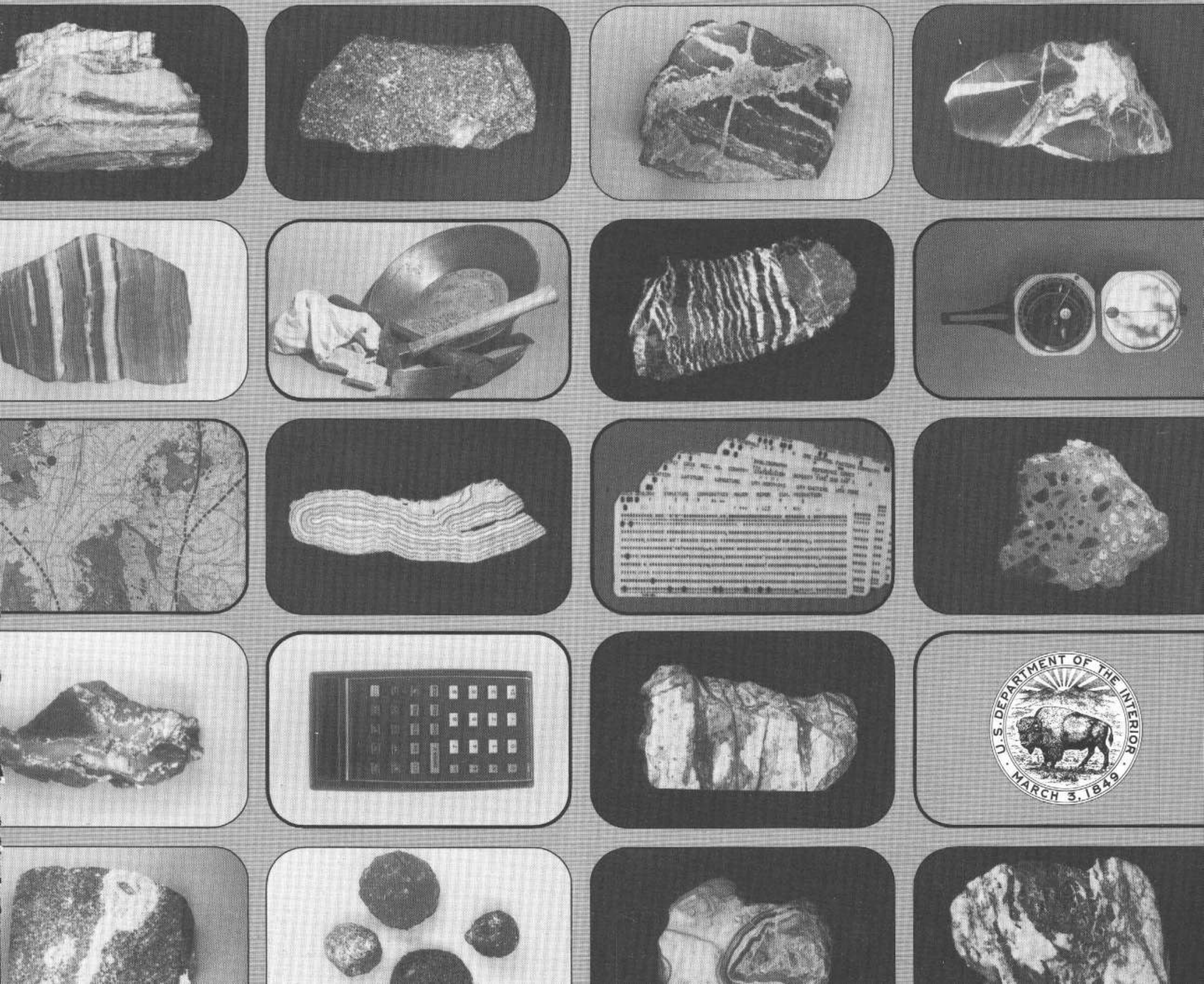
Geology and Resources of Base-Metal Vanadate Deposits

GEOLOGICAL SURVEY PROFESSIONAL PAPER 926-A



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Geology and Resources of Base-Metal Vanadate Deposits

By R. P. FISCHER

GEOLOGY AND RESOURCES OF VANADIUM DEPOSITS

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The general habits of base-metal vanadate deposits are described, the world distribution of these deposits is shown, and literature references are given

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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 estimates includes currently minable resources (*reserves*) as well as those resources not yet discovered or not presently 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 vanadium 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"
Professional Paper 933—"Geology and Resources of Fluorine in the United States"

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GEOLOGY AND RESOURCES OF BASE-METAL VANADATE DEPOSITS

By R. P. FISCHER

ABSTRACT

Almost all base-metal vanadate deposits occur in the oxidized zones of base-metal vein and replacement deposits. They consist of base-metal vanadate minerals and wulfenite, the molybdate of lead. These minerals replace the supergene base-metal minerals, form crusts on faces of open cavities, or are intergrown with residual clays in pockets. Vanadate deposits are largely restricted to tropical and temperate zones and regions of dry climate.

Three modes of origin for the vanadate deposits have been suggested: (1) supergene accumulation of vanadium and molybdenum from the sulfide minerals of the primary base-metal deposits; (2) ground-water leaching of vanadium and molybdenum from the country rock, especially shales, and precipitation of the oxidized base-metal minerals in the zone of oxidation; and (3) introduction of vanadium and molybdenum by hypogene solutions during and after oxidation of the primary sulfide deposits. Most students believe that the detected amounts of vanadium and molybdenum in the primary sulfides are inadequate to be the source of these metals in the vanadate deposits. And it seems unlikely that the phenomenon of late hypogene mineralization would occur widely enough to form all of the known vanadate deposits. Therefore, an origin by ground-water leaching of country rocks seems most likely.

The vanadate deposits have yielded about 35,000 short tons of vanadium, representing about 13 percent of the world's recorded production of vanadium. Future yields from these deposits probably will amount to only a small part of the world's vanadium supply.

INTRODUCTION

Base-metal vanadate deposits is a term commonly applied to occurrences of lead-, zinc-, and copper-vanadate minerals in the oxidized parts of base-metal deposits. These vanadate deposits have yielded a moderate amount of vanadium, they have attracted considerable mineralogic attention, and they present some interesting and puzzling genetic problems. This paper summarizes their geologic habits and distribution, discusses their genetic problems, and reviews their economic significance.

GEOLOGIC HABITS

The base-metal vanadate minerals are listed below; those that are generally not accepted because they are incompletely described or are regarded as unneeded synonyms are shown in italic.

Brackebuschite, $Pb_2(Mn,Fe)(VO_4)_2 \cdot H_2O$.
Calciovolborthite, $CaCuVO_4(OH)$ .... Same as tangeïte.
Chervetite, $Pb_2V_2O_7$.
Chileïte, $PbCu(V,As)O_4(OH)$ .... Impure mottramite.
Collieite, $(Pb,Ca)_5[(P,V)O_4]_3Cl$ .... Variety of pyromorphite.
Cuprodescloizite, $Pb(Cu,Zn)VO_4(OH)$ .... Synonym of mottramite.
Cuprovanadinite, $(Pb,Cu)_5(VO_4)_3Cl$ .... Variety of vanadinite.
Curienite, $Pb(UO_2)_2(VO_4)_2 \cdot 5H_2O$.
Dechenite, $PbZn(V,As)O_4(OH)$ .... Variety of descloizite.
Descloizite, $Pb(Zn,Cu)VO_4(OH)$.
Endlichite, $Pb_5[(V,As)O_4]_3Cl$ .... Variety of vanadinite.
Eosite, vanadate and molybdate of Pb.
Eusynchite .... Synonym of descloizite.
Francevillite, $(Ba,Pb)(UO_2)_2(VO_4)_2 \cdot 5H_2O$.
Heyite, $Pb_5Fe_2(VO_4)_2O_4$.
Mottramite, $Pb(Cu,Zn)VO_4(OH)$.
Mounanaite, $PbFe_2(VO_4)_2(OH)_2$.
Psittacinite .... Synonym of mottramite.
Pyrobelonite, $PbMnVO_4(OH)$.
Ramirite .... Synonym of cuprodescloizite.
Sengierite, $Cu(UO_2)_2(VO_4)_2 \cdot 8$ or $10\ H_2O$.
Tangeïte, $CaCuVO_4(OH)$ .... Same as calciovolborthite.
Turanite, $Cu_5(VO_4)_2(OH)_4$.
Uzbekite .... Probably identical with volborthite.
Vanadinite, $Pb_5(VO_4)_3Cl$.
Vanadite .... Synonym of descloizite.
Vesbine .... Probably identical with mottramite.
Vésigniéite, $Cu_3Ba(VO_4)_2(OH)_2$.
Volborthite, $Cu_3(VO_4)_2 \cdot 3H_2O$.
Wicklowite, vanadate of Pb.

Descloizite, mottramite, and vanadinite are the most common vanadium minerals in the vanadate deposits. Wulfenite, a molybdate of lead ($PbMoO_4$), is also common in vanadate deposits, and it has the same general habits as the vanadium minerals. Wulfenite may be even more commonly reported in oxidized base-metal deposits than are vanadate minerals, although wulfenite is not reported in the two most productive groups of vanadate deposits, those in the Otavi district, Namibia (formerly South-West Africa), and those at Broken Hill, Zambia (formerly Northern Rhodesia). Wulfenite was an ore mineral at the St. Anthony mine, Arizona (Creasey, 1950), and in some deposits in Mexico, Spain, Germany, Austria, and Yugoslavia (Newhouse, 1934, p. 216).

Where paragenetic relations have been reported, the vanadates and wulfenite are virtually the latest ore minerals. They commonly coat and partly replace the supergene base-metal minerals; in part they may also overlap or precede the last stage of supergene mineral formation (Creasey, 1950, p. 80; Taylor, 1954, p. 360). The vanadate minerals are later than wulfenite in the St. Anthony deposit, Arizona (Creasey, 1950, p. 80), and in the Los Lamentos deposit, Mexico (Foshag, 1934 p. 342). Once formed, the vanadates seem to be quite stable in the environment of the oxidized zone; these minerals persist from the surface to the bottom of the oxidized zone, and leaching and corrosion of them are rarely reported. In the Broken Hill district, Zambia, Taylor (1954) reported that the vanadate minerals extended to the depth of oxidation, as much as 1,150 feet (350 m), even though the water table was only 20 feet (6 m) below the surface when mining started in the district; and in the Otavi district, Namibia, Schwellnus (1946, p. 72) reported the occurrence of ore-grade accumulations of slightly abraded vanadate minerals in eluvium.

Vanadate deposits are restricted almost entirely to the oxidized parts of vein and replacement deposits that contain base-metal minerals; a few occurrences of vanadate minerals have been reported in rocks that contain sparse and disseminated base metals (Heyl and Bozion, 1962). The vanadate minerals mainly coat the surfaces of cavities and breccia fragments, partly filling the open spaces; they also may be mixed or intergrown with clay and other residual or supergene materials in leached cavities. They concentrate most abundantly along the edges of the oxidized base-metal bodies, and occasionally they accumulate in open ground nearby, but presumably only where supergene base-metal minerals have migrated. Characteristically, the vanadate minerals are irregularly distributed in any given deposit; they are richly concentrated in places and sparse to absent in other parts of the oxidized zone. Ore bodies, commonly with a high lead content, range in grade from about 1 percent V_2O_5 to as much as 10 percent; they vary greatly in size and shape. Only a few deposits have yielded enough vanadium-rich ore to justify special milling practices to make a vanadium concentrate, but a moderate number of deposits have yielded small tonnages of selectively mined ore, which has commonly been handpicked.

In the Otavi district, the copper-rich vanadate minerals, mottramite and cuprodescloizite, are reported (Schwellnus, 1946, p. 70) to be more abundant where the lead-zinc deposits are rich in copper than in the copper-lean lead-zinc deposits (where descloizite and vanadinite predominate). Schwellnus also noted a related observation of possible genetic significance, namely that vanadate minerals are not present in the Otavi district in oxidized copper deposits that are practically devoid of lead and zinc minerals. His suggestion that lead is essential for the formation of vanadate minerals may explain the absence or sparsity of vanadate minerals in oxidized copper deposits, such as those of the porphyry type.

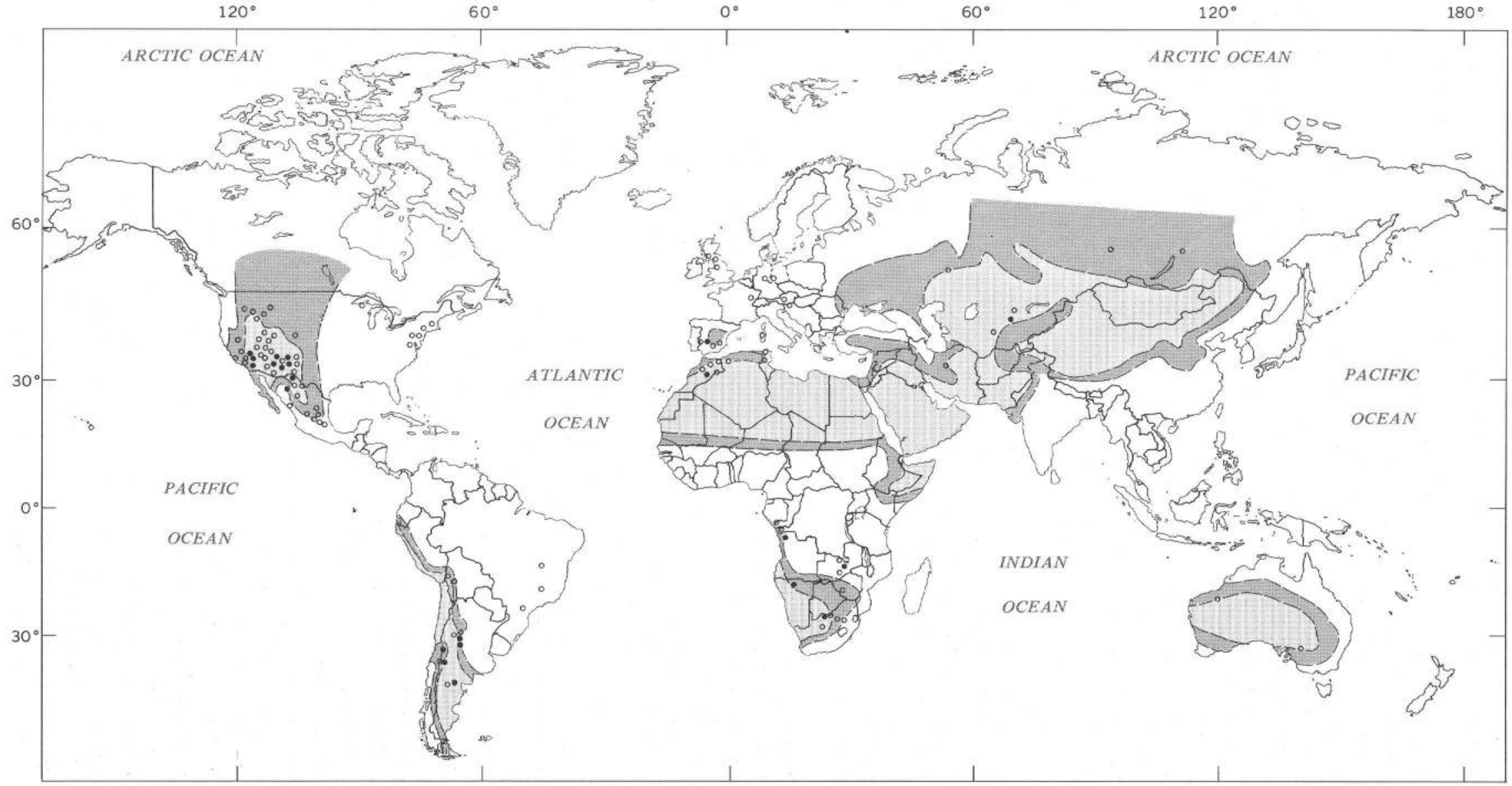
Country rocks for vanadate deposits and occurrences are varied in composition and origin; they include intrusive and extrusive igneous rocks, metavolcanic and metasedimentary rocks, and sedimentary rocks. The nature of the host rocks does not seem to be significant in the formation of vanadate deposits, although the more productive deposits are almost all in carbonate rocks.

Figure 1 shows the world distribution of vanadate deposits, including those reported as mere mineralogic occurrences, such as at Breckenridge, Colo. (Lovering, 1934), and in the Franklin area, New Jersey (Palache, 1935). It also shows the general regions of arid and semiarid climates. The deposits and occurrences shown represent all locatable ones found in a modest literature search, except in the southern parts of New Mexico, Arizona, Nevada, and California, where many more spots could have been added if the map scale had permitted. Undoubtedly other deposits and occurrences are reported in literature that was not studied, but those shown are thought to be representative of their total distribution for the following reasons: (1) the vanadate minerals are commonly on the walls of open spaces, (2) they are generally intensely colored and well crystallized, and (3) they are easily identifiable; thus they are conspicuous and sought for mineral collections. Although minor occurrences are reported far more abundantly in countries where mineral collecting is commonly practiced—United States and European countries—the frequency of minor occurrences in areas of a few major occurrences is probably as common in other parts of the world as in the southwestern United States. And the absence of reported occurrences probably means a true absence or sparsity of occurrences and deposits.

The high incidence of deposits and occurrences in tropical and temperate zones and in regions of arid and semiarid climates is clearly shown in figure 1. However, some deposits and occurrences, mostly minor, plot in areas where the present annual precipitation is moderate. Whether these occurrences originated under conditions of moderate precipitation or under earlier more arid climates is not evident from most published descriptions. At Broken Hill, Zambia, however, as noted earlier in this report, oxidation is deep but the present water table is shallow; the climate in the past was probably more arid than at present.

GENESIS AND GENETIC PROBLEMS

Vanadate deposits and occurrences are associated with the oxidized parts of base-metal deposits. The vanadate minerals, and wulfenite, where it accompanies the vanadates, are mainly later than the supergene base-metal minerals. These relations limit the possible modes of



EXPLANATION

- • Productive vanadate deposit
- ◦ Nonproductive vanadate deposit or occurrence

(light shading)	Less than 300 mm (11.8 in.) mean annual precipitation
(dark shading)	300–500 mm (11.8–19.6 in.) mean annual precipitation

FIGURE 1.—Distribution of vanadate deposits and regions of arid and semiarid climates.

origin to some extent, but within these restraints ideas differ as to the source of vanadium and its modes of transport and localization.

Stahl (1926) detected small amounts of vanadium in some samples of sulfides from the Otavi district, Namibia, and suggested that the vanadate ores formed by downward leaching of vanadium from sulfide bodies eroded from above the present surface. Moritz (1933) detected 0.001 to 0.01 percent vanadium in sulfide samples he collected from the same district and also concluded that the vanadium in the vanadate ores was leached from overlying parts of the sulfide deposits. Newhouse (1934) found 0.0X to 0.00X percent vanadium and traces of molybdenum in some samples of pyrite, galena, and sphalerite, some from localities not known to have vanadate deposits, and he concluded that much of the vanadium and molybdenum in the vanadate deposits probably was derived from the primary sulfide minerals.

Other students of the vanadate ores in the Otavi district (Clark, 1931; Schwellnus, 1946) and at Broken Hill, Zambia (Skerl, 1934; Taylor, 1954; Reeve, 1963), have concluded that the vanadium content of the primary sulfides is a quantitatively inadequate source of the vanadium in the vanadate deposits, and they have suggested that the vanadium in these deposits was derived from ground waters that leached it from the surrounding country rocks, especially from the argillaceous rocks. The vanadium was precipitated as base-metal vanadate minerals in the environment of the oxidized base-metal minerals. Schroll (1949) suggested the same origin for the vanadate and wulfenite occurrences in Austria.

The St. Anthony deposit, Arizona, has yielded 2,540,842 pounds (1,152,526 kg) V_2O_5 and 6,314,822 pounds (2,864,403 kg) of MoO_3 (Creasey, 1950, p. 67). Peterson (1938, p. 50) found no vanadium or molybdenum by chemical analyses of samples of base-metal sulfides. Creasey (1950, p. 81) carefully selected and analyzed spectrographically six samples each of galena and sphalerite and four samples each of pyrite, chalcopyrite, chlorite, and quartz-specularite. No molybdenum was found in any of the samples; a little vanadium was found in the gangue minerals; 0.001–0.0001 percent vanadium was found in the pyrite and chalcopyrite; 0.2 percent vanadium was found in one galena sample, but none was found in the other galena and sphalerite samples. On the basis of these analyses, neither Peterson nor Creasey could imagine deriving the vanadium and molybdenum from the primary sulfide and associated gangue minerals. Nor could they picture, on the basis of geologic history, the presence of any country rock in the vicinity of the deposit that might yield large quantities of vanadium and molybdenum, as was suggested in the preceding paragraph for the Otavi and Broken Hill deposits. For these reasons, both Peterson and Creasey suggested that the vanadium and molybdenum were introduced by hypogene solutions late in the history of the deposit—of "late Tertiary or Recent age" (Creasey, 1950, p. 81)—after oxidation of the primary sulfides. Heyl and Bozion (1962, p. A31) thought this hypothesis had merit for the St. Anthony deposit and perhaps warranted wider application.

The following factors are judged significant from the standpoint of genesis; some of these factors present puzzling genetic relations. The vanadate minerals and wulfenite are easily recognized and their distribution, geologically and geographically, is well established. They are virtually restricted to the oxidized parts of base-metal vein and replacement deposits; lead is a constituent part of almost all of these minerals, and its presence is probably essential in the formation of vanadate deposits. Where paragenetic relations have been defined, the vanadate minerals and wulfenite mainly formed after the supergene (oxidized) base-metal minerals formed; the vanadate minerals are later than wulfenite, and although they both occur almost exclusively in oxidized base-metal deposits, both are not present in all such deposits, and in any given deposit the vanadium minerals and wulfenite are not necessarily coextensive, at least not in concentrated amounts. The vanadate deposits are virtually restricted to the tropical or temperate zones and to regions of arid or semiarid climates. The source of the vanadium and molybdenum is obscure.

The crustal abundance of vanadium is on the order of 100–150 ppm (parts per million). Vanadium is one of the lithophile elements that occur mainly in silicate rocks, but it does not form an important part of any common rock-forming mineral. Among the igneous rocks, vanadium is most abundant (about 200 ppm) in the mafic ones, where it occurs in the insoluble 3-valent state and substitutes for iron and perhaps aluminum in iron and ferromagnesian minerals. In magmas it does not oxidize readily to the soluble 5-valent state, so not much vanadium is available for hydrothermal transport. Therefore, only a little vanadium (10–100 ppm) occurs in most hydrothermal ore deposits (Fischer, 1959, 1973), although many titanium-bearing vein deposits and some gold-quartz veins contain some vanadium, commonly about 1,000 ppm; in the gold deposits the vanadium is in roscoelite, which occurs as a gangue mineral. Although gold accompanies some of the base-metal deposits that are host to vanadate minerals, roscoelite is not reported in these deposits.

After normal weathering of igneous rocks, much of the vanadium in the ferromagnesian minerals goes into the clay minerals that are formed; however, it remains in the 3-valent state or is oxidized to the 4-valent state, both of which are relatively insoluble. As these clay minerals are removed by erosion and transported to places where they accumulate as sedimentary rocks, most of the vanadium must stay with them; shales commonly contain about as much vanadium as igneous rocks (100–200 ppm), whereas sandstones contain only about 20 ppm and limestones about 10 ppm. Most of the vanadium in the sandstones and limestones is probably in the argillaceous fractions. On intensive oxidation, as in arid climates, the vanadium in clay minerals probably oxidizes to the soluble 5-valent state and would be available for transport in ground waters.

Wulfenite is as much an intrinsic part of many of the vanadate deposits as are the vanadate minerals; it may or may not be as abundant quantitatively as are the vanadate minerals, but it is reported in the oxidized zones of base-metal deposits as frequently or perhaps more often than vanadate minerals. Molybdenum occurs in trace amounts in igneous rocks (about 1 ppm) and in shales (a few parts per million); it concentrates in hypogene deposits where the sulfide, molybdenite, is most common. With perhaps a few exceptions, molybdenite is not reported in the base-metal deposits that are host to wulfenite and the vanadate minerals. On the other hand, in deposits where molybdenite is a primary mineral, the common oxidized molybdenum mineral is ferrimolybdite; wulfenite is rarely reported. In other words, a molybdenum source other than molybdenite is probably required for most or all deposits containing wulfenite.

Because of the wide distribution of vanadate deposits in dry climates and the habit of these deposits to occur in the restricted environment of oxidized base-metal deposits, a common origin and a common source of vanadium and molybdenum seem requisite. Most students are unable to imagine enough of these two metals in the primary sulfide deposits to form the vanadate deposits. The writer has equal difficulty in imagining that these metals were introduced by late hypogene solutions, in all cases contemporaneous with or later than meteoric oxidation of the primary sulfide deposits in so many parts of the world. Rather, it seems easier to imagine deriving these metals from ordinary country rocks, especially shales, under conditions of intensive oxidation in dry climates, with leaching of the metals by ground waters and transport to the oxidized base-metal minerals. The vanadium in the vanadium-uranium deposits in sandstone was probably also derived by leaching from country rocks and probably was transported by ground waters, but in the sandstone deposits it was precipitated as oxide and silicate minerals by reduction in a reducing environment (Fischer, 1973, p. 683–684).

Although this ground-water concept seems compatible with many relations, it does not readily accommodate all relations. Ordinary ground waters, even in arid regions, contain only a little vanadium and molybdenum; a large amount of water and much time would be required to transport the large quantities of these metals in some of the vanadate deposits. The amount of molybdenum in ordinary rocks is about 50–100 times less than the amount of vanadium, and yet in general there is probably as much molybdenum in vanadate deposits as vanadium. In the few deposits where paragenetic relations have been reported, wulfenite is earlier than the vanadate minerals, but why should this sequence occur in a ground-water regime? In at least some deposits, the vanadate minerals and wulfenite are not wholly coextensive, whereas a more uniform distribution might be expected from ordinary ground waters. And in some mining districts, vanadate minerals (and wulfenite) are reported as occurring in only a few of the oxidized deposits instead of having a more ubiquitous distribution. These relations by themselves might favor a genetic association with late hot-spring activity, the waters of which might contain higher concentrations of metals than ground waters and might have a more limited distribution in a district.

ECONOMIC SIGNIFICANCE

The world production of vanadium, from 1907 to 1971, as reported by the U.S. Geological Survey (1907–23) and the U.S. Bureau of Mines (1924–31; 1932–71) totals about 270,000 short tons of vanadium in ores and concentrates. If estimates are added for sources for which quantitative figures were not published by the Bureau of Mines in recent years, the world's total production probably would be on the order of 300,000 short tons of vanadium. About 35,000 tons of vanadium has come from vanadate ores, representing a little more than 10 percent of the world's total vanadium production.

The sources of vanadate ores, compiled from various publications, are shown in table 1.

Reserves and resources of vanadate ore in the Otavi district, Namibia, are generally reported to be moderate, and a moderate production of vanadium concentrates

TABLE 1.—*World sources of vanadium from vanadate ores*

Country	Short tons V	Deposits, productive period, and remarks
Namibia	27,903	Otavi district, several mines, 1920–71.
Zambia	5,755	Broken Hill area, 1920–49, 1951, 1952, 1960–62.
United States	[1]800	710 tons from the St. Anthony mine, Arizona, 1934–44; the rest from several deposits in southern New Mexico, Arizona, Nevada, and California, mostly 1910–30.
Mexico	[2]233	Los Lamentos and San Antonio mines, Chihuahua, 1938–40(?).
Argentina	138	Several mines in Mendoza and San Luis provinces, almost every year 1939–64.
Angola	[3]35	Lueca mine, 1956–59.
Morocco	Small	Taouz mine.
Rhodesia	Small	Bulawayo area.
South Africa	1	Kafferskraal 214 area, 1920 or 1923.
Spain	Small	Azuaga district.
U.S.S.R.	Small	Suleiman-Sai deposit, probably in the 1930's.

[1]Partly estimated.

[2]Signer and Hewitt (1952, p. 461) reported "By 1940 * * * production of * * * 8,752 tons of vanadium * * *." This probably means tons of vanadate ore.

[3]Teixeira Faîsca (1960) reported 940 tons (probably metric tons of vanadate ore) produced, 1940–59.

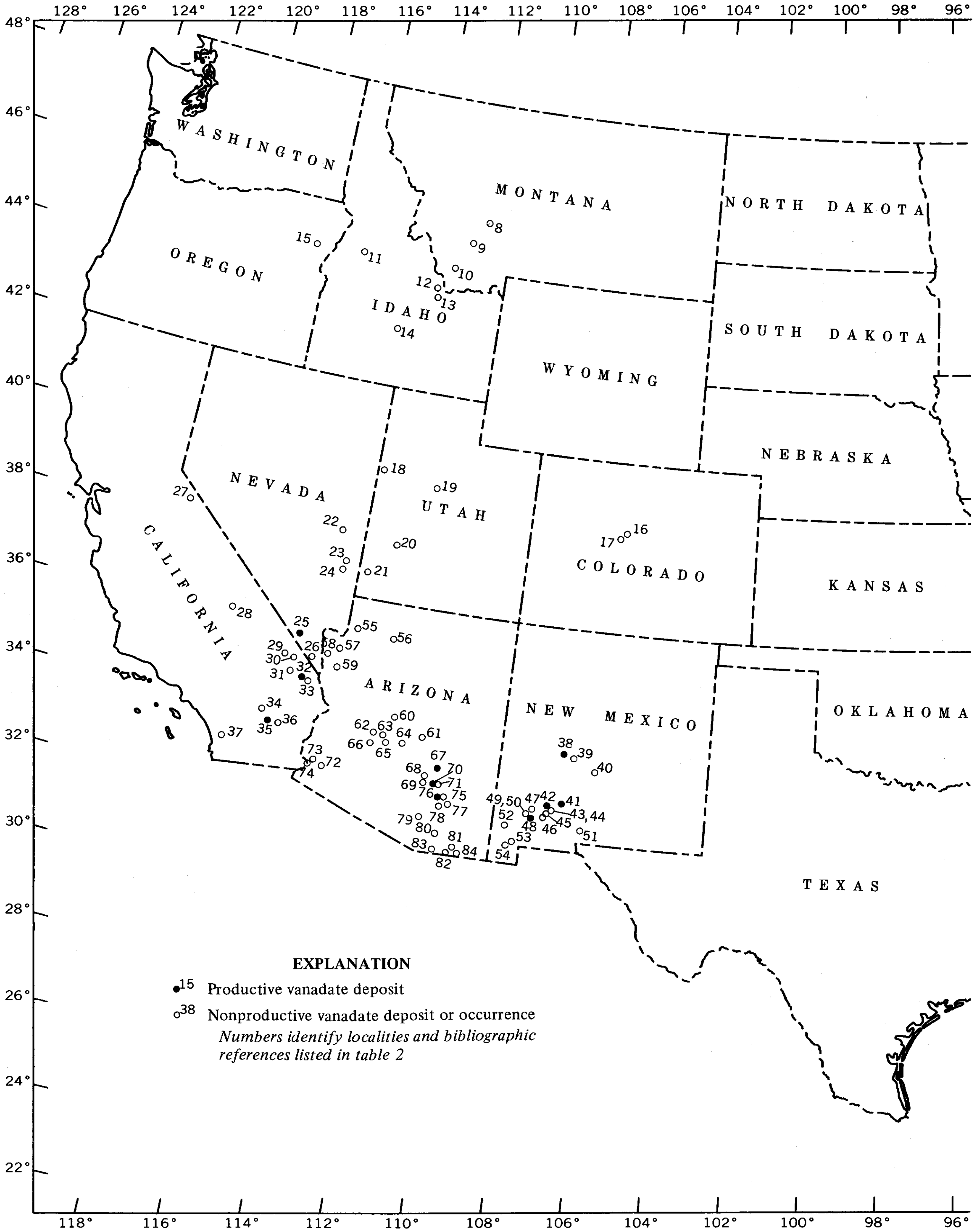
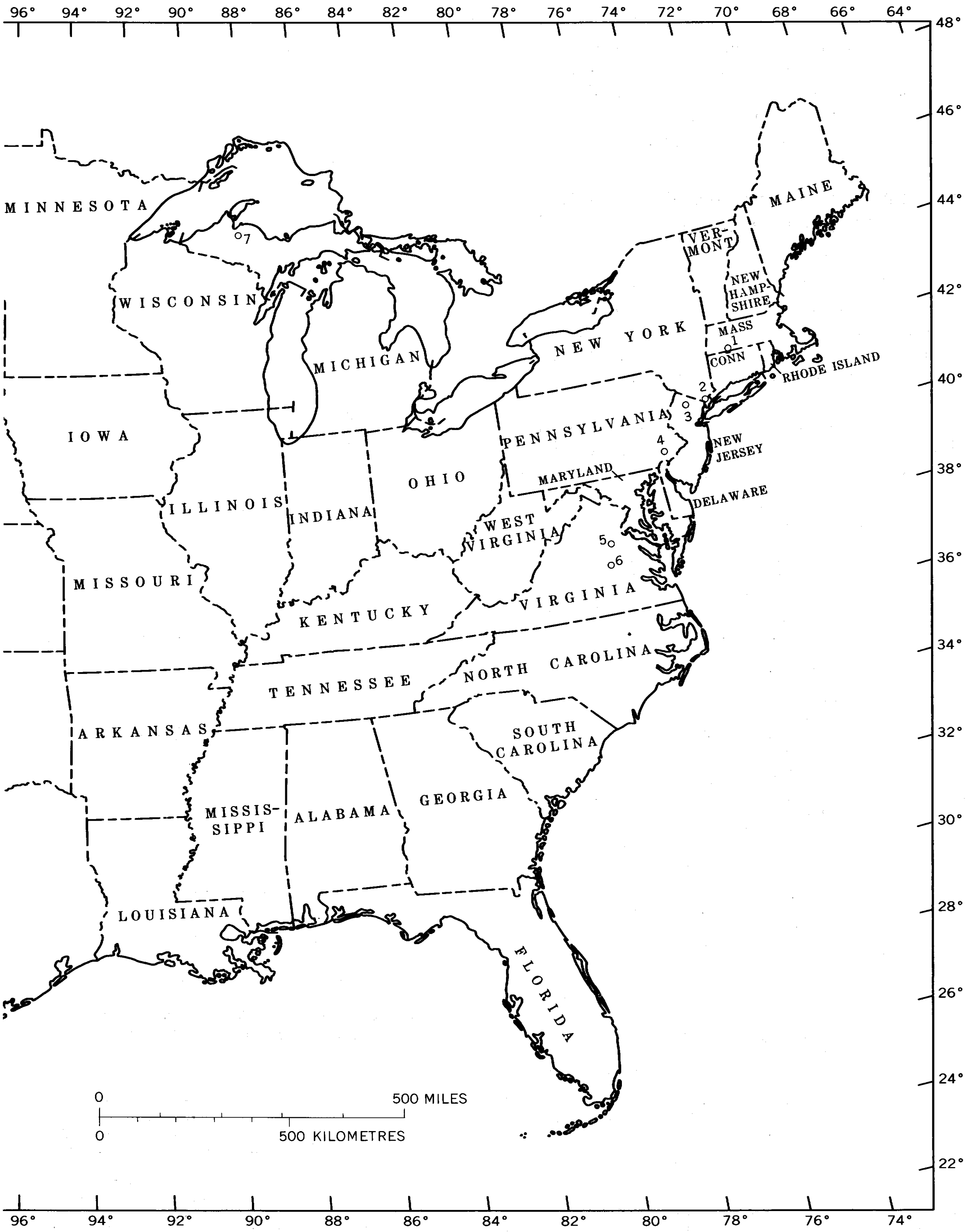


FIGURE 2.—Distribution of vanadate deposits



and occurrences in the United States.

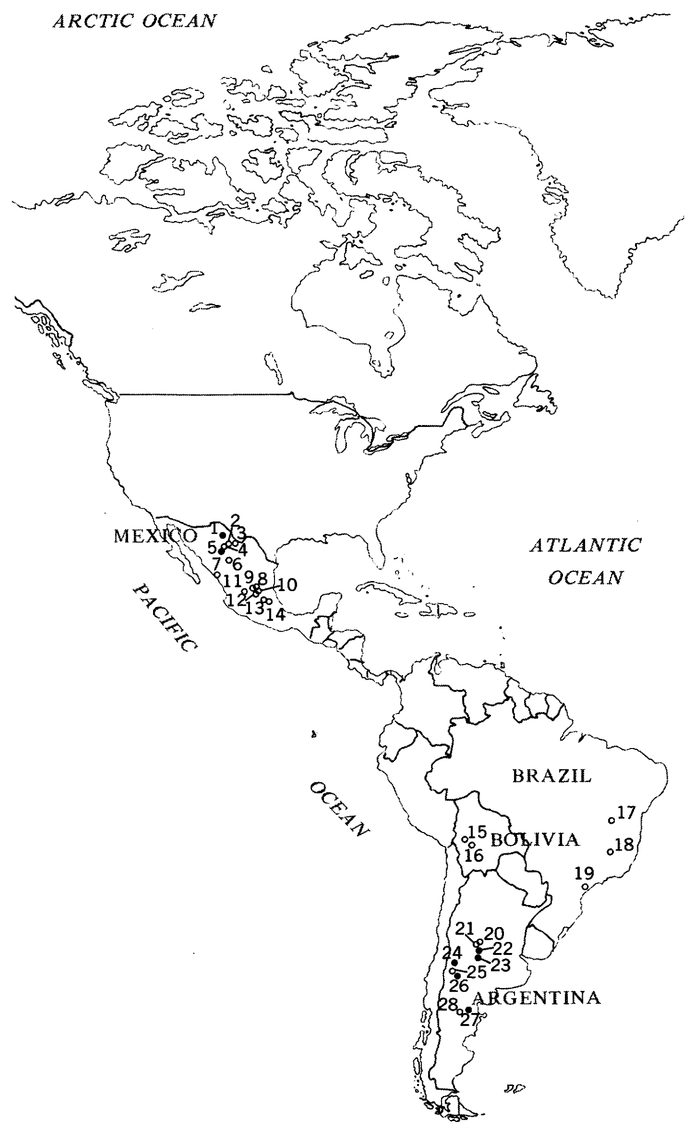
probably will continue. Resources of vanadate ore in the other productive deposits listed in table 1 probably are negligible to small, and no significant production is likely. It is also unlikely that any of the unproductive deposits shown in figure 1, or any undiscovered deposits, will yield significant amounts of vanadate ore in the future.

IDENTIFICATION OF VANADATE DEPOSITS AND OCCURRENCES

All locatable vanadate deposits and occurrences in the United States that were found in a modest search of published and unpublished material are plotted and numbered in figure 2; these are identified by the numbers in table 2, and at least one reference is given for each deposit or occurrence reported in the literature studied. The locatable deposits and occurrences in North and South America, exclusive of the United States, are plotted and identified in figure 3 and table 3, and those in Eurasia, Africa, and Australia are in figure 4 and table 4.

TABLE 2.—*Vanadate deposits and occurrences in the United States*
[Locality numbers are shown in figure 2]

1.	Massachusetts	Southampton area: Heyl and Bozion (1962).
2.	New York	Ossining area: Heyl and Bozion (1962).
3.	New Jersey	Franklin area: Palache (1935).
4.	Pennsylvania	Phoenixville area: Heyl and Bozion (1962).
5.	Virginia	United States mine: Pardee and Park (1948).
6.	Do	Moss mine: Pardee and Park (1948).
7.	Michigan	Skanee area: Fischer (1914).
8.	Montana	Elkhorn mine: Weed (1901).
9.	Do	Silver Star district: Heyl and Bozion (1962).
10.	Do	Bald Mountain district: Heyl and Bozion (1962).
11.	Idaho	Buckskin mine: Ballard (1924, p. 38).
12.	Do	Texas (Gilmore) district: Heyl and Bozion (1962).
13.	Do	Iron Mask mine: Stearns (1923).
14.	Do	Mineral Hill (Haley) district: Heyl and Bozion (1962).
15.	Oregon	Little Baby prospect: Lindgren (1901).
16.	Colorado	Breckenridge district: Lovering (1934).
17.	Do	Leadville district: Emmons, Irving, and Loughlin (1927).
18.	Utah	New Baltimore mine: Nolan (1935).
19.	Do	Tintic district: Heyl and Bozion (1962).
20.	Do	Harrington-Hickory mine, Star district: Butler, Loughlin, Heikes, and others (1920).
21.	Do	Escalante mine: Butler, Loughlin, Heikes, and others (1920).
22.	Nevada	Cave Valley mine, Patterson district: Schrader (1931).
23.	Do	Prince mine, Pioche district: Westgate and Knopf (1932).
24.	Do	Republic mine, Chief district: Callaghan (1936).
25.	Do	Goodsprings district (Ninety-nine, Pauline, Contact, Prairie Flower, Yellow Pine, Alice, Belle, Fredrickson, Mobile, Bill Nye, Whale, and Hoodoo mines): Hewett (1931); Albritton, Richards, Brokaw, and Reinemund (1954).
26.	Do	Searchlight district.
27.	California	Coleville area: Gary (1940, p. 106).
28.	Do	Darwin district (Darwin and Emperor mines): Hall and MacKevett (1962).
29.	Do	Shadow Mountain area: Hewett (1956).
30.	Do	Ivanpah Mountain area: Hewett (1956).
31.	Do	Columbia mine, Providence area: Hewett (1956).



EXPLANATION

•27 Productive vanadate deposit

∘17 Nonproductive vanadate deposit or occurrence
Numbers identify localities and bibliographic references listed in table 3

FIGURE 3.—Distribution of vanadate deposits and occurrences in North and South America, exclusive of the United States.

TABLE 2.—Continued

32.	Do	Leiser Ray mine: Hewett (1956).
33.	Do	Louisiana-California mine, Signal district: Tucker and Sampson (1940, p. 70).
34.	Do	Gold Park district: Tucker and Sampson (1931, p. 369).
35.	Do	Eldorado mine: Brown (1923).
36.	Do	Black Eagle mine, Eagle Mountains: Tucker and Sampson (1940, p. 47).
37.	Do	Pala Chief mine: Schaller (1911, p. 162).
38.	New Mexico	North Magdalena district: Lasky (1932).
39.	Do	Socorro Peak district (Torrence and Merritt mines): Lasky (1932).
40.	Do	Hansonburg district: Lasky and Wootton (1933).

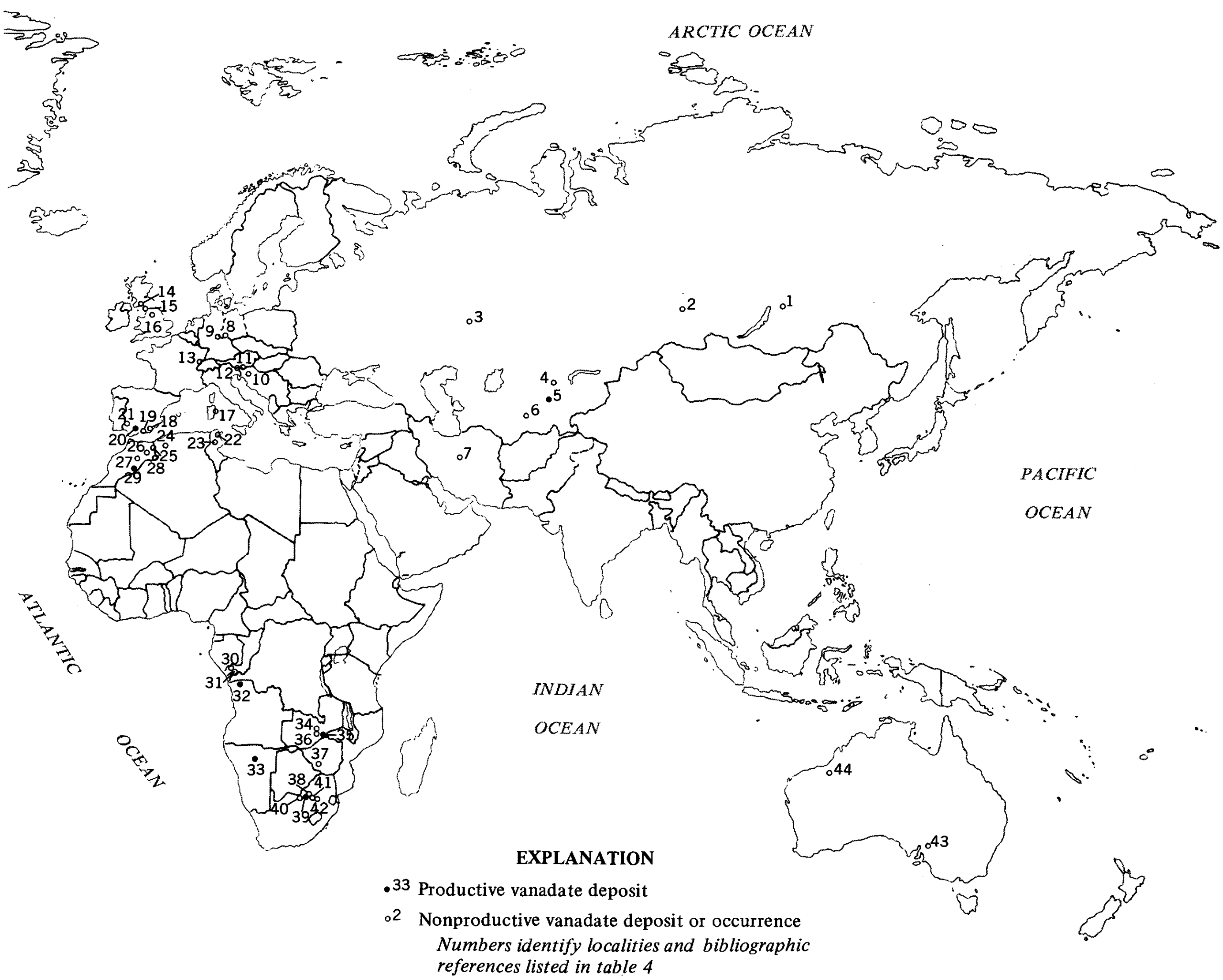


FIGURE 4.—Distribution of vanadate deposits and occurrences in Eurasia, Africa, and Australia.

TABLE 2.—Continued

41.	Do......................	Palomas Gap area: Kelley and Silver (1952).
42.	Do......................	Hall mine, Hillsboro district: Lindgren, Graton and Gordon (1910).
43.	Do......................	Hillsboro district: Anderson (1957).
44.	Do......................	Macy mine, Hillsboro district: Lindgren, Graton, and Gordon (1910).
45.	Do......................	Lake Valley district: Lasky and Wootton (1933).
46.	Do......................	Macho district: Harley (1934).
47.	Do......................	Georgetown district: Lasky and Wootton (1933).
48.	Do......................	Lucky Bill mine, Central district: Lasky and Wootton (1933).
49.	Do......................	Central district (Lion No. 2 and Groundhog mines): Lasky (1936).
50.	Do......................	Lone Mountain district: Lindgren, Graton, and Gordon (1910).
51.	Do......................	Organ Mountains.
52.	Do......................	Lordsburg district: Lasky (1938).
53.	Do......................	Wasp mine, Eureka district: Lasky (1947).
54.	Do......................	Silver Trail mine, Sylvanite district: Lasky (1947).
55.	Arizona.....................	Grand Gulch mine, Bentley district: Galbraith (1941).

TABLE 2.—Continued

56.	Do......................	Bridal Veil claim: Allen and Butler (1921, p. 11).
57.	Do......................	Gold Basin district (El Dorado and Climax mines): Galbraith (1941).
58.	Do......................	Gold Bug district: Schrader (1909).
59.	Do......................	Aurora mine, Wallapai district: Dings (1951).
60.	Do......................	Lincoln claim, Bigbug district: Lindgren (1926).
61.	Do......................	Payson district (Ox Bow and Zulu mines): Galbraith (1941).
62.	Do......................	Wickenburg district (Cochran and Doyle properties).
63.	Do......................	White Picacho district: Jahns (1952).
64.	Do......................	Maricopa mine, Cave Creek district: Wilson, Cunningham, and Butler (1934).
65.	Do......................	Hieroglyphic Mountains area: Galbraith (1941).
66.	Do......................	Vulture mine, Vulture Mountains: Ross (1923).
67.	Do......................	Globe-Miami district (Defiance, Irene, and Albert Lea mines): Peterson (1950).
68.	Do......................	Belmont mine, Superior area: Wilson (1950).

TABLE 2.—Continued

69.	Do	Ray district.
70.	Do	C and B group, Banner district: Ross (1925).
71.	Do	Banner district (Cowboy, Premier, and Seventy Nine mines): Ross (1925).
72.	Do	Diana claim, Castle Dome district: Wilson (1951a).
73.	Do	Chocolate Mountains area: Galbraith (1941).
74.	Do	Silver district (Silver Clip, Geronimo, Princess, Red Cloud, Cash Entry, and Papago mines and claims): Wilson (1933, 1951c).
75.	Do	Bluebird mine, Bunker Hill district: Kuhn (1951).
76.	Do	St. Anthony mine, Mammoth district: Peterson (1938); Creasey (1950).
77.	Do	Table Mountain mine, Galiuro Mountains: Galbraith (1941).
78.	Do	Lucky Strike claim, Redington district.
79.	Do	Old Yuma mine, Tucson Mountains: Jenkins and Wilson (1920).
80.	Do	Total Wreck mine, Empire district: Wilson (1951b).
81.	Do	Tombstone district (Lucky Cuss, Tribute, Toughnut, and Tombstone Extension mines): Butler, Wilson, and Rasor (1938).
82.	Do	Charleston area, Tombstone district: Galbraith (1941).
83.	Do	Mowry mine, Patagonia district: Schrader (1915).
84.	Do	Bisbee district: Galbraith (1941).

TABLE 3.—*Vanadate deposits and occurrences in North and South America, exclusive of the United States*

[Locality numbers are shown in figure 3]

1. Mexico	Los Lamentos district, Chihuahua: Foshag (1934); González Reyna (1956a, 1956b).
2. Do	Oruro mine, Cuchillo Parado district, Chihuahua: González Reyna (1956a).
3. Do	San Carlos mine, Chihuahua: González Reyna (1956a).
4. Do	Santo Domingo mine, Chihuahua: González Reyna (1956a).
5. Do	San Antonio mine, Santa Eulalia district, Chihuahua: Hewitt (1943); Signer and Hewitt (1952).
6. Do	Cigarrero mine, Jimenez district, Chihuahua.
7. Do	La Aurora mine, Sinalo: González Reyna (1956a).
8. Do	Catorce mine, San Luis Potosi: González Reyna (1956a).
9. Do	Venado mine, San Luis Potosi: González Reyna (1956a).
10. Do	Guadalcazar district (several mines), San Luis Potosi.
11. Do	Bilboa mine, Ojo Caliente district, Zacatecas.
12. Do	Pozos district (several mines), San Luis Potosi.
13. Do	Zimapan area (several mines), Hidalgo.
14. Do	Cardonal mine, Hidalgo: González Reyna (1956a).
15. Bolivia	Vanadio mine, Tana area, La Paz: Dittler and Hueber (1931); Ahlfeld (1954).
16. Do	Torotoro deposit, Potosi: Ahlfeld (1954).
17. Brazil	Itacarambi area (several mines), Minas Gerais: Guimarães (1961); Fróes Abreu (1962).
18. Do	Sete Legoas area, Minas Gerais: Rabello (1942).
19. Do	Iporanga area, São Paulo: Fróes Abreu (1962).
20. Argentina	Guaico district (several mines), Cordoba: Wright (1940); Angelelli and others (1970).
21. Do	Cerro Blanco mine, San Luis: Angelelli (1950)
22. Do	La Nelly mine, San Luis: Fester and Feira (1949); González (1957).
23. Do	La Sala mine, San Luis: González (1957).
24. Do	Santa Elena mine, Mendoza: Wright (1940); Fester and Feira (1949).
25. Do	Malargue district (several deposits), Mendoza: Angelelli (1956); Yrigoyen (1958).
26. Do	El Peseno mine, Mendoza: Angelelli (1950).
27. Do	Gonzalito mine, Rio Negro: Fester and Mazzola (1961).
28. Do	Rio Negro Province (several mines): Kittl (1957); Kittl and Villarroel (1965).

TABLE 4.—*Vanadate deposits and occurrences in Eurasia, Africa, and Australia*

[Locality numbers are shown in figure 4]

1. U.S.S.R.	Eastern Transbaikal, Siberia: Zuev (1959).
2. Do	Kutnetskom Ala-Tau area, south-central U.S.S.R.: Mikhaylova (1958).
3. Do	Bashkiria area, southern Ural region: Vakhrushev (1940).
4. Do	Central Kazakhstan (Kyzyl-Espe, Gul'shad, Kaskaigyr, and Perum deposits): Anosov and Chukhrov (1948).
5. Do	Suleiman-Sai deposit, Kazakhstan: Smol'yaninov (1928); Smirnov (1928); Yanishevskiy (1934); Sobolev (1933).
6. Do	Sidzhak area, Uzbekistan: Dunin-Barkovskaya and Tronenok (1972).
7. Iran	Anarak area (several mines): Bariand (1963).
8. East Germany	Friedrichrode area: Guillemin (1955).
9. West Germany	Bad Lauterberg area, Harz Mountains: Koritnig (1968).
10. Yugoslavia	Mezica (Mies) deposit: Grafenauer, Ottemann, and Strmole (1968).
11. Austria	Bleiberg area (several mines), Carinthia: Holler (1935); Schroll (1949, 1953).
12. Do	Ehrwald area (several deposits), Tirol: Schneider and Wolf (1969).
13. France	Vosges Mountains area: Longchambon and Longchambon (1932); Durand (1958).
14. United Kingdom	Leadhills area, Scotland: Collie (1889).
15. Do	Caldbeck area, Cumberlain: Kingsbury and Hartley (1956).
16. Do	Mottram area, Cheshire: Roscoe (1877).
17. Italy	Ozieri area, Sardinia: Lovisato (1904).
18. Spain	Oria area, Almeria: Marin (1942).
19. Do	Granada area: Moreno Martín (1932).
20. Do	Azuaga district (several deposits), Badajoz: Marin (1942).
21. Do	Santa Marta district, Badajoz: Marin (1942).
22. Tunisia	Djebba mine: Sainfeld (1952); Solignac (1935).
23. Do	Djebel el Agab: Sainfeld (1952).
24. Algeria	Saïda area: Lacroix (1908).
25. Morocco	Oujda district (several mines); Barthoux (1922); Agard and Permingeat (1952).
26. Do	Oued Tissof mine: Agard and Permingeat (1952).
27. Do	Midelt area (several mines): Barthoux (1924); Agard and Permingeat (1952).
28. Do	Haouanit mine, Bouarfa area: Agard and Permingeat (1952).
29. Do	Taouz mine: Eyssautier (1952).
30. Congo Republic	Niari Basin (River) area: Lebedeff and Choubert (1934).
31. Do	M'Passa mine: Picot, Scolari, and Troly (1963).
32. Angola	Lueca mine: Teixeira Faísca (1960); Millman (1960); Pauly (1962).
33. Namibia (formerly South-West Africa)	Otavi district (several mines): Bürg (1942); Clark (1931); Du Toit (1953); Moritz (1933); Schneiderhöhn (1919, 1929, 1931, 1959); Schwellnus (1946); Stahl (1926); Verwoerd (1957); Willemse, Schwellnus, Brandt, Russell, and van Rooyen (1944).

TABLE 4.—Continued

34. Zambia (formerly Northern Rhodesia)	Camarnor deposit: Reeve (1963).
35. Do	Broken Hill district: Bancroft (1961); Deans (1942); Heath (1961); Reeve (1963); Schneiderhöhn (1931); Skerl (1934); Taylor (1954).
36. Do	Lusaka district: Deans (1942).
37. Rhodesia (formerly Southern Rhodesia)	Bulawayo area: Amm (1940).
38. South Africa	Nooitgedacht 155, Transvaal: Willemse, Schwellnus, Brandt, Russell, and van Rooyen (1944).
39. Do	Kafferskraal 214, Transvaal: Willemse, Schwellnus, Brandt, Russell, and van Rooyen (1944).
40. Do	Doornhoek mine, Transvaal: Wagner and Marchand (1921); Kupferberger (1928); Willemse, Schwellnus, Brandt, Russell, and van Rooyen (1944).
41. Do	Roodekrans 203, Transvaal: Willemse, Schwellnus, Brandt, Russell and van Rooyen (1944).
42. Do	Dwarsfontein 21, Transvaal: Willemse, Schwellnus, Brandt, Russell, and van Rooyen (1944).
43. Australia	Broken Hill area, New South Wales: Hodge-Smith (1934).
44. Do	Braeside area, Western Australia: Blatchford (1925).

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