95 (0-29)		Nearly phenocryst-free, nonwelded to partly welded ash-flow tuff; partly vitric	No quartz phenos; thickens northward
	Pah Canyon Member	36-157 (11-48)		Air-fall and reworked tuff	Thickest in hole G2
		0-233 (0-71)		Nonwelded ash-flow tuff with sparse lithics; partly vitric	Bronze biotite; thickens northward
		29 (9)		Air-fall and reworked tuff	Thickest in hole G2
	Topopah Spring Member	942-1167 (287-356)	12.8	Mostly crystal-poor densely welded rhyolitic ash-flow tuff, cap crystal-rich; sparse lithics; partly vitric	Bronze biotite, rare quartz phenocrysts in cap; thickest in G1 and 25b
		3-56 (1-17)		Reworked tuff	Thickest in hole G2
Tuff of Calico Hills		134-948 (41-289)	12.9	Mostly crystal-poor nonwelded ash-flow tuff, crystal-rich near base in hole G2; part air-fall and reworked tuff; rare to common lithics; partly vitric in GU 3	Typically zeolitized; thickest in hole G2 where faulted off at base
Crater Flat Tuff	Prow Pass Member	350-545 (107-166)	13.1	Partly to moderately welded ash-flow tuff; moderately crystal rich; sparse lithics, mainly of mudstone; upper part partly glassy in hole GU 3	Quartz phenocrysts highly resorbed; orthopyroxene; thickest in hole G2
		13-34 (4-10)		Air-fall and reworked tuff	Thickest in hole G2
	Bullfrog Member	223-548 ft (68-167 m)	13.25	Densely welded to non-welded ash-flow tuff; moderate to abundant phenocrysts; sparse mudstone and intermediate volcanic lithics; trace pyrite near base in	Large resorbed quartz phenocrysts, thickest in hole 25b, thins to north
		20-71 (6-22)		Air-fall and reworked tuff	Thickest in hole G2
	Upper Tram Member	479-489 (146-149)		Crystal-rich moderately welded ash-flow tuff; sparse to moderately abundant rhyolitic and intermediate volcanic lithic fragments; thin air-fall breaks	Thins to north; allanite in basal 100m
	Lower Tram Member	341-725 (104-221)	ca. 13.4	Slightly to moderately welded ash-flow tuff; abundant lithics, mainly intermediate volcanic; moderate to abundant phenocrysts; pyritic in holes 25b, G1, and G3	Thickest in hole G3, thinnest in G2; allanite relatively abundant
		26-164 (8-50)		Air-fall tuff	Thickest in G2
		72-361 (22-110)		Dacite to rhyodacite lava and flow breccia; abundant phenocrysts	Only present in holes G1 and G2, thickest in G2
		26-46 (8-14)		Reworked tuff	Only present in G1 and
Lithic Ridge Tuff	bottom hole 25b	607-997 (185-304)	14.0	Nonwelded to partially welded ash-flow tuff; abundant rhyolitic to intermediate volcanic lithics; moderate to abundant phenocrysts; pyrite near base in hole G3	Relatively abundant sphene, thickest in hole G3, thinnest in G2
		10-23 (3-7)		Air-fall and reworked tuff	Thickest in G2
Older tuffs of G1	Units A and B bottom hole G3	46-508 (14-155)		Mostly moderately welded crystal-rich ash-flow tuff, sparse lithics	Sphene; thickest in hole G1, thinnest in G2
		43 ft (13)		Reworked and air-fall tuff	Only present in hole G1
	Unit C bottom hole G1	125-508+ (38-155+)		Crystal-rich, nonwelded ash-flow tuff with sparse to abundant lithics; nearly 20 percent bedded tuff	No quartz phenocrysts, only found in hole G1
		331 (101)		Flow-banded, spherulitic rhyolite flow and flow breccia; moderately abundant phenocrysts	Only present in hole G2
		433 (132)		Quartz latite lava and flow breccia; moderately abundant phenocrysts; altered with pyrite near top	Only present in hole G2
		33 (10)		Crystal-rich bedded and ash-flow tuff	Only present in G2; may be the same as unit C, G1
		217 (66)		Dacite lava and flow breccia; abundant phenocrysts	Only present in hole G2
		56-110 (17-34)		Reworked tuff, gray conglomerate, and ash-flow tuff (G2); conglomerate, volcanic and Paleozoic clasts	Only intersected by holes G2 and 25p
Calclitized ash-flow tuff		110 (33)		Crystal-poor calclitized ash-flow tuff; sparse lithics; plagioclase replaced by calcite	Only present in hole 25p
Older tuffs of G2	bottom hole G2	62 (19)		Crystal-rich ash-flow tuff; may be correlative with unit below	Only present in hole G2
Tuff of Yucca Flat (?)		130 (40)	15.1	Ash-flow tuff with moderately abundant phenocrysts and lithics	Only present in hole 25p
Lone Mountain Dolomite		1398 (426)	Silurian	Dolomite, massive to poorly bedded; conglomerate and intraformational breccia near base; local pyrite and drusy quartz	Only intersected by hole 25p
Roberts Mountain Formation	bottom hole 25p	444 (135)	Silurian	Dolomite with minor chert, locally laminated; local pyrite, fluorite, and drusy quartz	Only intersected by hole 25p

5.2 Geology of the controlled area

The stratigraphic section at Yucca Mountain in and adjacent to the potential repository site is shown in summary in Table 1. Volcanic units exposed at the surface in and near the proposed repository site make up a small portion of the total volcanic sequence that has been encountered in drill holes.

Outcrops in the Yucca Mountain controlled area consist mostly of ash-flow tuff of the Paintbrush Group, principally the Tiva Canyon Tuff and the underlying Topopah Spring Tuff (Scott and Bonk, 1984). A bedded tuff sequence occurs between the Tiva Canyon and Topopah Spring Tuffs. It contains layers of poorly lithified ash-flow tuff, air-fall tuff, water-worked tuff, and possibly some surge deposits. To the north, this bedded tuff unit is interbedded with mappable ash-flow tuffs of the Pah Canyon and Yucca Mountain Tuffs.

The Rainier Mesa Tuff of the Timber Mountain Group is exposed in the southern part of the Yucca Mountain controlled area. Minor amounts of a bedded tuff sequence that underlies the Rainier Mesa Tuff also crops out in this area. Canyons and washes in the controlled area contain Quaternary sand and gravel deposits

6. ECONOMIC GEOLOGY EVALUATION

6.1. Fluorspar

6.1.1. Geology of fluorspar deposits

The mineral fluorite is the world's main source of commercial fluorine. When a deposit of fluorite is considered commercial it is referred to as the commodity 'fluorspar.' Fluorite contains 51.1% calcium and 48.9% fluorine, ranges from colorless through white, yellow, green, purple to blue, and is commonly distinguishable by its high level of crystallinity, occurring in well-formed cubic crystals. It is also found in massive and earthy forms, and as crusts or globular aggregates.

Fluorite is most often found as an accessory mineral in a wide range of ore deposits associated with galena, sphalerite, barite, pyrite, quartz, calcite, and other carbonates. As an accessory mineral it can be deposited under a wide range of physical and chemical conditions, from deep-seated veins in granite and related igneous rocks to bedded deposits in poorly

consolidated sediments. Fluorspar deposits occur in a variety of settings :

- Stratiform replacement deposits in carbonate rocks
- Fissure veins in igneous, metamorphic, and sedimentary rocks
- Stock works and fillings in shattered zones
- Replacements in carbonate rocks along contacts with acid igneous intrusives
- Deposits at the margins of carbonatite and alkalic rock complexes
- Fillings in breccia pipes
- Pegmatites
- Residual concentrations from the weathering of primary deposits
- As a gangue mineral in metal deposits
- Stratiform diagenetic deposits in volcanoclastic rocks

Stratiform replacement deposits of fluorite are widely known, and these deposits are important producing ore bodies for fluorspar world wide. Fluorite content in mineable stratiform deposits generally exceeds 15%, and often the mineral is concentrated in areas of enhanced fracture porosity or in dissolution textures in rocks containing solution distribution networks dominated by faulting or fissure development and widespread fracturing. Carbonate rocks generally host such deposits. This type of deposit includes some of the largest high-grade fluorite accumulations, such as those that occur in the Las Cuevas Fluorite District of northern Coahuila State in Mexico as 'Mantos-style deposits' (Temple and Grogan, 1963). Individual fluorspar ore bodies range up to several hundred feet in length, are typically of the order 100 feet wide, and range between 2 and 15 feet in thickness. Although deposits are discontinuous and somewhat difficult to mine, they are predictable, easily defined, and extraction costs remain relatively low, considering that typical grades are 70% to 90% fluorite (Temple and Grogan, 1963).

Despite the grade and ease of mining for stratiform fluorspar deposits, the vast majority of producing deposits take the form of replacement or open-space filling deposits associated with faults, shear zones, and fractured and brecciated areas. The source of fluorine-rich solutions is generally considered to be hydrothermal. Hydrothermal activity can lead to wall-rock replacement in carbonate units, and vein and breccia formation in carbonates and other rocks. Such mineralization may occur in contact zones surrounding intrusive bodies which are often of granitic composition. Typically faults, fissures, fracturing and breccia zones at igneous contacts act as conduits for mineralizing fluids after igneous activity has ceased. Reactive host rock such as a limestone may be replaced outwards from the contact, either massively or along favorably reactive beds. On the whole fluorspar grades for these type of occurrences are usually only of the order

30%, and ore bodies tend to be discontinuous, structurally disordered, relatively smaller, and less predictable than stratiform deposits. Extraction costs are characteristically high, and fluorspar may be produced as a co-product of other mineral production (e.g. base-metals or barite).

6.1.2 Production, uses, grades, prices, and market outlook

There are three principal market grades of fluorspar, and specifications for these are fairly well defined, although requirements may vary in critical details for individual customers, depending upon processing and utility.

Acid-grade fluorspar (acidspars)

Fluorspar is used to manufacture hydrofluoric acid which serves as an intermediate product in the manufacture of organic and inorganic fluoride chemicals such as fluorocarbons, aluminum fluoride, and synthetic cryolite (calcium fluoride). The acid is an important catalyst in the manufacture of alkylate - an ingredient of high-octane fuels, and is used in steel pickling, glass etching and polishing, and in the electroplating industry. This grade for fluorspar is typically defined as containing not less than 97% CaF_2 . The moisture content of both acid-grade and ceramic-grades is usually specified to be not more than 0.10% H_2O . Generally a silica content of less than 1.5%, and a sulfur content of 0.03 - 0.10% is required, although individual users may specify their own limits for silica, calcium, carbonate, arsenic, lead, sulfide sulfur, phosphorous, and other deleterious substances.

Ceramic grades of acidspars

Nearly every user of ceramic-grade fluorspar has its own preferred specifications, and producers must often tailor their products to suit. On the whole this grade requires a minimum of 97% CaF_2 , but in some instances buyers may specify < 2.5% or < 3.0% silica, limited amounts of calcite, ferric oxide, and only traces of lead and zinc sulfides. This grade of fluorspar is used to make flint glass, white or colored opal glass, and baked enamels. It has also been used in the manufacture of magnesium or calcium metal, titanium oxide, aluminum smelting, some manganese chemicals, and welding rod coatings. Grades of lower purity are used in glass-fiber manufacture and in zinc smelting.

Metallurgical grade fluorspar (metspar)

In the U.S. (the world's largest fluorspar consumer), metspar has typically contained a minimum of 60% 'effective' fluorspar, and generally not over 0.30% sulfide sulfur and 0.25 -

0.50% lead. In markets outside the U.S, metspar may contain a minimum of 80% CaF_2 , and a maximum of 15% silica. To qualify as 'lump spar' or 'gravel spar' metspar is usually required to pass a 1 - 1.5 inch screen, and contain < 15% of - 0.065 inch size fraction. However, the development of fluorspar briquettes or pellets has enabled material previously regarded as fines to be better utilized. Metspar has historically served as a flux in steel making and iron-making, accounting for almost half of the world's fluorspar consumption. When added to metallurgical slags it reduces the melting point and surface tension of the slag, to allow greater fluidity and separation at lower temperatures. The adoption of the Basic Oxygen Furnace for steel making did initially lead to an increase in fluorspar consumption, although the arrival of modifications to this process, combined with environmental pressure to reduce fluorine emissions from smelters has reduced consumption in these areas in recent years.

China dominates as the world's leading fluorspar producer. In 1992, the six leading countries for production were China with 1.6 Mt, followed by Mexico as a distant second with 364,000 tons, the former USSR at 300,000 tons, Mongolia at 277,000 tons, South Africa with 258,000 tons, and France with 160,000 tons. China's share in world production has steadily increased in recent years, securing its place as the world's leading exporter of fluorspar. By the end of this century it is predicted that China will have 60% of the world market (Burger, 1991). World wide market penetration by Chinese fluorspar has been a continuing feature of the 1990s, and to a large extent China has set the world price for fluorspar in the last few years (Miller, 1995).

The United States remains the leading consumer of fluorspar and fluorine-based industrial products in the world, relying heavily on imports for both acid-grade fluorspar and metallurgical-grade fluorspar. In addition, insufficient ceramic-grade fluorspar is produced in the country to meet domestic demand. The rise of Chinese imports of fluorspar into the U.S. has been at the demise of Mexico and South Africa. In 1994, China was the leading source of fluorspar to the United States, with 61% of all imports, followed by South Africa with 24%, and Mexico with 13%. South Africa shipped 119,000 tons of acid grade fluorspar, and Mexico shipped 10,000 tons of acid grade and 53,000 tons of metallurgical grade fluorspar (Miller, 1995). In 1991, the U.S. had only one significant fluorspar producer that mined from three underground mines operating at between 200 and 300 m depth in southern Illinois (Burger, 1991). No fluorspar has been mined in Nevada since 1989, and since the early 1960s production in the state has followed a general downward trend (Fig. 2).

On the whole, fluorspar markets have been in transition for much of this decade, and market movement is still a major feature of the fluorspar industry. This has made longer term

predictions and future planning difficult. Of the three major markets for fluorspar in the U.S. - hydrofluoric acid (HF), aluminum production, and steel production - it is only the HF market that has shown recent improvements against overall declining consumption. In recent years the demand for HF has been steadily decreasing due to the enforced phase-out of chlorofluorocarbons (CFC's) which will be completed in the U.S. by 1996. The switch to alternative hydrofluorocarbons (HFC's) and hydrochlorofluorocarbons (HCFC's) may be providing a possible turnaround in demand for HF in the future. Fluorocarbon production accounts for over 60% of consumption of acid grade fluorspar. Domestic aluminum production has seen continued decline in the U.S. over the last eight years. In addition, significant shifts in alternative sources of fluorine for electrolytic smelting are now occurring. Miller(1995) reports that the aluminum industry could be fed from fluorosilicic acid derived aluminum fluoride, rather than fluorspar-derived material in the future. Declining U.S. steel production in the early 1990s has lead to a decline in markets for metallurgical grade fluorspar, which is expected to continue (Miller, 1995). This has been compounded by technological changes in the use of fluorine compounds.

Figure 2. Fluorspar production in Nevada, 1952-1989.

Source: unpublished U.S. Bureau of Mines data. Checkered pattern: Bare Mountain mining district; no pattern: rest of Nevada.

The rise in dominance of Chinese fluorspar has not come without difficulties for both China and the United States. For many years China has been prone to overproduction of the mineral, primarily for export. In 1994, China's central government imposed an export license and quota system for the export of fluorspar, partly in an effort to divert production to internal markets. The new system imposed stiff license fees and reduced export volumes. In combination with

other factors, the result has been a large increase in the price of Chinese fluorspar worldwide. Prices for all US Gulf port imports of acid grade fluorspar (dry bulk) have gone from \$95 to \$100 per ton at the end of 1993 to \$120 - 130 per ton at the end of 1994. European consumers of Chinese fluorspar have seen similar price increases, compounded by European anti-dumping duties imposed on imports of Chinese fluorspar in filter cake or powder form. The July, 1995, edition of the journal Industrial Minerals quoted the following prices for acid grade and metallurgical fluorspar:

•	US Gulf port, dry basis, acidspar	US \$140 - 150
•	Acidspar, Chinese wet filter cake, CIF Rotterdam	US \$145 - \$155
•	Mexican, FOB Tampico, Acidspar filter cake	US \$115 - \$120
	Metallurgical	US \$ 85 - 95
•	South African acidspar dry basis, FOB Durban	US \$100 - 115

To give some indication of price movement, Harben (1992, p.31) provides FOB price ranges for 1990 and 1991 for Mexican and South African acidspar at US \$135 - 140 per ton, and Mexican Metspar at US \$95 per ton.

On a world scale, reported reserves for fluorspar have been increasing for several decades. Increases in reserves probably reflect an increase in production to fill a growing demand for captive material supplies, or for quite specific new market opportunities. Shifting utility for fluorspar and fluorine products, fluctuating demand, and an excess in production capacity, as a result of catering to serve demand peaks, has historically lead to cycles of overproduction, closures, and price fluctuations which still plague the industry. The recent moves in China to limit exports of fluorspar is probably the most recent of these fluctuations.

Overall, fluorspar in its many grades is an internationally traded commodity. Production sites tend to be localized depending upon the type of resource or on by-production opportunities. Relatively high-value fluorspar products allow ample margins for international transportation to major industrial consumption centers. Beyond these structural features of the industry, environmental concerns over fluorine emissions have necessitated careful recycling and conservation, and reduced consumption in many industries. The effect has been to concentrate fluorspar production into fewer world localities. The relatively continuous and rapid shifts in markets for acid-grade fluorspar products, and the rapid substitution of environmentally sensitive fluorine-based products have made future predictions in markets and consumption uncertain. The certain trend towards less consumption of fluorine compounds in metal manufacture will likely

cause concern for longer-term outlooks for metspar. Nevertheless, there will be a continuing demand for fluorine-based products within industry that cannot be denied, and will have to be satisfied in the future.

6.1.3. Resources in the Yucca Mountain region

6.1.3.1. Region surrounding the controlled area

Metallurgical grade fluorspar was mined continuously for more than 60 years in the Bare Mountain district near Beatty (Horton, 1961; Papke, 1979). The district is considered one of three locations in Nevada which have potential for the production of fluorspar (Papke, 1979, Castor, 1993). When mining ceased in 1989 the Bare Mountain district had produced more than 300,000 short tons of fluorspar, more than 40% of the total production in Nevada (Fig. 2).

The Bare Mountain district is known for the production of gold, mercury, and fluorite. Fluorite is reported to occur as an associated mineral in both gold and mercury deposits. The mineral deposits are located in four distinct clusters along the northern and eastern margins of Bare Mountain, about 12 - 15 km to the west of the Yucca Mountain controlled area. The Thompson mine and Telluride areas are historic mercury producing areas, and the Mother Lode mine in the Telluride area produced gold in 1989 and 1990 (Bonham and Hess, 1994). The third area, known as the Panama-Sterling gold area, produced gold between 1983 and 1991 (Bonham and Hess, 1994), and the Sterling mine is currently being put back into production. The remaining area is distinguished solely for the production of fluorspar and is the site of the Daisy mine, but does contain subeconomic gold resources. Fluorite is reported present in all areas except that of the Thompson mine.

Mineral deposits on and around Bare Mountain are considered to fall into two categories: gold-base metal-quartz vein deposits hosted by Precambrian and Cambrian sedimentary rocks, and gold-mercury-fluorite deposits that occur in Cambrian sedimentary rocks, and in volcanic rocks of Miocene age. The four mining areas listed above are in the latter category. Bare Mountain is almost entirely composed of late Precambrian and early Paleozoic sedimentary rocks that have been intensely folded and faulted. These rocks are exposed along the western and southeast slopes of the mountain, with the remaining northeastern section made up of formations ranging in age from Ordovician through to Mississippian. Tingley (1984) reported that altered Tertiary rhyolite to rhyodacite dikes cut Paleozoic bedrock of Bare Mountain, and Carr (1986) reported that

these dikes are coeval with lava flows that underlie tuffs of the Crater Flat Group, so that their arcuate pattern, which is gently concave toward Crater Flat, may represent a system of outlying ring dikes beyond the western rim of the proposed Crater Flat caldera. Fluorite-rich breccia pipes are associated with these dikes at the Diamond Queen mine on the eastern edge of Bare Mountain, and the gold mineralization of the Sterling mine occurs in an area cut by these dike rocks (Tingley, 1984). On the basis of trace element associations in this area, Tingley (1984) concluded that two periods of mineralization occurred, and that the most recent period, represented by an As, Sb, Mo, Ag, Hg, and F elemental association, may be related to either the Crater Flat caldera system to the east or the Timber Mountain caldera complex to the north.

The Daisy (Crowell) mine area

The Daisy mine is located in Fluorspar Canyon, in the northern part of Bare Mountain, about 5 miles by road east of Beatty (Plate 1). Fluorspar was recognized at this site in 1906 during the Bullfrog gold boom, and the first claims, which are still valid, were located by J. Irving Crowell in 1919. The Continental Fluorspar Co. produced the first fluorspar ore in Nevada from this mine in small tonnages during the period 1919 - 1922. Table 2 provides a summary of production from the Daisy mine and nearby workings. Since mining ceased in 1989, small tonnages of fluorspar have been sold each year from stockpiled ore. In 1994 approximately 150 tons were shipped for steel and cement manufacture, and more than 2,000 tons of fluorspar remained in stockpile (Castor, 1995).

Table 2. Fluorspar production at the Daisy mine.

From Papke, 1979, and unpublished USBM data.

Period	Short tons
1919 - 1922	1,632
1928 - 1939	5,972
1940 - 1947	28,913
1948 - 1961	79,831
1962 - 1967	19,327
1968 - 1976	68,833
<u>1977 - 1989</u>	<u>30,800 est</u>
Total	235,308

Fluorspar ore bodies at the Daisy mine take the form of near-vertical pipelike hydrothermal replacements in dolomite of the Late Cambrian Nopah Formation (Papke, 1979). At the Daisy

mine the host dolomite occurs as a series of beds dipping to the southeast and most of the ore bodies are lenticular irregular masses of various sizes, with widths ranging from inches to 50 feet or more. Mineralized zones containing these ore bodies have a general northeast trend and steep southeasterly dips. Ore emplacement took place as ascending hydrothermal solutions channeled through the clay gouge of these fault zones (Papke, 1979). Typical ore is composed of fluorite, variable amounts of montmorillonite, with a small amount of quartz or calcite. The clay is the major source of silica contamination in the ore. On the basis of radioactivity studies, Chesterman and Main (1954) reported that six samples of fluorspar from this area contained 0.007 to 0.015% equivalent U_3O_8 .

The Daisy mine is developed on 13 levels to a depth of about 500 feet. Workings on the lowest level extend laterally for 900 feet. Access is via a decline of 50° to 70°. Mining was done selectively in open stopes, and the largest stope is 150 feet long, 80 feet high, and 20 feet wide (Papke, 1979, p.42). The ore body in the area of the mine has been defined with some 3,661 feet of coring from twelve drill holes, but limits to the ore zone are not defined.

Papke (1979) described the production from this mine as a metallurgical grade ore, which was sold to steel companies in the western U.S. In recent years, some lower-grade fluorspar has been sold to a cement producer, presumably as a mineralizer to facilitate clinkering. Most of the ore produced graded 70 - 80% CaF_2 with 2 - 4% SiO_2 . Metallurgical tests on the ore were carried out by the USBM (Geehan, 1946), and showed that the ore as extracted was not suitable as acid-grade material, but further concentration of the ore by flotation produced an acid-grade material at 97% CaF_2 with a recovery rate of between 85% and 93% (McCreedy, 1965). Until 1949, ore was simply washed and sized to remove clay at a small mill in Beatty (Kral, 1951). At that time reserves were considered sufficient for many years of operation at that current mining rate. Papke (1979) notes that two samples of the fluorspar ore which were used in metallurgical tests carried out by the USBM (Geehan, 1946) had the following compositions:

	<u>CaF₂</u>	<u>SiO₂</u>	<u>CaCO₃</u>	<u>Al₂O₃</u>	<u>Fe</u>	<u>Insol.</u>
Sample 1	77.5	2.4	3.9	2.9	.35	3.6
Sample 2	72.2	6.8	1.6	5.6	.86	11.2

Fluorspar was extracted from other workings in the Daisy mine area. The Lige Harris and Enif shafts are located 1,200 and 1,400 feet west of the Daisy mine shaft, and the Yellow Spar workings are located three quarters of a mile southwest of the Daisy shaft. The Lige Harris shaft is some 50 feet deep with limited drifts to the northeast and northwest. A nearby glory hole some

75 feet in diameter was developed in the late 1960s and early 1970s. The Enif shaft located 200 feet to the west is 70 feet deep with a drift extending 45 feet eastwards. The comparatively complex ore bodies near these two mines have a general E-W strike, and Papke (1979) reports no known relation between them and the ore bodies in the Daisy area. At the Yellowspar mine, fluorspar followed a gently declined stope extending some 20 feet from the surface. Sorted ore from this mine is reported as hard and of very high grade (Papke, 1979, p.43), and it was used to upgrade ore from the Daisy mine. Additional fluorspar discoveries were made in the vicinity of these outlying mines, particularly to the west of the Lige Harris - Enif area.

The Panama-Sterling gold area

On the eastern slope of Bare Mountain, fluorite is found with gold mineralization in breccias and breccia pipes at several mines and prospects north of Wildcat Peak. Fluorspar was mined from the Goldspar (Diamond Queen) and Mary Mines from the 1950's to the early 1970's (Papke, 1979). Grades and composition of ore have not been reported, but are likely to have varied considerably. Fluorite is locally present in hydrothermal breccias within the zone of disseminated-gold mineralization at the currently productive Sterling gold mine. To the north of the Sterling mine, fluorite and trace amounts of gold can be observed in breccia pipes at the Mary and Diamond Queen Mines. The breccia pipes appear to follow the trend of a number of northeast - striking rhyolite dikes. A variety of temporal associations between the fluorite mineralization and the brecciation are noted, suggesting the possibility of several periods of fluorite mineralization. Tingley (1984) noted that all of the breccia deposits which extend from the Panama mine northwards to the Mary fluorspar mine are aligned along a general north-striking zone of argillic alteration that is associated with a swarm of rhyolitic dikes.

At the Mary mine, fluorspar occurs as irregular, pipe-like ore bodies in dolomite of the Roberts Mountain Formation (Middle Silurian) and the Lone Mountain Dolomite (Upper Silurian). Papke (1979) noted that additional fluorspar occurrences had been located in diggings at two other sites approximately 1,000 feet from the Mary mine. At the Goldspar mine, a mile south of the Mary mine, fluorspar mineralization occurs in two areas. The main pit exposes a body some 600 feet long and up to 100 feet wide, and a smaller body less than 100 feet long is exposed in the northern pit (Papke, 1979). The host rock for these bodies is relatively pure dolomite in the Upper Cambrian Nopah Formation. The fluorite occurs in a breccia composed mainly of this dolomite; non-dolomitic clasts in the breccia may be partly replaced by fluorite. The ore consists largely of fluorite and quartz, but dolomite is often present with small amounts of sericite, kaolinite, K-feldspar, mica, and montmorillonite.

From 1958 to 1967 Monolith Portland Cement Co. produced fluorspar from the Goldspar mine to be used in cement manufacture in southern California. The ore was selectively mined and crushed, to give a grade of approximately 40% CaF_2 . Total production is estimated at approximately 75,000 tons (Papke, 1979).

The Telluride Mercury mine area

Small quantities of cinnabar have been mined from pipelike breccia bodies in limestone and dolomite at the Telluride mine. Fluorite, calcite, opal, and alunite occur in zones of disseminated mercury ore.

6.1.3.2. Controlled area

Fluorite has been identified in small amounts in core and cuttings from the Yucca Mountain controlled area. Caporuscio et al. (1984) identified fluorite in two samples of ash-flow tuff from the Tram Member of the Crater Flat Tuff from drill hole 25-b at depths of approximately 970 m and 2,000 m, but did not describe the occurrences beyond stating that the mineral was present in fractures. Scott and Castellanos (1984) reported fluorite in fractures in intervals 210.4 - 275.5 m, 318.2 - 386.4 m, and 1,430.8 - 1,485.3 m from drill holes G-3 and GU-3. Carr et al. (1986) reported fluorite in cuttings composed mostly of Silurian carbonate rock from 1,678 - 1,711 m in hole 25p, and noted that it was common in a sample from 1,687 -1,690 m.

Fluorine analyses for 189 samples of core and cuttings that were obtained from six drill holes in the controlled area ranged between < 0.02 and 2.44 wt % (Castor et al., 1993). White, green, and purple fluorite was identified on fractures and in veins as much as 1 cm thick in volcanic rock in several intervals in drill holes GU-3, G-3, and 25-b (Castor et al., 1992), and ten samples containing such fluorite were found to contain as much as 2.44 wt % F (Table attached). In holes GU-3 and G-3, fracture-coating or vein-filling fluorite was found in veins cutting units as shallow as the Topopah Spring Tuff of the Paintbrush Group at 318 m, and as deep as the ash-flow tuffs beneath the Lithic Ridge Tuff at 1,530 m. Fluorite was generally found with quartz in fracture coatings and veins, but also occurred with carbonate, clay, fibrous zeolite (probably mordenite), analcite, and barite. In addition to visually identified fluorite veins, anomalously high F analyses (more than 0.2 wt %) were measured in three samples containing veins in which fluorite was not identified (Table attached). Four samples of volcanic rock with anomalously high fluorine contents, but without any visible fracture-coating or vein-filling material were also identified (Table attached).

Cubic crystals of colorless to gray fluorite up to 2 mm in diameter, associated with finely

crystalline pyrite, were identified in cuttings from a depth of 5,530 - 5,590 feet (1,686.0 - 1,704.2 m) in hole 25p (Castor et al., 1992). A sample from this interval and one from an interval 420 feet (128 m) higher in the hole were found to have anomalously high F contents (Table attached). These samples, which are from intervals in the Cambrian Lone Mountain Dolomite and Roberts Mountain Formation (Carr et al., 1986), also have anomalously high contents of trace elements such as As, Hg, Pb, Mo, Sb, and Zn (Castor et al., 1993) that suggest a hydrothermal origin similar to that for fluor spar deposits in the nearby Bare Mountain mining district.

6.1.4. Resource assessment for the controlled area

Fluorite has been identified in samples from the subsurface in the Yucca Mountain controlled area. Fluor spar has been an important industrial mineral in the Bare Mountain mining district in the Yucca Mountain region, and Bare Mountain fluorite mineralization is considered to be of Tertiary age. Furthermore, fluor spar has been mined from deposits in volcanic rocks in Nevada outside the yucca Mountain region. Therefore, the presence of economic fluor spar deposits in volcanic rocks in the Yucca Mountain controlled area is possible. However, the likelihood of economic deposits is considered to be remote in the controlled area because fluorite-bearing veins in the volcanic section are thin and have low contents of F (no analyzed samples contain more than 2.44 wt %, which translates to about 1.2 wt % fluor spar). No fluorite was identified during the surface appraisal of the Yucca Mountain Addition (Castor et al., 1989), and although fracture-coating fluorite was found in core at depths as shallow as 318 m, thicker veins that carry fluorite (up to 1 cm thick) occur at depths of 970 m or more. We believe that vein fluor spar deposits of significant size, if any are present in volcanic rocks at Yucca Mountain, are likely to occur at substantial, and probably unmineable depths.

The fluor spar deposits in the Bare Mountain district are hosted by carbonate sedimentary rocks of Cambrian through Silurian ages, and contain anomalous amounts of As, Hg, Mo, Sb, and base metals. Fluorite and high-F rocks intersected by drill hole 25-p at depths in excess of 1,200 m in the controlled area also have anomalously high contents of As, Sb, Mo, Sb, and base metals. Therefore, we believe that there is potential in Paleozoic rocks beneath the controlled area for fluorite mineralization similar to that in the Bare Mountain district. However, hole 25-p is the only drill hole in the controlled area that intersects the Paleozoic basement beneath the Tertiary volcanic cover; other deep holes (with total depths ranging between 1,200 and 1,800 m) in the controlled area failed to reach Paleozoic basement. Therefore, Paleozoic rock-hosted fluor spar deposits, if present in the controlled area, are at depths of 1,200 m or more, clearly excessive

depths for fluorspar mining in the foreseeable future.

Fluorspar potential in the controlled area is considered to be low.

6.2 Clays

6.2.1. Geology of clay deposits and uses of clay minerals

Clay is a natural fine-grained material that is composed mostly of a group of crystalline minerals known collectively as the clay minerals. Clay is one of the most important domestic industrial minerals in terms of value and volume of production. The amount of clay sold or used in the United States in 1991 was approximately 44,000 metric tons, with a value in excess of \$1.5 billion (Virta, 1993).

Clay minerals are hydrous silicates composed mainly of silica, alumina, and water. Some clay minerals contain significant amounts of the alkali metals, alkali earths, and iron. The identification and classification of clay minerals is a complex subject because there are more than twenty major clay mineral species. They may be divided into five principal groups (after Deer et al., 1966).

- The kandite group (includes kaolinite and halloysite)
- The illite group
- The smectite group (includes montmorillonite, beidellite, hectorite, and saponite)
- Vermiculite
- The palygorskite group (includes attapulgite and sepiolite)

A variety of classification schemes have been proposed. Grim (1968) discussed classifications at some length, and has proposed the inclusion of the chlorite group of minerals in such schemes. He also addressed the derivation of individual clay mineral names.

As mineral commodities, clays can also be classified into several distinct groups. The U.S. Bureau of Mines has adopted a six-fold classification scheme based mainly on usage, subdividing clay commodities into the separate categories of kaolin, ball clay, fire clay, bentonite, fuller's earths, and common clay (Virta, 1993). A similar system was used in the latest edition (6th. edition) of 'Industrial Minerals and Rocks' published by the Society for Mining, Metallurgy, and Exploration.

Here clay commodities are subdivided into bentonite, common clay, hormites (palygorskite group), and kaolin.

Common clays

The common clays are mainly used in construction products, such as bricks, roofing tiles, and Portland cement. They are also used in pottery and as a filler in paint. The term encompasses a variety of naturally occurring materials, including illite, kaolinite, and smectite. Some common clays can be predominantly composed of minerals such as mica or chlorite. Common clay is now mined in every state in the United States, except Alaska and Rhode Island (Murray, 1994).

Bentonite

Bentonite is composed of one or more varieties of smectite (chiefly montmorillonite). Most bentonite has swelling properties that are dependent on the clay having sodium rather than calcium as the dominant exchangeable cation. The high-swelling or sodium bentonites have active colloidal properties, forming gel-like masses when added to water. They are widely used as drilling mud, and as a binder in foundry sand and pelletized iron ores. In the United States, valuable high-swelling bentonite is produced from Wyoming at a rate of about 2.5 million metric tons per year (Virta, 1993). High swelling bentonites of comparable quality are relatively rare in the United States, and only relatively minor amounts of such bentonite are produced from deposits in Nevada and California.

Kaolin

The states of Georgia and South Carolina contain the world's major kaolin producing center (Pickering and Murray, 1994). Here kaolin is produced at an annual rate of about 8 million metric tons. Kaolin has many industrial applications, including uses as fillers, coating agents, extenders, binders, whiting agents, and in ceramics. Nevada contains eight deposits of kaolinite and the related clay mineral halloysite (Papke, 1973) and California has several productive kaolin deposits.

Fuller's earth

Fuller's earth is now an antiquated term that was applied to clay materials or 'earths' used in cleaning wool of its natural greases. The term is now used more broadly for clays and other natural fine-grained mineral materials that are applied in industry to far more varied uses, particularly those involving absorption. Although the term has no compositional or mineralogical meaning (Elzea and Murray, 1994), it is often applied to smectite-type clays. Fuller's earths known in Nevada are composed of montmorillonite (Papke, 1970).

6.2.2. Production, prices, and market outlook

Production in the United States in 1994 was 42.2 million tons with a value of \$1.6 billion (U.S. Bureau of Mines, 1994b). Over the last ten years, annual domestic clay production has been quite stable at around 40 million tons (Fig. 3).

Fig. 3. Clay production in the United States, 1985-1994.

Sources: Ampian (1989); U.S. Bureau of Mines (1995).

Most clays are mined from open pits with waste-to-clay ratios ranging from 0.25:1 for common clays to 7:1 for kaolin (Virta, 1993). A small number of clay mines are underground operations. Because of wide variations in demand, quality, and processing costs, clay commodity values are highly variable. Common clays are the most inexpensive, with an average unit value of about \$5 per short ton (Virta, 1993). Wyoming bentonite sells for \$52 to \$470 per short ton f.o.b. ex plant (Industrial Minerals, 1995). Georgia kaolin sells for \$52 to \$470 per ton f.o.b. ex plant, based on purity and the type of processing, and the average unit value for Fuller's earth has been reported at about \$100 per ton (Virta, 1993).

High value clay commodities include high-purity, water washed hectorite which sells for as much as \$3.15 per pound, and the specially treated bentonite or hectorite-based organoclays which bring as much as \$4,500 per short ton in the United States (Russell, 1991). Such high value clays have generally undergone costly processing; costs of crude clays range from less than \$3 per ton for common clays to more than \$20 per ton for some of the higher quality materials (Virta, 1993).

Markets for both bentonite and fuller's earth (categories into which any clay produced from the Yucca Mountain area is likely to fall) are extremely complex because of the many different applications and quality specifications for these materials. Market competition is fierce and sales are dependent on rising costs of transportation and fuel. For example, the cost spread between truck or rail and ocean transportation has caused Wyoming bentonite producers to lose part of the market for iron ore pelletization in the upper midwestern United States to Greek clay producers (Elzea and Murray, 1994). In addition, bentonite is in some danger of a loss of the taconite pelletization market to a substitute material.

Domestic production has been static for ten years, but long-term market trends for all clays have been generally upward over the last 3-4 decades. Perturbations of this general trend due to overall economic conditions have been severe. Domestic bentonite production, which in the late 1950's was less than 1.5 million tons a year (Gillson, 1960), rose to about 4.2 million tons in 1980, and fell to about 3.5 million tons in 1991 (Virta, 1993). Bentonite is likely to remain the most widely used clay for drilling applications in the years to come, and therefore bentonite sales will be tightly tied to levels of exploration for oil, gas, and minerals. The potential for market growth for fuller's earth is expected to be higher than that for bentonite (Elzea and Murray, 1994).

World wide markets for specialty clays such as organoclad bentonite and purified white bentonite are likely to increase with general economic growth (Elzea and Murray, 1994). The weak U.S. dollar in the latter part of the 1980's encouraged domestic producers to seek out foreign markets, which in part explains the expansion of clay production by the largest Yucca Mountain region producer, IMV Division of Florigin Company. Future exports of specialty clays to foreign markets are expected to remain strong (Virta, 1993).

6.2.3. Resources in the Yucca Mountain region

6.2.3.1. Region surrounding the controlled area

Clay is currently mined at two sites in the Yucca Mountain region. It also occurs in abandoned clay mines and in unmined deposits. The largest clay producer in Nevada is the IMV Division of Florigin Co. (Castor, 1995), a subsidiary of U.S. Borax Inc. The company mines sepiolite, montmorillonite, saponite (Mg smectite), and hectorite from deposits in the Ash Meadows area in the Amargosa Valley of Nevada and southern California, which is located approximately 30 miles south of the Yucca Mountain controlled area (see Plate 1).

The company processes the clay at a plant near its Nevada mines, and markets more than 20 different standard and specialty clay products each year. This includes both low unit value bentonite and fuller's earth, as well as some high value clay products that sell for as much as \$3,600 per ton (Castor, 1992). Between 1989 and 1994, the company's annual production ranged between 25,200 and 45,000 short tons of clay (Nevada Bureau of Mines and Geology, 1990 through 1995).

The deposits of all four clay minerals mined by IMV occur in approximately correlative Pliocene (Hay et al., 1986) lacustrine and alluvial beds clustered in different parts of an essentially contiguous basin (Castor, 1992). Hay et al. (1986) proposed that the montmorillonite was either sedimentary in origin or formed by the alteration of volcanic ash, whereas Mg smectite and sepiolite were considered to have been chemical precipitates - an origin first proposed for the sepiolite by Papke (1972). The clay minerals are mined in open pits from flat-lying deposits with little overburden.

According to Kral (1951), bentonite was mined from bedded deposits in Ash Meadows as early as 1918, and the thickest bed was mined from the surface to a depth of 24 feet where mining was halted by ground water. However, Hosterman and Patterson (1992) reported that the average thickness of bentonite beds in the area is 0.6 - 0.9 m, and the overburden is 3 - 8 m. thick. No reserve figures for the deposits have been published, but clay pits up to 2,000 feet long and 700 feet wide were mapped by Papke (1970). According to analyses reported by Papke (1970), samples from clay pits in the main part of the Ash Meadows district are dominantly saponite (Mg-rich smectite) that contain as little as 10% impurities, mainly as quartz and feldspar. Clay from the eastern part of the district is composed of montmorillonite, with less than 6% impurities.

At the New Discovery (White Caps) mine, located 2 miles south of Beatty and 15 miles west of the Yucca Mountain controlled area, the Vanderbilt Minerals Company mines high-grade montmorillonite clay that is used in pharmaceutical and cosmetic products. The montmorillonite is of hydrothermal origin and occurs in fault-bounded bodies up to 200 feet long and 40 feet wide (Papke, 1970) in the Timber Mountain Group (Maldonado and Hausback, 1990). It is mined in shallow underground workings, crushed, blended, and shipped to Kentucky for further processing along with clays from other deposits in Nevada that are stockpiled on the New Discovery property. Samples of clay from the New Discovery mine were found to contain 42% clay-sized material (Papke, 1970), but no estimate of grades has been published. Estimates of reserves at the New Discovery mine site have also not been published.

Other clay deposits in the Yucca Mountain region are all composed of smectites. Those located within Nevada include abandoned or unmined hydrothermal montmorillonite deposits in ash-flow tuff near Beatty and Scotty's Junction (see Plate 1 for locations, and Papke, 1970 for further descriptions). Near Shoshone in California (to the south of the Yucca Mountain region shown in Plate 1) bentonite was mined from a bed of nearly pure montmorillonite (Hosterman and Patterson, 1992), that ranged between 2 and 3 m in thickness over an area of at least 100 km² with 1 - 4.5 m of overburden (Norman and Stewart, 1951).

6.2.3.2. Controlled area

Although minor amounts of sepiolite have been identified in samples from Yucca Mountain (Vaniman et al., 1984), this clay mineral is present in such small amounts that it cannot be considered to be potential industrial mineral commodities. On the other hand, previous work has demonstrated that smectite group clays are ubiquitous in Yucca Mountain rock (Bish, 1989), and that while most rocks from Yucca Mountain contain smectite minerals in relatively small quantities, two zones of abundant smectite occur in members of the Paintbrush Group (Bish and Vaniman, 1985).

The uppermost of these zones identified in drill hole G-2 consists of a 125-m-thick sequence of non welded to partially welded ash-flow tuff of the Yucca Mountain and Pah Canyon Tuffs of the Paintbrush Group, along with interbedded and underlying bedded tuff units (Maldonado and Koether, 1983) that contains an average of approximately 20% smectite and has yielded samples with up to 60% smectite (Bish and Vaniman, 1985). Drill hole G-4, located about 2.5 miles southeast of drill hole G-2, contains a sequence 33 m in thickness which contains an average of approximately 22% smectite, with a maximum content of $35 \pm 15\%$ smectite (Bish and Vaniman, 1985). The sequence includes the basal section of the Tiva Canyon Tuff, the Pah Canyon Tuff, and the underlying bedded tuff (Spengler and Chornack, 1984). Located about 5 miles to south of drill hole G-2, drill hole GU-3 contains a sequence 20 m in thickness that includes the basal part of the Tiva Canyon Tuff and the underlying bedded tuff in the Paintbrush Group (Scott and Castellanos, 1984). The sequence approximately correlates with the sequence in drill holes G-2 and G-4 which contains an average of approximately 10% smectite, with a maximum content of 24% smectite (Bish and Vaniman, 1985). The Yucca Mountain and Pah Canyon Tuffs are missing in the vicinity of GU-3.

Argillization was noted in intervals that are correlative with those in holes G-2, G-4, and GU-

3 in core from drill hole UE 25a#1 (Spengler et al., 1979), and in cuttings from drill holes WT-1 and WT-2 (Bish and Vaniman, 1985) but estimates of clay content from cuttings are probably not reliable because clay particles are easily washed out of cuttings. Montmorillonite was identified by X-ray diffraction analyses in surface samples of the bedded tuff sequence between the Topopah Spring and Tiva Canyon Tuffs in the southern part of the Yucca Mountain controlled area (Castor et al., 1990). Quantitative analyses were not performed on these samples, but clay mineral contents were judged to be subordinate to the amount of volcanic glass (Castor et al., 1990). Because the stratigraphic sequence that contains this clay, namely the sequence of ash-flow tuffs and bedded tuffs between the Topopah Spring and Tiva Canyon Tuffs, is extensively exposed in the controlled area at Yucca Mountain (Scott and Bonk, 1984), it may have potential for exploitation.

The lower zone of smectite enrichment in the Paintbrush Group is the basal vitrophyre of the Topopah Spring Tuff, and although it contains up to 45% smectite, it is neither as thick, nor as rich in smectite as the upper zone (Bish and Vaniman, 1985). This clay-bearing unit, which occurs at depths greater than 1,100 feet in drill holes G-2, GU-3, and GU-4 (Maldonado and Koether, 1983; Spengler and Chornack, 1984; Scott and Castellanos, 1984), does not crop out within the controlled area (Scott and Bonk, 1984). It is therefore unlikely that it has economic potential in the controlled area. In volcanic rock units that are stratigraphically below the Paintbrush Group, smectite in amounts that ranged up to 50% were identified at depths of 2,000 feet or more (Bish and Vaniman, 1985). However, due to the depth, it is unlikely that these units contain economic clay deposits.

A fracture lined with nearly pure white smectite was noted at a depth of 2,226 feet in drill hole GU-3, and clay mineral contents were found to be elevated in drill holes near faults in the Yucca Mountain area (Bish and Vaniman, 1985). It is therefore possible that fault-controlled clay deposits such as those at the New Discovery mine may be present at Yucca Mountain, but no such concentrations have been noted at or near the surface in the controlled area.

Clay mineral species in samples from the Yucca Mountain controlled area have been studied in some detail by X-ray diffraction, and near-surface clays have been identified as smectite-group clays, with interstratified smectite-illite and illite occurring at depths in excess of 900 m (Bish, 1989). The dominant species are dioctahedral montmorillonite - beidellites with variable amounts of Na, Ca, and K as exchangeable cations, but chemical analyses of Yucca Mountain clay minerals are rare because of the difficulty of obtaining accurate analyses of clay phases using the electron microprobe (Bish, 1989). However, Vaniman et al. (1984) described a

tendency towards increased amount of Na in shallower smectites and increased K in deeper smectites. However, they do not report analyses for clay minerals above the Lithic Ridge. Likewise, Caporuscio et al. (1985) reported clay mineral analyses for clay minerals below 3,600 feet in drill hole G-1. Levy (1984) reported clay mineral analyses for a few cuttings samples from drill holes H-4 and H-5, including an analysis for the shallow smectite-rich zone in the Paintbrush Group described above H-5, at 420 feet) that shows it to contain Mg-Ca smectite with less than 0.5% Na.

The total tonnage of smectite in the Paintbrush Group bedded tuff sequence may be estimated using the drill hole intercepts and grades cited above for drill holes G-2, G-4, and GU-3 from Bish and Vaniman (1985), and density measurements from Nelson and Anderson (1992), as follows :

Area between drill holes	$4.32 \times 10^6 \text{ m}^2$
Mean thickness of clay-rich intercepts	59.0 m
Volume of clay-rich beds	$2.55 \times 10^8 \text{ m}^3$
Tonnage of clay-rich beds	4.34×10^8 metric tons
Weighted average grade of clay-rich intercepts	20.7 wt %
Estimated clay resource	8.98×10^7 metric tons

This estimated clay reserve is conservative because it does not include material outside the triangle formed by the drill holes G-2, GU-3, and G-4. If the outcrop and buried area of the bedded tuff unit between the Tiva Canyon and Topopah Spring Tuffs within the controlled area is considered, the resource may be multiplied by a factor of twenty and put at about 1.8 billion metric tons.

6.2.4. Resource assessment for the controlled area

Although large amounts of smectite clay are clearly present in the controlled area at Yucca Mountain, most of the calculated resource is present at depths that make higher than acceptable strip ratios for clay mining. In addition, the grade of most of the material is probably not sufficient to compete with regional sources of clay. However, parts of the overall resource that are exposed at the surface may be prospective for economic development. The potential for economic deposits of clay in the controlled area is considered to be low to moderate.

The value of clay minerals is dependent on commercial quality and marketability, which is determined by testing to establish such parameters as brightness, swelling capacity, plastic

viscosity, gel strength, and slakeability, and such data are not available for Yucca Mountain clays. In addition, it is not clear what processes would be necessary to produce marketable clay commodities from the Yucca Mountain resource. Therefore, it is not realistic to assign a value to the clay resource at Yucca Mountain.

6.3. Zeolites

6.3.1. Geology of zeolite deposits

Natural zeolites have been known for two centuries, but have only been of commercial interest for about four decades (although tuffaceous rocks now known to contain zeolite have been used for building purposes for millennia). In 1756, the term 'zeolite' was created by Axel Cronstedt, a Swedish mineralogist, from two Greek terms meaning 'to boil' and 'stone' for minerals which expel water when heated and hence seem to boil. For nearly 200 years the known sources of natural zeolites were in vugs and cavities in mafic igneous rocks, and deposits of zeolites were not thought to be of economic value, although synthetic zeolites were being developed for commercial uses beginning in the 1940s. Interest in the economic potential of natural zeolites was spurred in the 1950s when geologists discovered that zeolites were present in large amounts in tuffs and volcanic sedimentary rocks in the western United States (Ames et al., 1958; Deffeyes, 1959; Regnier, 1958). Since the "rediscovery" of zeolites in the 1950s, more than 1,000 occurrences of zeolite minerals have been reported in rocks of volcanic origin in more than 40 countries (Mumpton, 1978). Much of the original work on western United States zeolite deposits was done by geologists working for the Union Carbide Company, Occidental Petroleum Corporation, and Anaconda Mining Company, and some early mining of zeolite for use in refining petroleum and natural gas was done by large oil companies. However, in recent years the development and mining of these industrial mineral commodities has mostly been the domain of small independent companies such as St. Cloud Mining in New Mexico, and Teague Mineral Products in Oregon.

At present, 48 species of zeolite minerals are recognized (Fleisher and Mandarino, 1991), but only five zeolite minerals have commercial potential: chabazite, clinoptilolite, erionite, mordenite, and phillipsite (Holmes, 1994), and only clinoptilolite and chabazite are mined in the United States (Eyde, 1995). Zeolites are hydrated aluminosilicates of alkali metal and alkali earth elements, in particular sodium, potassium, magnesium, calcium, strontium, and barium. They take the form of infinitely extending three-dimensional crystalline frameworks of silica tetrahedra linked

to each other by the sharing of all oxygens. Some of the tetravalent silicon is substituted by trivalent aluminum, giving rise to an unbalanced charge, compensated by cations of alkali metal or alkali earth elements. The crystalline framework of zeolites is very open so that void volumes of dehydrated species may reach 50% and the specific gravity of most zeolite species are low, at 2.0 - 2.3 (Deer et al., 1966).

Five zeolite minerals predominate in sedimentary and tuffaceous volcanic rocks: analcite, clinoptilolite, heulandite, laumontite, and phillipsite. Most zeolite occurrences in such rocks may be categorized into the following groups:

1. Deposits formed from volcanic materials in 'closed' saline lakes
2. Deposits formed in 'open' hydrologic systems
3. Deposits formed in deep marine environments
4. Deposits formed by burial diagenesis or low-grade metamorphism
5. Deposits formed by hydrothermal activity
6. Deposits formed in soils

According to Mumpton (1978), commercial interest is mainly in deposits that fall into the first four groups, and Holmes (1994) stated that the first two groups have been of the most economic significance.

6.3.1.1. 'Closed' saline lake deposits

Zeolites are common in deposits of saline, alkaline lakes, which are generally found in arid and semi-arid regions. The purest concentrations of zeolites are found in tuff layers deposited in this type of setting. Alkaline waters trapped during sediment diagenesis dissolve volcanic glass, biogenic silica, clays, and quartz, while precipitating zeolite. In addition to zeolites, sodium silicates and K-feldspar also form diagenetically in this environment. The most common zeolites formed in this way are erionite, chabazite, and phillipsite; and such deposits may include monomineralic or mixed beds up to a few meters thick of the large-pore zeolites erionite and chabazite, which are relatively uncommon in other environments (Holmes, 1994). An example of this type of system is the large Tecopa Lake, California deposit, studied by Sheppard and Gude (1968), in which authigenic minerals are zoned from an outer area in which volcanic glass is preserved, through a zone of zeolite, to an central K-feldspar area.

6.3.1.2. 'Open' hydrologic system deposits

Zeolite deposits of the open-hydrologic system type are of considerable economic importance, and may be several hundred meters thick and several tens of kilometers in lateral

extent. They result from the alteration of large masses of tuffaceous sediments by the action of subsurface water moving freely through the host material. Open-system deposits are most abundant in non-marine environments, but nevertheless some are known in sediments which were deposited in shallow marine environments. Descending ground water alters vitric material to zeolites and clay minerals. Open-system deposits commonly show more-or-less horizontal zones of authigenic silicate mineral assemblages that reflect the compositions of the circulating solutions. The tuffaceous Oligocene Vieja Group in Texas is an example of this sort of system. It contains an upper glassy zone, followed at depth by montmorillonite, clinoptilolite, and analcite zones (Walton, 1975).

6.3.1.3. Deep marine deposits

Zeolites are important diagenetic minerals in deep-sea sediments. Phillipsite and clinoptilolite are the two most abundant zeolites, and can make up as much as 80% by weight of sediments (Holmes, 1994). Other zeolites recognized in deep-sea sediments include analcite, erionite, and laumontite. In the marine setting, phillipsite is commonly associated with low-silica rocks, such as a basaltic tephra, and clinoptilolite is associated with siliceous tephra. Clinoptilolite is widespread and is found in pelagic detrital clays with biogenic silica. Analcite is found mainly in marine mafic volcanic sediments. Most of the zeolites deposited on the ocean floor were formed by the reaction of glass with saline pore water, with or without additions of biogenic silica.

6.3.1.4. Burial diagenetic deposits

These deposits, which occur in thick volcanoclastic sequences up to 12 km thick, also typically display vertical zonation of the zeolites and associated minerals that is related to a decrease in hydration with depth as a function of increasing of temperature. An upper zone may contain fresh glass, and successively lower zones may contain assemblages of mordenite and clinoptilolite, analcite and heulandite, and laumontite and albite. The laumontite-albite zone may grade downward into rocks rich in prehnite and pumpellyite typical of the upper greenschist facies of regional metamorphism. It is often difficult to distinguish burial effects from hydrothermal effects, and the resulting zonations may be a function of both. Zeolite rocks of the burial diagenetic type occur in New Zealand (Southland syncline), Japan (Motojuku district of north Kanto), and the United States (Aldich Mountain area of central Oregon).

6.3.1.5. Hydrothermal deposits

Hydrothermal zeolite deposits can be related to both active and fossil geothermal systems. Like the open system deposits, they display vertical mineralogical zonation. The more shallow and coolest zones are characterized by clinoptilolite or mordenite, and progressively deeper zones contain analcite or heulandite, laumontite and wairakeite. As with burial diagenetic deposits, dehydration with increasing temperature is considered responsible for the mineral zonation. Examples of hydrothermal zeolite deposits are in Japan (Onikobe), New Zealand (Wairakei), and the U.S.A (Yellowstone Park).

6.3.1.6. Soil deposits

Zeolites are formed from tuffaceous and non-tuffaceous sediments under surficial or near-surficial soil conditions in arid or semi-arid climates where the pH is high. Sodium carbonate solutions are periodically flushed downwards from the surface following rainfall, altering underlying materials to zeolites. The most commonly formed are phillipsite, chabazite, natrolite, and analcite. The lower alteration limit is probably the water table. Zeolite accumulations of this type are volumetrically minor and of little commercial interest.

6.3.2. Production, reserves, uses, grades, prices, and market outlook

Although for many decades zeolitized tuffs have been quarried for use as building stone in the United States, mining for specific zeolite minerals began in the United States in the 1960s. Mining of zeolite from the Bowie deposit in Arizona was begun in 1962 (Eyde, 1982) and Mobil Oil Corporation mined zeolites in Jersey Valley in northern Nevada beginning in 1968 (Papke, 1972). Since the 1960s United States zeolite mineral production has increased slowly, reaching a high of 42-44,000 metric tons in 1993 (Eyde, 1995). Production figures for domestic natural zeolite production are only available beginning in 1976, but they show relatively steady growth, although 1994 production is somewhat lower than that of 1993 (Fig. 4).

Internationally, zeolitic tuffs have been used for thousands of years as lightweight dimension stone and as cement additives (Holmes, 1994). The Neapolitan yellow tuff, which contains up to 80% phillipsite (Sersale, 1978) was used by the ancient Romans. Annual world-wide zeolite production has been about 1 million metric tons in recent years, with significant amounts of zeolites mined in Australia, Cuba, Germany, Indonesia, Italy, Japan, the Republic of

South Africa, Romania, Spain, Yugoslavia, and the former USSR. The former USSR is the largest producer of natural zeolites, mainly for use in cement and radioactive waste disposal. In Italy, where the supply of zeolites is considered "inexhaustible," chabazite- and phillipsite-rich tuffs are mined for use as cement additives (Sersale, 1978). In Cuba as much as 400,000 metric tons of zeolite are mined annually for use in cement and agricultural products, and reserves are estimated at 700 million metric tons with average grades of 45% clinoptilolite (Eyde and Shelton, 1991).

Figure 4. Natural zeolite sales in the United States.

Sources of information: 1976-1991, U. S. Bureau of Mines Minerals Yearbook; 1992-1994 U. S. Bureau of Mines Zeolites Annual Review.

Zeolite resources in the United States are conservatively estimated at 10 trillion tons, and the country probably has the world's largest potential resources of high-grade chabazite, erionite, and phillipsite (Sheppard, 1983). Zeolite deposits are particularly abundant in the western United States, which contains several hundred known occurrences that include deposits of all zeolite species with known commercial potential (Holmes, 1994). Resources of clinoptilolite, mordenite, and erionite are very large, while potential sources of chabazite and phillipsite are more limited.

Zeolite deposits of the western United States that have been mined, and some that have been investigated for commercial application, are listed in Table 3. This listing contains a fraction of the areas that may have potential for zeolite production in the region because information on zeolite assemblages, grade, thickness, and lateral extent for many areas is lacking (as it is for some of the mined deposits in Table 3).

Table 3. Some Zeolite Resources in the Western United States

Name	Zeolite Minerals	Grade	Thickness	Size	Production	Reference
Arizona						
Bowie	chabazite	60-90%	up to 20 cm	large, 1 x 7 mi area	1962-1982: 12,000 tons	Eyde, 1982; Holmes, 1994
Tonto Basin	chabazite		1.3-2.5 m		no	Holmes, 1994
California						
Ash Meadows	clinoptilolite	90%	46 m	very large	<1000 tpy	Santini and Shapiro, 1982
Gem Hills	clinoptilolite, mordenite	50%+	16 m		no	Holmes, 1994
Castle Butte	clinoptilolite	50%+			no	Holmes, 1994
Mud Hills	clinoptilolite	70-90%	3-5 m		>2000 tons	Sheppard and Gude, 1969; Holmes, 1994
Hector	clinoptilolite			small	small	Ames et al., 1958; Holmes, 1994
Spanish Canyon	clinoptilolite	50-75%	3 m		no	Holmes, 1994
Colorado						
Creede	clinoptilolite		up to 7 m		small	Holmes, 1994
Idaho						
Castle Creek	clinoptilolite	80%+	11 m	large, 1 km+ strike length	yes	Sheppard and Gude, 1983
Chrisman Hill	clinoptilolite		20 m	large	yes	Holmes, 1994
Nevada						
Ash Meadows	clinoptilolite	90%	122 m	very large	no	Santini and Shapiro, 1982
Pine Valley	erionite, phillipsite	95%+	0.2-0.6 m	moderate	no	Papke, 1972
Reese River	erionite, clinoptilolite, chabazite	75-100%	up to 4.5 m	moderate	no	Papke, 1972
Eastgate	mordenite				yes	Castor, 1995
Jersey Valley	erionite, clinoptilolite, phillipsite	up to 90%	up to 3 m	large, 5 km+ strike length	yes	Papke, 1972
Lovelock	ferrierite	80-100%	10-12 m	moderate, 0.2 x 1 km area	no	Sheppard and Gude, 1983; Rice et al., 1992
Fish Creek Mountains	clinoptilolite	75%	up to 80 m		no	Mumpton, 1978
Beatty Wash	clinoptilolite	75%	60 m+		no	Holmes, 1994
Beatty Mountain	mordenite, clinoptilolite	70-85%			no	Holmes, 1994
New Mexico						
Buckhorn	clinoptilolite	70-90%	1-1.5 m	moderate, 1 mi strike length	yes	Eyde, 1982
Winston	clinoptilolite				yes	Holmes, 1994
Oregon						
Durkee	chabazite, erionite	ca. 100%	up to 4 m	18 sq. km area	no	Sheppard and Gude, 1983
Harney Basin	clinoptilolite		20 m	very large	no	Holmes, 1994
Rome	Clinoptilolite, erionite, mordenite	50-100%	3 m		yes	Holmes, 1994
Sheaville	clinoptilolite	70%+	18 m		yes	Sheppard and Gude, 1983; Holmes, 1994
Utah						
Mountain Green	clinoptilolite	50-80%		> 240 Mt	no	Holmes, 1994
Keg Mountains	clinoptilolite	up to 90%		large	no	Tripp and Mayes, 1989
Topaz Mountain	clinoptilolite	60% +			no	Tripp and Mayes, 1989
Three Creeks	clinoptilolite	65-66%	3-10 m		no	Tripp and Mayes, 1989
Cove Fort	clinoptilolite	up to 87%		1.8 Gt	no	Tripp and Mayes, 1989
Trenton	clinoptilolite	up to 67%	7 m+		no	Tripp and Mayes, 1989
Wyoming						
Washakie Basin	clinoptilolite	50-90%	1-8 m		yes	Holmes, 1994
Beaver Rim	clinoptilolite				yes	Holmes, 1994

Prospecting for zeolite deposits is done by examining and sampling occurrences, particularly in tuffaceous rocks and volcanogenic sedimentary rocks. X-ray diffraction is the most commonly used method of analysis, and ammonia cation exchange capacity is an effective early screening technique used in commercial investigations (Holmes, 1994). Zeolites are mined by open-pit methods because of low unit value, and such excavation is generally done using conventional earth moving equipment at costs of \$3-6 per ton (Holmes, 1994). Zeolites for special high value uses may be recovered by very selective open pit mining, such as that performed at the Bowie, Arizona, deposit (Mumpton, 1978; Eyde, 1982).

Zeolitized tuffs have traditionally been used as lightweight dimension stone and in pozzolanic cements and concretes, but it has only been during the last few decades that the zeolite content of these materials has been recognized. Use in cement continues to be a major use of zeolite, particularly in Cuba, Italy, and the former USSR. Although zeolites are calcined at high temperatures for use as a strong, abrasive-resistant light weight aggregate, some zeolite materials used as pozzolans may not be beneficiated. For other, higher value, uses that are noted below, beneficiation and activation are required.

Zeolite is used in various types of waste treatment and in environmental clean up. Clinoptilolite is highly selective for NH_4^+ , and is used in the extraction of NH_4^+ from sewage and agricultural effluents. Applications in animal waste treatment includes the reduction of odor, control of moisture content, and purification of methane gas. Natural zeolite has found increasing use as pet litter in recent years; in 1994, more than 50% of domestic natural zeolite was consumed as pet litter (Virta, 1995). Zeolites such as mordenite and clinoptilolite are able to adsorb selectively up to 200 mg of SO_2 per gram of zeolite in stack gas from power plants. Pelletized mixtures of activated zeolite, expanded perlite, sodium carbonate, tartaric acid, and a binder consisting of 20% methyl siloxane solution is used as a sorbent in oil-spill cleanups. Clinoptilolite, which has an ion-exchange specificity for Cs^{137} and Sr^{90} , is used for the removal of those two radioactive isotopes from low-level waste streams of nuclear installations. Natural zeolites are considerably less expensive for these uses than organic ion-exchange resins, and more resistant to nuclear degradation. In 1982, about 1,800 metric tons of high-purity zeolite were mined by the Occidental Petroleum Company from the Mud Hills deposit in southern California and exported for use as ion exchange material by British Nuclear Fuels, Inc. As much as 1.5 million metric tons of zeolite was mined in one year in the former USSR to treat materials from the Chernobyl nuclear disaster (Eyde, 1990). On the basis of laboratory experiments, beneficiated chabazite (93% pure) from the Bowie deposit, Arizona, removed 95% or more Cu^{+2} ions from 10^{-3} molar solutions and 96% Pb^{+2} from 10^{-2} molar solutions (Mondale et al, 1978).

Sodium-exchanged clinoptilolite and mordenite remove almost all of the Cd^{++} from 10 ppm solutions of that ion.

Japanese farmers have used zeolitic tuffs in agriculture for many decades, although the reasons for its success remained unknown until recently. Recently, Cuban zeolite has been marketed in large amounts in Latin America for agricultural uses. The high selectivity of clinoptilolite for NH_4^+ has been used in chemical fertilizers to improve the nitrogen-holding capacity of soils and a slower release of ammonia. Clinoptilolite also allows a slow release of nutrients such as Fe, Cu, Zn, Mn, and Co. The addition of small amounts of clinoptilolite (5-10%) to animal diets contributes to an increase in durable weight gain, and to a decrease in both death rates and disease. Zeolites are also effective carriers of herbicides, fungicides and pesticides.

In addition to some use in petroleum distillation, which is mainly the purview of synthetic zeolite, natural zeolite has industrial manufacturing uses. Zeolite adsorption processes can be utilized to produce inexpensive oxygen-enriched streams of varying degrees of purity. Nitrogen is selectively adsorbed from air by several zeolite materials, yielding products containing up to 95% oxygen. Portable and file-cabinet sized units have been marketed in Japan, and large units are in use to furnish oxygen to fish-breeding ponds, for pollution control in the paper and pulp industry, and for sewage treatment. Mordenite appears to be the best natural zeolite for oxygen generation, followed by clinoptilolite and chabazite. By adsorption and desorption cycles, the same zeolites can be used to prepare nitrogen streams with up to 99.95% purity. Zeolites are used as fillers in high-brightness and light-weight papers, particularly in Japan. Kraft paper filled with clinoptilolite is bulkier, more opaque, easier to cut, and less susceptible to ink blotting than that filled with clays. Addition of 5-30% natural chabazite to conductive paper used in electrostatic reproduction results in a product having good copying qualities over a large range of relative humidities. Clinoptilolite and mordenite are used with organic dyes to produce colored papers.

Zeolite commodities from some domestic deposits are relatively high-value industrial minerals. Activated chabazite from the Bowie deposit has sold for \$1.50-1.60 per pound, and at production rates of 1000 tons per year (Eyde, 1982), annual production from the deposit is \$3 million. Although zeolite products for special applications such as radioactive waste treatment may bring high prices, natural zeolites are mostly sold into low-value industrial or agricultural markets as crushed or ground products that bring prices of \$30-120 per ton (Holmes, 1994).

Although domestic natural zeolite production has increased over the last two decades (Fig. 4), most of this increase has resulted from increased use in animal feed and pet litter, which

require relatively low-value products. In high-value and high-volume uses, such as molecular sieve absorption and catalytic petroleum processing, synthetic zeolites offer much better performance (Breck, 1983), and will continue to dominate markets. For its major domestic use, pet litter, natural zeolite is restricted to regional use because it competes with other low-value natural industrial minerals such as clay. For many uses, competition from foreign sources of mined zeolites may also limit domestic production as is has for other industrial minerals.

Increases in domestic sales and production of natural zeolites experienced between 1988 and 1993 are not considered likely to continue into the future, and domestic consumption for the next few years should be between 35,000 to 45,000 metric tons per year (Virta, 1995).

6.3.3. Resources in the Yucca Mountain region

6.3.3.1. Region surrounding the controlled area

An active zeolite mine and other known zeolite resources are present in the Yucca Mountain region (Plate 1, Table 3). The Ash Meadows clinoptilolite deposit is in zeolitized Tertiary ash-flow tuff that contains large tonnages of rock with 90% clinoptilolite over a strike length of 6 miles (Santini and Shapiro, 1982). The deposit, which is mined in California by American Resource Corp. (Castor, 1995) where it is as much as 46 m thick, extends into Nevada where it attains a thickness of 122 m (Santini and Shapiro, 1982). Anaconda Minerals Company originally developed this resource with a small open pit, removing and stockpiling about 18,000 metric tons of material for testing and to initiate production (Santini and Knostman, 1979). American Resources Corp. is still removing material from the old Anaconda stockpile and from the open pit and processing it in a crushing and screening plant in Nevada (Holmes, 1994). The plant has an annual capacity of 8,000 tons per year, but recent production has only been about 10% of capacity (Castor, 1989). Ash Meadows clinoptilolite has high ammonia cation exchange capacity (Holmes, 1994) and most sales are to the aquaculture industry, but sewage and waste water treatment markets are promising (Castor, 1989).

Unmined zeolite resources in the Yucca Mountain region include zeolitized ash-flow tuff in Beatty Wash (Plate 1) more than 60 m thick that typically contains 75% clinoptilolite, and Tertiary ash-flow tuffs on Beatty Mountain (Plate 1) that contain as much as 70-85% clinoptilolite and mordenite (Holmes, 1994).

6.3.3.2. Controlled area

Clinoptilolite-heulandite group zeolites and mordenite are known to be present in significant amounts in volcanic rocks of the Yucca Mountain controlled area, and a considerable body of literature is available on these occurrences because sorption and retardation of radionuclides by zeolites may be a factor in repository assessment and design (Bish and Vaniman, 1985). In addition, study of these minerals is important in understanding their potential reactivity in a repository environment, and age dates on zeolites have been used in attempts to date diagenetic or hydrothermal activity in the volcanic pile at Yucca Mountain (WoldeGabriel et al., 1993). The zeolite erionite occurs in small amounts in a single stratigraphic horizon at Yucca Mountain, along with rare phillipsite, chabazite, and stilbite (Bish and Chipera, 1991).

The genesis of zeolites at Yucca Mountain is a matter of continuing discussion. The geology and the general lack of chabazite and phillipsite indicate that closed saline lake deposition was not a factor. The distribution of zeolite minerals in Yucca Mountain is vertically zoned in a similar way to that in open hydrologic systems (Broxton et al., 1987), and such an origin was favored by Hoover (1968). However, elevated temperatures as indicated by clay mineralogy (Bish, 1986) suggest that burial diagenesis may have been a factor in Yucca Mountain zeolite formation, and Levy and O'Neil (1989) proposed that the zeolites formed while the host tuffs were cooling. On the basis of variations in zeolite mineral chemistry, Livingston (1993) proposed a hydrothermal origin for Yucca Mountain zeolite distribution.

Quantitative data on zeolite mineral contents of drill hole samples from Yucca Mountain are reported in Levy (1984) and Bish and Vaniman (1985), and provide some idea of zeolite mineral potential. Because zeolite mineral deposits in the western United States that are being mined, or have been investigated for economic potential, contain about 50% or more zeolite (Table 3), drill hole intervals identified as containing 50% or more clinoptilolite + mordenite have been compiled (Table 4) in order to estimate the size of the zeolite resource in the controlled area. Samples with 50% or more zeolite come from strongly zeolitized zones in ash-flow tuff and bedded tuff in several stratigraphic units. The zeolitized tuff probably represents the overlap of an alteration zone defined by the presence of clinoptilolite and mordenite (diagenetic alteration zone II of Broxton et al., 1987) with tuff that retained a large component of vitric material following the original cooling of the tuffs. The affected units include the basal part of the Topopah Spring Tuff of the Paintbrush Group, the Tuff and lava of the Calico Hills, all three members of the Crater Flat Tuff, and bedded tuffs associated with these units. Significant intervals of zeolite alteration were encountered in drill holes G-2, GU-3, G-4, H-3, H-4, H-6, and WT-1.

Table 4. Yucca Mountain drill intervals with total zeolite mineral contents greater than 50%.

* Grade is average of percentage range reported in Bish and Vaniman (1985), and is the sum of clinoptilolite and mordenite contents. † c = clinoptilolite m = mordenite

Drill Hole	Sample Type	Depth (m)	Grade*	Unit	Zeolite† Minerals
USW G-2	core	232.3	87.5	Paintbrush Tuff, Topopah Spring Mbr., near top	c
USW G-2	core	515.4	57.5	Paintbrush Tuff, Topopah Spring Mbr., near base	c>m
	core	531.9	47.5	Bedded tuff	c>m
	core	534.0	67.5	Bedded tuff	c>m
	core	548.0	72.5	Tuff and lava of Calico Hills	c>m
	core	563.3	72.5	Tuff and lava of Calico Hills	c>m
	core	578.8	72.5	Tuff and lava of Calico Hills	c>m
	core	595.0	57.5	Tuff and lava of Calico Hills	m>c
	core	609.9	57.5	Tuff and lava of Calico Hills	m>c
	core	633.4	60	Tuff and lava of Calico Hills	c=m
	core	657.8	52.5	Tuff and lava of Calico Hills	c=m
	core	685.2	60	Tuff and lava of Calico Hills	c>m
USW GU-3	core	571.2	50	Crater Flat Tuff, Prow Pass Mbr.	c
	core	590.0	60	Crater Flat Tuff, Prow Pass Mbr.	c
	core	605.3	70	Crater Flat Tuff, Prow Pass Mbr.	c
	core	607.5	60	Bedded tuff	c
	core	613.6	50	Crater Flat Tuff, Bullfrog Mbr.	c
USW G-4	core	785.6	50	Crater Flat Tuff, Bullfrog Mbr.	c
	core	436.5	75	Tuff and lava of Calico Hills	c
	core	438.3	75	Tuff and lava of Calico Hills	c
	core	448.1	77	Tuff and lava of Calico Hills	c
	core	470.6	70	Tuff and lava of Calico Hills	c>m
	core	488.3	52	Tuff and lava of Calico Hills	c>m
	core	513.6	65	Tuff and lava of Calico Hills	c>m
	core	640.1	60	Crater Flat Tuff, Prow Pass Mbr.	c=m
	core	649.5	50	Crater Flat Tuff, Prow Pass Mbr.	c>m
	core	671.2	50	Crater Flat Tuff, Prow Pass Mbr.	c>m
	core	678.5	50	Crater Flat Tuff, Prow Pass Mbr.	c>m
	core	682.1	75	Crater Flat Tuff, Prow Pass Mbr.	c>m
	core	827.8	80	Crater Flat Tuff, Bullfrog Mbr.	m
	core	832.4	73	Crater Flat Tuff, Bullfrog Mbr.	m>c
	core	851.0	87	Crater Flat Tuff, Tram Mbr.	c>m
USW H-3	sidewall	548.6	60	Crater Flat Tuff, Prow Pass Mbr.	c
	sidewall	579.1	75	Bedded tuff	c
	sidewall	731.5	75	Crater Flat Tuff, Bullfrog Mbr.	c
	sidewall	743.7	65	Crater Flat Tuff, Bullfrog Mbr.	c>m
	sidewall	759.0	70	Crater Flat Tuff, Tram Mbr.	c>m
USW H-4	cuttings	411.5	78	Tuff and lava of Calico Hills	c
	sidewall	432.8	70	Tuff and lava of Calico Hills	c
	cuttings	433.8	52	Tuff and lava of Calico Hills	c
	sidewall	443.5	70	Tuff and lava of Calico Hills	c>m
	sidewall	472.4	75	Tuff and lava of Calico Hills	c
USW H-6	cuttings	588.3	50	Crater Flat Tuff, Bullfrog Mbr.	c
	cuttings	670.6	60	Crater Flat Tuff, Bullfrog Mbr.	c
USW WT-1	cuttings	420.6-423.7	52	Paintbrush Tuff, Topopah Spring Mbr., near base	c>m
		460.2-463.3	53	Bedded tuff, Tuff and lava of Calico Hills	c>m
		472.4-475.5	52	Bedded tuff, Tuff and lava of Calico Hills	c>m

Using the data in Table 4, zeolite resources in the controlled area can be estimated. However, isolated samples (except for cuttings samples that represent a significant interval) may not be used in such a calculation because the vertical extent of zeolitization cannot be determined. Hence, a sidewall sample at 507.8 m from hole H-6, and core samples from 232.3 m in hole G-2 and 785.6 m in hole GU-3 are ignored (such samples are noted in Table 3, but are not utilized in the resource calculation). The area bounded by the drill holes noted above is utilized for the calculation. The grade used in the calculation is weighted by the thickness of the intervals over which grades are averaged in each hole. The bulk density of the zeolitized tuff as assumed to be 1.9 g/cm^3 on the basis of data presented in Nelson and Anderson (1992). Following these constraints, the resource calculation for zeolite in the Yucca Mountain controlled area is as follows:

1. Area between drill holes = $7.97 \times 10^6 \text{ m}^2$
2. Mean thickness of zeolite-rich intercepts = 104.3 m
3. Volume of zeolite-rich rock = $8.31 \times 10^8 \text{ m}^3$
4. Bulk density of zeolite-rich rock = 1.9 g/cm^3 (= 1.9 metric tons/ m^3)
5. Tons of zeolite-rich rock = 1.58×10^9 metric tons
6. Weighted average grade of zeolite-rich intercepts = 65.0%
7. Estimated zeolite resource = 1.03 billion metric tons

The zeolite resource estimate shown above for the Yucca Mountain controlled area is conservative because it is based only on the area between drill holes with usable grade information. On the basis of mineralogic abundance data and cross sections through Yucca Mountain in Bish and Vaniman (1985), it is believed that zeolitic alteration zones thin and become lower grade to the southeast of a line drawn through drill holes H-6 and G-3. However, thick zeolitic intercepts are probably present to the east of the area defined by drill holes G-2, GU-3, G-4, H-3, H-4, H-6, and WT-1. By visual estimate, the area within the controlled area that is underlain by significant thicknesses and grades of zeolitized tuff is about 8 times as large as the area for which the above resource was calculated, and the total resource may then be about 9.04 billion metric tons (about 9.9 billion short tons).

6.3.4. Resource assessment for the controlled area

A large resource of zeolite is clearly present in the Yucca Mountain controlled area. However, the stratigraphic units that contain this estimated resource do not crop out within the controlled area (see Scott and Bonk, 1984). Where zeolitized rock may reach the surface along the northeast border of the controlled area, within the controlled area, a short distance to the

south, it is covered by considerable thicknesses of tuff containing little or no zeolite (about 500 m in drill hole G-2). Because zeolite deposits are mined by open-pit methods, the amount of overburden is an important factor, and the identified zeolite resource in the Yucca Mountain controlled area clearly occurs at depths that render commercial extraction unlikely. The deposit is unattractive economically when compared with the large amounts of readily extractable higher-grade zeolite elsewhere in the western United States. For instance, nearby deposits in the Ash Meadows and Beatty areas (Plate 1) are of much higher grade (Table 3) and are more easily mineable. Many high-grade zeolite deposits in the western United States have been evaluated by mining companies, oil companies, and chemical companies, and their commercial potential has been known to industry for years; however, hundreds of millions of tons of zeolite have no commercial value if the total domestic market is only 35,000 to 45,000 tons per year.

As noted by Papke (1972), zeolite deposits of the type that is present in tuff at Yucca Mountain are extensive in Nevada, and have economic potential for uses that require only impure materials of relatively low unit value. Given their low commercial value, relatively low grades, and the poor mining situation, it is not likely that zeolites in the Yucca Mountain controlled area will be seen as a commercially attractive resource in the foreseeable future.

6.4. Construction aggregate

Construction aggregate consists of a variety of materials used to provide bulk and strength in portland cement concrete, asphalt concrete, fill, road base and loose road surfacing, railroad ballast, concrete block, and stucco. Mined natural materials provide most of the construction aggregate used in the United States, although recycled materials such as crushed glass, crushed concrete, and crushed brick may be used as well as smelter slag and manufactured lightweight aggregate. Sand and gravel, crushed stone, and volcanic cinders are mined materials that are currently used for construction aggregate in the Yucca Mountain region.

6.4.1. Geology of construction aggregate deposits

Sand and gravel deposits are unconsolidated stream-channel, flood-plain, or terrace deposits; alluvial fan deposits; glacial or glacio-fluvial deposits; and beach deposits of lacustrine or marine origin. In southern Nevada, almost all sand and gravel production is from alluvial fan deposits, with minor production from fluvial deposits in active washes. Sand and gravel that is

ideally suitable for most construction aggregate is composed of clean, uncoated, properly shaped and sized detritus that is sound and durable. Individual sand and gravel particles must be resistant to physical stress and to chemical and physical changes. Sand and gravels that contain excessive amounts of clayey material, organic matter, soluble minerals, or friable altered or weathered particles generally make poor aggregate, although some such materials may be removed by screening and washing. Sand and gravel deposits that reactive rock types, such as certain siliceous volcanic rocks, may not be suitable for use in portland cement concrete without special treatment (Goldman, 1994).

Many different rock types are used in crushed stone, and the types used are determined mainly by availability and rock quality. Such rock types must meet the same, or more stringent, soundness and durability requirements for sand and gravel, and therefore must not contain reactive minerals or be weakened by alteration. However, extremely hard or abrasive rock types are generally not used in crushed stone because of high crushing and screening costs. For most uses, it is important that the rock break into more-or-less equant fragments when crushed, and platy rocks such as slate generally make poor aggregate. Certain mineral components, such as mica in some schists, are deleterious in aggregate because they cause structural weakness. Some types of crushed stone are particularly desirable for specific uses. For example, fine-grained basalt is commonly used in asphalt concrete, and crushed rhyolite is used in lightweight portland cement concrete and in concrete blocks. As is the case with sand and gravel, certain siliceous volcanic rocks, including rhyolitic ash-flow tuffs, are unsuitable for portland cement concrete aggregate because of alkali-silicate reactivity (Malisch, 1978).

Volcanic cinder deposits are composed of loose, cheaply mined, fragments of scoriaceous basalt or andesite, and are generally in relatively young cinder cones. Because they have low density, but are relatively strong structurally, volcanic cinders are used in lightweight aggregate for portland cement concrete and in concrete block. High-quality cinder deposits adjacent to metropolitan markets (generally in the western United States) are prized because of low mining and crushing costs. Cinder finds minor use as decorative stone and barbecue rock.

Mining of all construction aggregate, whether for sand and gravel, crushed rock, or volcanic cinders, is by open-cast methods. Sand and gravel is mined from open pits and because most deposits are of unconsolidated material, drilling and blasting is not required. Some sand and gravel deposits are mined by dredging. Crushed stone generally comes from quarries where excavation requires drilling and blasting.

6.4.2. Production, uses, reserves, prices, and market outlook

On the basis of data from Tepordei (1993a, 1993b), the annual domestic production of construction aggregate has been over 1.5 billion short tons for more than 25 years, except during the recession years of 1981 through 1983. The annual amount used averaged 1.84 billion tons between 1970 and 1990, and reached a maximum of 2.17 billion tons during 1988 (Langer and Glanzman, 1993). The value of domestic crushed stone and sand and gravel, at more than \$10 billion in 1994 (Tepordei, 1995), exceeds the value of any other mineral commodity produced in the United States.

Production of construction aggregate in the Yucca Mountain region is minor, consisting of a few small sand and gravel pits and a volcanic cinder mine near Amargosa Valley (Plate 1). The largest market in the region is probably now U. S. Department of Energy construction work taking place at Yucca Mountain, but the Barrick Bullfrog gold mine near Beatty and local highway resurfacing are also important users. Volcanic cinders produced from a cinder cone northwest of the town of Amargosa Valley (Plate 1) are sold into the Las Vegas construction materials market, mostly for use in concrete block. No data are available about annual production in the Yucca Mountain region, but it is probably under 500,000 tons.

Production of construction aggregate in Nevada has increased fairly steadily since the early 1980s, rising from about 6 million tons in 1981 to about 28 million tons in 1994 (Fig. 5). The Las Vegas metropolitan area, which has undergone unprecedented growth and a tremendous boom in residential, commercial, and municipal building since the mid 1980s, consumes more than 60 percent of the states building aggregate. In 1991, 32 active construction aggregate mining sites, operated by 29 different companies, were identified in the Las Vegas area (Castor et al., 1992). In 1994, most of the 18 million tons of construction aggregate used in the Las Vegas area was from alluvial fan sand and gravel deposits in the Lone Mountain, Henderson, and Spring Mountain Road areas (Castor, 1995). In the Lone Mountain and Spring Mountain Road areas, gravel pits are in alluvial fans consisting almost entirely of Paleozoic carbonate detritus. In the Henderson area, the gravels mainly contain volcanic detritus. Crushed stone, consisting mainly of Paleozoic limestone and minor amounts of lightweight rhyolite, accounted for only about 10% of the total aggregate production in the Las Vegas area.

Sand and gravel (or sand alone) can be used for industrial purposes, such as in glass manufacturing and in foundries, and crushed stone may be used to make such products as cement and lime. However, sand and gravel and crushed stone are mainly used as aggregate by

the construction industry. Construction aggregate is used in nearly all residential, commercial, and industrial building construction and in most public-works projects such as roads and highways, bridges, railroad beds, dams, airports, water and sewer systems, and tunnels. The United States road system consumes vast amounts of aggregate; about 20% of aggregate production goes into road base and unpaved road construction and maintenance, and a single mile of four-lane interstate requires 85,000 tons of construction aggregate (Schenck and Torries, 1975). Residential construction is also a heavy user of aggregate; construction of an average six-room house utilizes 100 tons of aggregate (Langer, 1988). The largest use of construction sand and gravel is as aggregate in concrete, amounting to 26% of total sand and gravel use in recent years (Tepordei, 1993a).

Figure 5. Production of construction aggregate in Nevada, 1978-1994. Sources: The Nevada Mineral Industry, Nevada Bureau of Mines and Geology Special Publications MI-1978 through MI-1994.

Reserves of natural material that can be used as construction aggregate are almost limitless. However, environmental and commercial concerns preclude mining in some areas such as in or near metropolitan areas (where most aggregate is consumed) and availability of natural aggregates is limited in areas such as the Gulf Coast of the United States, where materials such as waste oyster shells are used in some applications. In the Las Vegas area, large tracts of public land have been identified as having good potential for aggregate potential (Castor et al., 1992). However, the U.S. Bureau of Land Management has generally been unwilling to issue new leases for aggregate mining or to extend existing leases in the Las Vegas basin, and private land in many

parts of the metropolitan area has more value as building sites than for sand and gravel mining.

Prices for aggregate vary with quality and application. Pit run sand and gravel can generally be used for fill, but base aggregate must be screened, and in cases where abundant oversize material is present it must be crushed as well. Aggregate used in portland cement concrete must be screened and washed, and is therefore more costly. The gravel pits in the Las Vegas area contain only minor sand size detritus (particularly in the productive Lone Mountain and Spring Mountain Road areas), requiring additional crushing to produce material suitable for use in portland cement concrete.

According to figures in Tepordei (1995), the average value for sand and gravel in Nevada in 1994 was \$4.40 per ton, whereas the average value for crushed stone (which includes some stone used to make cement and lime) was \$7.88. In large market areas such as Las Vegas, production costs may be lower than elsewhere in Nevada due to economies inherent in large-scale mining. However, rates for transporting aggregate are generally higher in congested metropolitan areas. According to Goldman (1994), a good estimate for transport is 6 to 10¢ per ton-kilometer. At 6¢ per kilometer, an increase of a few tens of km in the hauling distance would render most deposits outside the Las Vegas basin uneconomic for that market, and there are no large sand and gravel operations more than 20 km distant from the center of the Las Vegas urbanized area (see maps in Castor et al., 1992). Crushed stone is mined in large amounts at Apex and Sloan, no more than 30 km from the Las Vegas urban center. However, volcanic cinder and lightweight aggregate appear to have values that can cover the costs of longer transport. The former is shipped approximately 140 km by road from the mine near the town of Amargosa Valley in the vicinity of Yucca Mountain, and the latter is trucked from a site about 40 km south of Las Vegas.

Domestic use of construction aggregate should increase gradually in future years (Tepordei 1993a, 1993b). Increased work on the national infrastructure, which has declined constantly since the 1960s as a percentage of the gross domestic product, was projected to increase following the passage of the Intermodal Surface Transportation and Infrastructure Act of 1991. However, anticipated aggregate production increases due to this factor (Tepordei, 1993a) have not materialized, and production has not increased over highs for sand and gravel in 1978 and crushed stone in 1988 (Tepordei, 1993a, 1993b, 1995).

In the Yucca Mountain region, future use of construction aggregate will probably remain relatively small except for use by the U.S. Department of Energy and its contractors on Yucca

Mountain and on the Nevada Test Site. Aggregate use in the expanding Las Vegas metropolitan area may become a factor in the Yucca Mountain region, as it already has for volcanic cinder mining near Amargosa Valley, which could be extended northward into the Crater Flat area. If the explosive growth that the Las Vegas metropolitan area has seen since the mid 1980s continues and potential sand and gravel producing areas are preempted for residential and commercial construction, new sand and gravel producing areas will be needed. On the basis of information in Castor et al (1992), good potential for new sand and gravel mining sites lies in areas to the north, northwest, and southwest of Las Vegas.

Production of aggregate in southern Washoe County in northwestern Nevada was estimated to increase from less than 4 million tons per year to nearly 6 million tons per year between 1992 and 2012 (Bryan et al., 1994), an increase of more than 50% based on projected population increases of 2% per year and the present yearly consumption rate for aggregate (about 14 tons per capita). The estimated population of Clark County (which is predominantly in the Las Vegas metropolitan area) increased from 562,280 to 971,680 between 1985 and 1994 (Nevada State Demographer, 1994), an average rate of 5-6% per year. During this period, construction aggregate consumption rose from about 6 million tons to about 18 million tons, or about 12% per year, considerably outstripping the population increase, probably due to the construction of several large resort-casinos and to aggressive public works building during this time. On the basis of 1994 figures, yearly aggregate consumption in the Las Vegas metropolitan area is nearly 20 tons per capita. If population growth in the Las Vegas metropolitan area continues at a rate of 5.5% per year, yearly consumption of construction aggregate in the area could increase to about 25 million tons in the year 2000 and 74 million short tons in 2020. However, more conservative estimates put Las Vegas annual growth at about 3.2% between 1994 and 2000 due to increased investments by gaming corporations in states other than Nevada (Nevada State Demographer, 1993), which would decrease predicted aggregate production rates to 24 million short tons in the year 2000 and 72 million short tons in the year 2020.

Although sand and gravel production exceeds crushed stone production in the Las Vegas area by a large factor, crushed stone as a percentage of the Las Vegas market increased from less than 2% in 1989 to 10% in 1994 (Castor, 1990; 1995). If this trend continues, crushed stone that is produced from sites that are topographically less attractive to urban growth could make up possible shortfalls in sand and gravel production, obviating the need for movement of aggregate production to sites that are much more distant from Las Vegas than the present sites.

6.4.3. Construction aggregate resources in the Yucca Mountain region

6.4.3.1. Region surrounding the controlled area

Although construction aggregate production in the Yucca Mountain region is relatively small, the area contains vast resources of sand and gravel and huge amounts of material suitable for the production of high-quality crushed stone. Large amounts of sand and gravel derived from Paleozoic carbonate highlands (one of the preferred construction aggregates in Las Vegas) are available in alluvial fans along Highway 95 as are large exposures of Paleozoic carbonate rock (used in crushed stone in Las Vegas). However, the Yucca Mountain region (as delineated by Plate 1) is 100 km by road from the Las Vegas metropolitan center, rendering these resources uneconomic at the present time. Furthermore, there is no rail service between Las Vegas and the Yucca Mountain region, so that high-cost truck transport is necessary. It is therefore likely that the construction aggregate production will remain relatively minor in the Yucca Mountain region. However, high-quality sand and gravel and crushed stone are undoubtedly available from areas dominated by Paleozoic highlands such as the Specter Range on the Nevada Test Site, and these resources may be used for portland cement concrete in future construction on Yucca Mountain.

6.4.3.2. Controlled area

The canyons and alluvial fans in the Yucca Mountain controlled area contain minor amounts of high-quality construction sand and gravel in comparison to regional resources. Most of the detritus in these sands and gravels is probably sound, durable welded ash-flow tuff; however, some structurally inferior non-welded and bedded tuff fragments are probably also present. Abundant welded ash-flow tuff bedrock exposures in the controlled area undoubtedly include material that has adequate soundness and durability for many of the uses of crushed stone. For concrete aggregate, alkaline reactivity problems that are commonly associated with silicic rhyolite may make both sand and gravel and bedrock deposits in the controlled area less desirable.

6.4.4. Resource assessment for the controlled area

The Yucca Mountain controlled area has little or no potential for construction aggregate production under present conditions. Production of some construction aggregate for internal

use by the U.S. Department of Energy or its contractors is likely, but aggregate for portland cement concrete will probably have to be transported from outside the controlled area. The Yucca Mountain controlled area is more than 150 km from the Las Vegas metropolitan area on existing major paved roads, and truck haulage costs (at 6¢ per ton-km) would amount to \$9.00 per short ton, about twice the average price for construction aggregate in Nevada. Furthermore, large amounts of sand and gravel and of bedrock that are usable for high-quality construction aggregate are present in areas that are much less distant from Las Vegas than the controlled area. However, the establishment of rail service into the Yucca Mountain controlled area for haulage of materials to a nuclear waste repository could have the effect of making large amounts of crushed rock available for use in the Las Vegas metropolitan area at low cost. Large quantities of already extracted ash-flow tuff made available during repository excavation at Yucca Mountain might be attractive for rail haulage into the Las Vegas metropolitan area. Therefore, the potential for crushed stone production from Yucca Mountain, despite possible limitations as portland cement concrete aggregate, cannot be discounted.

6.5. Building Stone

6.5.1. Geology and building stone classifications

The term 'building stone' is used in this text for any natural rock that is shaped for specific uses. Most commonly it is quarried in large blocks which are later cut for further finishing. Building stone is utilized for construction of buildings, monuments, civil structures, in landscaping, for industrial needs, and for many other uses. Some building stone is sold in natural or broken sizes which remain unfinished, and which are used for building, paving, decorating, or other purposes (Power, 1994; Taylor, 1991).

Dimension stone is a type of building stone that is cut to specific sizes. This includes all building stone which is cut or broken to specific dimensions, often on all sides. Surfaces may be textured, smoothed, or polished to specification. Strict engineering requirements in modern building codes now limit the use of dimension stone for structural or load-bearing applications; concrete materials are more predictable under stress than natural stone. Most dimension stone is now used for non-load bearing walls, hanging panels, and veneers, and has a more decorative role in construction. Standards for applications in construction are well defined and relatively strict. Hanging panels of thin stone or composite light-weight panels of stone veneer on concrete backing are anchored to a structural wall or support structure through advanced suspension

systems which can accommodate structural movement, stresses, and even water drainage. In such applications, load-bearing requirements for a stone are limited to self-support. Developments have included the use of thinner panels of natural stone for light weight applications, light weight composite paneling, panels of reconstituted crushed stone, new methods of inserting suspension pins, protective coatings and sealants, and even impregnations to prevent staining.

Cut and trimmed dimension stone can take many forms. Tile is made from thin panels of stone cut into square or rectangular shapes and often has some form of finished surface. These forms are commonly used for flooring, on walls, and on counter tops. Most tile currently produced is made of marble due to the ease of cutting and polishing, but advanced cutting and polishing materials have now allowed various forms of granites to come onto the mass consumer market as well. Quarry blocks not suitable for preparing large panels may be used for tile. Large finished blocks of dimension stone are prepared as monumental stone, which includes grave markers, statuary, and larger structures such as memorials that contain elaborate carving. Granite and marble are the preferred stones for monumental use. The principal requirements are for uniformity of texture and color, freedom from flaws, suitability for polishing and carving, and resistance to weathering. Stone shaped into rectangular pieces along a natural breakage surface into irregular sizes can be used for wall construction as ashlar. They can be made from blocks unsuitable for cutting, or from rock that breaks along natural cleavages into rectangular shapes. Split-faced ashlar is a brick-shaped block made from sawed panels that are split to size. These are commonly produced from waste materials left from the production of dimension stone. Roofing slate, mill stock slate, and slate dimension stone are either naturally cleaved or smooth-finished slate pieces used for roofing, panels, tables, mantles, sills, steps and other structural purposes. Granite curbing blocks are used in large quantities for distinctive paving stones where resistance to weathering and abrasion is important.

There are several commercial varieties of stone sold and used in natural or broken sizes (Power, 1994). 'Field stone' can be gathered to make stone walls, fireplaces, and similar structures. There is no commercial connotation as to the nature of the stone to size, shape, or rock type, except that it can be set by hand. 'Rough construction-' and 'jetty-stone' includes large blocks of rough-hewn granite or other stone that can be used in retaining walls, seawalls, and bridge work. Requirements for this stone are that it resists weathering and erosion and that it breaks naturally into rectangular shapes that are easily set. 'Rubble' includes smaller sizes of broken stone for wall facing material in building construction. The primary purpose is aesthetic, but ease of setting, weather resistance, light weight, and an ability to bond well to mortar is also

important. It can be produced as a byproduct from other operations. Crushed stone is used to make terrazzo, a composite of broken stone and cement that is polished and cut into shapes for specific uses, such as tile. Thin slabs of stone used in paving are known as 'flagstone', as any naturally fissile stone having sufficient abrasion resistance. 'Paving blocks' are small rectangular cut blocks usually made of wear resistant granite that can be used to pave roads and other areas subject to heavy traffic. This market has all but disappeared except for ornamental paving and in areas where slope stability and erosion are a problem (Power, 1994).

The use of natural rock as building stone is principally governed by a combination of unique physical properties and aesthetic appeal. Aesthetic appeal has always been difficult to define and quantify. This subjective assessment may change regularly with building and decorating fashions. But physical properties are carefully defined in technical specifications and standards, and these form the basis of most selections of natural stone for a wide variety of construction applications.

Natural stone has many descriptive classifications. Within the stone industry purely scientific terminology is employed only to the level needed to guide non-professional operators, and architects. Commercial names for natural stone may have very little relevance to lithologic description. For instance, the commercial term 'marble' can include such rock types as onyx, travertine, serpentine (also known in the stone industry as verde antique), recrystallized limestone and dolomite. It is a general term applied to many forms of relatively softer natural stone associated in some way with carbonate rock. At the opposite end of the spectrum in terms of hardness, resilience, and preparation difficulty lies the commercial 'granite' which in the industry may encompass all granular or gneissic feldspathic rocks coarse grained enough to be seen with the naked eye. In the stone industry, 'sandstone' is considered a sedimentary rock composed mostly of sand-sized clasts cemented or bonded by silica, where fractures promulgate around and not through the constituent grains. Quartzitic sandstone and quartzite contain 90% and 95% silica, respectively, and fracture occurs through the constituent grains. 'Bluestone' is considered as a dense, hard, fine-grained stone that splits easily into thin slabs, and 'brownstone' is an iron oxide rich, medium-grained stone having a dark brown to red color. 'Limestone' is applied to sedimentary rock composed of calcite and / or dolomite, and is typically designated by location and texture. The term 'traprock' or 'black granite' usually refers to basalt as a dark volcanic rock. 'Soapstone' usually refers to a metamorphic rock composed principally of talc, and is renowned for its chemical inertness and heat resistance (Power, 1994; Taylor, 1991). 'Greenstone' usually refers to a metamorphic rock containing chlorite, epidote, or actinolite. 'Verd antique' is the traditional term used for massive serpentine that can take a high polish. ASTM publishes

standards covering material characteristics and physical requirements for specific stone types. 'Exterior marble' is defined under ASTM C-503 specifications, 'structural granite' under ASTM C-615 specifications, 'dimensional limestone' under ASTM C-568 specifications, 'building sandstone' under ASTM C-616 specifications, and 'slate' under ASTM C-629 specifications.

6.5.2. Production, uses, prices, and market outlook

There have been major changes in almost every sector of the building stone industry over the last decade. Architectural designs now incorporate new cladding systems for wall paneling employing advanced anchoring systems which can suspend unitized panels of polished stone, laminated panels of stone on concrete, and concrete panels finished in crushed stone. There has been a movement in personal tastes back to natural materials and finishes, and this has stimulated the market for polished natural stone. New fabrication techniques produce finished stone as unitized tiles and panels, which are thinner, often composite with a concrete backing, and lighter weight for suspension on specially designed hanging structures for building exteriors. Lowered costs have opened new markets and made finished stone available to a greater number of new construction projects. Prestige buildings and memorials are no longer the exclusive reserve of polished stone.

A modern trend in the industry has been a move away from the tradition of unique luxury use in building towards mass marketing of finished stone in the residential housing sector, quality furniture, commercial property, and public access paving for malls, plazas, walkways, and parks. On the whole, the market area has broadened vastly, and production techniques have lead the way for this trend. New mass production techniques and fully automated fabrication lines have been rapidly followed by standards and testing practices, stone preservation methods, maintenance and repair programs, new mounting designs, safety accreditation, water sealing and drainage, and new epoxy glues. Much of the industry is now automated, so that lower costs and greater use means that the industry has become more strongly tied to short-term economic outlook.

One of the most significant changes in the industry over the last decade or more has been a large increase in the choice of prepared stone materials, along with more distributors, and an increased transport of finished stone - both nationally and internationally. Transport costs have become more important. Solid and composite tiles and panels of polished stone, and veneers, along with ashlar, are now produced in unitized pieces in standard shapes and sizes which can

travel long distances to markets. Pricing for standard-size 12" X 12" X $\frac{3}{4}$ " marble tiles may typically vary from \$5 each for cream, beige, or gray colors; to \$ 12 - 20 for green, red and black marbles (U.S. wholesale price guidelines, f.o.b. plant). Granite tiles of the same size may range in price from \$8 / ft² for basic gray colors, to \$11 for pinks, \$12.50 for imperial reds, and \$40 for unique natural blues (Harben and Purdy, 1991). Unitized stone furniture components, and standardized architectural components such as lintels, arches, steps, balustrades, column pieces, are all mass produced and often sold from catalogs. It is now common for quarriers and fabricators to take international orders.

Within the US industry, building stone production may be divided equally between 'commercial work' which is dominated by standard sizings and mass production methods, and 'cut-to-size work' such as interior marble work and an emphasis on the fabrication of shapes for unique installations (Bergman et al., 1993). There is a vast difference between the two areas in terms of equipment, scale of production, unit costs of production, capital investment, labor costs and skills, and the design of fabrication plants around features such as material handling methods. That difference is often reflected in the quality of stone used. Less decorative stone is more often prepared for less costly utility service, such as commercial work. Fabrication for commercial work allows fully computerized machinery, robotics, and automated material handling for rapid throughput. Quantities handled are typically high, with 50 or 100 pieces at a time. Sawing and bridge-polishing machines are now highly automated, and trimming is often done with CAD / CAM robotic units with teach-in contour construction facilities, perhaps driving water jet cutters. In the quarry, chain saws and belt saws have replaced blasting and wire sawing methods for softer rock such as marbles and sandstones, allowing rapid production of trimmed quarry block. Turn-key tile fabrication lines can now be purchased and installed with a capital investment of some \$5 million. In contrast, cut-to-size work is dominated by greater skills, site fitting, finished quality, manually operated equipment, lower capital costs, and specialization in stone types, particularly decorative stone.

The building stone industry has seen steady growth in the use of building stone as a luxury building, landscaping, decorating, and furnishing item. The market outlook for the industry as a whole is one of continued long term growth. Although the industry's status is typically tied to short-term economic outlook, there are overall long-term trends which indicate a much healthier outlook in decades to come. As a relatively high-value item in construction, dimension stone has unique features that distinguish it from a normal industrial mineral product. Polished, decorative, natural stone is used to enhance prestige in corporate and institutional buildings, such as memorials, art galleries, corporate headquarters, reception foyers, and for government

administrative centers. The U.S. market for natural stone experienced strong growth during the more affluent latter half of the 80's, but has steadied and partially retracted in some sectors during the 90's as a reflection of a slowing in economic growth (Harben and Purdy, 1991). For 1994, U.S. production of dimension stone was down by 13% from 1993 figures (Taylor, 1995). Despite these short-term fluctuations, the long-term market outlook is one of continuing growth.

6.5.3. Building stone resources in the Yucca Mountain region

6.5.3.1. Region surrounding the controlled area

Only three notable attempts at quarrying dimension and building stone have been made in the Yucca region. Of these, only one is in operation today, producing cut stone from the Tertiary tuffs in the Beatty area.

In California, Amargosa Marble Company's travertine deposit, located on State Highway 190, 2.75 miles east of its junction with Ryan Road in Furnace Creek Canyon (Plate 1), was mined from several open cuts to feed a small plant consisting of a jaw crusher and screens. The travertine crops on both sides of the highway in beds that strike N. 20° W. and dip 20° E. The property is now idle (Norman and Stewart, 1951). The crushed travertine was used to make terrazzo tile.

The American Carrara Marble Co. owned and operated marble quarries on the southwest flank of Bare Mountain (Plate 1). The marble occurs in steeply dipping beds that have an outcrop length of more than 2 miles and a thickness estimated at 2500 feet (Lincoln, 1923). The grain is generally very fine and uniform, and the stone is capable of taking a high polish (Mineral Resources of the United States, 1913). It was once shipped to Los Angeles and San Francisco (Lincoln, 1923). Despite the occurrence of great quantities of statuary and commercial grade white marble, along with large amounts of black, gray and blue marble, this venture was unsuccessful due to intense fracturing and numerous veins in the marble (Cornwall, 1964).

Nevada Neanderthal Stone is the only building stone producer in the Yucca Mountain region today. As a division of D & H Mining, the company quarries and cuts 12 varieties of Tertiary tuff to produced unitized floor tiles, wall panels, and other stone products. Blocks weighing up to 25 tons are hauled to a cutting shop near Beatty which has the capacity to produce 2,000 square feet of tile per day (Castor, 1991). Nearly 100,000 square feet of tile were produced in 1993 (Castor, 1994). The stone, which comes in a variety of colors and textures, is relatively lightweight

and easily worked. It is marketed mostly as tile and slabs, but custom-cut shapes, such as pillars, can also be produced. Products were originally sold through brokers, but the company has begun its own marketing.

6.5.3.2. Controlled area

Considerable amounts of Tertiary tuff are accessible for surface extraction in the controlled area. Ash-flow sheets of both the Timber Mountain Group and the Paintbrush Group crop out as prominent ridges in the controlled area, and the former is the source of most of the building stone extracted by Nevada Neanderthal Stone in the vicinity of Beatty. Ash-flow tuff rock types are uniform over large lateral distances. Exposures of the Rainier Mesa, Tiva Canyon, Yucca Mountain, Pah Canyon, and Topopah Spring Tuffs provide a considerable range of lithologic textures and colors in the controlled area.

The Topopah Spring Tuff contains a series of lithologic zones that Scott and Bonk (1984) labeled on the basis of colors - the orange brick zone, the brownish orange brick zone, the grayish-red lithophysal zone, the orangish-red lithophysal zone, and the purplish-brown lithophysal zone. Other zones in this unit vary in color from light gray, to grayish-orange, brownish-orange, reddish-orange, pale reds, and orange-pink, and mottled pale red and orange pink (Scott and Bonk, 1984). The presence of lithic and pumice fragments provide textures that may be enhanced by fragments of differing colors, shapes, and sizes. The welded ash-flow tuff of the Rainier Mesa Member is grayish-pink to grayish orange pink in color and contains abundant phenocrysts and pumice fragments which range in size from 0.2 to 3 cm. 'Clinkstone' zones in the Paintbrush Group are solid, welded tuff in gray and red colors that contain pumice fragments 0.2 - 2 cm in size oriented along foliation planes (Scott and Bonk, 1984). On the whole, most of the tuffs are reported to be porous and not indurated, which better suits cutting and shaping of the stone, but not polishing. Densely welded or glassy types are less porous, presumably of greater strength, and would take a better polish. The presence of lithophysae, hollow, bubble-like structures composed of concentric mineral shells, in many of the tuff units could enhance the textural appeal of the stone. Where they are relatively sparse their presence does not weaken the structural integrity of the stone. However, some units contain abundant, large lithophysae, and this type of stone may not be suitable for cutting without crumbling.

Several units within the Timber Mountain and Paintbrush Groups which crop out in the controlled area exhibit distinctive fracturing styles which may be detrimental to building and dimension stone. The lower lithophysal and hackly zones of the Paintbrush Group show columnar

jointing (Scott and Bonk, 1984) associated with more glassy compositions, and with cooling effects during deposition. The welded part of the zone is reported to be characterized by thin, shingle-like partings parallel to the foliation plane (Scott and Bonk, 1984). These authors also describe hackly fracturing and exfoliation in the rocks of some zones in the Paintbrush Group, suggesting that the rock may show detrimental weathering effects as a building or dimension stone. Clinkstone zones in the Paintbrush Group exhibit uniform texture, but conchoidal fracturing in this rock might be an unfavorable factor in its potential as building stone.

6.5.4. Resource assessment for the controlled area

Large amounts of Tertiary tuff are available in the controlled area, and it is possible that some of this material could be used as building stone. The likelihood of extraction of ash-flow tuff from the controlled area for building stone is dependent on intangible factors such as future demand for particular colors and textures of stone. The tuff in the controlled area does not appear to have unique properties, either physical or aesthetic, that would make it especially valuable as a decorative dimension stone when compared with other tuffs outside the controlled area. As dimension stone that could be quarried and prepared in a tile or panel plant, tuff in the controlled area does not appear to have features that would make it more valuable for dimension stone preparation than the Tertiary tuffs currently being quarried by Nevada Neanderthal Stone at sites that are closer to its Beatty cutting plant.

It is unlikely that underground excavation of the repository by tunneling and mining equipment would produce blocks of rock equivalent to quarry blocks that could be used in a fabrication plant because breakage of such material is not controlled in terms of size and shape. The development of infrastructure in the controlled area, such as access roads, electrical power, and water supply would provide no significant advantages to building stone over those currently available in areas closer to presently developed areas in the region.

6.6. Barite

6.6.1. Geology of barite deposits

Barite (BaSO_4) is the most abundant ore mineral of the metal barium, but it is mainly used in the mineral form. Pure barite contains 65.7% BaO and 34.3% SO_3 and has a calculated specific

gravity of 4.5, but most natural barite deviates somewhat from these numbers. In some types of deposits, barite contains up to several percent strontium, which substitutes for the barium, and barite may be finely intergrown with other minerals, such as quartz or carbonate minerals, reducing its density. The high density of barite, its relatively inert chemical properties, and its abundance have made it an important industrial mineral commodity. Although barite occurs in large clear white, yellow, gray, and light blue orthorhombic crystals, it is present as finely crystalline irregular masses or beds in most commercial deposits.

Barite occurs in many geologic environments in sedimentary, igneous, and metamorphic rocks. Commercial deposits of barite may be divided into four types: bedded barite deposits; vein barite deposits; karst barite deposits; and residual barite deposits.

Bedded barite deposits are the most commercially attractive because they tend to be relatively large and high grade. Individual bedded barite deposits may contain several million tons of ore, and individual beds within these deposits contain as much as 95% barite that can be used with little or no beneficiation other than grinding (Brobst, 1994). Most bedded barite deposits occur in early to mid-Paleozoic sedimentary sequences that typically contain abundant chert and black shale and siltstone. The barite, which occurs in massive to laminated beds up to 30 m thick, is commonly dark gray to black in color. The origin of bedded barite deposits has been a matter of debate, with early researchers proposing hydrothermal replacement origin, and most later researchers arguing for some sort of synsedimentary genesis. The most favored explanation is that bedded barite deposits were of exhalative sedimentary origin; barite was deposited as a chemical precipitate from hydrothermal brines discharged during deep-sea sedimentation. In Nevada, bedded barite deposits are mainly in Ordovician and Devonian rocks in a well-defined, northeast-trending belt about 500 km long and 100 km wide that coincides with the Antler orogenic belt that was active in Late Devonian to early Mississippian time (Papke, 1984).

Vein barite deposits exhibit great variation in size and geometry; from long, relatively narrow tabular veins to stock work vein or breccia deposits. Vein barite occurs in sedimentary, metamorphic, and igneous (both plutonic and volcanic) rocks. Host rocks are Precambrian to Tertiary in age. Most barite in vein deposits is white to gray and is associated with sulfide minerals such as pyrite, galena, and sphalerite, and with other minerals such as quartz and calcite. In addition, most contain wall rock fragments. However, some vein deposits are of nearly pure barite. Vein barite deposits are mostly considered to have formed from low-temperature epithermal solutions, particularly those in the western United States (Brobst, 1994). Vein barite deposits are not as important as bedded barite deposits commercially, but still yield significant tonnages. In

Morocco, which has ranked ahead of the United States in barite production in recent years (Searls, 1993), barite is mined from vein deposits.

In Nevada, vein barite deposits generally occur within, or in a halo around, the belt of bedded barite deposits described above. Host rocks for the veins range in age between Precambrian and Miocene, with nearly 50% of the deposits in carbonate rocks. Igneous rocks - metavolcanic, volcanic, and intrusive - are the host for 28% of these vein deposits (Papke, 1984). A separate dolomite-replacement type of vein deposit has been defined in Nevada (Papke, 1984). Such deposits occur in Ordovician to Devonian carbonate rock and consist of low grade zones that contain less than 50% barite as pods or stock-work veins. Only two Nevada vein barite deposits have produced more than 1,000 tons of barite, and these are both dolomite-replacement type deposits. By comparison, 21 bedded barite deposits have produced more than 25,000 tons, and three have produced more than a million tons.

Vein barite deposits in Tertiary volcanic rocks are rare in Nevada. Papke (1984) identified only two such deposits, neither of which had more than 100 tons of production. The Camp Creek deposit in Elko County consists of veins of nearly pure barite up to 3 m wide and 75 m long in Miocene rhyolite. The Searway deposit in Clark County contains barite in a breccia mass up to 0.9 m thick within a steeply-dipping veined zone 65 m in length that occurs along a steeply dipping fault.

Karst barite deposits, in which barite occurs in circular deposits in cavern or collapse structures, occur in central Missouri. Karst barite ores are rich, but generally small (Searls, 1993). Karst barite deposits are not known to occur in Nevada.

Residual deposits are shallow, surface concentrations of unconsolidated material formed from weathering and erosion of other deposits. Size and grade of these deposits is highly variable. Four areas of residual or alluvial barite deposits are known in Nevada, and two have been mined. Neither produced more than 25,000 tons of barite (Papke, 1984).

Residual and bedded barite deposits are typically mined by open-pit methods, but some bedded and vein deposits may be mined by underground methods. All barite mined currently, or in the recent past, in Nevada is from open pit mines (Papke, 1984). Residual barite deposits are typically unconsolidated, so that a final product is often produced by washing techniques that remove unwanted materials and also further pulverize the ore. Bedded deposits may be tectonically deformed to the point that blasting is unnecessary, and grinding is often all that is

required to make a final product. Vein deposits typically require a flotation circuit to efficiently separate barite from gangue and produce a final concentrate (Brobst, 1994). Barite is processed for certain uses by a reduced roasting technique to make a barium sulfide form, which can be hydrolyzed and reprecipitated as chemically pure BaSO₄. Barium carbonate, barium chloride, and barium metal are also produced by further processing of the sulfide form.

6.6.2. Production, uses, reserves, prices, and market outlook

Approximately 5 million metric tons of barite are produced world wide, of which 90% is consumed by the petroleum industry as drilling mud additive (Brobst, 1994). China became the largest producer of barite in the 1980s, and importation of Chinese barite caused domestic production to plummet. Domestic production of barite has ranged between about 300,000 and 410,000 metric tons for the last five years (Bearden, 1995) and most of this barite has come from Nevada. Current Nevada barite production is only about 15% of the high point in production of more than 2 million metric tons that was reached in 1981 (Fig. B-1). Barite production in the state now comes from only four or five mines operated by four companies, whereas in the early 1980s barite was produced from more than 25 mines (Castor, 1993).

Figure 6. Production of barite In Nevada, 1952-1994.

Sources: 1952-1977: The U.S. Bureau of Mines ;1978-1994: The Nevada Mineral Industry, Nevada Bureau of Mines and Geology Special Publications MI-1978 through MI-1994.

The bulk of barite consumed in the world is used for production of high density oil and gas well drilling muds which cool and lubricate drill bits, clean and stabilize drill holes, and help contain high pressure gas and oil. Most domestic barite is sold into the United State's Gulf Coast, where major oil well drilling technology companies are located. Barite is also used in glass manufacture, as a high density filler and weighting agent in plastics and rubber, and when bleached, as a pigment. Barium sulfate is also radio opaque, and can be used as a relatively inexpensive radiation shielding material. In the medical field it is used as an indicator in X-ray photography.

American Petroleum Institute specifications for drilling-grade barite require a minimum of 90% BaSO₄ to provide a density of 4.2 or greater, no more than 250 ppm of alkaline earth metals, and only a few percent of iron oxide. It must be ground to 90% -44 micron mesh. Glass makers require very high purity barite ground to narrow size specifications. Manufacturers of barium chemicals usually require a minimum 95% BaSO₄ in their raw materials (Brobst, 1994).

The average value of domestic drill-grade barite f.o.b. mine was about \$42 per metric ton in 1994 (Bearden, 1995). Although China's growing position in world production had the effect of driving down prices for barite in the 1980s, recent equilibration of domestic rail shipping costs with ocean freight rates has made Nevada barite prices competitive with Chinese and Indian barite in the Gulf Coast (Griffiths, 1995). Barite products prepared for markets other than the oil field sector are priced higher than drill-grade barite. White, paint-grade barite (96-98% BaSO₄) sells for more than \$300 per metric ton delivered in the United Kingdom (Industrial Minerals, 1995).

Domestic barite consumption has grown each year for three straight years, primarily due to deeper drilling for natural gas in the Gulf Coast and Oklahoma (Bearden, 1995). However, Nevada barite production remains a shadow of its former glory (Figure B-1), mostly due to China's recent domination of the barite market. It is noteworthy that one major Gulf Coast drilling products company, Baroid Drilling Fluids Inc., reopened a barite processing mill in Nevada in 1992 (Castor, 1993) and Smith International, a worldwide provider of drilling technology, purchased a majority share of M.I. Drilling Fluids, Inc., a major Nevada barite producer in 1993 (Castor, 1995). Recent political developments between China and the United States, as well as internal factors within China, may provide an opportunity for resurgence of Nevada barite mining in the near future. Disruptions in the supply and quality of barite from China and India have, in part, led to increased production in the United States and Morocco, and this trend is likely to continue (Griffiths, 1995).

Barite consumption is mainly dependent on the amount oil and gas drilling. The growing world population will put pressure on existing energy resources and the pace of drilling will

probably increase in the long term as older oil and gas fields pass peak production years. The amount of barite needed to drill oil and gas wells will also increase as wells go deeper, particularly in North America. Thus the demand for barite is expected to increase in the long term, although byproduct barite from metal mining and reprocessing of barite tails ponds may partly offset higher demand.

6.6.3. Barite resources in the Yucca Mountain region

6.6.3.1. Region surrounding the controlled area

Only one significant barite occurrence has been reported in the Yucca Mountain region. It is located on Mine Mountain about 30 km northeast of the controlled area. Here white barite occurs in a 1.5-m-wide vein that is associated with quartz breccia and minor sulfide mineralization along a N10°W, 65°N fault in Paleozoic rocks (Quade et al., 1984). The vein is exposed along its strike for more than 90 m. Samples taken from this vein all contain over 0.5% Ba (the upper detection limit) along with anomalously high As, Pb, Sb, Sr, and Zn, all are said to be "very high in barite," and one sample was described as massive white barite (Quade et al., 1984). No barite production is recorded from this occurrence, and it is not considered to be an economically important barite deposit.

Minor barite has been identified with brucite along contact zones in altered Paleozoic rock in the central and southeastern parts of the Calico Hills about 5 km northwest of the controlled area. A single sample was found to contain more than 0.5% Ba (the upper detection limit) as well as elevated Sr. Some samples of quartz vein, gossan, and fluorite-calcite breccia from the Bare Mountain mining district about 12 km to the west of the controlled area also contain more than 0.5% Ba (the upper detection limit) along with anomalously high base metals, Sb, and As (Tingley, 1984). Smith et al. (1983) reported coarse barite in lenses of cryptocrystalline quartz with cinnabar and calcite along fissures in dolomite within the Bare Mountain district.

6.6.3.2. Controlled area

Barite occurs sparingly in core from drill holes in the Yucca Mountain controlled area. Caporuscio et al (1982) reported 5-mm-long barite crystals in a 1-cm-thick quartz-calcite vein at a depth of 5,696 ft (1,737 m) in hole G-2, and also recorded barite at about 4,200 ft (1,280 m) in G-2. Castor et al. (1993) identified barite in a vein sample from a depth of 5,636 ft (1,718 m) in hole

G-2 and in a 5-mm-thick vein sample from 3,938 ft (1,200 m) in hole 25b. In addition, a sample from 5,597 ft (1,706 m) in G-2 contains 0.64% Ba, suggesting that it contains minor barite.

6.6.4. Resource assessment for the controlled area

The geologic setting in the Yucca Mountain controlled area is not favorable for bedded barite deposits in Paleozoic rock except at depths of more than 1,200 m (the first penetration of Paleozoic basement rocks in hole 25-p), clearly excessive depths for open pit mining. Therefore, the potential for these types of barite deposits (from which all barite in Nevada is now produced) is considered to be nil in the controlled area. Minor amounts of barite occur in some thin veins in volcanic rock at depths of 1,200 m or more in Yucca Mountain. However, the Yucca Mountain controlled area is considered to have little or no potential for barite production because these barite occurrences are minor and at such great depths.

6.6. Perlite

6.7.1. Geology of perlite deposits

Perlite is defined commercially as any naturally occurring siliceous volcanic glass that, when heated to temperatures of 1400°-2100° F (Kadey, 1983), or about 760°-1150° C, will expand to the point that its bulk density is as low as 30 kg/m³ although more typically values are about 80 kg/m³ (Allen, 1992). Laboratory scale testing of perlite may be done in a lower temperature range, about 670°-820° C (Barker and Harris, 1990). Perlite expands or "pops" to form a low density cellular material because it contains 2-5% of chemical water held within the glass structure (Breese and Barker, 1994) that flashes into steam upon heating.

Non-hydrated volcanic glass (obsidian) typically contains less than 1.0 wt % total water bound in the silica framework, and perlite is thought to form by the incorporation of water in obsidian during slow post-emplacement hydration by meteoric water (Breese and Barker, 1994). Perlite may generally be distinguished from other types of volcanic glass by having a pearly luster, and fine (granular) or coarse (onion-skin) arcuate or perlitic fractures. However, this is not always the case because some commercial perlite does not exhibit pearly luster or megascopic perlitic fractures. Many perlite deposits contain remnants of black, non-hydrated glass (often referred to as "Apache tears"), spherulites or other devitrified masses, and phenocrysts of feldspar or other

minerals. Perlite deposits that contain large amounts of such impurities may well be uneconomic.

Most commercially mined perlite deposits are in parts of silicic volcanic domes or lava flows that were subjected to rapid quenching. However, perlite deposits may also be found in densely welded vitrophyric portions of ash-flow sheets or vitrophyres in high-level intrusions. According to Breese and Barker (1994), the perlite deposits at No Agua Peaks, New Mexico, provide a model for many perlite deposits in domes and flows world wide. The No Agua perlite occurs in an exterior mantle around a variably devitrified zone that surrounds interior crystallized felsite in an extrusive volcanic dome.

In the United States, perlite comes from mines in four western states, with New Mexico operations accounting for most of the production. In recent years, Nevada has been a relatively minor producer, but the state has large amounts of high-quality perlite resources.

Perlite is, or has been, produced from deposits in four counties in Nevada (Gemmill, 1964; Papke, 1973; Castor, 1995). In Lincoln County, which has had the largest production, perlite has been produced from three deposits. At present, about 4,000 tons of perlite are extracted annually from the Mackie (Delamar) deposit, which has been mined almost continuously since 1951 (Castor, 1988). Until 1987, perlite from this deposit was expanded at plants outside Nevada, but a small expansion plant is now in operation in the nearby town of Caliente. The perlite occurs as a layer in Tertiary tuffaceous rocks that is 3 to 30 m thick. Because of the geometry of the deposit, most of the perlite is mined underground (although this method also helps to keep the perlite dry, facilitating processing during the winter).

In 1994, Eagle-Picher Minerals, Inc. began producing expanded perlite filtration products from a new facility, with production capacity of 15,000 short tons per year, at its diatomite plant at Lovelock in northern Nevada (Castor, 1995). The perlite is mined from a location in Desert Mountains in Churchill County 16 miles south of Fallon, where perlite at least 10 m thick associated with rhyolite flows is exposed over an area of about 300 m by 500 m (Willden and Speed, 1974). Until 1988 United States Gypsum Company mined perlite from a 27-m-thick intrusive dome deposit in Pershing County near Lovelock (Johnson, M.G., 1977).

More perlite has been mined from the Hollinger mine in Lincoln County than from any other Nevada deposit (Tingley and Castor, 1991). Total production is estimated at 350,000 short tons (about 320,000 metric tons) between 1949 and 1971, when production ceased. The Hollinger deposit consists of flat-lying to shallowly dipping mass of nearly pure, gray to black,

granular perlite 800 m long and at least 50 m thick. The average exposed perlite width is 170 m, and mineable reserves are about 4.5 million short tons (Tingley and Castor, 1991). Glassy to devitrified pumiceous rhyolite breccia appears to underlie and overlie perlite at the Hollinger mine, but the perlite does not show any indications of brecciation. Devitrified rhyolitic flow rock or ash-flow tuff lies above perlite at the west end of the deposit. Minor amounts of spherulitic devitrification occurs within the perlite and appears to be more abundant near the west end of the deposit. The perlite contains less than 5 % of small quartz and feldspar phenocrysts. According to Gese (1985) the density of expanded Hollinger perlite ranges between 2.55 and 4.56 lbs/ft³, which indicates that it would be suitable for filter aids and cryogenics, as well as for construction material.

In Clark County, perlite was mined from two deposits by Nulite Insulated Homes and the Nevada Perlite Company until 1954 and 1955, respectively. At the former, perlite occurs in a flat-lying deposit about 2 miles long, 1 mile wide, and 50 feet thick, with reserves estimated at 200 million short tons; at the latter two widespread perlite layers with thicknesses of 21 feet and 100 feet have reserves estimated at 10 million short tons (Longwell et al., 1965).

Although perlite is mined underground in Nevada, it is typically mined by open-pit methods. Most perlite mines use either drilling and blasting or dozer ripping, or a combination of both. Crushing, drying, and screening are generally done near the mine because abundant unusable fines are produced, and most crude perlite is shipped to expansion plants near markets.

6.7.2. Production, uses, reserves, prices, and market outlook

Annual international consumption of perlite has been quite stable between 1988 and 1994, ranging between 1.44 and 1.59 million metric tons (U.S. Bureau of Mines, 1993a;1995). The United States is both the largest consumer and producer of perlite. Turkey, Greece and Japan, in that order, are other countries that lead in perlite production.

Annual production of processed perlite from domestic mines has been somewhat less stable than international production, falling sharply from nearly 600,000 metric tons in 1980 to just over 400,000 tons in 1983, remaining at 400,000 to 500,000 metric tons until 1992, then escalating rapidly to 644,000 tons in 1994 (Fig. 7). During the period 1989-1993, Nevada perlite production was small, ranging between 3,000 and 4,500 short tons (Nevada Bureau of Mines and Geology, 1990-1994). With the entry of Eagle-Picher Minerals Inc. into Nevada perlite production in 1994, Nevada perlite production should escalate.

Figure 7. Domestic production of perlite, 1980-1994.

Source: U.S. Bureau of Mines Mineral Commodity Summaries, 1982-1993; U.S. Bureau of Mines Annual Review, 1994.

Although unexpanded perlite has a number of uses, expanded products comprise most of the international consumption of perlite. Construction products such as insulation, ceiling tile, textured paint, and lightweight aggregate in concrete and plaster are the most important uses volumetrically for expanded perlite. Horticultural uses as soil conditioner and propagating medium have grown steadily in recent years. Milled expanded perlite is used in the filtration of food products, oils, industrial effluents, and other fluids; and as a filler in plastics.

International perlite reserves have been estimated at 700 million metric tons of crude ore in a reserve base (resource) of 2 billion tons. Of this, United States reserves have been estimated at 50 million tons in a reserve base of 200 million tons (Bolen, 1993).

The average price for all perlite sold or used by mining companies in the United States was about \$30 per ton (U.S. Bureau of Mines, 1995). Average prices for expanded perlite in the United States in 1994 ranged between \$132 and \$494, depending on application (U.S. Bureau of Mines, 1995).

Because perlite is mainly consumed by the construction market, perlite demand is directly related to the general world economy. Domestic crude perlite, mined entirely in the western United States, has encountered transportation cost disadvantages in some parts of the eastern

United States. Imports of perlite, mainly from Greece, have remained relatively stable at 60,000 to 70,000 metric tons for the past seven years. However, foreign interests have been actively pursuing opportunities for perlite exportation to the United States. Perlite competes with a variety of natural and manufactured products for most applications. In the near term, perlite sales are expected to experience modest growth (U.S. Bureau of Mines, 1995).

6.7.3. Perlite resources in the Yucca Mountain region

6.7.3.1 Region surrounding the controlled area

Perlite has been noted at two localities northeast of Beatty in the Yucca Mountain region (Plate 1). Little is known about the size or quality of the perlite resources at these occurrences. Kral (1951) reports 20 foot (6 m) widths of perlite lying between rhyolite flows and tuffs a few miles east of Beatty, but it is not known if this coincides with either of the perlite occurrences shown on Plate 1.

6.7.3.2 Controlled area

The Yucca Mountain controlled area contains no exposures or drill intercepts of glassy silicic domes, flows, or intrusions, although such rocks are present a few km to the north of the controlled area in the rhyolite of Forty Mile Canyon (Scott and Bonk, 1984). However the controlled area contains some dense vitrophyric welded ash-flow tuff layers that may contain expandable perlite.

The Tiva Canyon Tuff of the Paintbrush Group includes vitric rock in the controlled area. However, most of this is partly devitrified or consists of light-colored, non-welded to moderately welded rock with variable amounts of clay alteration. Maldonado and Koether (1983) describe cuttings of quartz latitic cap rock of the Tiva Canyon Tuff from drill hole G-2 as a 13.7-m-thick interval of densely welded, vitric ash-flow tuff. No data was found on water content or loss of ignition of this material, but it contains 10-15% feldspar phenocrysts, which together with its relatively low silica content as a quartz latite, suggests that it is not usable as commercial perlite. The Tiva Canyon Tuff cap rock is extensively exposed in the controlled area (Scott and Bonk, 1984).

The Topopah Spring Tuff of the Paintbrush Group in the Yucca Mountain controlled area contains dense gray to black vitrophyre near its top and base. The upper vitrophyre, which is part

of the quartz latitic cap rock of the member, is densely welded ash-flow tuff that contains 10-20% phenocrysts of feldspar, biotite, and hornblende, and ranges between 1 m and 4 m in thickness as measured in core from drill holes G-1, G-2, GU-3, G-4, and 25a (Spengler et al., 1981; Maldonado and Koether, 1983; Scott and Castellanos, 1984; Spengler and Chornack, 1984; Spengler et al, 1979). A search of the literature revealed no data on water content or loss on ignition for this unit, but it was described as perlitic in core from hole G-4 (Spengler and Chornack, 1984). Caporuscio et al. (1982) noted that vitrophyre in the upper part of the Topopah Spring Tuff in hole G-2 ranges from vitric to devitrified over small irregular intervals. The portion of the Topopah Spring Tuff that contains this thin vitrophyre unit is widely exposed in the controlled area (Scott and Bonk, 1984).

Vitrophyre in the basal part of the Topopah Spring Tuff is thicker than that in the cap rock. On the basis of intercepts in drill holes G-1, G-2, GU-3, G-4, 25a, SD-9, and SD-12, it ranges between 9 m and 25 m thick, and averages about 15 m thick (Spengler et al., 1981; Maldonado and Koether, 1983; Scott and Castellanos, 1984; Spengler and Chornack, 1984; Spengler et al, 1979; Drilling Support Division, 1995a; 1995b). On the basis of loss on ignition measurements ranging between 3.34 wt. % and 3.66 wt. % (reported in Singer et al., in press), it may contain sufficient amounts of structural water for use as commercial perlite. This vitrophyre is generally described as dark gray or black, densely welded ash-flow tuff with 2% or less phenocrysts and 2% or less lithic fragments. The part of the Topopah Spring Tuff that contains this vitrophyre is not exposed in the controlled area, but it does occur a few hundreds of meters to the northwest of the controlled area on the northeast slopes of Castellated Ridge (Scott and Bonk, 1984).

6.7.4. Resource assessment for the controlled area

Although the Yucca Mountain controlled area does not contain glassy silicic volcanic rock in the form of domes or flows, which are the most likely sources for perlite, ash-flow sheets in the controlled area contain dense vitrophyre that may have potential as perlite. In order to determine if such vitrophyre is usable as commercial perlite, expansion testing such as that described by Barker and Harris (1990) is necessary, and such testing is beyond the scope of this study.

The most likely source of perlite in the controlled area is in the lower vitrophyre zone of the Topopah Spring Tuff of the Paintbrush Group because it is present in mineable thicknesses. However, that unit is not exposed in the controlled area, and if it was found by testing to be suitable for the production of expanded perlite, it is unlikely that it would be mined because of the

large amount of overburden.

Considering the large amount of domestic perlite resources, the potential for perlite mining from the controlled area in the near or distant future is considered to be low.

6.8. Pumice and pumicite

6.8.1. Geology of pumice and pumicite deposits

Pumice is light colored, highly vesicular volcanic glass that typically has a bulk density of less than 1.0 g/cm^3 , and is therefore light enough to float on water. The term 'pumicite' refers to light colored, fine-grained pumice or glass shard deposits with individual fragments less than 2 mm in diameter. It is a commercial term for volcanic ash. Commercial pumice and pumicite deposits generally consist of unconsolidated accumulations, although individual pumice fragments may be a meter or more in diameter.

Pumice deposits can be classified into four major types: flows and domes, air-fall deposits, pyroclastic flows, and reworked deposits. Rhyolitic flows and domes, which are typically only a few km^2 in areal extent, may have rubbly carapaces of pumice. The pumice in such deposits is generally associated with nonvesiculated volcanic glass, and much of the pumice may be interlayered with nonvesiculated rock. The erratic nature of vesiculation can make exploration and development difficult, and the pumiceous material may only be usable as relatively low value lightweight aggregate. The Naturalite property in Storey County, Nevada, is a deposit of such material that has been used in the manufacture of lightweight concrete, building blocks, and portland-pozzolan cement (Papke, 1969).

Air-fall deposits are well-sorted pumice or pumicite deposits formed by explosive eruptions of pyroclastic material, and range from deposits of relatively coarse pumice close to a volcanic vent to fine-grained pumicite deposits at greater distances from the vent. Most high-value pumice deposits are air-fall deposits. In northern California, pumice is mined by the Glass Mountain Pumice Company from an air-fall deposit and sold as high-value stone-washing pumice and as low-value lightweight aggregate. In the Glass Mountain area, pumice has been mined from a coarse air-fall unit up to 18 m thick and 35 km^2 in areal extent and from block pumice deposits on the surface of a 3 km^2 rhyolite obsidian flow (Chesterman, 1956). In central Oregon, which is the leading state in pumice production, two companies mine pumice from 4.5- to 12-m-thick beds of

air-fall tuff in pits with overburden ratios up to 1:1 (Geitgey, 1990).

Nonwelded pyroclastic flow deposits may be exploited for pumice, but such deposits are poorly sorted and likely to be partly to completely lithified. They are less frequently exploited for pumice or pumicite than are air-fall deposits. Reworked deposits are bedded pumice or pumicite accumulations that are formed by transport and redeposition of pyroclastic material by water. Reworked pumicite deposits are mined in California and Kansas (Geitgey, 1994). Pumicite in the area that contains the Friant, California deposit is said to be up to 45 m thick (Chesterman, 1956).

Pumice and pumicite mining is carried out at the surface, either by open pit mining or by removal of large blocks from pumice exposures. Most deposits have minimal overburden. Processing generally consists of air drying, crushing, and screening. Pulverization may be necessary to produce fine abrasive products, filtration aids, and pozzolan.

6.8.2. Production, uses, reserves, prices, and market outlook

International production of pumice and related materials is about 11-12 million metric tons annually (U. S. Bureau of Mines, 1993b), most of which is probably sold into construction product markets as pozzolan and lightweight aggregate. Countries that produce and export large amounts of pumice are Turkey, Italy, and Greece. Domestic production ranges between 300,000 and 500,000 metric tons annually (Fig. 8), and about 80% of this is low-value material that is used in lightweight building products (O'Driscoll, 1990). Domestic pumice is produced by 12 companies in 6 western states, with Oregon and New Mexico yielding the most production (U.S. Bureau of Mines, 1993b). Most of the lightweight aggregate mined in Nevada is not light enough to qualify as pumice, and is referred to as pumiceous rhyolite (O'Driscoll, 1990).

Internationally and domestically, most pumice and pumicite is used in construction materials. Pumice is used as aggregate in cast portland cement concrete and in concrete blocks because it reduces weight, provides insulating value, enhances color, and promotes ease of construction. It is also used as base fill in special applications. Pumicite or finely ground pumice is added to concrete as pozzolan to promote strength and durability and to reduce cement consumption.

Figure 8. Domestic production of pumice and pumicite, 1980-1993.

Source: U.S. Bureau of Mines Mineral Commodity Summaries, 1982-1993.

Significant amounts of pumice are used in high-value applications, such as abrasives which consume about 5% of domestic pumice (U.S. Bureau of Mines, 1993). Pumice makes excellent abrasives because its vesicle walls make hard, sharp cutting edges, and fresh edges are continually exposed as the relatively friable material is used. Pumice abrasives include sawn and shaped blocks, lump pumice, pumicite or finely ground pumice granules or powders, and impregnated molded forms. Abrasive uses include scouring powders, soaps, and other home products; industrial polishing products, such as fine powders used for glass polishing; and lump pumice for stone washing denim clothing. Pumice that can be used for the latter brings a premium price. The average size for pumice stones used in stone washing is 3-5 inches (7.5-12.5 cm), and pure pumice of medium hardness is preferred because hard stone and impurities damage the cloth and soft pumice wears too quickly (McMichael, 1990). According to Geitgey (1994), pumice particles as small as 2 cm in diameter may be suitable for stone washing.

Other relatively high-value pumice and pumicite uses are varied. Pumicite mined in Kansas finds uses as filtering media. Fine granular pumice is used in potting soils, and coarse granules and pebbles are used for ground cover. Pumicite and finely ground pumice is also used as absorbents, fillers, and in non-abrasive laundry applications. Large blocks of pumice from near Lee Vining, in eastern California, is used as landscape rock (Geitgey, 1994).

The average price for pumice in 1992 was about \$31 per metric ton (U.S. Bureau of

Mines, 1993), but this price was dominated by low-value pumice used in construction products. As a class, pumice used in abrasives brought the highest price domestically, approximately \$130 per metric ton in 1992 (U.S. Bureau of Mines, 1993b). Pumice for specific abrasive uses has sold for higher prices. For example, Turkish lump pumice used for stone washing brought as much as \$300 per metric ton in the mid 1980s (McMichael, 1990).

The stone washing of denim strongly enhanced the international pumice market in the mid-1980s, particularly for high-value lump pumice, but demand and prices leveled off and began to decline in the early 1990s. Domestic pumice and pumicite production has been maintained at relatively steady levels since 1980 (Fig. 8). Lower value aggregate pumice markets, which constitute most domestic sales, depend on the amount of construction activity which is, in turn, dependent on general economic conditions. Various mineral products can replace pumice as ground abrasives; and clays, diatomite, and zeolite minerals compete with ground pumice as absorbents and carriers. Diatomite and expanded perlite find more general use than pumice as filter media. Domestic pumice and pumicite production is not likely to increase dramatically in the foreseeable future.

6.8.3. Pumice and pumicite resources in the Yucca Mountain region

6.8.3.1 Region surrounding the controlled area

Pumice deposits have not been reported in the Yucca Mountain region; however, a deposit of pumicite about 6 km northeast of Beatty (Plate 1) has had past production. According to Horton (1964), this deposit was mined at irregular intervals during the 1940s for use as aggregate in the manufacture of concrete blocks. No data are available on the size and reserves of the deposit.

6.8.3.2 Controlled area

Pumice-rich tuff layers are exposed in the controlled area in the bedded tuff sequence that separates the welded portions of the Tiva Canyon and Topopah Spring Tuffs of the Paintbrush Group. On the basis of lithologic descriptions of drill core (Spengler et al., 1981; Maldonado and Koether, 1983; Scott and Castellanos, 1984; Spengler and Chornack, 1984; Spengler et al, 1979) and descriptions in Diehl and Chornack (1988), this interval contains interbedded air-fall tuff, reworked tuff, and non-welded ash-flow tuff with some layers containing

up to 90% pumice fragments. To the north of drill holes H-6 and H-4 (Figure PP-2), welded tuffs of the Pah Canyon and Yucca Mountain Members occur within this sequence, separating it into three bedded tuff sequences. The bedded tuff sequence, or sequences, range in thickness from about 18 m in drill hole G-2, to 15 m in drill hole GU-3 (Diehl and Chomack, 1988).

6.8.4. Resource assessment for the controlled area

Although the Paintbrush bedded tuffs include pumice-rich layers, they are mostly considered to have low potential for pumice or pumicite production because they are on the whole moderately to well indurated, commonly contain 10% or more lithic fragments, and are variably altered to clay (see section 6.2.3.2, this report). During field examinations of the southwestern part of the controlled area (Castor et al., 1990) the bedded tuff sequence was not found to contain any layers of unconsolidated fragments of glassy lump pumice suitable for high value pumice products. However, it is possible that the bedded tuffs in the Paintbrush Group may include thin beds of fine-grained glassy pumicite of sufficient quality for use as pozzolan or fine abrasive. A 30-cm-thick bed of white to light-gray, well-sorted, poorly indurated air-fall tuff noted in outcrop by Diehl and Chomack (1988, p. 90), may be an example of such material.

The potential for pumice or pumicite production from the Yucca Mountain controlled area is considered to be low. No occurrences of economic pumice or pumicite are known, and the pumiceous material that is present in the Paintbrush Group appears to be too consolidated or impure for commercial use. In addition, large resources of domestic pumice and pumicite are available for sale into a relatively stable, long-term market. Therefore, it is highly unlikely that new pumice or pumicite mines will be opened in the near future.

6.9. Borates

6.9.1. Geology of borate deposits

While more than 150 boron-containing minerals are known, less than 30 are common and only a few of those contribute significantly to boron production. Kistler and Helvacı (1994) have divided borate minerals into three groups, according to their origin and geological environment as A) skarn minerals, B) magnesium oxides related to marine sediments, and C) hydrated sodium and calcium borates related to continental and volcanic activity. The bulk of world boron production

comes from the minerals borax, kernite, colemanite, and ulexite in deposits of the third type, major deposits of which are located in Turkey, China, and Southeast California in the United States (Kistler and Helvaci, 1994) .

Borax is soft and water soluble and therefore readily processed, and is the industry's most important borate mineral, occurring in large tonnages in deposits in Turkey, Argentina, and California. Kernite, colemanite and ulexite are harder and in varying degrees less soluble, but together constitute a major portion of most boron resources, and can be processed with relative ease.

The largest borate deposits originate as chemical precipitates interbedded with lacustrine sediments in closed non-marine basins. The deposits are closely related to thermal springs and hydrothermal fluids associated with volcanism. These deposits generally form in arid to semi-arid climates, which promote evaporative concentration of borates during deposition. Most of these deposits contain only borate salts, but deposits containing mixed salts or brines also occur.

In Europe, borate deposits of marine origin occur associated with Permian salt deposits, from which they have formed by remobilization and accumulation during leaching of the salt units. These are relatively small deposits that are developed as byproduct operations by large potash producers.

Some commercial grade boron deposits occurring in Russia and China originate from magmatic activity in pegmatites and contact metamorphic rocks containing borates such as tourmaline and datolite. Boron is carried in most magmas at low concentrations, but cannot readily incorporate into the crystal structure of common silicates, and as a result fractionates into a water-rich fluid phase when the magma crystallizes. Boron containing minerals form from this solution during late greisen formation and related hydrothermal activity.

6.9.2. Production, uses, reserves, prices, and market outlook

Most production comes from large open pits using bulk tonnage trucking and conveying equipment to move ore to a refinery. Smaller operations using small equipment and hand labor are common, particularly in South America, China and Turkey. Underground mining of borates occurs in China, the United States, and Turkey, and boron-containing brines are recovered in California and China. Processing of ores is controlled by the scale of the operation, ore type, and

final product. Borax is typically crushed and dissolved in hot water, clarified, and dried to produce various boron hydrates or is prepared as a feed for other products. Ulexite and colemanite are concentrated in mineral form and used as feed for boric acid production or glass melts. Boron is also recovered from brines by evaporation and carbonation (Kistler and Helvacı, 1994).

Boric acid is produced by most operations, but the greatest use of boron is in the production of glass, fiberglass insulation, and other glass fiber products for which boron minerals such as colemanite can be used directly. Much boron is consumed in detergents, bleaches, fluxes, enamels, fertilizers and fire retardant materials. Pharmaceuticals, cosmetics, adhesives, insecticides and metallurgical processes consume a large part of U.S. boron sales. Boron fibers are increasingly used as a reinforcer to produce lightweight, strong composite or reinforced plastics. Boron reagents and products may find increasing use in environmental and medical fields (Lyday, 1995; Kistler and Helvacı, 1994).

Boron mineral concentrate and mineral production in the United States in 1994 was about 1.05 M metric tons yielding 560,000 metric tons of B_2O_3 at an estimated value of \$370 million (U.S. Bureau of mines, 1995). Most of this production is from the Kramer borate deposit which has been a world class producer since 1976 and continues to be the largest source of borate in the world (Siefke, 1991).

Prices quoted per metric ton for August 1995 in the journal Industrial Minerals was \$257 for technical grade decahydrate borax, \$294 for refined pentahydrate borax, \$720 for dehydrated borax, and \$708 for technical grade granular boric acid, all FOB California. The price for technical grade granular pentahydrate borax increased continually from 1970 to 1990 (Harben, 1992), but while the price for ultra high-purity boron oxide increased in 1994, all other prices dropped (Lyday, 1995).

According to Harben (1992) the borate market continues to grow, and is most strongly influenced by the rate of construction and the economy. However, production of boron minerals and compounds has decreased between 1980 and 1994 (U.S. Bureau of Mines, 1995), possibly due to the short term influence of certain environmental concerns over demand (Lyday, 1995). The U.S. National Toxicology Program has listed fiberglass as a material reasonably anticipated to be a carcinogen.

Large-scale borate production is limited to the United States and Turkey, with considerably smaller production from the former USSR, Chile, China and Peru. Potential for

growth exists in Mexico, Argentina, Chile, Bolivia, and China (Harben, 1992).

6.9.3. Borate resources in the Yucca Mountain region

6.9.3.1. Region surrounding the controlled area

Death Valley, 30 km southeast of the controlled area, has been a borate mineral producing district since the 1880s. Bedded borates deposits in lacustrine sediments and sedimentary rocks in this basin have been mined nearly continuously since 1907 and colemanite is still being mined from the Billie mine, an underground operation (Lyday, 1995; Kistler and Helvaci, 1994). The California Desert Protection Act was signed into law in 1994, and Death Valley National Monument was upgraded into a park and acquired an additional 1.3 million acres (Lyday, 1995). Patented boron claims existing in the park, particularly American Borate Company's Billie mine, will undoubtedly come under increased scrutiny.

6.9.3.2. Controlled area

There are no known occurrences of borate-bearing minerals nor are there any geologic environments favorable for borate deposits in the controlled area.

6.9.4. Resource assessment for the controlled area

Potential for borate mineral mining in the controlled area is considered to be nil.

6.10. Silica

6.10.1. Geology of silica deposits

Silica is mainly mined from quartz sand, quartz pebble, sandstone, and quartzite deposits in the United States, but minor production comes from chert or flint (cryptocrystalline quartz) deposits, quartz pegmatites, and quartz veins. About 70 stratigraphic units in the country are known to have potential for economic silica production (Bolen, 1993). Most domestic silica comes from deposits in the eastern United States from such units as the Devonian Oriskany Sandstone

in Pennsylvania, and Maryland, the Ordovician St. Peter Sandstone in Wisconsin and Illinois, and the Cretaceous Raritan Formation in New Jersey (Zdunczyk and Linkous, 1994). In the western United States, most production came from Tertiary sandstone and Ordovician quartzite in California.

Cryptocrystalline silica is mainly mined in minor amounts for abrasive applications such as whetstones, and for grinding media in pebble mills. Quartz veins are now mined in small amounts for optical and electronic quartz, but in the past large quartz vein deposits were mined for metallurgical and refractory silica.

Silica production in Nevada is mainly from the Simplot Silica Products operation near Overton, about 70 km northeast of Las Vegas. The sand is mined from an open pit in Cretaceous Baseline Sandstone, beneficiated by washing in the pit, and piped as a slurry about 6 km to a screening plant and railhead near the town of Overton. The final product contains 99.2% silica with low alumina, iron oxide, and alkali contents (Castor, 1991). In 1994, Mining Enterprises, Inc. opened a vein silica deposit south of Goldfield in Esmeralda County (Castor, 1995). Production capacity for this operation is not known. In the past, rock containing 99.89% SiO₂ was mined from a vein near Hawthorne that is nearly 850 m long and 95 m wide (Peterson, 1976). The Eureka Quartzite was mined prior to 1950 as a source of silica in the Arrow Canyon Range about 30 km northeast of Las Vegas. This quartzite contains 99.5 wt % SiO₂ and 0.27 wt % Al₂O₃, along with very low contents of iron and other elements (Murphy, 1954).

6.10.2. Production, uses, reserves, prices, and market outlook

Annual production of silica from domestic sources is between 25-30 million metric tons, and two-thirds of this production is from east of the Mississippi River (Bolen, 1992). Except for uses such as optical crystal, silica imports into the domestic market are negligible at less than 200,000 metric tons per year. In Nevada, The Simplot Silica Products operation near Overton produces about 500,000 metric tons of high-quality silica sand annually (Castor, 1995). Silica sand mines in California produce about 2 million tons per year (Bolen, 1993).

Probably no other nonmetallic mineral has more diversified uses than silica. Most is used in the manufacture of glass, and in foundry sands used to cast iron-, aluminum-, and copper-base alloys (Bolen, 1993). Other major uses include refractory sands, abrasives, metallurgical applications, oil well fracturing sand, and fillers.

The average value for domestic silica sand, f.o.b. plant, is about \$17 per metric ton, but ground silica used in fillers is sold for about \$95 per metric ton (Bolen, 1993). Arkansas whetstone rock sells for nearly \$3/kg, and grinding pebbles for as much as \$2/kg (Zdunczyk and Linkous, 1994).

Annual domestic demand for glass sand is about 12 million tons and has decreased since 1987 because glass for containers has been partly replaced by plastic and aluminum. Consumption of foundry sand is mainly dependent on automobile production, which has increased domestically in recent years. In general, future domestic consumption trends may be downward, but total production value for silica should increase because of the increased unit value of specialized products (Bolen, 1993).

6.10.3. Silica resources in the Yucca Mountain region

6.10.3.1 Region surrounding the controlled area

Silica was produced intermittently in small amounts between 1918 and 1929 from the Silica mine (or Monarch group) north of Crater Flat (Plate 1). Silica content of the rock was said to be 99.7-99.8%, and recorded production in 1929 was 890 tons for \$3,452 (Kral, 1951). The silica is very fine-grained white material said to have formed by complete hydrothermal alteration of rhyolite (Cornwall, 1972). The silica was mined from small open pits along a ridge top and the rock was transported via aerial tram to a road in Beatty Wash. The material has been described as 'ceramic silica' (Kral, 1951; Cornwall, 1972), but its exact use is unknown.

6.10.3.2 Controlled area

Minor amounts of white to bluish-gray chalcedonic silica and occurrences of macrocrystalline and drusy quartz occur in thin veins in drill core from holes G-2, GU-3, and 25b in the Yucca Mountain controlled area (Castor et al., 1992), but no large masses of silica such as those at the Silica mine have been noted. Surface exposures of resistant silicified breccia, which mostly occurs along faults, is present in the south part of the controlled area. This breccia, which forms zones up to 6 m wide, is heterogeneous, consisting of clasts of ash-flow tuff set in mixtures of opal-CT and calcite with minor chalcedony (Castor et al., 1989).

6.10.4. Resource assessment for the controlled area

Neither the thin silica veins encountered in drill hole or the impure siliceous breccia found on the surface can be considered to have commercial significance as sources of silica. Volumetrically significant deposits of high-grade silica are not known to occur in the Yucca Mountain controlled area, and it is not considered to have any potential for silica production.

6.11. Talc

6.11.1. Geology of talc deposits

The mineral talc is a hydrous magnesium sheet silicate with lamellar structure. Shearing action easily delaminates stacks of talc lamellae, to give the mineral a greasy feel that is described in the industry as the property 'slip'. The industrial value of talc is tied to its exceptional physical properties: it has very low hardness which makes it soft as a powder; is chemically inert with a high melting point; is generally light colored; and has high absorbency for fat, oils, and resins.

The commodity term 'talc' as generally used in industry refers to various rocks composed to some extent by talc, along with other sheet silicate minerals, which may be more abundant than talc in some cases. Rocks composed of pyrophyllite are sometimes mined and produced as talc. Rocks composed of pure talc are quite rare, and nearly all talc mined contains impurities such as dolomite and quartz. Most mined talc is soft and earthy, but more compact forms of rock composed of talc are prized commodities. These are classified as soapstone, a granular to cryptocrystalline form of the mineral; and steatite, a massive cryptocrystalline form of the mineral that can be sawn into blocks and shaped by carving.

Talc mineral deposits are relatively widespread, and occur on every continent. The most common host rocks for the formation of talc are ultramafic rocks and dolomite. Most talc forms in hydrothermal environments during the final stage of regional or contact metamorphism. Hydrothermal supply of silica into Mg-rich rocks, such as dolomite, is one mechanism that has been proposed for the formation of talc. Talc and serpentinite, a common associate, are formed during later stages of retrograde metamorphism, when temperatures fall and other late-stage minerals, such as secondary calcite, are formed.

Commercial deposits of talc have several common features. They are found in three broad groups of geological settings: in ultrabasic rocks and serpentinites; in magnesite, dolomite and

dolomitic limestones that are in contact with an igneous intrusion; and as residual clastic deposits formed from the weathering of a primary deposit. Most commercial talc deposits occur within Precambrian rock units, or in rock units whose age is no younger than early Paleozoic.

The assessment of talc ore is different from that for some other industrial minerals because purity is not the key issue. Talc ore cannot be assessed on the basis of purity alone because the contents of associated minerals in large part determines its ultimate use. Commercially viable talc ore may contain magnesite, tremolite, chlorite, dolomite, pyrophyllite, quartz, or mica, or mixtures of these minerals.

6.11.2. Production, uses, reserves, prices, and market outlook

World wide production of talc was reported by the U.S. Bureau of Mines at about 8-9 million metric tons per year between 1990 and 1994. China is now the leading world producer of talc, taking that lead from the United States over just the last two or three years. The United States remains the leading consumer of talc, with domestic sales of 923,000 tons. Imports to the United States increased 55% in tonnage and increased 38% in value from \$10.8 million to \$14.9 million, with China, Canada, and Japan supplying 85% of all talc imports. This trend is expected to continue as domestic producers come under pressure from imports, primarily those from China. Piniaskiewicz et al. (1994) noted that many of the large tonnage uses of talc are closely related to the degree of industrialization of a country.

The uses for talc have increased steadily for many years. The commodity has great versatility in industrial applications, but talc producers must face increasing demands for higher purity and greater quality. Key specifications for talc are particle size, structure, aspect ratio, brightness, and color. Crude talc is usually white to pale green in color, but may range through gray to black. Ore is processed using traditional dry grinding methods, such as Raymond mills. Column flotation for removing quartz and other minerals has been widely adopted. Talc may be calcined or bleached for physical stability, and to enhance whiteness.

Ceramic applications are the largest single end use for talc in North America (Piniaskiewicz et al., 1994). Talc replaces clay in many ceramic uses; it is a raw material for formulation in traditional refractories, such as ceramic substrates for catalytic convertors in cars, and it is used in glazes, electroceramics, and vitrified ceramics. Micronized talc is used as extenders and filler pigments in paint. It disperses easily to prevent settling, and is used in emulsion and anti-

corrosive paints. Talc is used in the paper industry as a filler, for coating, and for pitch control. This is one of talc's most important and rapidly growing market sectors. Talc is used as a filler in polymer plastics, reducing polymer use and providing structural strength. Silane coupling agents are used for surface-treating talcs for use as anionic dispersants, reinforcing plastics, and in rubber. The whitest purest talcs are usually derived from dolomitic limestone, and make the most likely candidates for the highest quality cosmetic and pharmaceutical-grade talc.

The average value of crude talc for 1993 and 1994 was \$33 per ton. Paint-grade, 400 mesh talc produced in New York State was sold for \$165 per ton, off-color grades of talc produced in Vermont were priced at \$150 per ton, Norwegian ground talc at \$165 - 185 per ton, and micronized talc produced in Canada and Montana at \$225 - 250 per ton (Harben, 1992). The brightest and purest grades are used as cosmetic talcs, which command high prices for exacting specifications; Harben (1992) quoted a price of \$300 - 320 per ton f.o.b. for Italian cosmetic grade talc, and Industrial Minerals (1995) quoted \$420 per ton for South African cosmetic talc f.o.b. Durban.

The U.S. Bureau of Mines world talc reserves were at 377 million metric tons in 1991, but that figure did not include large reserves in the former USSR and China. The resource base for these reserves was considered to be in excess of a billion metric tons at that time. Reserves of talc in the United States were put at 136 million metric tons in 1991.

The world markets for talc are growing overall, but there are significant changes in some sectors of the market. Domestic consumption of talc is expected to grow slowly throughout this decade, as the economy improves. Ceramics are expected to be the major domestic end use for talc in the United States with markets remaining relatively stable, followed by paper, paint, roofing products, plastics, and cosmetics. The use of talc in plastics and roofing materials is expected to grow. The cosmetics market for high quality talc is increasing steadily, as are markets for talc in adhesives, joint compounds, sealants, and automobile body patch compounds. However, talc is facing challenges from limestone and dolomite filler products in the paint, paper, and plastics sectors. The world market for carbonate fillers is growing at the fastest rate of any mineral filler because limestone and dolomite deposits are widespread and can be strategically located to serve nearby markets as low-cost white mineral fillers. The switch to alkaline sizing in paper has favored calcium carbonate and limestone over talc, and that trend will continue. In addition, wollastonite, nepheline syenite, and feldspar compete with talc in ceramics, and talc faces growing competition from low cost specially treated clays in rubber, paper, and paint.

6.11.3. Talc resources in the Yucca Mountain region

6.11.3.1. Region surrounding the controlled area

Talc was mined from the Warm Spring - Galena Canyon area in the southern Panamint Range on the west side of Death Valley in the Yucca Mountain Region (Plate 1). The talc deposits, some of which were mined almost continuously between the early 1940's and the 1970's, were mined by companies with long-standing industrial mineral reputations such as Cyprus Industrial Minerals, and Pfizer Inc. A single talc mine was operating in the Death Valley area in 1994, and this mine is located outside the area shown in Plate 1. In 1976, recoverable talc reserves in 16 deposits in Death Valley area were given as 1 million short tons, and indicated resources were put at another 3 million short tons (Evans et al., 1976).

The Death Valley talc deposits are all in contact metamorphosed zones as much as 60 m or more thick, in a single limestone and dolomite member of the Precambrian Crystal Spring Formation adjacent to or near a diabase sill or diabase dikes (Evans et al., 1976). Impurities are tremolite, carbonate minerals, iron oxide, and wall-rock inclusions (Piniaskiewicz et al., 1994). Death Valley talc was mined by both open-pit and underground methods. The Big Talc and Number 5 mines of the Johns-Manville Corp. were mined underground between depths of about 15 m and 200 m (Evans et al., 1976).

Talc was produced between the mid-1920's and about 1980 from mines in the Palmetto and Sylvania districts in Esmeralda County, Nevada, which is northwest of the boundary of Plate 1. In these districts talc deposits occur as irregular elongate or pod like masses in Precambrian to Early Cambrian limestone and dolomite (Papke, 1975). Although much of the mined material was nearly pure talc, impurities included chlorite, carbonate, and tremolite.

6.11.3.2. Controlled area

Talc has not been reported to occur in the controlled area. Regional host rocks for talc deposits are Pre-Tertiary carbonate rocks and these occur at depths in excess of 1,200 m in the controlled area, too deep for traditional open-pit or underground talc mining.

6.11.4. Resource assessment for the controlled area

The Yucca Mountain controlled area is not considered to have any potential for talc deposits.

6.12. Limestone and dolomite

6.12.1. Geology of limestone and dolomite resources

Limestone and dolomite compose almost 15% of all sedimentary rocks available for exploitation, and are the most useful and widely utilized of all the industrial minerals and rocks. Both limestone and dolomite are carbonate rocks. Limestone is a sedimentary rock composed of 50% or more of carbonate minerals of which calcite or aragonite predominate. Dolomite is a similar rock, but the mineral dolomite predominates. Both calcite and aragonite are composed of CaCO_3 ; dolomite is composed of $\text{CaMg}(\text{CO}_3)_2$. Mixtures of both calcite and dolomite in a carbonate rock (either a limestone or a dolomite) thus have a considerable range in possible CaCO_3 and MgCO_3 contents. Most limestones and dolomites contain non-carbonate impurities, most commonly these are clay, chert, and organic matter. The purity of a deposit of carbonate rock, its size, and its lithological and compositional consistency depend on the environment of deposition and its mineralogical and tectonic history. Most carbonate deposits are associated with marine organisms which produce shelly and skeletal carbonate materials, which may accumulate after destruction as lime sands and cementing lime muds containing fossil materials, fecal pellets, peloids, and oolites. Some limestones and dolomites are composed of remnants of extensive algal- and coral-reef colonies, or may form as mound-like accumulations of shelly materials. Extensive accumulations of carbonate sediments have often occurred in areas essentially free of terrigenous sediment input such as clays and sands, so that resulting carbonate deposits tend to contain few impurities. Carbonate rocks are prone to recrystallization as calcite and dolomite, often soon after deposition and burial. The size and sorting of clastic lime particles in a rock is often a reflection of the energy of an aqueous depositional environment, and an understanding of depositional patterns (lithofacies analyses) can help in the selection of exploitable carbonate rocks.

Limestone deposits may occur as beds of chalk, as a fine-grained, nearly pure, white limestone or lime mudstone. Limestone or dolomitic marl is usually a white to gray mud deposited in lake or shoreline basins. The deposit forms as a precipitate induced by photosynthesis of algae, and often microlaminated by algal growth layers. Oolitic lime sands deposited by chemical precipitation in shallow, warm water marine shoals lithify after burial into oolitic limestone beds. Banded and colored inorganic precipitates of carbonate minerals around hot springs and geothermal sites form aprons and eventually complex deposits of calcareous tufa and travertine. Large volumes of limestone rock can undergo dolomitization, as a conversion of CaCO_3 minerals to dolomite takes place after deposition or burial in a process normally associated with the introduction of ground waters rich in magnesium.

Geological assessment of the industrial potential of limestone and dolomite rock may be based initially on its bulk chemical composition, its carbonate mineral content, and the levels of clay, silica and other contaminant materials. Physical attributes of the rock, such as compressive strength, porosity, density, hardness, cleavage, and color may also be important. For example, high-calcium lump lime is generally produced from very-fine grained limestone because most coarsely crystallized carbonate rock decrepitates during calcination. Physical attributes are dependent on the lithology and textural features of the whole rock, which generally can be related to its depositional and tectonic history. Many classification systems for carbonate rocks allow for interpretation of these factors and, combined with models for deposition and tectonic history, allow some predictability in the selection of satisfactory carbonate rocks for industrial applications.

6.12.2. Production, uses, grades, prices, and market outlook

Beyond the utilization of limestone rock for the production of crushed aggregate and dimension stone, there are four major areas of application:

6.12.2.1. Portland cement

Raw materials for cement making are used in an essentially untreated form; limestone is the most common source of Ca, and it is blended with shale or clay as a source of silica and alumina. In most cases limestone is the most important ingredient, and cement plants are sited close to substantial deposits of satisfactory limestone. In cement plants, a multi-component mix of raw materials provides strictly controlled chemistry which on conversion in a kiln at temperatures of about 1,450° C forms a cement clinker of complex silicate and aluminate mineralogy. The clinker is generally ground with gypsum and, in some cases, local pozzolanic material to provide cement powder.

The quality of limestone at each cement plant is based on raw material criteria such as the Lime Saturation Factor (LSF), the Silica Ratio, the Alumina-Iron Ratio, and the C3S value (Lea, 1970; Knill, 1978). The general requirement for a Lime Saturation Factor of 90 - 100% limits the bulk CaCO_3 content for a limestone to greater than 70 - 75% in most cases. Magnesium is generally the most critical impurity in cement limestone rock, and the content of MgCO_3 is limited to about 5 wt% in any raw mix. This places limits on the use of limestones which have been partially dolomitized or are associated with talc, serpentine, or other metamorphic or hydrothermal alteration mineralogies. The content of Na and K, also critical, is generally based on the amount of clay minerals or shale within the limestone. P, Mn, S (as sulfides or sulfates) and F also play a

critical roles in selecting limestones for cement making.

6.12.2.2. Lime

Limestone is calcined at temperatures of between 1,000° and 1,300° C to form quicklime (CaO). Quicklime is unstable, and when allowed to react with water forms the more stable form of hydrated lime. Lime products are also produced from dolomite; dolime is prepared as a hydrated dolomitic lime and dead-burned dolomite is used as a refractory material. The chemical composition of lime products varies according to the chemical composition of source rocks - primarily limestone or dolomite. O'Driscoll (1988) lists some 30 different lime products currently available on world markets that differ in chemical composition, degree of calcination, degree of hydration, and their solid and liquid forms. On the whole, the suitability of a limestone for calcination can only be subjectively tested under actual kiln conditions, and test results may depend upon firing conditions, type of kiln, particle sizing, porosity of the limestone feed, and mineral crystallinity. The completeness of calcination is expressed in terms of available lime content (as CaO). Common impurities in limestone such as silica, iron, and aluminum usually account for 3 - 5% of available lime content, so that usable limestone may only have an available lime content of 95% as CaO. Calcination grades of limestone are generally limited to >98.6% CaCO₃ and <1% SiO₂ (Harben, 1992).

The steel industry is a major consuming market for lime. The basic oxygen furnace uses approximately 80% of the lime sold for steel production. Lime fluxes combine with and remove impurities or unwanted components from molten metals. Limestone, dolomite, lime and dolomitic lime are used in large quantities to produce iron and steel. Generally, dolomitic quicklime is used with high-Ca lime to extend refractory life. Fluxed pellets are often carefully blended with smelter feed stocks to provide a specific, controllable flux chemistry. Approximately 4.3 million tons of limestone and 0.64 million tons of dolomite was consumed as fluxes in 1989, and more than 15 million tons of lime and dolomitic lime was consumed for the same purpose in that year (Kokal and Ranade, 1994).

Hydrated lime has many applications in chemicals manufacture. It plays a critical role in the manufacture of soda ash in the Solvay process and is used to causticize sodium carbonate solutions to produce sodium hydroxide (caustic soda). Lime is used to manufacture inorganic chemicals such as detergent phosphates, for purifying salt brines, in masonry paints, varnish manufacture, pigments, as well as a wide range of organic chemicals.

Clean Air Act Amendments were passed to the new source performance standards in 1990, requiring a much higher level of sulfur removal from flue gases. Lime is used in new scrubber technologies for stack gases, for wet, dry and fluidized bed scrubbing systems, as well as specialized forms of reactive lime such as Dravo Corporation's special Thiosorbic lime. Present U.S. consumption of scrubbing reactants is estimated at 1.5 m tons per year of lime, and 2.0 m tons per year of limestone.

For water treatment, lime is preferred in municipal and industrial applications over limestone. Over 1.36 m. tons of lime are used annually in the treatment of municipal potable water and industrial waste water (Freas, 1994). Lime is also used to neutralize acid mine drainage, for heap leaching operations, for coal washing, and to treat chemical and pharmaceutical plant waste.

6.12.2.3. White fillers and extenders

A range of fine-grained carbonate fillers is produced from high quality limestone and dolomite. White carbonate fillers are prepared in different size ranges for a variety of applications. Coarse fillers with a mean particle size of 22 - 40 microns are used for joint cement, carpet backing, and asphalt roofing. Fillers of medium sizing range from 12 - 20 microns in particle size and are used for caulking compounds, putty, sealants, and in rubber. A fine filler ranges from 3 - 10 microns in particle size and is used in paint, paper, plastics, and rubber. Ultrafine filler sizes range from 0.7 - 2 microns for paper, paint and plastics (Harben, 1992, Champine, 1989). In this ultrafine size range, the product is often called 'ground calcium carbonate' (GCC), and is prepared through a sophisticated wet grinding process (Russell, 1989).

6.12.2.4. Agricultural limestone and dolomite

Calcium and magnesium carbonate are important as a plant nutrients and as soil conditioners. Both are used as liming materials to modify soil pH and to enhance plant growth. Hoffman and Austin (1994) estimate 22 million tons of agricultural liming materials were consumed in the U.S. in 1991.

Numerous deposits of limestone are mined in the southwestern states of the United States, most supplying the construction aggregate, cement, and lime industries, especially in populous southern California, and to a lesser extent Nevada, Arizona, and New Mexico. California leads the country in cement clinker production, two thirds of which is produced from eight plants in southern California. The sole cement producer in Nevada is Nevada Cement Co., supplying

about 400,000 tons per year of cement from its Fernley plant near Reno to markets in Nevada and northern California. There is currently no cement production in the Las Vegas area, with most of this region's cement apparently coming from southern California plants. The closest plant in southern California is Mitsubishi Cement Corp.'s Cushenbury cement plant in the Lucerne Valley limestone district of San Bernardino County.

The Lucerne Valley district is the site of large reserves of limestone, magnesian limestone, and dolomite, which form the basis for the largest production center in the southwestern U.S. for chemical-grade limestone, and ground limestone for industrial uses. Here Pluess-Staufer and Pfizer exploit pure white limestone and marble of Upper Devonian, Mississippian, and Permian ages. Pluess-Staufer is currently mining three ore bodies by open pit, with a further pit currently under development. At current rates of mining, reserves have been estimated in excess of 20 years. The company produces a full range of coarse, fine, and ultra-fine, high brightness, high purity, calcium carbonate products (Brown, 1994). These products are mainly targeted for the high-value end of the filler markets in paint and plastics. The company also serves markets for glass, agriculture, and animal feeds, mostly in the western United States. Overall, these products represent a total estimated market of 2.5 million tons of calcium carbonate (O'Driscoll, 1990). From its open pit mine at Marble Canyon in the Lucerne Valley, Pfizer produces about 1 million tons per year of calcium carbonate products. Reserves are estimated at 10 - 12 million tons for selective mining to produce high-calcium limestone ore. The company produces three groups of limestone products for markets in the Los Angeles basin and the western United States, including screened limestone products for glass, floor tile, animal feed, steel flux, and roof and landscaping markets. Pulverized limestone is produced for building products (joint cements, caulking compounds, and stucco), synthetic marble, pesticide carriers, and roofing tile fillers. Fine ground limestone products are produced for paint and plastic fillers. The building products sector is Pfizer's largest limestone consumer, taking 50 - 60% of its production, followed by chemical grade limestone for the glass industry, which consumes about 30% of production.

Chemical Lime Co. produces over 1 million tons per year of lime products from two plants in California, one in Arizona, and two in Nevada. This company produces high-calcium lime at Apex just northeast of Las Vegas, and dolomitic lime in Henderson from dolomite mined at Sloan, south of Las Vegas (Castor, 1994). Continental Lime Inc. produces 400 short tons per day of high-calcium lime at their plant near Wendover in Nevada (O'Driscoll, 1992) for use predominantly in the regional gold processing industry.

Dolomite is currently mined at Sloan, 10 miles south of Las Vegas. The rock is used for production of dolomitic lime or 'dolime' that is used in construction products and metallurgical processing. The dolomite is mined from the Bullion Dolomite Member of the Mississippian Monte Cristo Limestone at a rate of about 200,000 tons annually. The deposit consists of nearly pure dolomite, and is considered to have originated through hydrothermal replacement of limestone (Deiss, 1952). In the past dolomite was also mined from the Dawn Limestone Member of the same formation.

Prices for limestone, dolomite, lime products, cement depend substantially on the grade of limestone and dolomite, or lime, or the specific product requirements, and are here quoted from Harben (1992). Crushed limestone for aggregate uses, agricultural applications, and for cement making is generally priced at \$3 - 5 per ton. Chemical grade limestone for glass making and flue gas desulfurization is priced between \$15 and \$25 per ton. The prices for fillers are \$25 - 50 per ton for coarse to medium fillers, and \$50 - 200 per ton for fine to ultra-fine fillers. Quicklime is generally available as lump lime, crushed or pebble lime, ground lime, pulverized lime, and pelletized lime, and may also be graded as high-calcium, magnesium or dolomitic lime. Despite these grades, price is quoted by Harben (1992) at about \$50 per ton, f.o.b. plant. Dolomitic lime produced from the Sloan deposit is currently sold for \$75 or more per ton. Grades for cement powder may also vary considerably, but Solomon (1995) gives an average domestic price for portland cement in 1994 at about \$60 per ton. Cement prices increased by about 5% in 1994, as they did in 1993; before 1993, prices remained constant for at least a decade.

The long-term demand for limestone and dolomite is expected to grow at an annual rate of about 2 - 2.5% pa (Carr et al., 1994). As a primary material for crushed stone and cement manufacture, limestone demand is expected to match approximately the demand for new construction, and will be partially stimulated by the need for repair and replacement of the nation's deteriorating infrastructure. The demand for chemical grade carbonate rock used in industrial and agricultural applications is expected, at a minimum, to equal the growth of the U.S. population (Carr et al., 1994). This demand could be greatly stimulated by need for limestone and lime for flue gas desulfurization based on the 1990 Clean Air Act Amendment.

As a commodity, limestone and dolomite will continue to be produced and sold in a highly competitive market, so that producers will continue to address costs in production and to institute new technologies to increase production. In the industrial and agricultural production areas, the industry is expected to continue to undergo consolidation, and to accept an increasing role played by foreign ownership.

The long-term prospects for lime (both high-calcium lime and dolime) are also good, although there is current domestic over capacity. It can also be anticipated that there will be additional consolidation, and a potentially expanded foreign ownership of U.S. lime producers (Freas, 1994). The major growth area for lime sales throughout the next decade will probably be in environmental applications. Developments for flue gas desulfurization made necessary by the 1990 Clean Air Act Amendments are expected to provide a continuing boost to the lime industry through the use of lime-based wet and dry flue gas scrubbers, particularly for electrical generation plants. The Clean Water Act has brought pressure to bear on the enhanced performance of municipal and industrial sewage treatment plants, and this is expected to continue to lead to expanding lime markets.

During 1994, the U.S. cement industry continued to see an increase in cement consumption. It expanded 7% to 84 million tons from 78.4 million tons in 1993 (Solomon, 1995). In 1992, U.S. consumption had risen by 6% and 4% respectively. In the Mountain District of the U.S. (Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, and Utah) cement consumption increased by about 3% during 1994. The long-term outlook for cement consumption is one of steady but moderate growth.

6.12.4. Limestone resources in the Yucca Mountain region

6.12.4.1. Region surrounding the controlled area

Several major units of limestone are available for possible exploitation in the nearby region of the controlled area, and have been described in some detail by Cornwall (1972).

The Cambrian Carrara Formation crops out extensively on Bare Mountain and in hills to the north and south of it and east of Yucca Flat. The Formation consists of interstratified shale and limestone with minor amounts of sandstone and siltstone. Limestone predominates in the upper sections of the Formation. The base consists of alternating beds of sandstone, siltstone, shale and limestone, progressing upwards into several hundred feet of shale and interbedded limestone. At the top is a massive, dark-gray, algal limestone bed, commonly 30 m or more thick which may be seen as cliffs in areas of outcrop. Above the algal limestone are several hundred feet of shale and siltstone, overlain by as much as 300 m of brightly colored limestone which is somewhat clayey or silty. In addition, the Goodwin Limestone, the limestone of the Ninemile Formation and the Antelope Valley Limestone also crop out on Bare Mountain to the east of the

controlled area. These formations, which have an aggregate thickness of 450 m, comprise part of the Ordovician Pogonip Group. The Goodwin Limestone consists of laminated to thick bedded gray limestone, in part containing abundant silty and shaly partings and local chert nodules and lenses. The Ninemile Formation consists of interbedded gray nodular thin-bedded limestone and calcareous siltstone and shale; limestone is more abundant towards the top of this sequence. The Antelope Valley Limestone comprises three units; a lower sequence of fine-grained gray limestone with some siltstone, a middle unit of silty, olive gray limestone containing silty layers, and an upper unit consisting of thin-bedded, commonly silty, gray limestone with some thick-bedded gray limestone. Resistant lens-shaped bioherms have been found in several places in the lower half of the middle unit of the Antelope Valley Limestone, and these are generally composed of a very pure aphanitic limestone. The largest is about 800 m long and 90 m thick.

Within the Ordovician Ely Springs Dolomite there are extensive patches of dark-gray limestone locally present in outcrop at Bare Mountain. The formation is largely composed of medium to dark gray aphanitic to very fine grained, laminated to thin-bedded dolomite. Chert makes up 10% of the rock, and sections towards the base of the formation tend to be sandy. The Devonian Nevada Formation on Bare Mountain includes an upper unit about 65 m thick of aphanitic to fine-grained limestone and dolomite containing white to pink sandstone. The Devonian Devils Gate Limestone is composed of gray limestone with minor dolomite, and is in the Mine Mountain area. The Mississippian Monte Cristo Limestone crops out in the northern Spring Mountains on the eastern margin of Nye County. It has a measured section containing about 300 m of dark to light-gray limestone that is medium- to coarse-grained, highly fossiliferous, and cherty. The Tippipah Limestone of Pennsylvanian age is present small exposures around Yucca Flat, and consists of limestone with interbeds of pebbly and silty limestone.

In the Yucca Mountain region there are many sequences of dolomitic rocks that could be available for exploitation if needed. Many of these sequences are exposed on the western, southern and northeastern flanks of Bare Mountain, about 15 m east of the controlled area. The Precambrian Johnnie Formation is composed of quartzite, sandstone, siltstone, and shale with several thin interbeds of dolomite, and is exposed on the southern and western flanks of Bare Mountain. The dolomite is distinctively oolitic. The Cambrian Bonanza King Formation crops out as a thick-bedded dolomite, containing some limestone, in a 1000-m-section exposed on the southern part of Bare Mountain. The Cambrian Nopah Section contains varicolored dolomite in its type section in the Nopah Range in Inyo County, California. This formation is also exposed on the western and southern flanks of Bare Mountain. The Ordovician Ely Springs Dolomite is composed largely of medium to dark gray, aphanitic to very fine grained laminated to thin-bedded blocky

dolomite on Bare Mountain. Chert composes approximately 10% of this rock, and extensive patches of dark-gray limestone are locally present. The Silurian Roberts Mountain Formation consists of upper and lower dolomitic units about 60 m thick and a middle limestone unit about 120 m thick. It occurs in the northeastern part of the Bare Mountain area and in the Bullfrog Hills west of Beatty. The Devonian Nevada Formation is dominantly dolomitic on Bare Mountain.

Despite these occurrences, no limestone or dolomite deposits in the Yucca Mountain region have been mined for the production of limestone, dolomite, lime, or cement. The extent of carbonate sequences in southern Nevada provide excellent potential for limestone and dolomite mining.

6.12.4.2. Controlled area

Limestone or dolomite does not crop out in the controlled area. However, considerable thicknesses of dolomite were encountered in the base of drill hole 25p (Carr et al., 1986) in the Silurian Lone Mountain Dolomite and Roberts Mountain Formation. Rocks of the Lone Mountain Dolomite extend from a depth of 4,080 feet (1,244 m) to 5,470 feet (1,668 m) as a continuous sequence of generally light gray, aphanitic to medium crystalline dolomite, which is poorly bedded and often brecciated with sparry dolomite and secondary calcite filling vugs and veins. The dolomite of the Roberts Mountain Formation, encountered in the between 5,470 feet (1,668 m) and the base of the hole at 5,923 feet (1,807 m), is generally dark gray, finely to medium crystalline, and commonly contains breccia material. The dolomite contains sparse secondary calcite, gray to black chert layers, and poorly preserved pelmatozoan debris (Carr et al., 1986).

6.12.5. Resource assessment for the controlled area

Limestone and dolomite are generally mined in surface quarries, although rare underground extraction of these commodities is done at relatively shallow depths. Given its low unit value, economic extraction of such rock is not possible at the depths at which it is known to occur in the controlled area. Quantities of dolomite occurring at depth in the controlled area cannot be estimated from a single drill hole intersection. The controlled areas is considered to have no potential for production of limestone or dolomite.

6.13. Diatomite (diatomaceous earth)

6.13.1 Geology of diatomite deposits

Diatomite is a fine-grained rock or sediment composed chiefly of the microscopic siliceous skeletal remains, or frustules, of diatoms: a unicellular aquatic plant species. 'Diatomaceous earth' is the commercial term that covers commodities produced from diatomite. More than 12,000 species of diatoms live in marine, brackish, or lacustrine water bodies, as well as in moist soil, and on rock and vegetation surfaces. Under ideal aquatic conditions of abundant light in warm nutrient-rich waters with an abundant source of silica diatoms can flourish to the extent that the sea or lake floor receives a continuous and steady 'rain' of skeletal remains. Over time such accumulations can develop as uniform or minutely laminated beds of frustules which extend for considerable distances over ocean or lake floors. Under ideal growth and preservation conditions for diatom accumulations, continuous beds can develop to thicknesses of hundreds of feet. The formation of economic deposits of diatomite takes place under continuing stable environmental and depositional conditions that provide abundant sources of both plant nutrients and silica.

Favorable marine depositional environments, such as those observed in present day settings along the coastlines of Peru, Africa, and California, receive nutrient rich, biologically productive upwelling currents which provide steady growth conditions for diatoms over a long period of time. Economic diatomite accumulations are protected from the influx of terrigenous sediments, such as clays and silts from continental erosion, which effect light transmission in water, and dilute the content of diatoms in sediments through admixture. Regions of upwelling bottom currents along distal continental margins in mid and low latitudes, where river-borne suspended sediments cannot effect growth or accumulation rates make ideal settings for economic accumulations of diatomite.

Lacustrine environments generally provide less stable aqueous environmental settings, and are prone to influxes of sediments. However, they can produce significant economic deposits where lakes are sited in volcanic terrains which can supply a rich silica source from the weathering of volcanic rocks, particularly siliceous tuffs. Caldera moat lake settings, or those in the subsiding valleys of the Basin and Range province make excellent sites for rich accumulations of diatomite (Breese, 1994). Periods of tectonic stability in such settings, combined with favorable growth conditions in water bodies may allow thick accumulations to develop. Diatomite accumulations may be preserved as economic deposits if they are protected from erosion, dissolution, metamorphism, and high temperatures after deposition. For this reason, economic

deposits of diatomite are seldom of significant geologic age.

Diatom frustules are complex and delicate symmetrical structures of amorphous or opaline silica with intricate patterns of pores and openings that provide a large surface area. The size, structure, and design of each diatom skeleton is distinctive for individual species (Breese, 1994). Lacustrine deposits may differ significantly in diatom species from marine deposits, effecting the form and application of the unique suite of frustules in each deposit. Such differences also occur between lacustrine deposits, and between marine deposits. The predominant form of frustules in a deposit can influence the areas of applications for the diatomite. Some frustules are large and massive allowing the structural strength needed for use in filtering beds. Small, delicate frustules would quickly collapse under the stresses of loading and water transmission in filtration columns. Larger frustules do not favor rapid calcination, but frustules with finer structures may quickly succumb to calcination temperatures, sealing off many openings and reducing surface area and filtration effectiveness.

The silica content of diatomite typically varies from 80 to 90%, but can be as high as 97%. Frustules are composed of both amorphous and opaline silica, with opaline material containing as much as 9.6% water. Sand, clay, and organic materials make up the minor impurities in economic diatomite deposits, and account for aluminum, iron, titanium, phosphate, calcium, magnesium, sodium and potassium contents.

6.13.2 Production, uses, prices, and market outlook

In the United States, component costs production of diatomite are processing 60%, packaging 30%, and mining 10%, with energy consumption making up 35% of the total cost (Breese, 1994). Diatomite is generally extracted by open pit methods throughout the world, and blasting is not necessary. Ore is broken, ripped, allowed to dry by evaporation, and then moved in bulk to specialized mills which gently disaggregate the delicate frustules to separate them from contaminants and eventually dry the processed material. The milled product can be separated at this point into coarse filtering products and fine filler products. The milled product can also be calcined at temperatures to 1,200° C to produce more resilient filler and filter products with additional performance features not provided by natural diatomite. Calcination may alter pore size, bulk density, increase hardness and whiteness, and affect surface area, providing differences in filtering characteristics, abrasiveness, grindability, and filler and flattening applications.

Of the diatomite sold in the United States, 73% was used for filtration products, 14% was used in filler applications, and applications as absorbents, in insulation, and in other products accounted for the remaining 13% (U.S. Bureau of Mines, 1994). The wide variety of product applications in these areas requires the industry to provide tight control over specifications for many products. Filter products must have high fluid flow rates and durability, and must produce a clear filtrate. Fillers may act as bulking and extending agents, or may serve to improve the properties of final products in which they are used.

The commercial value of a given type of diatomite is tied to its suitability as a finished product in a specific application, making any evaluation of a diatomite resource case dependent. Diatomite brightness, weight, microscopic structure, abrasiveness, surface area, filtering characteristics, dry and wet densities, and chemical composition are all specified physical characteristics that are utilized to control the final value of a diatomite product.

World production of diatomite in 1994 was estimated at 1.4 m tons, with the United States being the world's leading producer, followed by France, the former USSR, and Korea. These four countries accounted for 73% of world production. World production has declined slightly since 1990, while United States production has remained relatively constant over the same period. In the United States, California is the leading producer, followed by Nevada, Oregon, and Washington. The average unit price for processed diatomite in 1994 was \$284 per ton, approximately the same price as in 1993, but considerably higher than in the period 1990 - 1992. Diatomite consumption is expected to increase slightly over the next few years (U.S. Bureau of Mines, 1994; U.S. Bureau of Mines, 1992).

6.13.4. Diatomite resources in the Yucca Mountain region

6.13.4.1. Region surrounding the controlled area

All producing diatomite deposits in Nevada are of lacustrine origin and of Miocene to Pliocene age (Castor, 1993). The Yucca Mountain region is not distinguished for diatomite occurrences. However, beds of diatomaceous earth occur near U.S. Highway 95 about 17 miles southeast of Beatty (Plate 1). One diatomite exposure at this locality covers an area of approximately 60 m by 100 m feet in a bed about 3 m thick (Kral, 1951).

6.13.4.2. Controlled area

No occurrences of diatomite are known in the controlled area, and it is unlikely that exposed diatomite could have been overlooked during surface mapping. A lacustrine setting large enough and stable enough to host beds of pure diatomite, despite the high levels of solution silica available, is not known to be present in the controlled area. Reworked tuffaceous rocks in the controlled area may contain some diatomite frustules, but the geologic setting was such that diatom deposition would have been overwhelmed by the influx of volcanic material.

6.13.5. Resource assessment for the controlled area

The controlled area is considered to have no potential for economic diatomite deposits.

7. SUMMARY ASSESSMENT

The development and production of industrial minerals and rocks deposits have been important economic factors in the Yucca Mountain region, and will undoubtedly remain so in the future. Industrial minerals and rocks with present production in the region are clays, borate, zeolite, talc, construction aggregate, and building stone. Industrial minerals and rocks produced in the past, but not presently mined in the region, are fluorspar, pumicite, and silica. In addition, the region has undeveloped resources of perlite, limestone, and dolomite.

The Yucca Mountain controlled area has been evaluated in this report for the following industrial minerals and rocks that are known to occur there, or have been mined or identified in the surrounding area:

7.1. Fluorspar

Fluorspar has been identified in thin veins in core from drill holes in the Yucca Mountain controlled area. The amounts of fluorspar identified do not constitute a significant resource and fluorspar potential is considered to be low in the controlled area.

7.2. Clays

Significant amounts of smectite is present in exposures of the bedded and ash-flow tuff sequence that lies between the Topopah Spring and Tiva Canyon Tuffs, and may have potential for development. Detailed sampling and testing would be required to determine potential value and reserves of this clay. Large amounts of smectite that occur in the subsurface and have been quantified using drill hole data are probably not of commercial value because of the amount of overburden. The controlled area is considered to have low to moderate potential for clay.

7.3. Zeolites

A large resource of clinoptilolite and mordenite has been estimated in the subsurface in the Yucca Mountain controlled area on the basis of drill hole data. This resource is not considered to have economic potential because of the amount of overburden.

7.4. Construction aggregate

The Yucca Mountain area contains large amounts of sand and gravel and rock that may be suitable for crushed stone. However, because the distance that this low-value material would have to be transported to potential markets is large, the potential for development is considered to be low.

7.5. Building stone

The Yucca Mountain controlled area contains large amounts of ash-flow tuff that may have potential as ornamental building stone. The amount of similar material in the Yucca Mountain region is high, and potential for building stone production from the controlled area is considered to be low to moderate.

7.6. Barite

Very minor amounts of barite have been identified in thin veins in drill core from depths of more than 1,200 m in the controlled area. The potential for barite production from the controlled area is considered to be nil.

7.7. Perlite

Volcanic glass that may have potential as expandable perlite occurs in the Yucca Mountain controlled area, but mineable thicknesses of such material are not present except at depths that make economic extraction unlikely. The controlled area is considered to have low potential for perlite production.

7.8. Pumice and pumicite

No unconsolidated pumice occurrences are known in the controlled area, but exposures of pumiceous material in bedded tuffs that lie between the Topopah Spring and Tiva Canyon Tuffs may have potential for development as pumicite. Because these potential pumicite beds are thin when compared to commercial pumicite deposits, the potential for commercial use of controlled area pumicite is considered to be low.

7.9. Silica

Quartz and chalcedony has been identified in thin veins in core from drill holes in the Yucca Mountain controlled area, and silicified breccia has been identified on the surface. However this silica is either not pure enough or not present in large enough amounts to constitute a significant resource. Silica potential in the controlled area is nil.

7.10. Borates

No borate minerals are known to occur in the Yucca Mountain controlled area and the geologic setting for such deposits is lacking. Borate mineral potential for the controlled area is nil.

7.11. Talc

Talc is not known to occur in the Yucca Mountain controlled area and the geologic setting for such deposits is lacking except at great depths. Talc potential for the controlled area is nil.

7.12. Limestone and dolomite

Limestone is not present in the controlled area, and dolomite has only been found in a single drill hole at depths greater than 1,200 m. Limestone and dolomite potential for the

controlled area is nil.

7.13. Diatomite

Diatomite is not known to occur in the Yucca Mountain controlled area and the geologic setting for such deposits is lacking. Diatomite potential for the controlled area is nil.

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APPENDIX 1

Location of industrial mineral occurrences shown in Plate 1, numerically listed.

Map Number	Deposit Name	Commodity	Latitude	Longitude
1	Unnamed	bentonite	36.957	-116.565
2	Unnamed	bentonite	36.963	-116.631
3	Black Top and Red Group; Red Placer Claims	fluorspar	37.095	-116.688
4	Butler Prospects	fluorspar	36.877	-116.694
5	Carrara Quarries	marble	36.825	-116.672
6	Cinder Cone Mine	cinders	36.638	-116.509
7	K-B Clay; Ewing Deposit	clay	36.544	-116.369
8	Crow Mine	travertine	36.836	-116.002
9	Daisy Mine	fluorspar	36.885	-116.693
10	Unnamed	diatomaceous earth	36.708	-116.588
11	Eciyalde or Shepard Kaolinite Deposit	kaolinite	36.932	-116.639
12	ENIF Prospect	fluorspar	36.883	-116.697
13	Future Group	bentonite	36.937	-116.659
14	Goldspar Mine	fluorspar	36.838	-116.636
15	HG 1 and 2 Claims; Black Cone; Crater Flat	cinders	36.814	-116.564
16	K-B Deposit; Ewing Claims	montmorillonite	36.529	-116.376
17	Lige Harris; ENIF area	fluorspar	36.883	-116.696
18	Mary Mine	fluorspar	36.855	-116.640
19	Unnamed	fluorspar	36.849	-116.652
20	Unnamed	fluorspar	36.861	-116.648
21	Mine Mountain	barite	36.991	-116.144
22	Pahute Mesa Deposit	montmorillonite	37.350	-117.007
23	Unnamed	perlite	36.946	-116.677
24	Gismo, Gary, Blondie and Pumice Placer Claims	pumice	36.947	-116.720
25	Unnamed	pumice	36.947	-116.720
26	RE-HG Claims 1- 4	cinders	36.794	-116.579
27	Roswell Deposits	montmorillonite	36.893	-116.779
28	Sage, Bud, Eve, Iolanth, and Rika Claims	clay	36.544	-116.347
29	Unnamed	bentonite	36.896	-116.774
30	Sarcobatus Flat Deposit	montmorillonite	37.291	-116.970
31	Shorter White Claims	fluorspar	36.877	-116.701
32	Silicon Mine	silica	36.959	-116.646
33	Silver Pearl Group	perlite	36.912	-116.700
34	Surprise No. 1 Claim	montmorillonite	36.909	-116.747
35	Vandenberg Mine	bentonite	36.888	-116.771
36	Vanderbilt Mine	bentonite	36.888	-116.768
37	White Caps Mine	bentonite	36.877	-116.869

APPENDIX 1 (Contd)

38	Wonder No. 1 Claim	montmorillonite	36.896	-116.744
39	Montgomery Talc	talc	36.000	-116.931
40	White Chief Talc	talc	36.007	-116.918
41	White Eagle Talc	talc	36.014	-116.917
42	Mammoth Talc	talc	36.018	-116.909
43	Mongolian Talc	talc	36.015	-116.907
44	Bonnie Talc	talc	36.016	-116.894
45	Widdow Mine	borate	36.300	-116.664
46	Oakley Borax	borate	36.301	-116.672
47	Grand View Borax	borate	36.305	-116.676
48	Buddy McCarthy Borax	borate	36.314	-116.676
49	Sigma Borax	borate	36.313	-116.688
50	Billie Borax	borate	36.331	-116.690
51	Thompson Borax	borate	36.330	-116.695
52	Debaly Borax	borate	36.361	-116.741
53	Corkscrew Borax	borate	36.363	-116.761
54	Monte Blanco Borax	borate	36.379	-116.774
55	Unnamed	zeolite	36.409	-116.729
56	Gower Gulch Borax	borate	36.417	-116.825
57	Old Harmony Borax	borate	36.479	-116.874
58	East Coleman Borax	borate	36.480	-116.863
59	Amargosa Marble Company	travertine	36.373	-116.681
60	Lila C Borate	borate	36.247	-116.494
61	Maria Borate	borate	36.270	-116.499
62	Terry Borate	borate	36.292	-116.500
63	Sidehill Clay	bentonite	36.387	-116.471
64	Unnamed	hectorite	36.420	-116.468
65	Gerstley Mine	borate	36.015	-116.235
66	Death Valley Junction Zeolite, NV	zeolite	36.339	-116.328
67	Ox Plus Inc. Clay	clay	36.416	-116.377
68	Ash Meadows Montmorillonite	montmorillonite	36.424	-116.394
69	Ash Meadows Montmorillonite	montmorillonite	36.429	-116.399
70	East Ash Meadows Distirct	montmorillonite	36.462	-116.316
71	East Ash Meadows Distirct	montmorillonite	36.458	-116.322
72	Kinney Bentonite Deposit	bentonite	36.453	-116.316
73	Moretti Pit	sepiolite	36.461	-116.241
74	Eagle Borax Works	borate	36.200	-116.867
75	Played Out Borax	borate	36.377	-116.661
76	Western Talc Clay	clay	36.465	-116.243
77	Death Valley Junction Zeolite, CA	zeolite	36.337	-116.331
78	Winters Borate	borate	36.510	-116.918
79	Bob Clay	clay	36.802	-116.928

APPENDIX 1 (Contd)

80	Unnamed	sepiolite	36.510	-116.287
81	Unnamed	sepiolite	36.502	-116.233
82	Unnamed	gravel	36.656	-116.488
83	Unnamed	gravel	36.697	-116.164
84	Bond and Marks Clay	clay	36.899	-116.655
85	Elizalde Kaolinite	kaolinite	36.933	-116.624
86	Spicer Quarry	stone	36.970	-116.647
87	Spicer Quarry	stone	36.995	-116.605
88	Unnamed	gravel	36.872	-116.757
89	Spicer Quarry	stone	37.002	-116.587
90	Spicer Quarry	stone	37.009	-116.589
91	Spicer Quarry	stone	37.011	-116.586
92	Spicer Quarry	stone	37.014	-116.597
93	Unnamed	zeolite	36.955	-116.663
94	Unnamed	zeolite	36.903	-116.746

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Contour Interval 40 Feet

Figure 1. Location of Drill Holes in the Yucca Mountain Controlled Area that are Cited in the Text.

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