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World Nonbauxite Aluminum Resources— Alunite

By ROBERT B. HALL

GEOLOGY AND RESOURCES OF ALUMINUM

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1076-A

*A summary of domestic and foreign alunite resources
including discussion of possible use of alunite as a
nonbauxite ore of aluminum*



UNITED STATES DEPARTMENT OF THE INTERIOR

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Library of Congress Cataloging in Publication Data

Hall, Robert B

World nonbauxite aluminum resources—alunite.

(Geology and resources of aluminum) (Geological Survey professional paper ; 1076-A)

Bibliography: p.

1. Aluminum ores. I. Title. II. Series: United States. Geological Survey. Professional paper ; 1076-A.
TN490.A5H34 553'.492 77-608357

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

Stock Number 024-001-03103-5

APPRAISAL OF MINERAL RESOURCES

Continuing appraisal of the mineral resources of the United States is conducted by the U.S. Geological Survey in accordance with the provisions of the Mining and Minerals Policy Act of 1970 (Public Law 91-631, Dec. 31, 1970). Total resources for purposes of these appraisal estimate include currently minable resources (*reserves*) as well as those resources not yet discovered or not currently profitable to mine.

The mining of mineral deposits, once discovered, depends on geologic, economic, and technologic factors; however, identification of many deposits yet to be discovered, owing to incomplete knowledge of their distribution in the Earth's crust, depends greatly on geologic availability and man's ingenuity. Consequently, appraisal of mineral resources results in approximations, subject to constant change as known deposits are depleted, new deposits are found, new extractive technology and uses are developed, and new geologic knowledge and theories indicate new areas favorable for exploration.

This Professional Paper discusses aspects of the geology of aluminum as a framework for appraising resources of this commodity in the light of today's technology, economics, and geologic knowledge.

Other Geological Survey publications relating to the appraisal of resources of specific mineral commodities include the following:

- Professional Paper 820—"United States Mineral Resources"
- Professional Paper 907—"Geology and Resources of Copper Deposits"
- Professional Paper 926—"Geology and Resources of Vanadium Deposits"
- Professional Paper 933—"Geology and Resources of Fluorine in the United States"
- Professional Paper 959—"Geology and Resources of Titanium in the United States"

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WORLD NONBAUXITE ALUMINUM RESOURCES—ALUNITE

By ROBERT B. HALL

ABSTRACT

Alunite, $KAl_3(SO_4)_2(OH)_6$, has been used for centuries to make alum, especially in Italy and China. During World War I, alunite veins near Marysvale, Utah, were mined to extract potassium sulfate fertilizer, and during World War II, both veins and disseminated replacement deposits were investigated as possible sources of aluminum that would yield a potassium sulfate byproduct. However, no commercial developments ensued both for economic reasons and because the resources at Marysvale were considered inadequate to support an alumina industry. Since 1970, large deposits of low-grade alunitic rock in the southern Wah Wah Mountains of Beaver County, Utah, and in other Western States have been investigated by a private consortium; this consortium has announced its intention to establish an alumina-from-alunite industry that is planned to have the capacity to produce 454,000 t/yr (metric tons each year) of cell-grade alumina (alumina suitable for reduction to aluminum in Hall-Héroult-type electrolytic cells), 227,000 t/yr of potassium sulfate, and 408,000 t/yr of sulfuric acid, if the industry can be shown to be economically feasible. Presently, the only alumina-from-alunite plant in the world is in Azerbaijan, U.S.S.R.; it was established in the early 1960's.

Three main types of alunite deposit are recognized: (1) veins; (2) replacement deposits; (3) sedimentary deposits. The large-tonnage low-grade replacement deposits in hydrothermally altered volcanic rocks of rhyolitic to dacitic composition constitute the principal alunite resource. In general, a body should contain at least 90 million metric tons having a content of at least 30 percent alunite to be considered potentially minable. Large replacement deposits are characteristically zoned: (1) siliceous core zone; (2) quartz-alunite zone; (3) inner argillic zone containing quartz, alunite, kaolinite, dickite, sericite assemblage, minor iron and titanium oxides, and occasionally containing minor pyrophyllite, diaspore, and zunyite; (4) outer argillic zone containing quartz, kaolinite, sericite, illite, and less abundant chlorite and montmorillonite; (5) propylitic zone of weakly altered rock containing quartz, epidote, chlorite, zeolites, pyrite, relict feldspar and mica; original rock texture is preserved. Propylitized rock grades outward into relatively unaltered country rock.

The principal domestic alunite reserves and potential resources are in the southern Wah Wah Mountains, Beaver County, Utah, and are identified as being about 630×10^6 t of rock containing about 30 percent alunite. Southern Nevada

has identified resources of several hundred million metric tons of alunitized rock, although the alunite content of much of it is less than 30 percent. One deposit of 200×10^6 t containing roughly 25 percent alunite is in Santa Cruz County, Ariz., and a deposit of 250×10^6 t that may contain 30 percent or more of alunite is in Hinsdale County, Colo. Other alunite deposits in the United States are numerous but less promising.

Large identified alunite resources are in the U.S.S.R., the Peoples Republic of China, Australia, and Mexico. Resources of lesser magnitude have long been known in Italy and France. Other countries having at least modest alunite resources, part of which eventually may be proven to have commercial potential, include Argentina, Greece, Iran, Japan, Pakistan, Republic of Korea, Spain, and Turkey.

INTRODUCTION

HISTORICAL BACKGROUND

Alunite, $KAl_3(SO_4)_2(OH)_6$, has been mined in Italy since the 15th century as a source of potash alum, and alunite-rich altered volcanic rock in Chekiang Province, China, has been mined since the 17th century, also as raw material for making alum. During World War I, when the supply of potash fertilizer from Germany was interrupted, attempts were made by several companies to develop alunite veins of the Marysvale district, Utah, as a source of potassium sulfate fertilizer. These deposits had been recognized and reported only a few years before the outbreak of the war (Butler and Gale, 1912). An estimated 238,000 t (metric tons) of vein alunite were produced for fertilizer during World War I (Thoenen, 1941, p. 21). Extraction of alumina from alunite was not attempted except on a laboratory scale. During World War II, the supply of imported bauxite from Surinam and other sources was threatened so that the Marysvale alunite deposits again received attention, this time as a source of alumina that would yield potassium sulfate as a byproduct. A plant was erected in Salt Lake City, and in 1943, about 10,800 t of vein alunite were treated

by the Kalunite process (Fleischer, 1944). No permanent operation resulted, and after the war, alunite was relegated to the status of a potential submarginal aluminum resource. The veins at Marysvale are high grade but do not contain sufficient reserves to support an industry. Low-grade replacement-type deposits in altered volcanic terrane neighboring the veins at Marysvale, Utah, and in similar deposits in other Western States contain a much larger reserve than the high-grade veins; however, these low-grade deposits were considered very costly to process because formidable problems of metallurgical extraction had to be solved, and so these deposits were deemed to be not competitive with bauxite (Natl. Materials Advisory Board, 1970, p. 62). Between 1934 and 1945, an experimental plant in Japan produced more than 7,000 t of alumina from alunite-rich rock. The process was considered to be a technologic success but an economic failure (Allen, 1947, p. 72-75). During both World Wars, alunite was mined in Australia for potash fertilizer and later was investigated in laboratory tests as an ore of aluminum (Australia Advisory Council Sci. Ind., 1917; Fitzgerald, 1945; Bayliss and others, 1951).

In 1970, a private firm headquartered in Golden, Colo., discovered large replacement deposits in altered Tertiary volcanic rocks of the southern Wah Wah Mountains in Beaver County, Utah, 87 km northwest of Cedar City. By 1974, the company and its consortium partners had announced a proven reserve of more than 91×10^6 t that was estimated to contain 35-40 percent alunite. Indicated and inferred reserves amounting to 544×10^6 t also were reported (Walker and Stevens, 1974). From 1973 until the end of 1976, the consortium partnership operated a pilot plant in Golden, Colo., to perfect an economic process for treating low-grade siliceous alunite ore. The consortium has proposed to establish a full-scale commercial plant adjoining the Beaver County deposits; the plant will be designed to produce 454,000 t/yr of cell-grade alumina (alumina suitable for reduction to aluminum in Hall-Héroult-type electrolytic cells), 227,000 t/yr of potassium sulfate fertilizer, and 408,000 t/yr of sulfuric acid. The acid may be reacted with phosphate rock transported by railroad to the plant from southeast Idaho to make phosphate fertilizer (Parkinson, 1974, p. 78; Thompson, 1976, p. 684).

The activities of this consortium have revived interest in alunite as a potential nonbauxite source of aluminum. In 1974, the U.S. Geological Survey began an updated inventory of domestic alunite resources to determine the place of alunite among various poten-

tial domestic nonbauxite resources; updating the inventory was in response to a growing national concern over near-total dependence on imported bauxite and alumina. The only presently operating commercial plant in the world extracting cell-grade alumina and byproduct potassium sulfate from alunite ore is in Azerbaijan, U.S.S.R. (see p. A24).

CHARACTERISTICS OF ALUNITE DEPOSITS

MINERALOGY

The formula for pure alunite is $KAl_3(SO_4)_2(OH)_6$, and the theoretical composition is K_2O , 11.37 percent; Al_2O_3 , 36.92 percent; SO_3 , 38.66 percent; and H_2O , 13.05 percent. The formula for the sodium isomorph, natroalunite, is $NaAl_3(SO_4)_2(OH)_6$; its theoretical composition is Na_2O , 7.79 percent; Al_2O_3 , 38.42 percent; SO_3 , 40.23 percent; and H_2O , 13.56 percent. However, virtually all natural alunite contains at least a small amount of Na in substitution for K, and natroalunite invariably contains appreciable K. By convention, the mineral is called natroalunite when the atomic (not *weight*) ratio of Na:K equals or exceeds unity. If the Na:K atomic ratio exceeds 1:3, the mineral may be called sodian alunite, although no rule is consistently followed, and this term is sometimes mistakenly interpreted as a synonym for natroalunite. Parker (1962) could not synthesize 100-percent-pure end members by using the purest available reagents; apparently, small amounts of Na and K leached from laboratory glassware entered the crystal lattice of Parker's synthetic products. A solution in which the Na:K atomic ratio was 93:7 yielded synthetic alunite having a Na:K ratio of 42:58 (Parker, 1962, p. 128-129), indicating strongly preferential uptake of K in the lattice. This preferential uptake of K accounts for the predominance of K over Na in most natural alunites, even in areas where host rocks contain more Na than K. The K-rich alunite has greater commercial value than natroalunite because potassium sulfate fertilizer can be recovered as a valuable byproduct of the alumina. Theoretically, salt cake (Na_2SO_4) also can be recovered from alunite, but it is less valuable than K_2SO_4 . During World War II, a small amount of soda alum ($NaAl(SO_4)_2 \cdot 12H_2O$) was recovered at the experimental alumina-from-alunite plant at Shikama, Hyogo Prefecture, Japan (Allen, 1947, p. 38-40, 72-75), but except for this Japanese experiment, no process designed to recover both K_2SO_4 and Na_2SO_4 from alunite has been reported.

Other minerals listed as belonging to the "alunite group" include jarosite, $KFe_3(SO_4)_2(OH)_6$;

natrojarosite, $\text{NaFe}_3(\text{SO}_4)_2(\text{OH})_6$; ammoniojarosite, $(\text{NH}_4)\text{Fe}_3(\text{SO}_4)_2(\text{OH})_6$; argentojarosite, $\text{AgFe}_3(\text{SO}_4)_2(\text{OH})_6$; plumbojarosite, $\text{PbFe}_6(\text{SO}_4)_4(\text{OH})_{12}$; and beaverite, $\text{Pb}(\text{Cu,Fe,Al})_3(\text{SO}_4)_2(\text{OH})_6$ (Palache, Berman, and Frondel, 1951, p. 555–570). These isostructural chemical relatives may be formed in environments similar to those where alunite or natroalunite form, but, except jarosite and possibly natrojarosite, they are much rarer than alunite and natroalunite.

The crystal form and physical properties of alunite are well described in mineralogy textbooks and journals, and it is pointless to repeat these data here, especially because the bulk of alunite resources exist, not in veins of pure mineral, but in large bodies of altered volcanic rock where fine-grained alunite is intimately mixed with microquartz, commonly associated with kaolinite, halloysite, dickite, opaline cristobalite, muscovite (“sericite”), rutile, anatase, and hematite, and less commonly with pyrophyllite, diaspore, zunyite, and other alteration minerals. These alunitized rocks bear little resemblance to the ideal crystals and museum specimens of alunite described by mineralogists. Identification of alunite-bearing rock in the field is not easy. A field test developed by Schaller was described by Butler and Gale (1912, p. 63). A simple quick test using pH-sensitive paper to measure acidity of water driven off the powdered sample and condensed in a test tube is fairly reliable if used with discretion (Cunningham and Hall, 1976). Powder X-ray diffraction patterns can be used to estimate K:Na ratios and to distinguish between K-rich and Na-rich alunite (Cunningham and Hall, 1976, p. 1597). Ultimately, a combination of X-ray analysis, examination under the petrographic microscope, and chemical analysis is needed to determine accurately the composition and possible commercial value of a given material.

TYPES OF DEPOSITS

Three main types of alunite deposits are recognized: (1) veins; (2) replacements; (3) sedimentary deposits. Type 3 has two subdivisions: (3a) nodular layers and thin seams formed supergenically in clayey or micaceous sedimentary and metasedimentary rocks; (3b) lacustrine kaolinic sediments that have been diagenetically or supergenically alunitized. Veins, type 1, contain the highest grade of alunite, but reserves are small and costly to mine. Nodular layers, type 3a, are numerous and widespread but have little economic importance; lacustrine deposits, type 3b, have been reported only in Australia where some were mined briefly for potash fertilizer, but

they have limited economic potential. The bulk of United States and world alunite resources are type 2, large bodies of relatively low grade hydrothermally and solfatarically alunitized ignimbrites, tuffs, flows, agglomerates, and feeder intrusive porphyries and associated volcanic rocks of dacitic to rhyolitic composition. Although these bodies are low grade, rarely containing more than 30 percent alunite, equivalent to only 11 percent Al_2O_3 , they can be mined by large-scale low-unit-cost open-pit methods.

VEINS

Alunite vein deposits are best exemplified by the high-grade veins and lenses found on Alunite Ridge in the part of the Marysvale district in Piute County, Utah; these deposits were first described by Butler and Gale (1912), and a summary description was given by Callaghan (1973, p. 66–81). The veins here are steeply to moderately dipping fissure fillings of sinuous trend in altered rhyolitic tuff and breccia of Oligocene age (Callaghan, 1973, p. 10, 67–81). They persist along strike for distances ranging from a few meters to 500 m and have widths of from less than 0.3 m to 20 m; local widths of 6 m are not rare. Pinching and swelling along both strike and dip are marked, and irregular branches and offshoots from principal veins or lenses are common. Some veins persist to depths of 130 m below the surface, but few have been developed so thoroughly that all dimensions are known. Unlike replacement-type rock, alunite veins are fairly pure; they consist of fine- to coarse-grained crystalline aggregates of pinkish alunite and only minor amounts of diluting minerals, such as kaolinite, veinlets of dickite, microquartz, and iron oxides. A faint banding parallel to walls is common. Inclusions of altered volcanic wallrock may be locally dispersed in the vein matter, and vein walls are silicified, alunitized, kaolinized, and pyritized. However, the content of alunite in the altered wallrock generally is low. Although resources in veins are relatively high grade, they are too small to support processing plants of economic size; the veins can be mined only by high-cost underground methods. The most likely use for alunite veins is as a supplementary millfeed or “sweetener” of low-grade replacement rock in areas where both types of deposit are found.

REPLACEMENTS

Replacement deposits constitute the bulk of alunite resources, both in the United States and in the rest of the world. Deposits of this type are known in Utah, Nevada, Arizona, Colorado, and New Mexico, although it has not yet been proven that even the largest and richest of them can be mined and proc-

essed profitably. Vein deposits in the Marysvale district of Utah were mined commercially on a small scale for potash fertilizer during World War I (Loughlin, 1916; Phalen, 1917; Callaghan, 1938); pilot-plant testing for extraction of alumina from both vein and replacement deposits at Marysvale was done during World War II (Fleischer, 1944; Hild, 1946; Callaghan, 1973, p. 66, 89). Presently, large replacement deposits in the southern Wah Wah Mountains of Beaver County, Utah, are considered the most promising for commercial development, and approximately 1,800 t of alunite rock from this district have undergone test processing at a pilot plant in Golden, Colo. (Thompson, 1976).

In general, a replacement deposit may be considered as potentially exploitable if it contains at least 90 million metric tons of rock containing on average at least 30 percent alunite (W. W. Walker, Earth Sciences Inc., oral commun., 1974). The rock should consist mainly of a microquartz-alunite mixture and should contain only small amounts of reactive silica as opaline cristobalite, clay, or mica. Quartz is not unduly troublesome in the metallurgical treatment. However, cristobalite and the phyllosilicate minerals break down in the caustic leach and contaminate the alumina solution with silica; the removal of silica in order to make an acceptable alumina product adds appreciably to processing costs and loss of alumina and soda.

The typical replacement deposit is formed in Tertiary volcanic terrane in a thick pile of ash-flow tuff, ignimbrite, and breccia of andesitic to rhyolitic composition, where hot sulfuric-acid-charged fluids have moved upward and laterally through fissures or vents during the late fumarolic stages of a volcanic episode. Rock adjacent to the conduit is strongly leached and altered, but also great volumes of surrounding rock are affected by the fluids permeating outward through minute pores and fractures. The hypogene alunite process is not fully understood, but it includes leaching of soluble alkaline constituents (Na, K, Ca, Mg) and destruction of the lattice of the feldspar, mica, amphibole, and other primary minerals in the original volcanic rock (Hemley and others, 1969). The breakdown of the original rock is facilitated by relatively high porosity and the typical fine granular to glassy texture. The process entails volume-for-volume metasomatic replacement of feldspar, mica, and other primary minerals in such a way that the pyroclastic texture of original tuff or breccia may be surprisingly well preserved in spite of the profound change in chemical and mineral composition. The relict primary texture may not be evident in hand specimen but commonly is recognized in thin section. Quartz phenocrysts may be left

intact, except for corroded edges, but silica is liberated (presumably as gel) during the breakdown of the primary aluminosilicate rock minerals and is recrystallized as a very fine grained mosaic (microquartz) intermixed with fine shreddy alunite. The rock may resemble chert, except that the microquartz mosaic is seen under the microscope to have interstices filled with fine granular flakes or shreds of alunite. Russian geologists call this kind of hydrothermally altered siliceous rock "secondary quartzite" (Kashkai, 1961, 1970, v. 1, p. 245; Naboko, 1958, 1963; Kirova, 1959; Kerimov, 1959; Rusinov, 1966). In some areas, milky near-opaline cristobalite may constitute the major silica phase instead of microquartz. Cristobalitic rock is undesirable because of its greater susceptibility to Bayer caustic-leach attack and consequent high silica contamination of the alumina solution.

Large replacement deposits generally are characteristically zoned:

(1) Siliceous core zone. The innermost zone typically is whitish and highly siliceous. The original rock is leached of alkaline components and much of the alumina and is metasomatically replaced by finely crystalline quartz (microquartz) or, less commonly, milky opaline cristobalite. The texture may be so porous as to resemble siliceous sinter. Native sulfur locally may fill pores and cavities in "spongy" chert. This porous zone is believed to represent the main vent for hot, strongly acid fluids. Probably corrosive solfataric gases accompanied boiling water and steam in what has been called a hydrosolfatara (Naboko, 1958). Original rock texture is obliterated, and alunite and other minerals are sparse.

(2) Quartz-alunite zone. Variegated grayish-white to pink bleached rock consisting of fine-grained microquartz intimately mixed with fine shreds and flakes of alunite forms an envelope around the siliceous core. Small amounts of clay mineral, usually kaolinite or dickite, may be present, and goethite or hematite and anatase or rutile are normal minor accessories in alunite rock. This zone contains the best "ore" because alunite content may be 30 percent or higher and because the principal gangue is microquartz. Original pyroclastic texture may be blurred but still recognizable in thin section.

(3) Inner argillic zone. Bleached appearance of the rock still is strongly evident as the quartz-alunite zone grades outward into a broad argillized envelope in which the alunite content decreases as the amount of fine-grained kaolinite or kaolinite-sericite mixture increases. Dickite may be present instead of, or in addition to, kaolinite. Quartz content equals or exceeds phyllosilicate content. Minor amounts of iron and titanium oxides are ubiquitous, and less com-

monly, pyrophyllite, diaspore, and zunyite also may be present. This material is a less likely source of aluminum and potash than that in the quartz-alunite zone because of its lower alunite content and because the intermixed phyllosilicates are undesirable contaminants. Original rock texture may appear blurred in hand specimen but distinct in thin section.

(4) Outer argillic zone. The inner argillic zone grades into the outer argillic zone, which is characteristically dull gray or brownish gray and contains little or no alunite and an increasing amount of kaolin minerals. Quartz always is present, partly as an unaltered original rock constituent, and partly as a very fine grained metasomatic replacement mineral accompanying phyllosilicates in the alteration assemblage. Sericite is common and may exceed kaolinite in total amount. Illite, which is degraded sericite or muscovite (sometimes called "hydromica" in this form), may be the principal mica constituent, especially toward the outer margin of this zone; however, positive distinction between sericite and illite in X-ray patterns and thin sections of these rocks is difficult. Likewise, chlorite, montmorillonite, and mixed-layer clay species may appear in this zone, but identification usually is uncertain. Feldspar, biotite, and other primary rock minerals may be preserved in badly corroded relict crystals.

(5) Propylitic zone.¹ The outer argillic zone grades into a dark grayish-green zone of propylitized rock composed essentially of partially sericitized potassium feldspar, saussuritized plagioclase, quartz, chloritized or uralitized mafic minerals and interstitial carbonate or zeolite, and dispersed tiny pyrite crystals. Montmorillonite or mixed-layer clay species commonly are present as subordinate alteration products; alunite is rare or absent. The propylitic zone grades into rock relatively unaffected by hypogene alteration, although it may be weathered in outcrop.

The preceding description is of an "ideal" replacement deposit, rarely observed in nature, although alunitized volcanic terranes in the Western United States commonly show at least three of the above-described alteration zones.

SEDIMENTARY DEPOSITS

The most common and geographically widespread kinds of sedimentary alunite deposits are the nodular layers and associated thin seams. Ellipsoidal nodules are found along disconformities in argillaceous sediments; most are only a few centimeters across, but

some in Australia are as much as 60 cm across, and some at the Madriat deposit in France are as much as 2 m long. Nodules a few centimeters across are found dispersed in some bauxites in Hungary and Greece (Bárdossy, 1959; Bárdossy and Mack, 1967). Ground water containing sulfuric acid derived from the oxidation of disseminated pyrite in adjoining rock is the agent usually invoked to explain formation of the nodules. Many nodules are sodic alunite or natroalunite, suggesting much higher availability of Na^+ than of K^+ .

Lacustrine deposits are found in Australia where shallow ephemeral lagoonal basins are filled with alunite-rich clayey sediment whose origin is unclear; King (1953) postulated sulfate-charged ground water acting upon original kaolin sediment to explain deposits at Pidinga, South Australia. The Australian alunitic sediments are high grade, but the total resource may not exceed a few tens of millions of metric tons.

ALUNITE AS AN ALUMINUM RESOURCE

PURE ALUNITE VERSUS ALUNITIC ROCK

Although alunite contains only 37 percent alumina, treatment of the pure mineral is relatively easy. If nearly pure alunite existed in 10-million- to 100-million-metric-ton bodies, it could easily compete with, or perhaps even be preferred to, bauxite, which commonly contains about 50 percent alumina. Unfortunately, "pure" alunite is found only in veins of limited extent that must be mined by high-cost underground methods, or in sedimentary rocks as thin nodular layers minable only by small-scale methods, if at all. The only alunite resource of economically minable size is in the 90-million- to 200-million-metric-ton low-grade quartz-alunite replacement bodies in hydrothermally altered volcanic rocks. Such bodies rarely contain as much as 40 percent alunite, and even 30 percent is uncommon. Therefore, industry must develop methods of profitably mining and processing alunitic rock containing only 11–15 percent Al_2O_3 . Prior to and during World War II, research on treatment of low-grade alunitic rock was carried out in the United States, Australia, and Japan. More recent work was done in Mexico and other countries. However, only the Soviet Union has a commercial alumina-from-alunite operation, established in the early 1960's. Since 1973, the Alumet partnership comprising Earth Sciences, Inc., National Steel Company, and Southwire Company has devised its own process, based in part on a roasting technique purchased from the Russians (Thompson, 1976). Economic success of the Alumet process will be proven only when the company's proposed plant,

¹"Propylitic" is applied here to weakly altered, that is, "propylitized," igneous rocks ranging in composition from andesite to rhyolite. Strictly defined, a propylite is mildly hydrothermally metamorphosed andesite, typically containing secondary calcite, chlorite, epidote, quartz, and pyrite.

which has been projected to have the capacity to produce 454,000 t/yr of alumina, actually is built and operating. If successful in Utah, this project could lead to more alumina-from-alunite operations in other Western States and in other countries having large resources of low-grade alunitic rock.

PROBLEMS

The treatment of low-grade mixtures of fine-grained quartz, alunite, and lesser amounts of other minerals is much more difficult than treatment of pure alunite. Hardly more than a third of the bulk handled is alunite. Experiments on concentration, notably by differential flotation (Gabriel and Dasher, 1942), have not proven any concentration method to be practical. Thus, low-grade run-of-mine material must be taken through the Alumet extraction process, and considerable energy must be expended on gangue. Furthermore, the fluidized-bed roasting must be carried out under narrow and complex restraints (Thompson, 1976, p. 683). Following evolution of some SO_2 , which is converted to H_2SO_4 by-product, the potassium sulfate is removed in solution by water leach and is precipitated in separate vessels to make fertilizer-grade K_2SO_4 byproduct. The filter residue contains about 23 percent Al_2O_3 and consists mainly of fine granular quartz and aluminum trihydrate. It is treated by a modified Bayer caustic soda-leach process to dissolve the alumina; after filtration, undissolved fine silica sand is passed to the tailings. The filtrate is desilicated and then seeded to precipitate synthetic gibbsite $\text{Al}(\text{OH})_3$, which is calcined to make the final alumina product (Thompson, 1976).

The Alumet process has an advantage in that alumina in the filter residue dissolves at lower pressure and temperature than alumina in raw bauxite treated by the conventional Bayer process. Also, the iron oxide content of alunitic rock is much lower than that of most natural bauxites, and thus does not cause the "red-mud" problem. However, alunitic rock, because it contains much less alumina than bauxite, must be as free as possible from phyllosilicate minerals, like kaolinite or sericite, or relatively soluble forms of silica such as cristobalite; otherwise, too much alumina and soda are lost during the desilication process that precedes precipitation of the pure (or nearly pure) alumina as synthetic gibbsite. Microcrystalline quartz is not reactive under the relatively mild conditions of the modified Bayer process used in the treatment of alunitic rock; thus, it is a "benign" gangue constituent, in contrast to clay, mica, and opaline cristobalite.

Finding alunitic rock that is free of soluble forms of silica is difficult because of the nature of the de-

posits themselves. Hydrothermally altered rock bodies tend to be nonuniform; samples taken a few meters apart can differ in mineral composition, even if they appear identical. The ideal "ore" is alunite mixed with microquartz, which does not dissolve readily in the caustic leach. This kind of rock is typical of the central, mostly intensely altered zone, but avoiding contaminants such as kaolinite and sericite is not always easy because the rock may not be altered uniformly over a great distance. This nonuniform alteration may be due to variations in spacing of fractures or channels through which the fluids passed, rate of flow and chemical activity of the fluids, permeability, temperature, grain size, and other factors. The alunite-rich zones of the southern Wah Wah Mountains are reported to be unusually homogeneous, but heterogeneity is more characteristic than homogeneity of most hydrothermally altered areas, irrespective of the broad-scale zoning that may be evident. This clearly is a limitation on the utilization of alunitic rock as an ore of aluminum.

Nevertheless, continuing the effort to overcome problems inherent in the economic extraction of alumina from alunite is worthwhile, because large resources of alunitic rock are available within our national boundaries; utilization of these resources could alleviate growing dependence on imported alumina and bauxite. Alunitic rock is unlikely, however, to become a major substitute for bauxite in the foreseeable future, even in bauxite-deficient countries that have large alunite resources.

ACKNOWLEDGMENTS

Much helpful information was given by personnel of Earth Sciences, Inc., Golden, Colo.; in particular, the advice and cooperation of William W. Walker of that company is especially appreciated. Personnel of the U.S. Geological Survey (U.S.G.S.) assisted both in compilation and in interpretation of data. J. A. Crowley, U.S.G.S., kindly supplied data on alunite deposits that he examined in Nevada, Arizona, and California. Useful consultation was provided by State survey officials, especially Keith G. Papke, Nevada Bureau of Mines and Geology, and George S. Austin, New Mexico Bureau of Mines and Mineral Resources. Unpublished alunite-resource information from Louis S. Gardner, formerly of U.S.G.S., now in Pleasant Grove, Utah, was very useful, as were the published reports of Eugene Callaghan, Salt Lake City, Utah.

DOMESTIC RESOURCES

The locations of alunite reserves and resources in the conterminous United States are shown in figure 1, and the index to the localities appears in table 1.

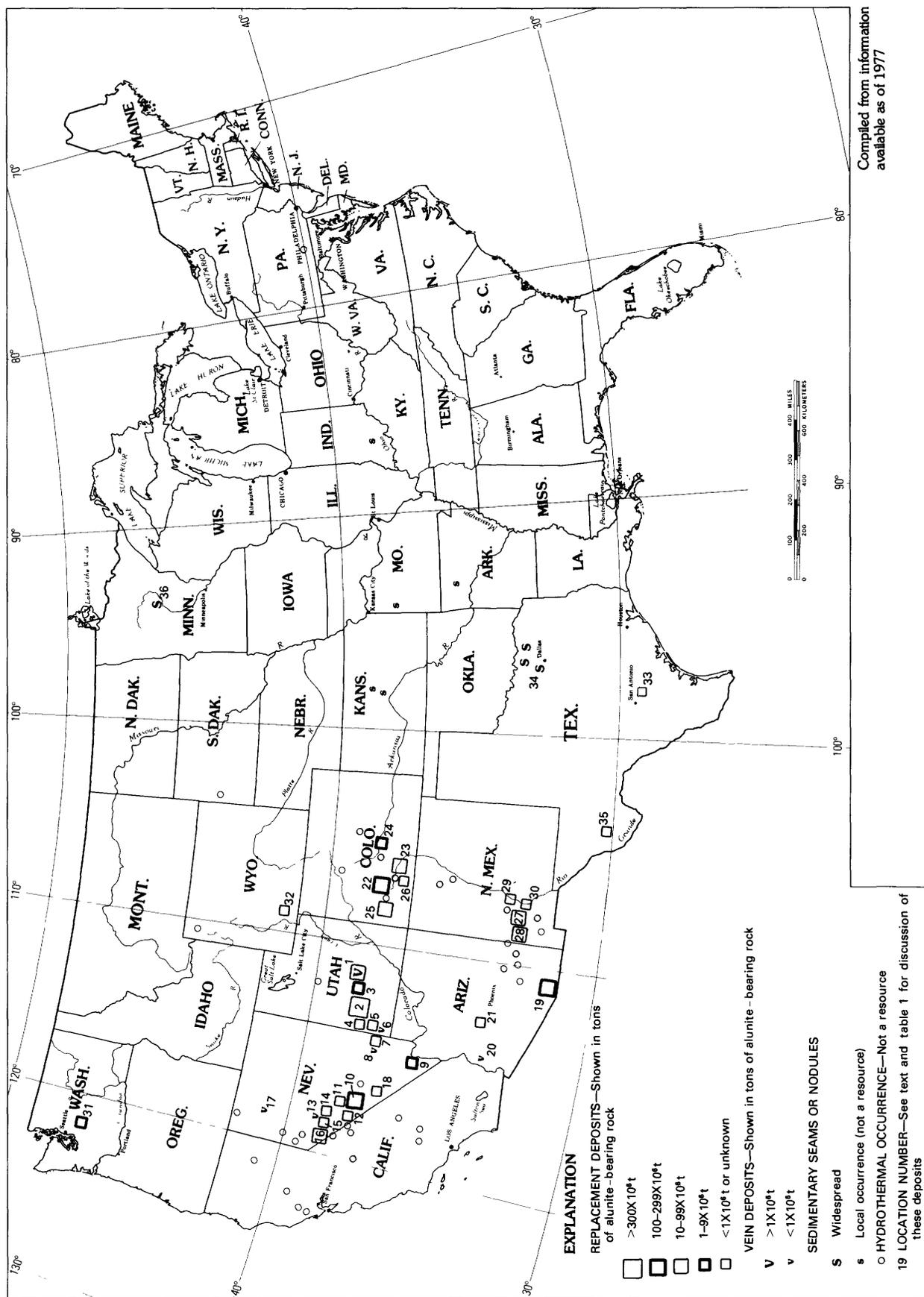


FIGURE 1.—Locations of alunitic reserves and resources in the conterminous United States. Numbered deposits are indexed in table 1 and discussed in the text.

TABLE 1.—Index to numbered alunite localities in the conterminous United States (see fig. 1 for map)

[Hydrothermal alunite occurrences and very local sedimentary alunite occurrences having negligible resource potential are located on the map but are not numbered; they are discussed briefly in the text. V, veins; R, replacement deposits; S, sedimentary deposits. Question mark (?) after a number indicates a very high degree of uncertainty. Dash leaders (----) indicate insufficient data. All reserve and resource figures are subject to revision as further data become available.]

Loc.	District or deposit	State, County	Deposit type	Remarks	References	Reserves (10 ⁶ t)	Estimated alunite content (percent)	Potential resources (10 ⁶ t)	Estimated alunite content (percent)
1---	Marysvale	Utah, Piute, Sevier.	V and R	Veins on Alunite Ridge exploited during both World Wars. Low-grade replacement deposits are larger resource than the veins.	Butler and Gale, 1912; Callaghan, 1938, 1973; Loughlin, 1916; Thoenen, 1941; Hild, 1946.	V-1.38 R-7.36	88 43	0.74 33.26	79 23
2---	Southern Wah Wah Mtns.	Utah, Beaver, Iron.	R	Alumet consortium developing "NG" lease area. District also includes SX and PV deposits south of Beaver County-Iron County line and west end of White Mtn. area. Most promising domestic alunite resource recognized so far.	Walker and Stevens, 1974; Parkinson, 1974.	232	33	402	28
3---	Sheep Rock	Utah, Beaver	R	Alunitized Tertiary rhyolite forms prominent white hill 8 km northeast of Beaver.	Loughlin, 1916; Thoenen, 1941.	2	30	----	----
4---	Big Pinto Spring.	Utah, Beaver	R	Siliceous sporadically alunitized volcanic rock.		----	----	----	----
5---	Modena	Utah, Iron	R	Alunitized tuff breccia		----	----	----	----
6---	Beauty Knoll	Utah, Washington.	V	Alunite vein in halloysite-bearing altered andesite.	Crawford and Buranek, 1948.	.45?	80?	----	----
7---	Clover Mtns.	Nev., Lincoln	R	Parts of 18-km ² area in T. 7 S., R. 70 E., underlain by altered Tertiary volcanic rocks; extent of alunitization unknown.		----	----	----	----
8---	Boyd	Nev., Lincoln	V	Lens of alunite mined briefly in 1920's.	Hewett and others, 1936; Thoenen, 1941; L. S. Gardner, unpub. data, 1943.	.04 .29	29 21	----	----
9---	Railroad Pass.	Nev., Clark	R	Irregular localized alunitization in Tertiary volcanic rocks.	Hewett and others, 1936; Thoenen, 1941; Phalen, 1917; L. S. Gardner, unpub. data, 1944.	1.8	27	4	6
10---	Goldfield	Nev., Esmeralda	R	Main mined area at Goldfield not a likely resource; areas south and west of town are more favorable.	Ransome, 1907, 1909.	----	----	Main mined area—150? CTR leases—100? MTZ lease—60?	10? 22? 20?
11---	Monte Cristo Range.	Nev., Esmeralda	R	Alunitized Tertiary volcanic rocks, extent unknown.		----	----	----	----
12---	Boundary Peak.	Nev., Esmeralda	R	Alunitized Tertiary volcanic rocks associated with mercury deposits.	Bailey and Phoenix, 1944.	----	----	----	----
13---	Bovard	Nev., Mineral	V	Thin alunite veins in altered rhyolite at old Gold Pen mine.	Schrader, 1913; Thoenen, 1941.	.007	50	----	----
14---	Gabbs Valley Range.	Nev., Mineral	R	Locally alunitized Tertiary tuff and granite; resource may be large, but alunite content is low.		----	----	----	----
15---	Corey Peak	Nev., Mineral	R	White alunitized rhyolite exposed in shallow bulldozed trench: deposit high grade but small.	Archbold, 1966	----	----	.9	40
16---	The Elbow	Nev., Mineral, Lyon.	R	Irregularly alunitized Tertiary volcanic rocks in area straddling Mineral County-Lyon County line near "The Elbow," bend in East Walker River; leases applied for by private consortium.		----	----	40?	20?
17---	Sulphur	Nev., Humboldt	V	Alunite veins in altered Tertiary volcanic rocks, mined briefly in 1917.	Clark, 1918; Vanderburg, 1938; Thoenen, 1941; L. S. Gardner, unpub. data, 1944.	.026 .186	75 70	----	----
18---	Beatty	Nev., Nye	R	Area of strongly bleached, locally alunitized Tertiary volcanic rocks, 11 km east of Beatty. Cristobalite also abundant locally.		----	----	----	----
19---	Red Mountain-Patagonia.	Ariz., Santa Cruz.	R	"Red Mountain" volcanic complex pervasively alunitized; kaolinite, sericite, pyrophyllite also present; porphyry-type copper mineralization beneath alunitized upper part of the mountain.	Schrader, 1913, 1915; Simons, 1974; Corn, 1975.	----	----	200	25?

WORLD NONBAUXITE ALUMINUM RESOURCES—ALUNITE

A9

TABLE 1.—Index to numbered alunite localities in the conterminous United States—Continued

Loc.	District or deposit	State, County	Deposit type	Remarks	References	Reserves (10 ⁶ t)	Estimated alunite content (percent)	Potential resources (10 ⁶ t)	Estimated alunite content (percent)
20---	Sugarloaf Peak.	Ariz., Yuma	V	Veins, localized stockworks in sheared sericitized dacite of uncertain age, 8 km west of town of Quartzsite.	Heineman, 1935 ; Thoenen, 1941.	0.232	55	-----	-----
21---	Hassayampa River.	Ariz., Maricopa	R	Alunitized and kaolinized Tertiary rhyolite in 130-hectare area, 16 km south of Wickenburg, along margins of Hassayampa River Valley.	Sheridan and Royse, 1970.	-----	-----	-----	-----
22---	Red Mountain-Lake City.	Colo., Hinsdale	R	Alunitized silicified quartz latite of Miocene age on summit area of Red Mountain, 5 km south of Lake City.	Larsen, 1913 ; Steven and others, 1974.	-----	-----	250	30
23---	Marble Mountain.	Colo., Rio Grande.	R	Alunitized Tertiary andesitic volcanic rocks on ridge 5 km north of old Jasper mining camp.	L. S. Gardner, unpub. data, 1943.	5.2	37	9	30
24---	Rosita Hills	Colo., Custer	R	Mount Robinson and Democrat Hill volcanic vents, rhyolite tuff locally alunitized. Minor diasporite at Mount Robinson.	Cross, 1891, 1896 ; Thoenen, 1941 ; L. S. Gardner, unpub. data, 1943.	-----	-----	2.7	15
25---	Calico Peak	Colo., Dolores	R	Strong silicification, local alunitization in hydrothermally altered Tertiary latite volcanic plug. Muscovite, kaolinite, minor pyrophyllite also present.	Cross and Spencer, 1900 ; Thoenen, 1941 ; Serna-Isaza, 1971 ; L. S. Gardner, unpub. data, 1943.	-----	-----	2 9	17 15
26---	Alum Creek	Colo., Conejos	R	Local alunitization in Tertiary volcanic vent complexes above Alum Creek, immediately south of Rio Grande County boundary.	Calkin, 1967	-----	-----	-----	-----
27---	Alum Mountain.	N. Mex., Grant	R	Pervasively alunitized and kaolinized Tertiary latite tuff-breccia on Alum Mountain and both sides of Alum Canyon. Local supergenic alum encrustations.	Hayes, 1907	-----	-----	90	20
28---	Saddleback Mountain.	N. Mex., Grant	R	Strongly silicified, locally alunitized Tertiary volcanic rocks at extreme northwest end of Steeple Rock mining district.		-----	-----	60	30
29---	Juan Peak	N. Mex., Sierra	R	Strongly silicified alunitized Tertiary rhyolitic tuffs and breccias 10 km northwest of Monticello.		-----	-----	-----	-----
30---	Rattlesnake Canyon.	N. Mex., Luna	R	Silicified alunitized Tertiary volcanic rocks in low hilly terrain near mouth of Rattlesnake Canyon, 14 km northwest of Florida rail siding.		-----	-----	-----	-----
31---	Enumclaw	Wash., King, Pierce.	R	Locally alunitized Tertiary andesitic volcanic rocks; clay minerals accompany the alunite in much of the rock.	Thoenen, 1941 ; Hunting, 1966 ; Livingston, 1971.	1.1	48?	-----	-----
32---	Quaking Asp (Aspen) Mountain.	Wyo., Sweet-Water.	R	Alunitized tuffaceous siltstone exposed in bottom of trench excavated in Tertiary terrestrial sediments 20 km southeast of Rock Springs.	Love and Blackmon, 1962.				
33---	Wilson County.	Tex., Wilson	R?	Alunite in "decomposed trachyte" in 8-hectare area 48 km southeast of San Antonio.	Braun, 1921				
34---	North-central Texas.	Tex., Fannin, Grayson, Denton, Tarrant, Johnson.	S	White natroalunite nodules along unconformity between Cretaceous Woodbine Formation and overlying Eagle Ford Group, exposed intermittently in roadcuts and outcrops over a 5-County area, ranging 215 km from northeast to southwest. However, nodular layer is discontinuous and only 15-30 cm thick.	Stephenson, 1946 ; Ross and others, 1968.				
35---	Medley	Tex., Jeff Davis	R	Alunite dispersed in hydrothermally altered Tertiary rhyolite-trachyte flows 27 km west of Ft. Davis. Cristobalite, kaolinite, iron oxide also present.	Shurtz, 1951				
36---	Cuyuna North Range.	Minn., Crow Wing.	S	Alunitized black argillite in Rabbit Lake Formation of Precambrian X age in localities 16 km apart in Cuyuna North Range iron-ore district.	Schmidt, 1963				
Total						252.521	-----	1,413.6	-----

UTAH

MARYSVALE DISTRICT (PIUTE AND SEVIER COUNTIES)

"The Marysvale alunite region embraces parts of the Tushar Mountains, the Antelope Range, the Sevier River Valley, and the Sevier Plateau in the High Plateaus of southwest-central Utah" (Callaghan, 1938, p. 91). Alunite was first recognized in the Marysvale area (fig. 1, loc. 1) in 1910, and attempts to develop it as a commercial resource were described briefly by Butler and Gale (1912), Loughlin (1916), Phalen (1917, p. 110-113), and Callaghan (1938). High-grade veins on Alunite Ridge were worked first as a source of potassium sulfate, and the first shipments of this product were made in September 1915. The impure aluminous residue was recognized as a potential source of aluminum, but no market or process to treat it economically was available. Operations were suspended in 1920 following World War I, except for desultory small-scale mining of vein alunite for direct-application potash fertilizer. At about this time, replacement bodies of alunite were recognized north and east of Marysvale in Piute County and adjoining Sevier County. Although lower grade than the veins on Alunite Ridge, the replacement bodies contained a much larger reserve, and their potential use as an ore of aluminum yielding a potassium sulfate byproduct called for their reassessment (Callaghan, 1938). Immediately prior to the entry of the United States into World War II, the U.S. Bureau of Mines (Thoenen, 1941) published a comprehensive summary of all domestic alunite resources that emphasized those at Marysvale. By then the interest in alunite was as a possible alternative to imported bauxite that would yield potassium sulfate as a valuable byproduct. The deposits at Marysvale were considered to be the most promising of all alunite resources in the United States known in 1941. Attempts at development of the Marysvale alunite deposits during World War II did not achieve an economic breakthrough, although significant technological advances were made (Fleischer, 1944). Callaghan (1973) incorporated information obtained during and since World War II in his excellent summary of information on the Marysvale alunite resources.

Estimates of reserves and potential resources in vein deposits and in replacement deposits in the Marysvale district are given in tables 2 and 3, respectively.

Although more information has been published about the Marysvale district than about any other alunite district in the United States, the resource

TABLE 2.—Reserves and resources of alunite in vein deposits, Marysvale district, Utah

Deposit name	Reserves ² (metric tons)	Weight percent alunite ²	Potential resources ³ (metric tons)	Weight percent alunite ³
Mineral Products-				
Bradburn ¹ -----	1,168,000	89.4	647,000	80
L & N -----	145,000	75	73,000	70
Sunshine-Christmas-				
Aetna (Edna) Peak ¹ -----	69,000	87	22,000	80
Total -----	1,382,000	88	742,000	79

¹ Properties described as a unit by Callaghan (1973, p. 67, 75.)

² Estimate from Thoenen (1941, p. 25). Callaghan (1973, p. 81) gave different tonnages (alunite content unspecified), but total is of the same order of magnitude as Thoenen's.

³ Estimate by author, arbitrary but conservative. None of the vein systems have been completely delimited by exploration. If alunitized wallrock were included, estimates of resources would be appreciably larger, but estimates of alunite content would be much lower.

TABLE 3.—Reserves and resources of alunite in replacement deposits, Marysvale district, Utah¹

Deposit	Reserves (10 ⁶ metric tons)	Weight percent alunite	Potential resources (10 ⁶ metric tons)	Weight percent alunite
Yellow Jacket ² -----	0.038	59	7.2	27
Close In -----	.38	52	--	--
Marysvale Peak -----	--	--	9	20
Aluminum Bar -----	--	--	4.4	30
Winkelman -----	2.88	40	--	--
White Hills ² -----	--	--	2.9	24
			1.9	16
Pittsburgh -----	--	--	5.7	15
Close In -----	1.985	42	--	--
White Horse -----	1.0	54	--	--
Manning Creek ² -----	--	--	.7	40
Big Star -----	.009	50	1.3	20
Marys Lamb -----	.76	33	--	--
J and L ² -----	.24	43	.05	25
Aluminum Queen -----	.04	45	--	--
Al Kee Mee -----	--	--	.1	40
Potash Butte -----	.03	50	--	--
Sunny Slope ² -----	--	--	.01	15
Total -----	7.362	43	33.26	23

¹ Distinction between "reserves" and "resources" is somewhat arbitrary. Estimates are from Thoenen (1941) except where otherwise indicated. Ore containing 30 percent alunite or less is classed here as a potential resource, although it was listed as a reserve by Thoenen (1941) or by Callaghan (1973). Some small bodies estimated to contain more than 30 percent alunite are placed in the potential-resources column because the ore is highly sodic or is believed to contain a high percentage of clay or other deleterious matter.

² Estimate from Callaghan (1973).

base here appears to be inadequate to support a major aluminum industry. More recently discovered deposits in Beaver County, 139 km west of Marysvale, show greater promise for commercial development.

SOUTHERN WAH WAH MOUNTAINS
(BEAVER AND IRON COUNTIES)

The discovery in 1970 of very large replacement deposits in altered volcanic rocks of the southern Wah Wah Mountains (fig. 1, loc. 2) in Beaver Coun-

ty, Utah, 87 km northwest of Cedar City and 54 km southwest of Milford, dramatically enhanced the possibility of eventually developing alunite as a domestic source of alumina and aluminum. This discovery is credited to Earth Sciences, Inc., of Golden, Colo. Since 1971, a consortium partnership (Alumet) comprising Earth Sciences, Inc., National Steel Company, Pittsburgh, Pa., and Southwire Company, Carrollton, Ga., has explored the deposits by extensive drilling and sampling and has operated a pilot plant in Golden, Colo., to develop an economically feasible process for treating the alunitic rock (Walker and Stevens, 1974; Parkinson, 1974; Thompson, 1976).

Table 4 summarizes the resources estimated to exist within areas for which applications for lease have been submitted to the U.S. Bureau of Land Management by the Alumet partnership. Some areas in Iron County to the south also are included. The figures are largely inferred by the author, influenced by data published by Earth Sciences, Inc. (Walker and Stevens, 1974; Parkinson, 1974; Earth Sciences, Inc., 1976), and supplemented by X-ray and chemical analyses of samples taken by the author.

TABLE 4.—Reserves and resources of alunite in replacement deposits in southern Wah Wah Mountains district, Utah¹

[NG, SX, and PV areas are shown as loc. 2 on figure 1]

Deposit	Reserves (10 ⁶ metric tons)	Weight percent alunite	Potential resources (10 ⁶ metric tons)	Weight percent alunite
NG, Subarea C -----	118	35	45	30
NG, Subarea A -----	27	32	45	29
NG, Subarea B -----	23	32	122	29
NG, Subarea D -----	18	31	122	29
SX ² -----	14	30	14	27
PV ² -----	32	28	54	24
Total -----	232	33	402	28

¹ Earth Sciences, Inc. (1976, p. 5), published reserves as follows: 136 million metric tons proven plus probable, containing 38 percent alunite, in area NG, Subarea C, and an additional 500 million metric tons of "similar" grade in the combined measured-indicated-inferred categories for the other properties listed above. The numbers in table 3 are the author's estimates made by conservatively transferring parts of the company's published reserves into the potential-resources column, owing to a lack of confirming data available to the author. Reserve estimates are conservative; estimates of alunite content are more uncertain than estimates of tonnages.

² Part of the SX area and all of the PV area are in Iron County; also, PV may properly be considered as an outlier of the Needle Range rather than of the Wah Wah Mountains.

Specific data on sample analyses, tonnage calculations, and average grade are proprietary and not available for publication here. Accordingly, the figures in table 4 are preliminary, subject to revision as more information becomes available. The figures in table 4 suggest that total alunite resources in the southern Wah Wah Mountains are at least 13 times

greater than those in the Marysvale district. The consortium hopes eventually to erect a full-scale commercial plant in Beaver County, near the deposits; the plant is projected to have the capacity to produce 454,000 t/yr of cell-grade alumina, 227,000 t/yr of potassium sulfate fertilizer, and 408,000 t/yr of sulfuric acid. The acid may be used to acidulate phosphate rock transported by rail from southeast Idaho to make phosphate fertilizers (Walker and Stevens, 1974; Parkinson, 1974; Earth Sciences, Inc., 1976; Thompson, 1976). If the average content of alunite in the resources of the southern Wah Wah Mountains is 35 percent (Walker and Stevens, 1974), production at the above rates would require annual throughput of 3,901,000 t of raw ore, or monthly mine production of 326,000 t. The deposits can support this rate of production for at least 27 years.

DEPOSITS IN OTHER AREAS

Deposits of alunitic rock having small commercial potential have been reported to be elsewhere in Utah. Stringham (1963) described alunitized zones in altered volcanic rock near White Mountain in Beaver County. Small patches of alunitized rock also are present in the southern San Francisco Mountains, 22 km west of Milford, Beaver County (Stringham, 1964, 1967). Sheep Rock (fig. 1, loc. 3), located 8 km north of Beaver, comprises about 2×10^6 t of rock having an alunite content of 30 percent; the deposit is too small to be exploitable (Loughlin, 1916; Thoenen, 1941, p. 27). Highly siliceous sporadically alunitized volcanic rock is present along the crest of an east-trending ridge, summit altitude 2,654 m (8,708 ft), at Big Pinto Spring (fig. 1, loc. 4) in the Indian Peak Range, about 25 km west-southwest of the Earth Sciences, Inc., "NG" lease area. Although a lease application was submitted for this deposit (W. W. Walker, oral commun., 1977), which is in Beaver County adjoining the Iron County line, the author's samples indicate considerable kaolinite with sporadic relatively low-grade alunitization. A hill having a summit altitude of 1,861 m (6,107 ft), 2 km northwest of Modena, Iron County (fig. 1, loc. 5), is composed of silicified and alunitized tuff breccia; part of the breccia contains as much as 30 percent alunite, but the total resource here does not appear to be large enough to merit development. An alunite vein 8 m wide and 460 m long, associated with halloysite in hydrothermally altered andesitic flowrock, has been reported at Beauty Knoll (fig. 1, loc. 6) in Washington County; the reserve is estimated at 454,000 t of rock containing 80 percent

alunite (Crawford and Buranek, 1948), but this could not be confirmed by the author. Lovering and others (1949) described alunite as a local product of acid sulfate alteration associated with quartz, kaolinite, sericite, and other hypogene alteration minerals at the East Tintic mining district, Juab County. The alunite here is interesting as it relates to the zoning of alteration around ore deposits, but it has no commercial potential.

NEVADA

LINCOLN COUNTY

An area of approximately 18 km² in T. 7 S., R. 70 E. in the Clover Mountains (fig. 1, loc. 7), Lincoln County, contains altered Tertiary volcanic rocks that are locally alunitized; the deposits have not been well explored, partly because of poor accessibility. The content of alunite may be too low for the deposits to be considered ore. A better known alunite deposit is near Boyd rail siding (fig. 1, loc. 8) in Rainbow Canyon, 22 km south of Caliente (Callaghan, *in* Hewett and others, 1936, p. 145-146). Thoenen (1941, p. 19) reported reserves in two lenticular bodies, one of 43,000 t averaging 29.3 percent alunite, another of 289,000 t averaging 21.5 percent alunite. The Boyd deposit is too small and low grade to merit development.

CLARK COUNTY

The Railroad Pass alunite deposit (fig. 1, loc. 9) is 6.4 km west-northwest of Boulder City, Clark County, on the northeast side of U.S. Highway 93. Alunite-bearing altered volcanic rock here was investigated as a possible source of potassium sulfate in World War I (Phalen, 1917; Hewett and others, 1936) and of alumina in World War II (L. S. Gardner, unpub. data, 1944), but the reserve is too small and grade is too low to merit development as is shown in table 1.

ESMERALDA COUNTY

F. L. Ransome (1907, 1909) first recognized alunite associated with gold-bearing veins at Goldfield, Esmeralda County, but did not consider it to be a minable resource. Roger Ashley (written commun., 1974) has tentatively estimated a potential resource of 153×10^6 t of rock containing as much as 10 percent of alunite in the principal mined altered area east of the town of Goldfield (fig. 1, loc. 10; the symbol indicates the entire Goldfield district, which here includes not only the main mined area, but also the

"CTR" and "MTZ" lease applications of Earth Sciences, Inc., and its partners; see table 1 and description below). Although small local masses containing 20 percent alunite may be present within the main mined area at Goldfield, large uniform bodies of alunitized rock minable by open pit are not present.

Other areas 16 km south of Goldfield near the old Cuprite camp may be a little more promising, including the "CTR" lease applications (fig. 1, loc. 10). There are two areas of alunitized volcanic rock, one area about 1.5 km west of U.S. Highway 95, the second and larger area a like distance east of the highway. Patches of rock in the west area contain 30 percent alunite, but strong silicification and local zones containing dispersed native sulfur dilute the alunitized body. The east area is about 3 km north-south by 1.5 km east-west, more than twice as large as the west area, but, except for small local patches, the rock contains appreciably less alunite than the west area. Much of the rock has been completely silicified to what Russian geologists call "secondary quartzite." Microcrystalline quartz is the principal component; in many specimens it constitutes 90 percent of the whole rock. Opaline cristobalite is a common constituent in some places, and the alteration pattern may be more complex than shown by Abrams and others (1977, fig. 1A). Localized alunite-bearing zones are irregularly distributed within this area of intensively hydrothermally altered and silicified pyroclastics of Miocene age (Abrams and others, 1977; J. A. Crowley, written commun., 1977). Although the total resource of alunitized rock may be considerable, much of it is low grade, intermixed with microquartz and opaline cristobalite; the latter is an undesirable constituent. The author infers a potential resource of 100×10^6 t of rock containing 22 percent alunite in the combined east and west "CTR" areas, but more data are needed.

A similar area of hydrothermally altered partially alunitized volcanic rocks is 6.4 km west of Goldfield on the east flank of the Montezuma Range (fig. 1, loc. 10, "MTZ" lease application). Sampling by J. A. Crowley of the U.S.G.S. (written commun., 1977) indicates that average alunite content is well below 30 percent. Alunite distribution is spotty, and deleterious constituents such as clay, mica, and cristobalite are present in much of the rock. A potential resource of 60×10^6 t having an average alunite content of 20 percent is inferred by the author for the "MTZ" area, but this estimate, like that for the "CTR" area, is very tentative.

Alunitic rock has been reported to be in a poorly

accessible part of the Monte Cristo Range (fig. 1, loc. 11) in northern Esmeralda County (W. W. Walker, oral commun., 1974). Information on resource potential is not available.

The old Fish Lake Valley mercury-mining district in the extreme western corner of Esmeralda County, near Boundary Peak (fig. 1, loc. 12), contains "opalite" rock having a fairly high content of alunite in some places (Bailey and Phoenix, 1944, p. 66-75; J. A. Crowley, written commun., 1977). Opalite at the old B and B mine (fig. 1, loc. 12) is a very fine grained porcelaneous "opalitized" and alunitized welded rhyolite tuff, glaring white where exposed, although hand specimens may show a faint reddish or purplish mottling from iron oxide. Tiny flecks of red cinnabar are very sparse, and the average content of mercury must have been low because mining-retorting operations evidently were not very profitable (Bailey and Phoenix, 1944, p. 67). The highest Hg content of any specimen collected by the author was 28 parts per million. The vitric volcanic dust matrix has been replaced by very fine grained milky opaline cristobalite and alunite. Some tiny ash particles and crystal fragments have been partially replaced by very fine grained mosaics of alunite; kaolinite is an abundant constituent in some of the rock. Alunite is a major constituent locally, but the abundant opaline cristobalite would be detrimental to any caustic leach process used in the extraction of alumina. No estimate of alunite resources has been made.

MINERAL COUNTY

Thin veins of alunite are found at the old Gold Pen mine in the Bovard district, Mineral County (fig. 1, loc. 13), 53 km northeast of Hawthorne (Schrader, 1913) but are too small to constitute a resource, as are similar alunite deposits in the old Rawhide district (Thoenen, 1941, p. 19; Archbold, 1966, p. 30). Alunitized tuff and granite are reported to be in the Gabbs Valley Range (fig. 1, loc. 14), 16 km northwest of Luning (Miles Silberman, written commun., 1974; F. M. Byers, Jr., oral commun., 1976). Resources here could be large, but the alunite content appears to be less than 30 percent (J. A. Crowley, written commun., 1977).

Alunitized rhyolite tuff of Tertiary age is present on a southwest-facing slope about 4.4 km south-southwest of Corey Peak (fig. 1, loc. 15) and 16 km southwest of Hawthorne (Archbold, 1966, p. 30). The white powdery material exposed in an 18-m-long trench contains 60 percent alunite, but the altered

zone appears to be local and shallow, too small to justify development.

Locally alunitized Tertiary volcanic rock has been found in an 800-hectare tract in western Mineral County, about 0.4 km south of the Lyon County line and 3.2 km northeast of the California-Nevada State line (fig. 1, loc. 16; this location also includes adjoining alunitized ground in Lyon County, described below). Several samples taken in the area by the author and by J. A. Crowley (written commun., 1977) suggest that the rock contains too little alunite to be considered as a potential source of aluminum.

LYON COUNTY

Immediately north of the above-mentioned Mineral County tract is an adjoining hilly area of similar altered volcanic rocks in Lyon County, between the county line and the East Walker River, south and east of a sharp bend in the river called The Elbow (fig. 1, loc. 16). Alunitization is sporadic and generally low grade; thus, the resource potential cannot be considered great, although several samples containing 40 percent or more of alunite have been reported (J. A. Crowley, written commun., 1977). Some of the more strongly alunitized rock in this district forms a ridge at an altitude of 1,830 m (6,000 ft), in the north half of sec. 29, T. 7 N., R. 27 E. about 1.5 km northeast of the Flying M (or Ravenal) ranch. Parts of this body contain 30 percent or more of alunite and natroalunite, but natrojarosite and cristobalite also are common constituents, vitiating its resource potential. The author tentatively infers a potential resource in this district of 40×10^6 t of rock having an average alunite content of 20 percent.

HUMBOLDT COUNTY

Alunite veins in altered Tertiary volcanic rocks are found near Sulphur, Humboldt County (fig. 1, loc. 17), 91 km west of Winnemucca (Clark, 1918; L. S. Gardner, unpub. data, 1944). Although native sulfur had been mined intermittently since 1875, alunite was mined only briefly in 1917 when 450 t of vein alunite was shipped to California, presumably for direct-application potash fertilizer (Vanderburg, 1938, p. 44). Total reserve of alunite in veins is estimated by L. S. Gardner (unpub. data, 1944) to be 212,000 t. The wallrock is too weakly alunitized to constitute a significant resource.

Alunite also is an alteration mineral at the Cordero-McDermitt mercury district near the Oregon-Nevada State line but does not constitute a resource (E. E. Foord, oral commun., 1977).

DEPOSITS IN OTHER AREAS

Alunite is found at various other localities in Nevada: in Washoe County, it is an incidental alteration mineral at Steamboat Springs (Schoen, White, and Hemley, 1974) and is present in altered Tertiary rhyolite in the Pah Rah Range near the south end of Pyramid Lake (Charles Bauer, oral commun., 1974); in Storey County, alunite is in hydrothermally altered andesitic tuff and breccia at the Virginia City district (Whitebread, 1976, p. 14-20); in Nye County, it is at Chicken Hawk Hill, 35 km east of Goldfield (Thoenen, 1941, p. 16), and in bleached rhyolitic tuff 11 km east of Beatty (fig. 1, loc. 18). Alunitization east of Beatty may be extensive, but the alunite content probably is not more than 17 percent, and cristobalite also is abundant, at least locally. Knopf (1916, p. 68) mentioned "complete silicification and alunitization in belts hundreds of yards long and as much as 200 feet [60 m] wide." The presence of sporadic low-grade mercury mineralization in these intensely altered Tertiary rhyolitic tuffs and flows (Knopf, 1916; Bailey and Phoenix, 1944, p. 143) is reminiscent of the Fish Lake Valley district in western Esmeralda County.

Alunite deposits in Nevada are numerous and varied, but none appear to equal those in the southern Wah Wah Mountains of Beaver County, Utah. Nevertheless, southern Nevada may be considered second only to southwest Utah in alunite-resource potential.

ARIZONA

SANTA CRUZ COUNTY

The most promising deposit of alunite in Arizona is within a 970-hectare area covering the greater part of Red Mountain (fig. 1, loc. 19), 5 km south-southeast of Patagonia in Santa Cruz County. The summit (1,942 m) and upper slopes have been explored by means of shallow percussion drillholes to depths of 45 to 60 m (W. W. Walker, oral commun., 1975). Red Mountain also has been explored by means of much deeper diamond drillholes for porphyry-type copper mineralization which underlies the alunitized summit (Corn, 1975). The mountain is a complex assemblage of flows, tuffs, tuff-breccias, and intrusive porphyries of rhyolitic-latitic to andesitic composition and of early Tertiary (Paleocene?) age. The assemblage has been strongly hydrothermally altered in a zoned pattern (Corn,

1975). Alunitization is pervasive, and alunite content is claimed to be 30 percent in the explored upper part of the mountain mass (W. W. Walker, oral commun., 1976). However, random spot sampling by the author suggests that overall alunite content may be closer to 25 percent. Moreover, appreciable amounts of sericite, kaolinite, and pyrophyllite are present in much of the alunite-bearing rock; these phyllosilicates are undesirable in the alumina extraction process. Surficial sampling of the Red Mountain area by Crowley also did not confirm the 30-percent-alunite figure; he estimated about 20 percent alunite for the west slope, and a lower alunite content (10 percent?) in other parts of the mountain (J. A. Crowley, U.S.G.S, written commun., 1977). Corn said "alunite content seldom amounts to more than 10 to 15 percent of the altered rock" (Corn, 1975, p. 1442). Although there is uncertainty about the average alunite content, the tonnage of available alunite rock may be estimated conservatively at 200×10^6 t.

Alunitized rock adjacent to sulfide veins was reported long ago at the old 3-R copper mine and elsewhere in the Patagonia mining district south of Red Mountain (Schrader, 1913, 1915). An elongate zone of alunitic alteration about 5 km long and 1 km wide has been mapped by Simons (1974) in the Patagonia Mountains, but the zone contains much less alunite and the alteration is more heterogeneous than at Red Mountain.

An extensive area about 4 km northeast of Red Mountain on the northeast side of Harshaw Creek, encompassing Kunde Mountain, North Saddle Mountain, and Saddle Mountain, also contains zones of alunitic rock (W. W. Walker, oral commun., 1975). J. A. Crowley (written commun., 1977) considered Kunde Mountain to hold a prospective alunite orebody, but further exploration would be required to confirm this.

YUMA COUNTY

Alunite (or natroalunite) veins 1-25 cm wide are present as irregular stockworks in sheared altered dacite at Sugarloaf Peak (fig. 1, loc. 20) in Yuma County, 8 km west-southwest of Quartzsite (Heineman, 1935; Thoenen, 1941, p. 11; L. S. Gardner, unpub. data, 1942). The reserve in veins is estimated at 232,000 t averaging 55 percent alunite (Thoenen, 1941, p. 11). The veins alone are not minable, and the wallrock is sericitized rather than alunitized; therefore, the Sugarloaf Peak deposit is an unlikely alunite resource.

DEPOSITS IN OTHER AREAS

Tertiary rhyolite has been partially alunitized and kaolinized in a 130-hectare area, 16 km south of Wickenburg along the margins of the Hassayampa River Valley in Maricopa County (fig. 1, loc. 21); however, only a little kaolinite has been mined (Sheridan and Royse, 1970). This deposit evidently has little commercial potential.

Alunite is a minor accessory alteration mineral in porphyry copper deposits in Pima, Pinal, Greenlee, and Graham Counties, Ariz. At least part of the alunite in these deposits may be supergene. Although not itself an economic resource in this association, alunite may be significant as a "guide" mineral in porphyry-copper districts as well as in other metalliferous districts.

COLORADO

HINSDALE COUNTY

The most promising deposit of alunite so far recognized in Colorado is at Red Mountain (fig. 1, loc. 22) in Hinsdale County, 5 km south-southwest of Lake City. Red Mountain is a volcanic neck or vent composed of quartz latite of Miocene age (Steven and others, 1974); it has been strongly hydrothermally altered and alunitized above an altitude of 3,700 m (summit is at 3,909 m). Average alunite content is estimated by the author to be at least 30 percent, and a resource estimate of 250 million metric tons is conservative. A representative of Earth Sciences, Inc., has been quoted as stating that the Red Mountain deposit may hold two billion tons containing 35–40 percent alunite (Lyle, 1977); however, without confirming data, the author prefers to list his own more conservative figures in table 1. If alunite ever is mined commercially in Colorado, Red Mountain appears to be a likely site for development.

Quartz-alunite rock is reported as part of the alteration assemblage at the old Carson mining camp, 13 km south of Red Mountain, and in altered andesite at Slumgullion Gulch, 8 km east of Red Mountain (Larsen, 1913, p. 181); however, the rock at these localities has been more strongly kaolinized and sericitized than alunitized, except very locally. Similar deposits of alunite in quartz-rich alteration zones are reported at the head of the Middle Fork of the Piedra River near the Mineral County boundary (Larsen, 1913), but accessibility is poor in this rugged terrain, and little is known of the deposits here.

RIO GRANDE COUNTY

The Marble Mountain alunite deposit (fig. 1, loc. 23) in Rio Grande County occupies a broad ridge at an altitude of 3,600 m, 5 km north of the old Jasper mining camp. The deposit is a fine-grained mixture of quartz (63 percent) and alunite (37 percent) that has metasomatically replaced andesitic tuff and breccia of Tertiary (Oligocene?) age. The surface of the ridge is covered by coarse talus slabs of alunitized rock. Minor amounts of cristobalite and kaolinite also are present locally, and iron oxide imparts a light purplish tint to some of the rock. L. S. Gardner (unpub. data, 1943) estimated a total reserve of 5.2 million metric tons containing about 37 percent alunite. The grade at Marble Mountain is satisfactory, but the reserve is small.

Alunite occurs sporadically in local alteration zones associated with metalliferous veins in the Summitville district, southwestern Rio Grande County, 12 km west-southwest of Marble Mountain, but individual alunite bodies are small and scattered (Steven and Ratté, 1960, pl. 3).

CUSTER COUNTY

Alunite in the Rosita Hills (fig. 1, loc. 24), 10 km east-southeast of the twin towns of Westcliffe-Silver Cliff, was reported first by Whitman Cross (1891, 1896). The deposits are at Mount Robinson and Democrat Hill, volcanic vents about 2 km apart, through which rhyolitic tuff and ignimbrite were erupted, followed by hydrothermal fluids and solfataric gases that alunitized rock in and around the vents (Cross, 1896, p. 302, 314–319). L. S. Gardner (unpub. data, 1943) estimated that the two deposits together contained 2.7×10^6 t having an average alunite content of 15 percent, too small and low grade to be considered for development.

DOLORES COUNTY

Alunite at Calico Peak (fig. 1, loc. 25) in Dolores County, 5 km west-northwest of Rico, was reported first by Cross and Spencer (1900). The summit (altitude 3,666 m) and upper part of the mountain are covered with coarse talus blocks pigmented by iron oxide to variegated hues of yellow and red that give the peak its name. The peak is a volcanic plug composed of Tertiary latite porphyry (Pratt, McKnight, and DeHon, 1969; Serna-Isaza, 1971) that has been hydrothermally altered to a fine-grained aggregate of quartz, muscovite, kaolinite, and alunite, and sporadic minor pyrophyllite. Alunite-rich

parts of the mountain are small and localized. Thoenen (1941, p. 15) estimated a reserve of 5.4×10^6 t containing 17 percent alunite; L. S. Gardner (unpub. data, 1943) estimated a total reserve of about 2×10^6 t containing 17 percent alunite; in addition to Gardner's estimate, the author estimates a further "potential" resource of 9×10^6 t containing 15 percent alunite. The author's estimate and Gardner's reserve estimate are both shown in table 1 (loc. 25) under potential resources because Gardner's "reserve" is too low grade to be classed as a true reserve. Thoenen's estimate is not listed in table 1.

DEPOSITS IN OTHER AREAS

Alunite occurs sporadically in solfatarically and hydrothermally altered rhyolite around volcanic vents above Alum Creek (fig. 1, loc. 26), adjacent to the Rio Grande County boundary, 5 km northwest of Platoro in northern Conejos County (Calkin, 1967). A minable alunite body has not been proven, although the Alum Creek area has been investigated by several mining companies as a porphyry copper prospect.

Altered Tertiary volcanic rocks of the Red Mountains (Nos. 1, 2, and 3), 10 km north of Silverton, locally contain appreciable amounts of alunite (Cross, Howe, and Irving, 1907; Burbank and Luedke, 1964; Leedy, 1971). Most of the altered area is in southern Ouray County, but some of the area overlaps into adjoining northern San Juan County. Finely crystalline sodic alunite in local pockets and seams was reported at the old National Belle mine near the west base of Red Mountain No. 3 (Hurlburt, 1894). However, none of these deposits appear to represent a minable resource.

Alunite also is reported to be in several localities in Saguache County (Burbank, 1932; Eckel, 1961, p. 41-42; Ratté, 1964) and to be a minor accessory vein or wallrock alteration mineral at Cripple Creek in Teller County and at Red Cliff in Eagle County (Ratté, 1964, p. 157; Eckel, 1961, p. 41-42).

Although deposits of alunite-bearing rock are in Colorado, only the deposit at Red Mountain, 5 km south of Lake City in Hinsdale County, is known to have commercial potential. However, calderas of the San Juan Mountains are likely sites for additional exploration.

NEW MEXICO

GRANT COUNTY

Local secondary crusts of alunogen and halotrichite are present on "alum rock" in a 260-hectare

area encompassing the north slope of Alum Mountain and both sides of Alum Canyon (fig. 1, loc. 27) in Grant County, N. Mex., 56 km north of Silver City via New Mexico State Road 15 (Hayes, 1907). The alums are of mineralogical interest only, but the "alum rock" described by Hayes forms a large body, probably at least 90 million metric tons, consisting mainly of microquartz, sodic alunite, kaolinite, and minor iron oxide. Local zones contain 30 percent alunite and have quartz as the other major constituent, but elsewhere the rock composition is variable, and the kaolinite content is equal to or greater than the alunite content. Commercial potential of the deposit has not been evaluated.

Alunitized rhyodacitic flows, tuff, and breccia of probable Late Cretaceous age cover an area of roughly 200 hectares on Saddleback Mountain (fig. 1, loc. 28) at the northwest end of the old Steeple Rock mining district in western Grant County, adjacent to the Arizona boundary. Duncan, Ariz., the nearest population center, is 20 km south-southwest of the alunitized area. Commercial potential of this deposit also is undetermined, but alunite is a major constituent, 30 percent or more in much of the rock, and a potential resource of 60×10^6 is a conservative estimate. Saddleback Mountain may be the most promising among all the alunite deposits recognized to date in New Mexico.

SIERRA COUNTY

Alunitized Tertiary volcanic rock is reported in a several square-kilometer area at Juan Peak (fig. 1, loc. 29) in Sierra County, N. Mex., 10 km northwest of the small settlement of Monticello and 43 km northwest of Truth or Consequences (W. W. Walker, oral commun., 1977). Spot samples taken by the author at the summit and on the southern and eastern slopes of Juan Peak show that alunite-rich rock is restricted to the summit area. Alunite content ranges from about 10 to a little more than 30 percent; kaolinite (dickite?) and jarosite are locally abundant associates of the alunite. Accordingly, the Juan Peak deposit is not considered to be a favorable prospect, but data are insufficient for an adequate evaluation.

Alunite also is found in the Black Range Wilderness, northwestern Sierra County, as a minor alteration mineral in bleached Tertiary rhyolite that has been hydrothermally altered to a fine-grained mixture consisting mainly of kaolinite and cristobalite. The deposit, which is on the Continental Divide, is accessible by New Mexico State Road 59 and is approximately 95 km west-northwest of Truth or

Consequences. The material has been test-marketed as paper-filler clay and also as animal-litter clay, but no permanent operation ensued. Alunite content is generally low, averaging perhaps no more than 8 percent, but the deposit is significant as evidence of alunite in this part of the State (G. S. Austin, New Mexico Bur. Mines and Min. Resources, oral commun., 1975). One sample from the main clay pit, now idle, contained an estimated 35 percent of alunite, about 37 percent of cristobalite, and 28 percent of kaolinite. Even if the greater part of the deposit contained this amount of alunite, it would not be a satisfactory aluminum ore because of the high content of cristobalite and kaolinite.

LUNA COUNTY

Alunitized volcanic rock of Tertiary age is in a 15-hectare area of low rounded hills near the mouth of Rattlesnake Canyon (fig. 1, loc. 30) on the east flank of the Cooke Range, about 14 km northwest of Florida rail siding (W. W. Walker, oral commun., 1975). Sampling by the author indicated that the rock, which is a hydrothermally altered lithic tuff, is more kaolinized than alunitized; the deposit, therefore, cannot be considered as a promising commercial prospect. Judging by X-ray diffraction patterns, the kaolin mineral probably is dickite; very well ordered kaolinite or a mixture of kaolinite and dickite are alternative possibilities. A small amount of jarosite accompanies the alunite locally.

DEPOSITS IN OTHER AREAS

Abundant alunite associated with halloysite is reported as being in lower Tertiary volcanic wallrock adjacent to gold-bearing veins in the Cochiti-Bland district near the southeast margin of the Jemez Mountains in eastern Sandoval County (Bundy, 1958, p. 39). Alunite, cristobalite, and lesser kaolinite and quartz were identified by the author in an X-ray powder diffraction pattern of a sample of altered rhyolite of Quaternary (Pleistocene?) age, 200 m south of Sulphur Hot Springs near the western margin of Valles caldera, Jemez Mountains, north-eastern Sandoval County. The Jemez Mountains volcanic complex may contain several alunitic zones having dubious commercial potential.

Alunite veinlets are in altered granodiorite porphyry at the Santa Rita open-pit copper mine, Grant County (Kerr and others, 1950). Similar veins of alunite are reported in altered quartz monzonite porphyry at the Tyrone open-pit copper mine, southwest of Silver City (Kolessar, 1970, p. 131). Al-

though not a resource, the alunite in the porphyry copper deposits of Grant County may be significant as a "guide" mineral in porphyry-copper type mineralization, as previously mentioned for Arizona. The Red Mountain deposit near Patagonia in Santa Cruz, Ariz. (fig. 1, loc. 19), is a good example of this relationship. Also, it is interesting to note that the Morenci open-pit copper mine in Greenlee County, Ariz., can readily be seen from the alunite deposit on the summit of Saddleback Mountain (fig. 1, loc. 28) in Grant County, N. Mex., 30 km southeast of the Morenci mine.

WASHINGTON

Alunite is found in altered andesitic flows, tuff, and breccia of Tertiary age, 13 km east of Enumclaw, Wash. (fig. 1, loc. 31). The deposits are along the valley of the White River, which forms the boundary between King and Pierce Counties, and were explored during World War II by pitting, trenching, and drilling. Four discrete bodies were recognized, the largest estimated to contain 5.4×10^5 t; the total reserve is estimated at about 1.1×10^6 t (Thoenen, 1941, p. 35; Huntting, 1966; Livingston, 1971, p. 36). Thoenen (1941, p. 35) reported alunite contents ranging from 35 to 77 percent; however, Kelly, Strandberg, and Mueller (1956, p. 32) reported alunite contents ranging from 21.4 to 30 percent. Much clay and silica are said to accompany the alunite in the altered andesitic volcanic rocks. The Enumclaw deposits are not a likely resource.

CALIFORNIA

Known deposits of alunite in California are mainly of mineralogical or scientific interest and have small commercial potential. The deposits include alunite: (1) associated with pyrophyllite on a silica-capped hill at Tres Cerritos, 42 km southwest of Mariposa in Mariposa County (Turner, 1898); (2) as a minor accessory with andalusite in felsic meta-volcanic rocks of probable Permian or Mesozoic age, White Mountain, Mono County (Kerr, 1932; Crowder and Sheridan, 1972); (3) as an incidental accessory in kaolinite formed by hydrothermal alteration of Pliocene and Pleistocene volcanic rocks in Little Antelope Valley, Mono County (Cleveland, 1962); and (4) in altered volcanic rocks near the old gold-mining camp of Masonic, also in Mono County (J. A. Crowley, written commun., 1977). This locality is near the Nevada State line, about 6 km south-southwest of the Lyon-Mineral County deposits (fig. 1, loc. 16), described previously for Nevada.

Other deposits include alunite (5) in altered volcanic rocks at Trinity Peak near Glen Ellen, Sonoma County; (6) as thin white veins associated with an assortment of hypogene alteration minerals at the Geysers, Sonoma County (Vonsen, 1947); (7) at Sulphur Creek, Colusa County (California Div. Mines, 1950, p. 237); and (8) in veins in altered rock around the old Winkler mine at Middle Butte near Mojave, Kern County. Sampling by J. A. Crowley of U.S.G.S. (written commun., 1977) demonstrates that alunite is fairly widespread in the Middle Butte area; natroalunite is abundant in at least one locality. Some of Crowley's samples, presumably of vein matter, contain 98 percent alunite (J. A. Crowley, written commun., 1977). Alunite is also present (9) as a local minor constituent in altered rhyolitic volcanic rocks at Soledad Mountain, also in Kern County, 8 km east of Middle Butte (J. A. Crowley, written commun., 1977); (10) associated with cinnabar, opal, and other hypogene alteration minerals in the Coso geothermal area, southern Inyo County (Austin and Pringle, 1970); and (11) as an "almost ubiquitous" minor alteration mineral in volcanic rocks at Lassen Volcanic National Park, Shasta County (Anderson, 1935, p. 242). Probably other alunite deposits are in California. For the present, alunite resources in California can be classified only as speculative.

WYOMING

A curious 1-m-thick bed or lens of alunitic "claystone" is exposed along the bottom of a 9-m-deep bulldozed trench cut in a sequence, 100 m or more thick, of Tertiary terrestrial sediments (fig. 1, loc. 32), 20 km south-southeast of Rock Springs, Sweetwater County, Wyo. (Love and Blackmon, 1962). The thin white alunite-bearing layer or lens was discovered while holes were being drilled for natural gas near the base of Quaking Asp (Aspen) Mountain (E. R. Keller, oral commun., 1974). Origin of the alunite is enigmatic. The lens evidently has no great lateral extent and so appears to have negligible commercial potential (Clair Adams, oral commun., 1974). No other deposit of alunite has been reported in the State except minor solfatara and hot-spring deposits in Yellowstone National Park (Allen and Day, 1935; Raymahashay, 1968).

TEXAS

Several alunite deposits have been reported to be in Texas, but none are known to have commercial potential. Alunite is said to be present in "decomposed

trachyte" (Braun, 1921) in Wilson County (fig. 1, loc. 33), 48 km southeast of San Antonio. One sample supposedly typical of an 8-hectare area was reported to contain 93 percent alunite and 2.7 percent silica (Braun, 1921).

White natroalunite nodules are in a limonitic sandy matrix along the disconformable contact between the Woodbine Formation and overlying Eagle Ford Group, both of Late Cretaceous age. The nodules have been observed in outcrops and roadcuts in north-central Texas (fig. 1, loc. 34) from Fannin and Grayson Counties south of the Red River, through Tarrant and Denton Counties, to Johnson County southwest of Dallas, a total distance of 215 km (Stephenson, 1946, p. 1764; Ross and others, 1968, p. 1156). Although widespread geographically, the nodule layer is less than 30 cm thick through most of its extent and so does not represent an economically exploitable resource. The origin of the natroalunite nodules is uncertain but probably they are supergenic; they may have formed through the action of sulfuric acid derived from the oxidation of pyrite disseminated in clay or shale, in general accordance with the model suggested by Keller, Gentile, and Reesman (1967) to explain sodic alunite nodules in shale in Bates County, Mo.

Alunite is dispersed with opaline cristobalite, kaolinite, quartz, and iron oxide in hydrothermally altered Tertiary rhyolite-trachyte flows (fig. 1, loc. 35) at Medley, 27 km west of Ft. Davis, Jeff Davis County (Shurtz, 1951). Alunite content ranges from 0 to 30 percent (Shurtz, 1951, p. 62); the average alunite content is too low for the flows to be of commercial interest. Similar altered volcanic rocks in west Texas might be more promising.

DEPOSITS IN OTHER STATES

MINNESOTA

Alunite is reported to be in the Cuyuna North Range (fig. 1, loc. 36) in Crow Wing County, Minn., as a local constituent in black argillite of the Rabbit Lake Formation of Precambrian X age, in localities as far apart as 16 km (Schmidt, 1963, p. 27; oral commun., 1976). Information on the alunite content is inconclusive, and no estimate has been made of the potential resource. Origin is enigmatic, but the alunite may have been formed by sulfuric acid, derived from oxidation of pyrite disseminated in the argillite, locally converting the argillite to alunite (Schmidt, 1963, p. 27). It is unclear whether the oxidation of pyrite and resulting partial alunitization of argillite took place during or after the Pre-

cambrian Era. Alunite in the Cuyuna North Range presently is classified as a highly speculative resource, possibly deserving a closer look if alunitic rock becomes a proven economic source of aluminum in the United States.

ARKANSAS

Nodules, first thought to be a newly discovered variety of kaolin (Brackett and Williams, 1891) and later shown to be a mixture of halloysite and alunite (Foshag, 1926; Ross and Kerr, 1934, p. 138-139), are imbedded in clayey shale of Mississippian(?) age in Sneed's Creek, Newton County, Ark. Evidently the nodules are only of mineralogical interest.

KANSAS

Oblate spheroidal nodules of white alunite are in Graneros Shale (Lower and Upper Cretaceous) at two localities in Ellsworth County, and at one locality in Lincoln County, central Kansas (Hattin, 1965, p. 17). The nodules probably were formed as a diagenetic alteration of clay-shale beds that were attacked by ground water containing local concentrations of sulfuric acid produced by oxidation of fine-grained iron sulfide, which is widely disseminated in the Graneros Shale (Hattin, 1965, p. 63-64). These nodules have no commercial potential, judging from the brief published description.

MISSOURI

Small white nodules of sodic alunite associated with allophane are found locally in a 1- to 2-cm-thick seam parallel to bedding in Pennsylvanian-age shale in Bates County, Mo. (Keller, Gentile, and Reesman, 1967). These nodules are of no importance as a resource, but the mechanism postulated to explain their origin (Keller, Gentile, and Reesman, 1967) may be applicable (with modification) to similar deposits of nodular alunite in sedimentary rock observed elsewhere.

INDIANA

Very minor amounts of alunite are found in lenses of endellite (hydrated form of halloysite—material from this locality also has been called "indianaite") along the unconformable contact between sediments of the Chesterian Series (Mississippian) and the overlying Mansfield Formation (Pennsylvanian), at Gardner Mine Ridge, Lawrence County, Ind. (Callaghan, 1948). Photomicrographs show that the alunite is present in two modes: (1) as a finely crystalline matrix in which are dispersed

shardlike particles of halloysite (Callaghan's endellite); (2) as tiny veinlets filling cracks in porcelain-like "indianaite" (Ross and Kerr, 1934, pl. 29). The endellite deposits probably were formed by ground water bearing sulfuric acid derived from oxidation of pyrite disseminated in superjacent sandstone (Callaghan, 1948, p. 42; Keller and others, 1966, p. 118-119). The alunite is an incidental accessory in the endellite, both minerals seemingly formed by the same supergenic process; alunite is not a significant resource in these deposits.

SOUTH DAKOTA

Alunite is reported as an accessory gangue mineral in low-grade gold ore in a breccia zone in Tertiary rhyolite-trachyte porphyry at the Rattlesnake Jack prospect, 8 km southeast of Lead in Lawrence County, S. Dak. Origin of the alunite is unclear, but its close association with unoxidized pyrite suggests that it is probably hypogene (Grout and Schwartz, 1927). The alunite here apparently has no commercial potential.

PENNSYLVANIA

Traces of alunite are reported in white kaolinitic clay in the Tomstown Formation (Cambrian) near Mount Holly Springs, Cumberland County, Pa. This is not a significant alunite resource, but the presence of a small amount of alunite is cited as evidence that hydrothermal fluids may have played a role in genesis of the clay, which has been used as a paper filler and as raw material in making light-colored bricks and white cement (Hosterman, 1969).

ALASKA

Akun Island, part of the Aleutian volcanic archipelago, is the site of geologically recent solfataric activity that has altered andesitic effusive rocks in a 2-hectare area to sulfur-impregnated siliceous material containing numerous white 1- to 4-cm-wide veinlets filling fissures. A sample of the hypogene vein matter contained 69 percent alunite, 17 percent dickite, 7 percent chalcedony and quartz, 5 percent combined pyrite and limonite, and less than 1 percent apatite (Byers and Barth, 1953, p. 385). Although not itself a significant resource, this occurrence suggests that alunite probably is common in the Aleutian archipelago.

HAWAII

Natroalunite of enigmatic origin, first thought to be clay, was found in an area of basalt near the mid-

dle of the desert strip of Molokai, Hawaii, 5 km from the ocean. One small outcrop was found, as were numerous pieces of white chalky natroalunite scattered over a considerable area (Laudermilk, 1935). Further information is lacking, but this natroalunite evidently is not a significant resource. One might suppose that the volcanic environment of Hawaii would favor formation of numerous deposits of alunite or natroalunite, but no other has been reported.

PUERTO RICO

Large deposits of quartz-alunite rock and associated kaolinite, sericite, pyrophyllite, and other alteration minerals are on the Cerro La Tiza highland, 25 km southwest of San Juan, Puerto Rico. The deposits were formed by hydrothermal alteration of basaltic andesite of Late Cretaceous or early Eocene age (Hildebrand and Smith, 1959; Hildebrand, 1961). Cerro La Tiza is estimated to contain a reserve of 1.44×10^9 t of rock having an "average" composition of 35 percent quartz, 20 percent sodian alunite, 15 percent pyrophyllite, 15 percent kaolinite and halloysite, and 15 percent combined sericite, iron oxides, and miscellaneous minor constituents (Hildebrand and Smith, 1959, p. 23). Composition of the rock seems to vary sharply within short distances, and the deposits do not have the zoning characteristic of similar hydrothermally altered areas observed in other parts of the world (Hildebrand and Smith, 1959, p. 23). Cerro La Tiza is a large but submarginal resource, not economically exploitable by means of present technology.

SUMMARY OF UNITED STATES RESOURCE POSITION

Although data on many known deposits outside of Utah are too sketchy to serve as a base for reserve estimates, a total *potential* resource in the United States of at least 2 billion metric tons of alunite-bearing rock probably is conservative. Average alunite content in much of this rock is not well established, but probably ranges between 10 and 35 percent in most bodies. If 30 percent alunite (equivalent to 11 percent contained Al_2O_3) is accepted as the minimum average grade rock that may be processed economically by means of present technology, a reserve of 300 million metric tons of alunite ore may be conservatively estimated. Table 1 summarizes presently recognized alunite resources in the United States. An adequate base exists for a domestic alumina-from-alunite industry, providing that quartz-alunite rock containing at least 30 per-

cent alunite can be used to produce alumina at a cost competitive with that of alumina made from imported bauxite. Deposits in the southern Wah Wah Mountains are the most promising recognized so far.

FOREIGN RESOURCES

NORTH AMERICA

CANADA

Alunite-pyrophyllite deposits formed by hydrothermal alteration of dacitic tuff of Triassic to Jurassic age exist at Kyuquot Sound, northwest Vancouver Island, British Columbia, Canada (Clapp, 1915). One quartz-alunite body contains an estimated 600,000 t; a second body nearby is "much smaller" (Clapp, 1915, p. 76). The alunite is sodic, and alunite content ranges from 20 to 45 percent in the larger mass. One company proposed to mine the alunitic rock to make alum, but no operation followed. Adjacent pyrophyllitic zones were mined on a small scale for ceramic raw material and household cleansing powder (Clapp, 1915, p. 77-78).

A unique body of rock composed of fine granular quartz, specularitic hematite, and alunite in alternating thin bands is present at Hickey's Pond, southeastern Newfoundland (Howland, 1940). The specularite and alunite are presumed to have been formed contemporaneously along shear zones in Precambrian schist by a process not fully understood (Howland, 1940, p. 41). The rock is of particular scientific but not economic interest.

MEXICO

Alunite has been recognized as a constituent in hydrothermal kaolin deposits of Mexico since the mid-1940's (Knížek and Fetter, 1950, p. 203). A nationwide investigation of alunite resources was undertaken in the 1950's, although a preliminary study in Guanajuato was begun as early as 1934 (Yris Roviroso, 1964). Mexican alunite deposits are mainly disseminated replacements containing local veins in hydrothermally altered Tertiary volcanic rocks; some are replacements in limestone adjacent to volcanic pipes. Deposits are in widely separated parts of the country so that the total resource probably is great, but, so far, no individual deposit has been demonstrated unequivocally to have commercial potential. A process to extract alumina, aluminum sulfate, sulfuric acid, and potassium-ammonium sulfate fertilizer was developed on a laboratory scale at the University of Guanajuato

(Parkinson, 1971; Eng. and Mining Jour., 1972, 1975; Lopez, 1977); however, the plan to erect a full-scale plant at Salamanca, Guanajuato, to process alunitic rock from nearby deposits was suspended.

The Juventino Rosas district, 25 km northwest of Celaya, Guanajuato, holds a total reserve estimated at 110×10^6 t averaging 22.6 percent alunite (Yris Roviroso, 1964, p. 52–56). Guanajuato may be the most promising State in Mexico for alunite resources.

Hydrothermal replacements are found in folded argillaceous beds of the Aurora Limestone (Lower Cretaceous), 58 km northwest of Torreon, Durango. The deposits are believed to be related to intrusions of rhyolite porphyry. Alunite content is 50 percent or more in local zones, but the estimated reserve is only about 7×10^6 t; kaolinite, jarosite, gypsum, and other hypogene alteration minerals are said to be associated with the alunite (Yris Roviroso, 1964, p. 57–62).

Additional deposits of small or unknown potential are reported in the States of Chihuahua, Aguascalientes, Morelos, Michoacan, Hidalgo (Yris Roviroso, 1964, p. 41), and Puebla (Yris Roviroso, 1964, p. 65–70). Localized alunite-rich zones are in refractory kaolin deposits formed by volcanic pipes penetrating limestone in Hidalgo, Guerrero, and Zacatecas States (Keller and Hanson, 1968; Hanson, 1975, p. 85). Alunite is a minor alteration mineral accompanied by kaolinite, cristobalite, and traces of mercury near fumaroles in Sierra San Andres, 27 km north of Ciudad Hidalgo, Michoacan (Kesler, 1970; Hanson, 1975, p. 85). The volcanic terranes of Mexico are a favorable hunting ground for alunite.

SOUTH AMERICA

ARGENTINA

Deposits of "silicified" alunite were reported by Catalano and Fernández Segura (1953) and Bertello (1957) as being near the small Atlantic port of Camarones, Chubut Province, southern Argentina. These authors described in detail laboratory experiments intended to demonstrate feasibility of extracting aluminum sulfate (to be used in domestic water-supply treatment) from the alunitic rock, but they gave little information about the deposits other than that the alunite is present in crystals 5–9 μ m long dispersed in an opaline silica matrix (Catalano and Fernández Segura, 1953, p. 141). The reserve estimates range from hundreds of thousands to millions of metric tons within an area of 30,000 hectares (Bertello, 1957, p. 25). Single analyses given by Catalano and Fernández Segura (1953, p. 140)

and by Bertello (1957, p. 26) are of high-grade material, but whether their samples are typical of a large body is not known.

According to Dr. Edmundo G. Macchiaverna of Aluminio Argentino (written and oral commun., 1977), some deposits in the Camarones district contain 60 percent or more of alunite, but the available tonnage (20×10^6 t?) is not sufficient to support industrial development. The presence of kaolinite and cristobalite also is an unfavorable condition for any caustic leach process. Origin of the alunite at Camarones is unclear but the description of alunite "bochones" (boulders, nodules), ranging in length from 10 to 150 cm, in bentonitic tuffs of Paleocene age (Angelelli, Schalamuk, and Arrospide, 1976, p. 19) suggests that they are a supergenic product of acid ground water.

Alunite associated with dickite, the latter having been mined for industrial uses, is reported at Cerro Bayo, Argentine Andes, near the Chilean border (Angelelli and others, 1976). The deposit is said to be zoned; a 15-m-thick layer of nearly pure porcelainous alunite overlies the dickite-rich zone, formed by hydrothermal alteration of rhyolitic tuff. No firm information is given concerning reserves (Angelelli, Schalamuk, and Arrospide, 1976).

Alunite is reported as a hypogene alteration mineral at the Mi Vida copper deposit in Catamarca Province, northwestern Argentina (Koukharsky and Mirré, 1976). The alunite, accompanied by zunyite and quartz, is in an intensely altered Tertiary rhyolite breccia pipe above the copper orebody. The central alunite-bearing zone covers an area of about 2 km², and alunite is said to be present to a depth of 300 m below the surface (Koukharsky and Mirré, 1976, p. 856–858); therefore, a large body of alunitized rock is indicated, but no information is given on alunite content. The presence of this body suggests that the Argentine Andes may contain additional alunite resources. For example, alunite is reported to be associated with pyrite, chalcedony, and clay minerals at El Queva mine, Cerro Queva district, northwest Argentina (Sillitoe, 1973, p. 811).

BOLIVIA

Alunite is a minor accessory with sericite, quartz, kaolinite, pyrite, and other hypogene alteration minerals in dacite-quartz latite porphyry wallrock of silver-tin veins at the Potosí and Oruro mining districts, southwest Bolivia (Turneure, 1960, p. 252–253; Ahlfeld and Schneider-Scherbina, 1964, p. 130).

CHILE

The El Salvador porphyry-copper deposit in the Andes of northern Chile, 110 km inland from the port of Chañaral, is capped by an extensive zone of sericitic alteration containing local alunite-rich zones (Gustafson and Hunt, 1975, fig. 20B). The altered cap covers nearly 2 km² and extends to a depth of several hundred meters so that the total quantity of alunite contained within it probably is great. Speculative alunite resources may exist in the Chilean porphyry-copper belt; the association of alunite with native sulfur at Cerro Marquéz and Choquelimpie in northern Chile (Sillitoe, 1973, p. 811) lends support to this theory. Also, alunite is common in parts of some hydrothermal kaolin deposits in central Chile (Tabak, 1969).

PERU

Alunite exists with quartz, dickite, zunyite, pyrite, epidote, and zoisite in the intensely altered quartz monzonite porphyry wallrock adjacent to sulfide veins in the Cerro de Pasco mining district (Graton and Bowditch, 1936).

EUROPE

FRANCE

The alunite deposit at Mont-Dore in the Puy-de-Dôme region, Department of Haute Loire, 350 km south of Paris, France, was mined for raw materials to make alum during the early 19th century (Charrin, 1940, 1948). It consists of branching veins in altered trachyte tuff. The wallrock apparently is alunitized also (Charrin, 1940, p. 2), but presumably only the vein alunite was used to make alum at a plant in Clermont-Ferrand, 66 km by road northeast of Mont-Dore.

The deposit at Madriat, also in the Puy-de-Dôme region, is of a different character than that at Mont-Dore. According to Lacroix (1962, p. 141), ellipsoidal masses of alunite 2–3 m long and 1.5 m wide, having long axes vertical, are in a red-clay bed. The alunite, is “relatively homogeneous and pure” (Lacroix, 1962, p. 141), but mode of origin is not well understood. The material was used for alum manufacture for a time after 1876, but operations were abandoned in 1896 (Gautier, 1940). No reserve estimate is available, but at least some material in the Puy-de-Dôme region is high grade.

Other occurrences, presumably of mineralogical interest only, are reported at Chizeuil, Department of Saône-et-Loire in east-central France, at Saint

Jacut, Department of Morbihan, Brittany Peninsula, and near Realmont, Department of Tarn, southern France (Caillère and Maratos, 1958; Lacroix, 1962, p. 141–142).

SPAIN

An alunite deposit near Riaza in Segovia Province, Spain, recently was investigated to determine its potential for commercial development (Kühnel, Koster, and Roorda, 1975; R. A. Kühnel, written commun., 1975, 1976). The alunite and associated halloysite and kaolinite apparently are products of superegene attack on pyrite-bearing Silurian shale by acidic ground water resulting from oxidation of the pyrite (Kühnel and others, 1975). Information on size or alunite content of the reserve has not been released.

A deposit of a mineral called “galafatite” (but which apparently is either alunite or natroalunite) was reported near Benahadux, 10 km north of Almería (Preus, 1911). Few details were given; the white compact mineral is said to be in veins 5–6 m wide. It is not clear whether Preus’ “galafatite” is the same mineral as the “almeriite” studied by Hoyos de Castro and Alías (1963), which was proved to be identical with natroalunite. Alunitic clay and nodules of alunite are associated with deposits of native sulfur in dolomitic limestone of Triassic age in the Sierra de Gádor district, a few kilometers west of Benahadux (Williams, 1936). According to Williams (1936, p. 17), alunite is “widespread” in the district and has been mined to make potassium sulfate and alum.

Alunite is a gangue mineral in gold-bearing veins and also in the hydrothermally altered Tertiary volcanic wallrock at Rodalquilar, near the Mediterranean coast, 40 km east-northeast of Almería (Friedrich, 1960; Lodder, 1966). These occurrences are an unlikely alunite resource.

Alunite accompanied by kaolinite is near the summit of Teide Peak in Santa Cruz de Tenerife, Canary Islands (Hoyos de Castro and Mata, 1958). Some of the material is high grade, but no estimate of the available reserve is available.

ITALY

The famous Tolfa district in Italy, 14 km northeast of Civitavecchia and 55 km northwest of Rome is, perhaps, the longest known of the world’s alunite districts (De Launay, 1907, p. 679–686). Commencing in 1460 and for five centuries thereafter, the Tolfa alunite veins were a source of raw material for making aluminum sulfate and potash alum. The

enclosing volcanic rocks, which include ignimbrites and rhyolitic and quartz latitic lava domes of late Pliocene to early Pleistocene age, have been pervasively altered (Negretti, Lombardi, and Morbidelli, 1966; Lombardi, 1967; Lombardi and Sheppard, 1977); however, in general, the altered volcanic rocks are more strongly kaolinized than alunitized. De Launay (1907, p. 685) mentioned "quarries of kaolin in the midst of quarries of alunite." The "Providenza" alunite vein, which supplied virtually all the alunite used for making alum after 1874, is said to have been 10 m wide in places, but it was not mined where less than 80 cm wide (De Launay, 1907, p. 682). According to Lombardi, Mattias, and Uras (1977, p. 18), "Alunite was exploited in the area until very recent times. From 1462 to 1798 some 800 workers digged [sic], processed and transported to Civitavecchia the alum produced from alunite, and this industry has been one of the most important revenues of the Papal State for many centuries. A total of over 18 million tons of alunite has been extracted from this area. Only a few hundred thousand tons of probable ore is left."

The alunite at Tolfa is of supergene origin, according to Lombardi and his coworkers (Field and Lombardi, 1972; Lombardi and Sheppard, 1977), who base their conclusion on the similarity of sulfur-isotope ratios in the alunite to the ratios in hypogene pyrite in the same area. Oxidation of primary pyrite is believed by them to have generated sulfuric-acid-charged water which reacted with the argillized host volcanic rocks to form alunite. Curiously, oxygen- and hydrogen-isotope analyses by Lombardi and Sheppard (1977) suggest that kaolinite and dickite, which also are alteration minerals in and around the alunite-bearing zones of Tolfa and Allumiere, were "formed in a meteoric-hydrothermal [sic] environment of acid hot spring type at about 80° C" (Lombardi and Sheppard, 1977, p. 147). The sulfur-isotope ratios as interpreted by Field and Lombardi (1972) are thought by them to support De Launay's (1907) original hypothesis of a supergene origin for the alunite. This is in contrast to the more generally accepted hypogene origin for most of the alunite in very similar altered volcanic terranes elsewhere in the world. Even in other parts of Italy, alunite and associated argillic alteration seem to have been produced by the action of hydrothermal fluids and therefore are hypogene according to the customary definition of that term. For example, halloysite and minor alunite at Gradoli and Piano del Pazzo, some 54 km north of Tolfa, and near Civitacastellana, 55 km northeast of Tolfa,

are said to be products of hydrothermal alteration (Lombardi, Mattias, and Uras, 1977, p. 32-42).

Alunite associated with kaolin clays, cristobalite, and other alteration minerals in Pleistocene and possibly Holocene pyroclastic rocks is reported to be (1) in the Phlaegrean Fields volcanic complex between Naples and Pozzuoli, (2) on the island of Ischia 30 km southwest of Naples, and (3) on the west side of the island of Lipari, 35 km north of the Sicilian coast. Some of these materials have been used in past centuries for the manufacture of alum (Gianni Lombardi, written commun., 1977). Kaolinization rather than alunite seems to have been the dominant alteration process in parts of Tuscany, 75-150 km northwest of the Tolfa deposits, but alunite is a locally abundant constituent near Volterra, Campiglia Marittima, Montioni Vecchio, and Torniella, and on Monte Argentario peninsula and the island of Giglio, 20 km west of Monte Argentario. Some of these deposits formerly were a minor source of raw material for making alum, but modern exploitation, apparently sporadic, has been for kaolin, not alunite (Gianni Lombardi, written commun., 1977). Alunite is a minor alteration mineral in kaolin deposits on the island of Sardinia (Moretti and Pieruccini, 1969, p. 205; Lombardi, Mattias, and Uras, 1977, p. 3-10).

According to Gianni Lombardi (written commun., 1976), preliminary research has been undertaken to determine the feasibility of using Italian alunite deposits as a source of alumina and fertilizer products; however, commercial development seems unlikely at any time in the foreseeable future.

GREECE

Alunite deposits on the island of Milos, Greece, are reported to be under investigation for possible future commercial development, but details are unavailable (U.S. State Dept., unpub. data, 1976).

Alunite nodules 10-20 cm across are present along the unconformable contact between altered Permian phyllite and overlying Mesozoic limestone and dolomite, near Khania on the island of Crete (Caillère and Maratos, 1958). The nodules are of supergenic origin and of mineralogical interest only.

Alunite is a minor accessory in gray boehmitic pisolitic bauxite formed on Lower Cretaceous limestone in the Kiona Mountains of central Greece (Bárdossy and Mack, 1967, p. 342). Oxidation of diagenetic pyrite in local parts of the bauxite generated the sulfuric acid which reacted with aluminous minerals to form the alunite (Bárdossy and

Mack, 1967, p. 347). This alunite also is of mineralogical but not commercial interest.

CZECHOSLOVAKIA

Solfataric alteration of andesitic effusive rocks near Viglasska Huta in western Slovakia, Czechoslovakia, has formed zones containing alunite, opal, kaolinite, anhydrite, and pyrite (Kuthan, 1956). Alunite in what are called "hydroquartzites," formed by solfataric alteration of volcanic rocks near Dekys, central Slovakia, is reported by Forgáč (1972). Information on resources is not given by either author.

HUNGARY

Nodules of alunite, or more commonly natroalunite, are found in bauxites of the Bakony-Vértes belt, Hungary, north of Lake Balaton (Vadász, 1943; Gedeon, 1947; Bárdossy, 1959). Apparently the nodules are supergenic, formed by downward-percolating sulfuric-acid-charged ground water reacting with near-surface bauxite or clay (Bárdossy, 1959, p. 42-43). The acid was derived from oxidation of pyrite disseminated in superjacent rock. The nodules do not constitute a minable resource.

RUMANIA

Rădulescu and Dimitrescu (1966, p. 21) listed four deposits of alunite in Rumania but gave no information on resource potential or other details.

BULGARIA

Quartz-alunite zones are in hydrothermally altered andesitic volcanic rocks of the Panagjurishte district, Bulgaria, 73 km east-southeast of Sofia, and also in the Breznik district, 35 km west-northwest of Sofia (Radonova and Velinov, 1970). Alunite content is said to range from 5 to 80 percent at depths ranging from 10 to 200 m, but no estimate of resources is given.

UNION OF SOVIET SOCIALIST REPUBLICS

Probably the U.S.S.R. has greater alunite resources than any other country in the world because it is so vast and because it contains extensive regions of ancient volcanism where hydrothermal and solfataric processes have altered feldspathic rocks of diverse types and ages to form alunite and associated minerals. The comprehensive treatise on alunite by M. A. Kashkai (1970), besides being an excellent general reference, also contains the best available summary of Russian alunite resources.

(Unfortunately this work is not available in English translation.)

AZERBAIJAN

The only alunite deposit in the world presently mined as a commercial source of alumina is at Zaglik, a few kilometers northwest of Dashkesan, Azerbaijan. A plant to extract alumina, potassium sulfate, and sulfuric acid from the alunite ore is at Kirovabad, 30 km northeast of Dashkesan. A reduction plant making metallic aluminum from the Kirovabad alumina is at Sumgait on the west shore of the Caspian Sea near the great Baku petroleum center, 300 km east of Kirovabad.

Altered tuffaceous rocks of Late Jurassic age locally contain as much as 50 percent of alunite, although the average alunite content of feed to the Kirovabad plant probably is lower than that. Microquartz is the main gangue mineral; varying amounts of iron and titanium oxides, and minor clay, mica, and other alteration minerals are also present. According to Sokoloff (1964, p. 769), 6.6 t of ore yield 1 t of Al_2O_3 , 0.5 t K_2SO_4 , and 1.15 t of H_2SO_4 (gravity unspecified). These figures suggest an alunite content of at least 40 percent; however, it is not known whether ore mined since Sokoloff's report is of the same grade. Kashkai (1970, v. 1, p. 364-365) gave analyses of 22 samples from Zaglik; 19 contained 40 percent or more of alunite. The average K:Na ratio is about 2.6:1, and the average Fe_2O_3 content is about 4.4 percent, calculated from Kashkai's data. Anderson (1936, p. 340) reported the Zaglik reserve to be 100 million metric tons containing 50 percent alunite, but this estimate probably has been revised since commencement of large-scale mining in 1966.

KAZAKHSTAN

Alunite exists in significant amount in nine districts of Kazakhstan (Kashkai, 1970, v. 1, p. 306-311; v. 2, p. 12-29). One area 150 km southeast of Karkaralinsk, east-central Kazakhstan, contains a reserve estimated at 150 to 200 million metric tons of rock containing at least 30 percent alunite (Markov, 1939). Volcanic rock, mostly of Paleozoic age, has been hydrothermally altered to quartz-alunite mixture associated with a characteristic suite of alteration minerals including kaolinite, dickite, sericite, pyrophyllite, diaspore, pyrite, hematite, and rutile. Tourmaline, andalusite, corundum, topaz, and zunyite are local minor accessories in some deposits (Kashkai, 1970, v. 1, p. 306-311). Microcrystalline quartz is such a dominant constituent in metasoma-

tically altered rocks like those in Kazakhstan that Russian geologists call them "secondary quartzites" (see for example, Naboko, 1958, 1963; Kirova, 1959; Kerimov, 1959; Kashkai, 1961, 1970, v. 1; Rusinov, 1966). Few American geologists apply the term "quartzite" to rocks other than orthoquartzites, ancient sandstones subsequently cemented with silica. The "secondary" quartzites are deutero-genic, formed from alkalic volcanic rocks by the attack of strongly acidic hydrothermal fluids.

UKRAINE

Alunite deposits in the Ukraine apparently have small commercial potential but are of special geologic interest. Flows and tuffs of late Tertiary (Neogene) age in the Beregovo-Bergansk district near the Hungary boundary have been metasomatically altered to quartz-alunite rocks containing opal, clay minerals, sericite, pyrite, and minor base-metal sulfides (Kashkai, 1970, v. 1, p. 304-305, 387-392). Of presumed supergenic origin are alunite-jarosite veinlets in Oligocene claystone on the southern flank of the Ukraine massif; alunite in Paleozoic sedimentary rocks near Krivoi Rog in south-central Ukraine; alunite in bauxitic clay in the Donbas basin (Kashkai, 1970, v. 1, p. 304-305, 392-396). Similarly, supergenic alunite veinlets are in bauxite formed on schist of Archean age near Nikopol, southern Ukraine (Kashkai, 1970, v. 1, p. 306-307, 396). Those veinlets are examples of alunite formed by weathering rather than by hydrothermal processes, and they are not a promising resource.

ARMENIA

Near Martuni, on the south shore of Lake Sevan, volcanic rocks of Oligocene age are altered zonally and have quartz-alunite cores grading outward into quartz-sericite rock. The Aragatz volcano in northwest Armenia near the Turkish frontier has local alunitized zones in altered dacite-liparite flows (Kashkai, 1970, v. 1, p. 302-305, 378-381). No assessment of potential resources is available.

GEORGIA

Near Madneulsk, southern Georgia, alunite is associated with quartz, opal, chalcedony, kaolinite, and sericite in altered andesite porphyry and albitophyre of Late Cretaceous age. Similar deposits are reported near Adzhariya (Kashkai, 1970, v. 1, p. 304-305, 381-386). Resource data are unavailable.

URAL MOUNTAINS REGION

The central Ural region from Krasnovishersk

southward to Chusovoy and Perm, and southeasterly to Sverdlovsk, contains alunite deposits of diverse origins in widely differing types and ages of host rock. Judging from the descriptions given by Kashkai (1970, v. 1, p. 306-307, v. 2, p. 7-12), few of these deposits are likely to be commercially promising.

ALTAI

Postmagmatic-postvolcanic alteration of Devonian-age porphyry and associated volcanic rocks has formed alunite rock near Zmeinogorsk and Ust Kamengorsk in southern Altai, adjoining northeast Kazakhstan (Kashkai, 1970, v. 1, p. 312-313, v. 2, p. 29-32; Kirova, 1959). Whether these deposits have economic potential is unclear.

UZBEK

The mountainous volcanic region of southeastern Uzbek contains alunite deposits of hydrothermal origin formed in volcanic rocks of Paleozoic age. One of the deposits shows a well-defined zoning, but their resource potential was not discussed by Kashkai (1970, v. 2, p. 41-42).

KURIL ISLANDS - KAMCHATKA

The Kamchatka peninsula and Kuril archipelago contain numerous deposits of alunite in Quaternary and upper Tertiary basaltic and andesitic volcanic rocks. Solfataras and hydrothermal alteration processes are still active in many localities. Even if some alunitized bodies were proven large and rich enough to be potentially minable, their development in this remote ocean-bounded region seems unlikely. Summary descriptions of some deposits were given by Naboko (1963), Rusinov (1966), Zotov (1967), and Kashkai (1970).

DEPOSITS IN OTHER REGIONS

Alunitized rocks are found in other regions of the U.S.S.R., including Turkmen, Tadzhik, and Kirgiz north of Afghanistan, the Sikhote Alin cordillera north of Vladivostok, and the Amur and Khabarovsk regions adjoining Manchuria (Kashkai, 1970). Most of these alunitized rocks are volcanogenic, but information on resource potential is not available.

ASIA

PEOPLES REPUBLIC OF CHINA

Deposits of alunite in the Pinyang-Fanshan district near the coast in the southeast corner of Che-

kiang Province, Peoples Republic of China, 450 km south-southwest of Shanghai, have yielded a "great quantity" of alum during a period of more than 200 years (Yih, 1931). The alunitic rock was produced by hydrothermal and solfataric alteration of a thick sequence of rhyolite tuffs and flows of probable Cretaceous age that were intruded by a hypabyssal quartz-monzonite stock (Yih, 1931, p. 3). Original rock textures are preserved in spite of the strong alteration, and the rock consists mainly of micro-quartz intergrown with fine shreddy alunite. A reserve of 2 billion metric tons containing an average of 50 percent alunite is inferred for the Fanshan district (Yih, 1931, p. 30). The Fanshan deposit may be one of the largest in the world.

Alunitic rock ("alumstone") also is present in Fukien Province, southwest of Fanshan, and in Anwei Province, northwest of Fanshan, but details are unavailable. Mainland China may have the largest resources of alunite in the Far East (Yih, 1931, p. 31). Ikonnikov (1975, p. 357) cited alunite resource estimates as follows: Chekiang Province, 1,021,000,000 t; Fukien, 750,000,000 t; Anwei, 13,000,000 t. Alunite content and other characteristics of the deposits are not given. Alunite is said to be found in 18 provinces (Ikonnikov, 1975, p. 366); however, the resource potential of most of these deposits is not known. Li and Hsieh (1946) and Kleinhans (1948, p. 3) presented reserve estimates of about 200 million metric tons for Chekiang Province, considerably more modest than the estimates given by Yih (1931) and Ikonnikov (1975). So far as known to this author, the Chinese deposits have been used solely as a source of alum (Yih, 1931, p. 29-30).

JAPAN

Several alunite deposits in Japan were described by Iwao (1949, 1953). A dozen or more deposits are scattered from Hokkaido to Shikoku, but the most important are on the island of Honshu. The Ugusu and Nishina deposits in Shizuoka Prefecture and the Fukuyama deposit in Hyogo Prefecture are three of the largest, but their total combined reserve is estimated to be only 43 million metric tons. Ugusu, the largest, is estimated to contain 30 million metric tons of rock having alunite contents ranging from 20 to 40 percent (Iwao, 1949). All these deposits were investigated prior to and during World War II as a possible source of alumina and potash fertilizer, and the Ugusu and Nishina deposits on the Izu peninsula supplied feed for a brief time to

alumina plants at Shimizu in Shizuoka Prefecture and at Niihama in Ehime Prefecture, and to a small experimental plant at Shikama in Hyogo Prefecture. Between 1935 and 1945, the Shikama plant produced 7,628 t of alumina from alunitic rock, and byproduct potassium and sodium sulfates. However, most of the alunite feed for the experimental plant came from southern Korea (Allen, 1947, p. 38-40, 72-75).

REPUBLIC OF KOREA

Gallagher and others² have said:

Alunite is known to occur in a dozen deposits in the southern part of Korea * * *. These deposits are altered zones in acidic tuffaceous rocks * * *. The altered zones consist of various mixtures of alunite, kaolinite, and quartz, accompanied in some places by diaspore, pyrophyllite, and a little pyrite. The material is distinctly nonuniform * * * showing wide variations in composition even within a few centimeters, so that mining and separation of monomineralic products offers difficulties.

Several deposits of alunitic rock were mined prior to and during World War II, while Korea was under the control of Japan. A strong effort was made then to develop a satisfactory method to extract alumina from the alunitic rock. At least 335,000 t of alunite "ore" was produced from South Korean deposits from 1917 through 1944, the last year for which figures were available (Gallagher and others²). Presumably all this material was shipped to Japan for processing. The small experimental alumina-from-alunite plant at Shikama, Hyogo Prefecture, Japan, received most of its raw material from Korea between 1935 and 1943 (Allen, 1947, p. 72-73). Probably most of the Korean alunite production was used for manufacture of potash alum, aluminum sulfate, and potassium sulfate fertilizer. The most promising deposits are in the Songsan area between Haenam on the east and Usuyong on the west, along the south coast of Cholla Namdo. Some of the altered rhyolitic volcanic rocks here contain kaolinite or pyrophyllite coextensive with or adjoining alunitic bodies.

DEMOCRATIC PEOPLES REPUBLIC OF KOREA

Alunite is reported to be in hydrothermally altered volcanic rocks in the Democratic Peoples Republic of Korea (North Korea). Locations are not given in the brief English abstract of the report by Kim and others (1971) available to the author. The alteration

² Gallagher, David, Klepper, M. R., Overstreet, W. C., and Sample, R. D., 1946, Mineral resources of southern Korea: Tokyo, General Headquarters, Supreme Command Allied Powers, Natural Resources Sec., unpub. mimeo. rept., pages not numbered.

apparently is zoned; quartz-rich rock grades into quartz-alunite, then into quartz-kaolinite rock (Kim and others, 1971). Information is lacking on available resources and the possibility of industrial utilization.

PAKISTAN

Alunite was mentioned as an incidental constituent in solfatarically altered andesitic agglomerate and lava with native sulfur deposits near the Miri crater of the great Koh-i-Sultan composite volcano, 37 km north of Nok Kundi, Baluchistan, northwest Pakistan (Ahmad, 1953). Large areas of extensively altered volcanic rocks and active solfataras exist here, but alunite resources can be classed only as speculative until more information is available. An area of hydrothermally altered alunitized volcanic rocks, 70 km northwest of Mashki Chah, has been under investigation for possible porphyry copper deposits (Schmidt, Clark, and Bernstein, 1975). Alunite is a major constituent of the altered rock in two localities, but the full extent of alunite is not known (R. Gordon Schmidt, written commun., 1977).

IRAN

Tentative plans have been announced to investigate and develop a "billion ton" deposit of alunite near Takestan, Iran, 150 km west-northwest of Tehran. Alunite content and other characteristics of the deposit were not reported (World Mining, 1977, p. 57).

MIDDLE EAST
SAUDI ARABIA

Alunite of enigmatic origin was reported to be in laterite at two localities in the As Sarat Mountains, Asir region, southwest Saudi Arabia, 590 km southeast of Jiddah (Overstreet, and others, 1977). The laterite blanket covers an area of 1,000 km², but the alunite appears to be very local fracture fillings in clay-ball conglomerate. The alunitic material is mixed with kaolinite, quartz, and iron oxide so that it is not a promising resource.

TURKEY

Three alunite deposits in "decomposed effusive rocks" of Turkey have been mentioned as possible sources of potassium sulfate fertilizer (Tolun, 1974, p. 287). They are:

- (1) Şaphane, Kütahya Province, 7×10^6 tons, 33 percent alunite.
- (2) Şebinkarahisar, Giresun Province, 30×10^6 tons, 22 percent alunite.
- (3) Foça, Izmir Province, small deposits, 36 (?) percent alunite.

Additional deposits of alunite with kaolinite, of probable hydrothermal origin, are in western Anatolia, but their economic potential is unknown (Seyhan, 1969).

ISRAEL

Alunite is an incidental constituent in hydrothermally kaolinized trachyte dikes of Late Jurassic age along the west base of Mt. Ardon, central Negev, Israel, 90 km south-southwest of Beer Sheva (Bentor, 1966, p. 23-28, 84).

Minor amounts of alunite of apparent supergenic origin are also found in bentonitic sediments of Early Cretaceous age in the Makhtesh Ramon district (Bentor, 1966, p. 37, 78) and in shale of the Paleocene Taquiya Formation in the Zin Valley, 55 km south of Beer Sheva (Bentor, 1966, p. 72). Thin seams and nodules of diagenetic sodic alunite are associated with flint clay beds of Jurassic age in the Makhtesh Ramon district (Goldbery, 1978). The known Israeli alunite deposits are not a significant resource judging from available information.

AFRICA

EGYPT

Natroalunite, quartz, and gypsum are minor constituents in kaolin clay on the Sinai Peninsula (Gad and Barrett, 1949). Specific location and details of the geology were not given by Gad and Barrett (1949). This deposit is not a likely alunite resource.

MOROCCO

Alunite is a minor accessory associated with halloysite in altered epiclastic-pyroclastic Tertiary sediments at Maazza, 7 km west of Melilla, north-eastern Morocco (Martin Vivaldi, 1963, p. 332-339). White and pink ellipsoidal nodules, 30 to 40 cm across, of porcelaneous natroalunite are present along a well-defined horizon in thinly laminated argillaceous schist of Late Silurian age near Tazzarine in southern Morocco, 350 km south of Rabat (Destombes and Lucas, 1956). The nodules apparently were formed by a supergene weathering process. Neither the Maazza deposit nor the Tazzarine deposit is a likely alunite resource.

Alunite is a minor accessory in pyrophyllitic rock, which also contains quartz, kaolinite, and zunyite, in the High Atlas Mountains south of Azrou, central Morocco (Dietrich, 1965, p. 105). This association is typical of hydrothermally altered volcanic terranes and suggests that this region might be favorable hunting ground for alunite deposits.

TANZANIA

Alunite was mentioned by Bassett (1954) as an incidental associate of pickeringite, jarosite, and other minerals at two widely separated localities in Tanzania. Apparently this alunite is of mineralogical interest only.

NIGER

Nodules and cauliflowerlike masses of alunite exist in 1- to 2-m-thick layers and lenses in several localities in southwest Niger and adjoining Mali, and also in southeast Niger, at the unconformity between pre-Tertiary rocks and overlying Tertiary continental sediments (Faure, Greigert, and Martinet, 1959). The alunite is thought to have been formed during the deep weathering that produced lateritic and bauxitic soils in the Eocene Epoch (Millot, 1970, p. 152, 273). Analyses given by Faure, Greigert, and Martinet (1959, p. 176) are of nearly pure alunite; however, the resource potential of these deposits probably is small.

AUSTRALIA

Alunite deposits have been recognized in Australia since the 1890's, and some were exploited as a source of potash alum and aluminum sulfate during the pre-World War I era. During World War I, alunite was used in Australia as a source of potassium sulfate fertilizer, following cutoff of potash salts from Germany. During World War II, some Australian alunite deposits were mined as a supplementary source of potash fertilizer, but also research was undertaken to develop alunite as a source of alumina for making aluminum. Since then, very large bauxite deposits have been discovered in Australia, and they now are mined on a large scale; accordingly, interest in Australian alunite has subsided.

SOUTH AUSTRALIA

An alunite deposit at Carrickalinga Head, a promontory in South Australia overlooking the sea 64 km south of Adelaide, was mined on a small scale during World War I, and 250 t of high-grade alunite were shipped to England to make alum. The alunite

is present as white nodules, 15–60 cm across, in black argillaceous rock described as "decomposed slate" (Australia Advisory Council, Sci. and Industry, 1917, p. 10). The nodules are nearly pure alunite, but the available reserve evidently is too small to support an economic operation. Details of the geology and mode or origin were not discussed by the Australia Advisory Council of Science and Industry (1917), but most nodular alunite in argillaceous sediment is believed to have been formed supergenically (see Keller, Gentile, and Reesman, 1967, for a logical mechanism that may with modification, be invoked to explain the formation of alunite or natroalunite nodules in a sedimentary environment).

Another deposit of alunite is 14 km southeast of Warnertown and 200 km north of Adelaide. It is described as a 1-m-wide "lode," having undetermined lateral and vertical extent, in "reddish decomposed slate" (Australia Advisory Council Sci. and Industry, 1917, p. 10–11, 26–27). The deposit was prospected prior to 1917, and a 50-t stockpile of alunite was produced. Although the material is high grade, the reserve is small.

Alunite deposits quite different from those mentioned above are at Pidinga, near the eastern edge of the great Nullarbor Plain, about 600 km northwest of Adelaide. The alunite is a constituent in kaolinitic clay beds deposited in shallow saline-lake basins (now dry) during the Tertiary Period (King, 1953). Sulfate ground water derived from oxidation of pyrite, disseminated both in interbedded lignite beds and in the granitic-gneiss upland from which ground water and surface water drain, is deemed to be the agent that diagenetically altered a part of the original kaolin fill to alunite. The necessary potassium is thought to have been adsorbed by the kaolin as it was formed by weathering of the feldspathic gneiss (King, 1953, p. 698–702). The well-alunitized parts of the Pidinga lagoonal fill are high grade, but the largest body was estimated by Armstrong (1950, p. 128) to contain only 211,400 t.

NEW SOUTH WALES

The alunite deposit at Bullahdelah, New South Wales, 95 km northeast of the port of Newcastle, was mined during the period 1891–1917 as raw material for potash alum and aluminum sulfate. Apparently operations were suspended at the end of World War I. The deposit consists of hydrothermally or solfatarically alunitized rhyolite flows interbedded in sedimentary rocks of Carboniferous and Permian age and occupies a 1.6-km-long reach of Alum Mountain, which rises 275 m above the surrounding

lowland (Pittman, 1901). Although the amount of high-grade alunitic rock may be less than was formerly believed, a large resource is apparent; however, no estimate has been made of tonnage. Published analyses suggest that even the lower grades of rock may contain 30 percent or more alunite (Australia Advisory Council Sci. and Industry, 1917, p. 25; Pittman, 1901).

WESTERN AUSTRALIA

During the 1920's, alunite was identified as a constituent in dark clay underlying Lake Campion, a shallow ephemeral lake near Chandler, Western Australia, 300 km east-northeast of Perth. The deposit was exploited during World War II as a source of potassium sulfate fertilizer (Fitzgerald, 1945). Alunite-rich sediment fills the lake to a depth of 6 m and can be mined by conventional loaders and scrapers. According to Fitzgerald (1945, p. 241-242), the sediment contains 60 percent alunite, the balance being mainly detrital quartz, mica, and a little iron oxide; the grade remains fairly constant throughout the entire deposit. Reserve has been estimated conservatively at 12 million metric tons (Fitzgerald, 1945). Origin is not well understood; possibly a mechanism similar to that postulated by King (1953) to explain the lacustrine alunite at Pidinga, South Australia, played a role in forming the alunitic sediment at Lake Campion. Mining was suspended following World War II; however, research continued for some time afterward in an effort to develop an economic method of extracting alumina from Lake Campion material (Bayliss, Ewers, and Miles, 1951).

Nodules and irregular "flatly inclined veins" of sodic alunite are in clayey sediment of unstated age in the Kanowna district, 25 km northeast of Kalgoorlie (Blatchford, 1919). Origin is unclear, but mode of occurrence suggests that the alunite is supergenic. Although widespread in this area, the nodules and veins are not a likely economic resource.

PACIFICA

NEW ZEALAND

Alunite is a minor alteration mineral in several hot-spring and fumarole areas and in hydrothermally altered volcanic rocks, but no deposit of potentially minable size and grade has been reported to be in New Zealand. Steiner (1953) described alunite at Wairakei, 10 km north of Taupo; Hutton (1947, p. 360-361) mentioned alunite in altered andesite-dacite near Thames, 70 km southeast of Auckland, and at Whangarei, 130 km northwest of Auckland.

SUMATRA

Sulfuric-acid-charged volcanic exhalations have locally altered rhyolitic tuffs at Lake Toba, northern Sumatra, to alunite-diaspore rock, which apparently is only of mineralogical interest (Leinz, 1933).

PHILIPPINES

Patches of alunite are reported to be in kaolin deposits formed by hydrothermal alteration of volcanic rocks at Batangas, southern Luzon, Philippine Islands (Comsti, 1969). The reserve, mainly kaolin, is estimated at 50×10^3 t (Comsti, 1969, p. 41); therefore, the quantity of alunite must be much less. However, hydrothermally altered volcanic terranes elsewhere in the Philippines also may contain alunite.

SUMMARY OF FOREIGN RESOURCE POSITION

Although alunitized volcanic rock exists in many countries, not all these countries are known to possess deposits of a size and grade that could support an alumina-from-alunite industry. Mexico has numerous deposits of alunitic rock (Yris Roviroso, 1964), and methods for its utilization have been tested on a laboratory scale (Lopez, 1977). On the South American continent, only the deposit near Camarones, Chubut Province, Argentina, has been proposed for development (Bertello, 1957; Catalano and Fernández Segura, 1953). However, large volumes of alunitized rock in the upper parts of porphyry-copper deposits in the Andes of Argentina and Chile (Koukharsky and Mirré, 1976; Sillitoe, 1973; Gustafson and Hunt, 1975) suggest that this part of the world may hold potentially exploitable alunite resources. Deposits in the Puy-de-Dôme district of France, although not mined for more than a hundred years, have been suggested as a potential source of aluminum as well as of potash and alum (Charrin, 1940). A deposit of apparent supergene origin in Segovia Province, Spain, is being considered for commercial development (R. A. Kühnel, oral commun., 1976; W. W. Walker, oral commun., 1977), and deposits in Italy also are receiving renewed attention (Gianni Lombardi, written commun., 1976). The alum industry, once the mainstay of alunite miners at Tolfa, has long declined in favor of the sulfuric acid treatment of high-grade bauxite or alumina. Sketchy reports from Iran (World Mining, 1977) and Greece (U.S. State Dept., unpub. data, 1976) indicate that deposits in those countries are being investigated for industrial development; details are not available. The U.S.S.R. has an alunite plant that has the capacity to produce 200,000 t of

alumina per year, but some question exists as to whether or not this operation would be competitive in an open world economy (Shabad, 1976). Assuming that this type of operation is economic or can be made so in the future, the U.S.S.R. has alunite resources to support an industry appreciably larger than the present one. The Peoples Republic of China also has adequate resources for an alunite industry, if the description by Yih (1931) of the Pinyang-Fanshan deposit in Chekiang Province is reasonably accurate. Deposits in Japan and the Republic of Korea are relatively small but were mined during World War II as emergency sources of aluminum and potash. Several nodular alunite deposits in argillic sediments, alunitic lacustrine sediments, and one hydrothermal volcanic deposit in Australia were worked intermittently from the late 19th century until the end of World War II; the material mined was used primarily for making alum and potassium sulfate fertilizer. Research on Australian alunite as a potential ore of aluminum was suspended after development of Australia's enormous bauxite deposits started in the 1950's.

Clearly world resources of alunitic rock are adequate to support industries based on this raw material; the question is not one of availability but of economics. Only when it is demonstrated that rock containing 30 percent alunite can be processed at a cost competitive with that of processing imported bauxite is it likely that alumina-from-alunite plants will be established. Conceivably, some bauxite-deficient countries might eventually establish such plants as a matter of national policy, in order to achieve some degree of self-sufficiency in alumina and aluminum supply.

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