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AVAILABILITY OF U.S. CHROMIUM RESOURCES

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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By Gary A. Kingston, Robert A. Miller, and Fred V. Carrillo

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AVAILABILITY OF U.S. CHROMIUM RESOURCES

by

Gary A. Kingston,[1] Robert A. Miller,[2] and Fred V. Carrillo[3]

ABSTRACT

Chromium resources in the United States are estimated at 1.8 million tons of recoverable chromium contained in 22.5 million tons of chromite-bearing material. Additional resource is presumed existent in large, but as yet undetermined, quantities of material containing less than 10 percent Cr_2O_3. No domestic resources are being mined presently (1969).

Excluding transportation charges to domestic consuming areas, the total 1.8 million tons of chromium is estimated to be available, in ore or concentrate, at costs up to $0.64 per pound; 63 percent of the total is available under $0.11 per pound; and 38 percent under $0.08 per pound. It is judged that transportation from the resource areas to the existing market centers would add nearly $0.05 to the cost of a pound of chromium contained in ore or concentrate.

Technically effective beneficiation methods have been developed for much of the known domestic resource, and further development might reduce costs of processing these materials. However, at present, domestic chromium resources are noncompetitive with foreign sources.

INTRODUCTION

Knowledge of the Nation's ability to supply its future needs for chromium from domestic sources is a responsibility of the Bureau of Mines. The objective of this report is to estimate the quantity of domestic chromium mineral resource that might be available at various long-term prices by estimating the cost of mining and beneficiating resources considered available for extraction.

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The costing procedure applied to the resource estimates is a first approximation of cost, based in part on cost experience during the Federal chromium stockpiling program (1950's). The reader is cautioned to regard the numbers in that context. Costs of shipping the ore and/or concentrate to markets and smelting to metal products have not been included.

When tons are referred to, the reference is to short tons (2,000 pounds) unless otherwise designated. Chromite ore and concentrate is sold on a long ton (2,240 pounds) basis, and resources are often referred to in the literature as long tons.

Chromium ore is classified into metallurgical, chemical, and refractory grades, signifying the use to be made of the ore based on its chemical composition. This breakdown has become less definitive as technology has provided the means by which to utilize chemical-grade ore for metallurgical and refractory uses. No differentiation is made in the resource and cost estimates, but types are indicated in the individual State resource descriptions.

A 1962 Department of Commerce publication (3),[4] "Materials Survey--Chromium," studied the relationship between world chromium resources and U.S. supply and demand.

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DOMESTIC CHROMIUM RESOURCES

Chromium resources in Montana, Oregon, Washington, California, and Alaska are estimated to be 1.8 million tons of recoverable chromium contained in 22.5 million tons of chromite material (table 1), which, if mined and milled, would theoretically yield 6,759,000 tons of ore or concentrate averaging 38 percent chromic oxide.

Since 1962, U.S. requirements for chromite have been met entirely by imports. U.S. resources are mostly low grade, and, with several significant exceptions, most deposits are small. Moreover, they are remote from the consuming industries and would have a high transportation cost. Foreign deposits, particularly in Africa, are large and well delineated.

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[4] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

TABLE 1. - *Estimated recoverable U.S. chromium resources*

State	Ore (tons)	Contained recoverable chromium (percent)	Recoverable chromium (tons)	Distribution of total chromium (percent)
Montana.........	15,743,400	8.4	1,327,630	75.5
Alaska..........	1,245,300	15.2	189,582	10.8
Oregon..........	4,669,600	3.2	148,807	8.5
California......	337,700	20.9	70,688	4.0
Washington......	518,500	4.0	20,933	1.2
Total......	22,514,500	7.8	1,757,640	100.0

Reports on many of the prospects show only an approximate percentage of chromite ore to country rock, resulting in only an estimate of Cr_2O_3 content. There are references to areas that contain zones of low-grade disseminated chromite (below 10 percent), but little work has been done to outline the zones or to estimate the average grade (25, 38).

Very sketchy estimates of quantities of low-grade chromite described in the literature have implied that an excess of 70 million tons of submarginal ore may be present in high-iron concentrations of from 2 to 10 percent Cr_2O_3 in the various localities described. However, because of a lack of accurate measurement, these deposits are not considered as a possible resource at present. It is possible that large-scale open-pit methods would be adaptable to certain extensive areas of disseminated ore should ever an interest develop in resources containing less than 10 percent chromic oxide.

The chromium ores of northern California and southern Oregon occur as random pods conducive to short-term extraction comparable with the mining of pocket gold deposits. The pod ores generally have been mined by open pitting on surface outcrops. The unpredictable character of pod occurrences and their frequent small size have made the risk factor so high as to discourage significant underground mining in Oregon and California. During the last domestic chromite purchase program, numerous individuals made shipments of ore mined by cruising the chromite occurrence areas with a truck and picking up high-grade float. A comparatively high price offered per ton by the Federal Government during the stockpiling program and the availability of Government purchasing depots made this possible.

The stratiform deposits of the Montana Stillwater complex can be mined by large-scale mining methods. The Mouat mine was mined generally by a shrinkage stoping method from 1953 to 1959 by The American Chrome Co. During that period, the company improved its mining technology by adapting better methods of ore breaking, stope drawing, chute construction, and the use, in some mine areas, of long-hole stoping. These and other improvements reduced mining costs 47 percent during the 7-year period of operation (24). This deposit and several similar deposits in the same district represent the bulk of the domestic chromium resource estimated to be available.

Resources by State

Montana

Montana's estimated resources are 15.7 million tons of ore containing 1.3 million tons of recoverable chromium. The largest resources are in the Stillwater complex, predominantly in the Mouat and Benbow mines. (See fig. 1.) Two other areas, Red Lodge and Sheridan, have small tonnages of available resources.

Stillwater Complex

The Stillwater igneous complex is an intrusion of ultramafic rocks of lopolithic form (basin-shaped). After emplacement, crystallization and gravity settling resulted in formation of mineralogically different layers. Faulting and tilting of the igneous complex resulted in the present dip and offsets of the mineral horizons (11, 13, 23).

Chromite is found in the center of a pyroxene-olivine horizon that is referred to as the Ultramafic zone. Eleven distinctive chromite horizons (A to K) are discernible, mostly in the lower and middle part of the Ultramafic zone. Only the G and H bands are considered minable; however, very little information is available on the grade and extent of the other horizons (23).

Three areas within the northwestern trending complex contain chromite deposits which have either been partially mined or explored.

The Mountain View area where the Mouat mine is located is the most important. This area has a long history, dating from the late 1880's, when the Nye Corp. was developing copper-nickel deposits. Actual exploration for chromite in and near the Mouat mine was started in July 1939 by the Bureau of Mines. As a result of this exploration and as an agent for the Government, The Anaconda Company, from 1941 to 1943, mined chromite ore and produced 29,538 tons of chromite concentrate. In the next decade, during and after the Korean War (1953 to 1961), American Chrome Co. mined almost 2 million tons of chromite ore from the Mouat deposit and produced 900,000 tons of chromite concentrate at a grade of 38 percent Cr_2O_3 or better; additional ore was used by the company to produce ferrochromium. Actual grade of concentrates ranged from 38 percent Cr_2O_3 to 42 percent Cr_2O_3 with an average chromium-to-iron ratio of 1.6:1. Reserves are published as 4.4 million tons of ore containing 22.5 percent Cr_2O_3 (24).

Two other areas in the complex, which were mined or explored, are the Benbow mine area and the Gish area. The Benbow mine was mined by The Anaconda Company in 1941 to 1943. Average grade of concentrate was 41 percent Cr_2O_3 with a chromium-to-iron ratio of 1.6:1 to 1.7:1. The Gish mine, in the northwestern part of the chromite zone, has been explored, but has no recorded chromite ore production. Mill tests on Gish ore attained a concentrate containing 37.8 percent Cr_2O_3 with a chromium-to-iron ratio of 1.2 to 1. Both mines have chromite resources available for mining.

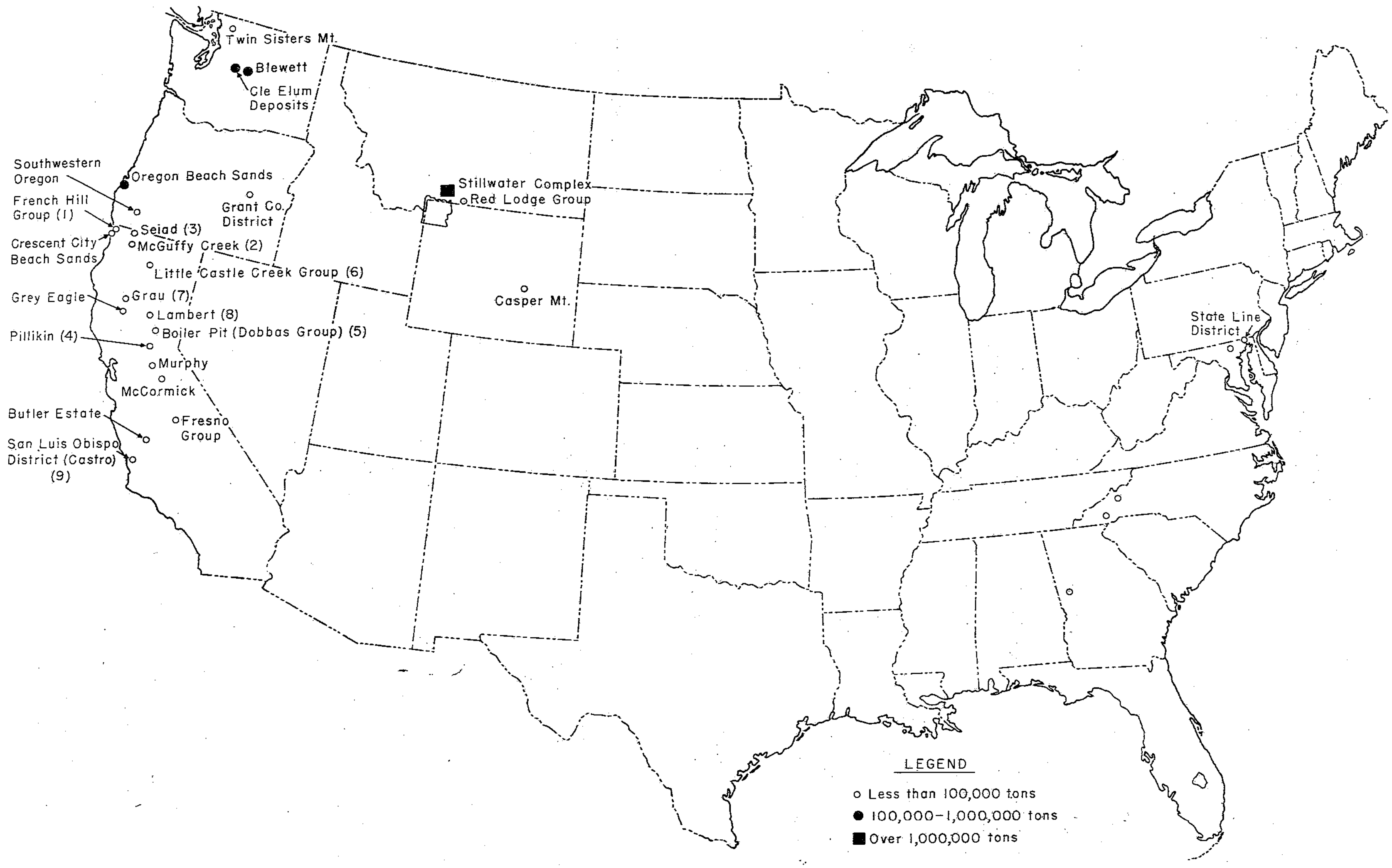

FIGURE 1. - Significant Chromite Deposits in the United States (Exclusive of Alaska).

Red Lodge Area

The Red Lodge area has a much smaller estimated resource tonnage than the Stillwater complex area, but chromite ore was mined when the Government price support was in effect.

The area is about 15 miles to the southwest of Red Lodge, Carbon County. All known deposits are within 5 miles of U.S. Highway 212.

Ten properties yielded ore in the early 1940's. Chromite is found in lenses and pods that are scattered through masses of serpentine surrounded by gneisses and granite. While the grade of mined ore is rarely over 40 percent Cr_2O_3, mechanically cleaned chromite ranges from 35 to 53 percent Cr_2O_3 (16). Chromium-to-iron ratio of the cleaned chromite ranges from 0.66:1 to 2.1:1. No shipments of chromite have been recorded since 1943.

Sheridan Area

The Sheridan area contains several prospects and deposits. A small quantity of ore has been shipped from one deposit. Chromite, found in lenses of coarse diorite, has a chromium-to-iron ratio of 1 to 1.

Alaska

Alaskan deposits are almost wholly contained in two main groups on the Kenai Peninsula. The Red Mountain deposits are 6 miles from Jakolof Bay and are scattered in small deposits over a rugged area 4 miles long. The deposits on Claim Point are at the shore near the southern tip of Kenai Peninsula and occur in an intrusion of ultramafic rock that underlies all of Claim Point, Chrome Bay, and an area on the mainland extending 800 to 1,000 feet from the shore of Chrome Bay. The chromite deposits are irregularly distributed throughout the dunite without apparent pattern. Results of drilling and surface sampling indicate 295,000 tons of 17.8 percent Cr_2O_3 ore is available at Claim Point. About 2,000 tons of ore was mined there in 1917 and 1918. Total production from the Alaskan deposits has been about 27,800 tons of lump ore averaging 42 percent Cr_2O_3, having a chromium-to-iron ratio of 2.75 to 1.

Alaskan resources are divided about equally between the two groups of deposits. Exploration by the Bureau of Mines during World War II indicated a total of 500,000 to 530,000 tons of ore ranging from about 15 to 45 percent Cr_2O_3. The ore can be concentrated, with an 80- to 90-percent recovery, to a product containing about 45 percent Cr_2O_3, with a chromium-to-iron ratio of 2.7 to 1. The ore shipped has been mined from the higher grade parts of the ore bodies, with no attempt to mill the lower grade ores.

Additional small scattered deposits have been described throughout the State but are not considered important sources of chromite. A small deposit of chromite occurs in a serpentinized ultramafic intrusive mass on Baranof Island in southeastern Alaska. Eight separate deposits at Red Bluff Bay are known, which contain a total reserve estimate of 570 tons of ore and about 29,000 tons of low-grade material averaging 12 percent Cr_2O_3 (10, 27, 31).

Several additional small occurrences have been reported in Alaska, but no significant tonnages have developed from these localities (37).

Oregon

Available chromium in Oregon's estimated resources is 137,200 tons contained in 4.6 million tons of ore. About 40 percent of the chromium is contained in material that averages 4 percent Cr_2O_3. The bulk of the Oregon resource is located in two areas: (1) southwestern Oregon, in Curry, Coos, Josephine, Jackson, and Douglas Counties, and (2) the John Day district, Grant County, in eastern Oregon.

Southwestern Oregon

Coastal areas in Curry and Coos Counties contain black sand deposits found as present beaches and raised marine terraces (9). Black sands averaged 3 to 5 percent Cr_2O_3. Other heavy minerals found in the beach sands include ilmenite, rutile, garnet, magnetite, and zircon. These sands occur as layers and lenses ranging from inches to 42 feet in thickness, tens of feet to 1,000 feet in width, and a few hundred feet to a mile or more in length. Overburden varies up to 75 feet.

Portions of these sands were mined in 1943, and approximately 87,800 tons of concentrate was produced with an average grade of 25 percent Cr_2O_3. Part of these rough concentrates was later re-treated to yield a product averaging about 39.3 percent Cr_2O_3 with a chromium-to-iron ratio of 1.6:1. Only about 37 percent of the Cr_2O_3 in the sand was recovered in the final concentrate (3).

Southwestern Oregon chromite lode deposits are found in serpentine and dunite. The average deposit consists of lenses, pods, and small stringers of relatively high-grade chromite. Many areas containing numerous prospects or small mines remain to be sampled, especially areas of low-grade disseminated chromite. Actual reserves are small, but the large number of prospects and mines characteristically show that chromite is widespread.

High-grade ore has an average grade of between 40 and 45 percent Cr_2O_3, with a chromium-to-iron ratio of 2:1 to 2.5:1. Ore is not being mined at present because of the inaccessibility of many of the districts, the nature of the high-grade ore which is found in small lenses and pods, and the high cost of shipping ore to markets in the Eastern United States.

John Day District

The second chromite area in Oregon is the John Day district, Grant County. Most of the chromite in this district is of the refractory or high-alumina type, containing as high as 27 percent alumina (34).

Chromite ore is found as irregular lenses in peridotites and serpentine. High-grade ore has been mined in the area, and cutoff grade was 25 percent or more chromic oxide. Shipments of concentrates have averaged 47 to 48 percent Cr_2O_3 with a chromium-to-iron ratio of about 2.8 to 1 (3, p. 16).

California

Chromite is found scattered throughout California in an area extending from the Oregon border, south to the San Rafael Mountains in the southern Coast Ranges, and from the Sierra Nevada to the coast. The Sierra Range chromite deposits are principally irregular, lenticular to tabular bodies of the podiform type (35) that occur only in peridotite and serpentinite as massive chromite or disseminated grains. Smaller occurrences are found as placer deposits in beach sands or river deposits. The known podiform deposits range in size from a few pounds to about 150,000 tons of ore, the size of the ore body that was mined out at the Grey Eagle mine in Glenn County (21).

Disseminated grains in some localities are concentrated into irregular layers and lenses of varying thickness.

The available chromium resources of California are estimated to be 337,781 tons of ore containing 70,700 tons of recoverable chromium.

Nine areas within the State have been designated as having important occurrences of chromite and contain the bulk of the reported California chromite resources. These include (1) the Del Norte County area (including the French Hill Group); (2) the McGuffy Creek area in Siskiyou County; (3) the Seiad Quadrangle area in Siskiyou County; (4) the Pillikin area in El Dorado County; (5) the Dobbas Group area in Placer and El Dorado Counties; (6) the Little Castle Creek area in Siskiyou and Shasta Counties; (7) the Noble Electric Steel Group (Grau) in Tehama County; (8) the Lambert mine area in Butte County, and (9) the San Luis Obispo district.

Other areas in the State which contained important deposits of chromite, but which are now mined out or where no resources are considered available at present, include the Grey Eagle (Black Diamond) area in Glenn County, the Butler mine area in Fresno County, the McCormick mine (Chinese Camp) area in Tuolumne County, and the Clear Creek placers of San Benito County. Although no resources are considered available at present, these areas merit attention, because resumption of exploration in these districts may uncover additional chromite deposits in the future.

The Crescent City beach sands in Del Norte County are also considered to have some chromite available which could be recovered from the rather large amounts of black sands found along the beaches.

Del Norte County (40)

Del Norte County area is one of two relatively small areas, the other being the San Luis Obispo district, which have yielded over 40 percent of the recorded State total of chromite produced. Almost half of the district's production of over 80,000 tons of chromite came from the French Hill mine, about 16 miles east of Crescent City (17); output from the other mines in the district ranges from 50 to over 10,000 tons. The variable size and shape of chromite deposits in the county make it difficult to estimate accurately the remaining resource, but an estimated 60,000 tons of metallurgical-grade chromite resources should be available.

The chromite deposits occur as both disseminated and pod-type ore bodies (40). Most of the deposits in Del Norte County are pod-type deposits of metallurgical-grade ore in peridotite and serpentine that underlie more than a quarter of the county.

McGuffy Creek

The McGuffy Creek deposit is in a tabular mass of peridotite trending northwest for 8 miles across the Klamath River Valley in Siskiyou County. Ore-grade reserves were mined nearly simultaneously with their discovery, and almost all of the ore in sight has been mined. Minable resources in the area probably do not exceed 25,000 tons. The chromite deposits are not found at any particular position within the peridotite masses, and there is no apparent relationship between the distribution of the deposits, making exploration for new ore bodies and reserve estimations difficult. Many occurrences of disseminated chromite, which are in concentrations too low to be considered ore, are known to be scattered throughout the area. However, when taken as a whole, they may contain considerable amounts of chromite. No accurate determinations of the tonnages of these deposits have been made, but estimates suggest that they may run into millions or tens of millions of tons of less than 5 percent Cr_2O_3 rock.

Seiad Quadrangle (43)

The Seiad Quadrangle in Siskiyou County is estimated to contain 40,000 tons of chromite resources, but milling tests have not achieved satisfactory recoveries from this ore (8). The principal ore body is a tabular mass of peridotite, similar to the previously described McGuffy Creek deposit. The Seiad Creek deposit contains one of the largest ore bodies in California, and considerable amounts of low-grade ore are known to be disseminated throughout the peridotite mass. No accurate measurement has been made of the submarginal deposits known to occur in this district.

Pillikin Area (5, 42)

The disseminated chromite deposits of the Pillikin area in El Dorado County differ in size. Some deposits contain only a few hundred pounds of ore; others like the Pillikin mine, the most productive mine in the county, have yielded many thousand tons of ore. Because of the erratic distribution and the highly irregular shapes of the chromite ore bodies, chromite was generally mined as found, and presently known resources are very small. Indicated resources from surface exposures and underground workings are estimated to be near the order of 62,500 tons of 48 percent Cr_2O_3, although much of it is in bodies too small to mine by cheap methods. Potential resource at considerable depths may be very large, but the cost of finding and mining any such ore bodies has been prohibitive, and no attempt has been made to measure such reserves. Estimates of milling ore in the area are in the order of 4 million tons containing 5 to 10 percent Cr_2O_3.

Little Castle Creek Area (41)

This area on the border of Siskiyou and Shasta Counties has produced slightly over 20,000 tons of chromite ore. Small podiform deposits containing 4,000 tons of 38 to 48 percent Cr_2O_3 are still available.

Noble Electric Steel Group

A number of small properties are located in the Elder Creek area of Tehama County. Production from this area has been nearly 20,000 tons of chromite ore. Additional resources of 24,000 tons of chromite are estimated to be contained in disseminated deposits throughout the area (29).

Grey Eagle Mine Area

Over 140,000 tons of ore was extracted from mines in the Grey Eagle and Black Diamond area of Glenn County as of 1944. Exhaustion of the deposits forced the Rustless Mining Corp. to close down the mill, and apparently very little chromite ore remains in the district (7).

Dobbas Group (Boiler Pit)

A large number of limited size pod-type ore bodies are found in the area of the Dobbas mine in El Dorado and Placer Counties. No attempt has been made to estimate reserves, but the only pod in the area known to reach 1,000 tons was the Boiler Pit deposit. Additional exploration might disclose the presence of a considerable amount of ore.

Lambert Mine Area (28)

The largest deposit of massive chromite ore yet found in the ultramafic rocks of the northern Sierra Nevada occurs at the Lambert mine, about 2 miles southwest of Magalia in Butte County. The Lambert deposit has yielded under 10,000 long tons of ore; one other deposit in the county has yielded slightly over 1,000 long tons of ore, and another has yielded a little less than 1,000 tons. Of the other deposits that have been worked, one has produced a little more than 500 long tons of ore, and five have yielded between 100 and 300 tons. Although there is reason to believe that further prospecting may lead to the discovery of additional deposits, because of the nature of the ore bodies, it is impossible to make accurate estimates of the remaining resources of the district. It would appear, however, that ore bodies in the vicinity contain approximately 2,000 tons of chromite ore.

San Luis Obispo District (39)

Since the early 1870's, more than 75 mines and prospects from San Luis Obispo County have produced a total of more than 128,000 long tons of chromite ore; thus San Luis Obispo County ranks first among the chromite-producing counties of California. The chromite is associated with masses of dunite that occur in serpentinized ultramafic bodies of the northwest-trending Franciscan Formation in the western part of the county. The larger properties were examined in 1940 and 1941 by the U.S. Geological Survey and are described in a report by Smith and Griggs (30). It is not possible to make a valid estimate of the total resources of disseminated ore in the Santa Lucia Range of San Luis Obispo County, but mining and exploration in the area would uncover additional small ore bodies. In 1943, it was estimated that the known deposits of San Luis Obispo County contained 35,000 tons of ore. During the 1952 to 1958 period when ore from the area was being accepted at Government stockpiles, 66,000 tons of ore was produced in the county. Although the reserves were mined about as fast as they were developed during the period the stockpile purchase program was in operation, indications from the development that has been done is that at least 15,000 tons of ore remains as extensions from the known pods and disseminated ore zones throughout the dunite zone in the district.

McCormick Mine Area (4)

The Chinese Camp area in Tuolumne County includes several deposits of massive ore in sheared serpentine zones, the largest of which is the McCormick mine, which has produced somewhat more than 3,000 tons of chromite. The district has been thoroughly prospected, and no new discoveries have been made since World War I. Most of the deposits of massive ore have been exhausted, but considerable low-grade milling ore remains. Water is a problem in most of the mines, and pumping is necessary. No estimates of resources is available, but a number of small unexploited deposits are known to occur in the area.

Crescent City Beach Sands (40)

On the landward side of the foreshore and backshore along the arcuate beach south of Crescent City in Del Norte County, large tonnages of black sand are known to contain about 7 percent Cr_2O_3. Although the proportion of black sand concentrated in the deposit varies considerably, estimates have been made that a strip 2 miles long, 250 to 370 feet wide, and 3 to 5 feet deep should contain at least 500,000 cubic yards of heavy sand of this grade.

Clear Creek Placers

Stream gravel deposits, occurring along Clear Creek in southeastern San Benito County, Calif., contain black sands with appreciable quantities of chromite, but because of their low chromium content and high iron content, attempts at making shipping-grade concentrates have not been successful. The principal deposit extends for over a mile along Clear Creek, and preliminary sampling of the gravels indicates portions containing 8 pounds of Cr_2O_3 per cubic yard. Although not considered a source of chromite at present, it might possibly become a source of chromium-iron ore in the future.

Washington

Resource estimates of available chromium in Washington total 21,000 tons of chromium contained in 518,000 tons of ore. The ore grade ranges from 5 to 42 percent Cr_2O_3.

Twin Sisters Area

The largest reserves and resources are in the Twin Sisters Mountains in Skagit and Whatcom Counties (fig. 1). Chromite occurs as lenses and pods in peridotites. The ore can be concentrated to a high-grade product of 53 percent Cr_2O_3 with 75 percent recovery or a 47-percent Cr_2O_3 product with 87 percent recovery (3, p. 16). The chromium-to-iron ratio ranges from 2.3:1 to 3.0:1.

Blewett-Cle Elum Area

Potential resource of chromium in Washington is the iron ore in the Blewett Pass and Cle Elum areas. It is estimated that at least 10.5 million tons of material in the Blewett Pass conglomerate will average 0.86 percent Cr_2O_3, 11.6 percent iron, and 0.39 percent nickel (2, 19). In the Cle Elum areas, iron deposits contain a potential of over 6 million tons of material averaging 2.4 percent chromium, 40.8 percent iron, and 0.8 percent nickel (20). These estimates are not included in any of the figures or tables. Chromium would probably be in the form of the alloy ferrochromium (6, 26).

Other prospects are noted in the literature, but reserves and resources are very small.

Wyoming

The only significant known chromite deposit in Wyoming is 10 miles south of Casper in Natrona County (3, 12).

The chromite occurs mostly as individual crystals disseminated through a talcose amphibole schist that is surrounded by altered igneous rocks. Although no economically important deposits are present, several large schist bodies contain large tonnages of low-grade, high-iron chromite in significant quantities which someday may be minable. One lens contains 4,162,000 tons of inferred material averaging 2.45 percent Cr_2O_3, including 575,000 tons of schist averaging 8.7 percent Cr_2O_3, which could be mined selectively from within 100 feet of the surface (12).

Drilling shows the schist extends at least 500 feet deeper, but a complete estimate of the available chromite at this site has not been made. The drilling was insufficient to delineate the boundaries of the schist at depth, but it showed that they are extremely irregular.

Pennsylvania-Maryland (18, 22)

From 235,000 tons to 500,000 tons of lode chromite ore was produced from 27 mines prior to 1900. The most careful estimate is between 230,000 to 280,000 tons. Also, about 20,000 tons of placer concentrates was produced. Both massive and disseminated deposits occur in forms so irregular and unpredictable that they defy description. The ores for the most part were good chemical grade. Insofar as can be judged from the remaining dump material and old ore pods, much of the chromite in Maryland and Pennsylvania, although too rich in iron to meet present-day nonpenalty specifications, was nevertheless comparable in quality with lower grades of chromite that are being used more and more in the metallurgical industry. The remnants at the dumps contain the only visible resource in the area (4,000 tons 10 to 30 percent and 1,200 tons 48 to 50 percent Cr_2O_3).

Placer resources in the State Line district are estimated at 25,000 to 45,000 tons of concentrates ranging in grade from 32 to 54 percent.

Idaho

Resource estimates do not include Idaho. Twenty-five tons of chromite ore was shipped from Idaho in 1942, but information is not available to estimate potential resources.

North Carolina

Chromite deposits in North Carolina are restricted to a belt 5 to 25 miles wide and 200 miles long across the west end of the State. No large ore bodies of chrome ore have been discovered in North Carolina, and as the pockets were commonly mined out as fast as they were found, known resources are practically nonexistent. Less than 500 tons of production has been reported from the State (14).

Georgia

Small chromite deposits are reported in Troup County. Disseminated grains of chromite associated with asbestos are concentrated in serpentinized peridotite which intruded the biotite gneiss country rock. Much of the chromite is found as float in the surface wash. The tonnage and grade of the chromite deposits are low, probably not exceeding 2,000 tons. Eighteen tons of chromite was extracted from an open cut and sent to a steel mill in 1929. The shipment assayed 33.76 percent Cr_2O_3 and 17.78 percent FeO, but because of its low grade, it was rejected (1).

RESOURCE BENEFICIATION TECHNOLOGY

The problems of chromium ore beneficiation generally are directly related to the chromium content of the ore, the magnesia and alumina contained therein, and the mineralogical relationship of the chromium to all other elements with which it is associated in the occurrence. The objective is to increase the chromic oxide content by liberating it as much as physically possible from as much of the silica, alumina, magnesia, ferric oxide, and other gangue constituents with which it is associated. This has been accomplished most frequently by first determining the optimum size to which the ore should be crushed and ground, to free the chromium mineral from gangue minerals, and then separating the chromium-bearing mineral from the waste (tailings) by gravity separation (utilizing the heavy specific gravity of chromite), by magnetic separation (the associated iron gives chromite magnetic susceptibility), and by electrostatic separation (reaction to an induced electrical charge). Even in the best circumstances, a significant percentage of the gross chromium mineral content of the ore is lost to the tailings. The percentage generally is in proportion to the grade of the ore.

A higher grade ore will allow higher recovery than a low-grade ore. This points up the compounded problem of working with low-grade chromium resources. Not only does more material have to be handled as the ore grade decreases, but the percentage recovery of contained chromium declines rapidly. This means higher total mining cost per ton of recovered concentrate, higher concentration cost due to the increased volume of material processed, and further losses in potential value occur because of decreased recovery efficiency.

Sullivan and Workentine (33) reported beneficiation research on the Montana Stillwater complex resources (Mouat, Benbow, and Gish properties). They found that a process applied to Mouat chromite ore containing 9.95 percent Cr_2O_3, combining high-tension electrostatic separation and tabling (a gravity concentration method), produced a concentrate of about 42 percent Cr_2O_3 content, with a chromium recovery from the ore of about 85 percent. A 7.75-percent Cr_2O_3 material from the Benbow and Gish properties was similarly processed to yield a 40-percent Cr_2O_3 concentrate with recovery dropping to approximately 70 percent.

Sullivan and Stickney (32) researched the flotation process as a means of concentrating Pacific Northwest low-grade chromite resources. Their studies were limited primarily to fine-grained, disseminated chromite--characteristic of much of the domestic resource potential--which generally is poorly concentrated by gravity processes. The result of this work demonstrated that flotation is technically feasible for low-grade chromite of the above character. It was reported that the grade of concentrate producible by flotation was more dependent upon the mineralogical composition of the chromite mineral than it was upon the grade or character of the ore. The effectiveness of flotation was said to be, in several cases, from 78 to 91 percent chromium recovery in a concentrate of 90 percent or more chromite.

Hunter and Sullivan (15), investigating the beneficiation and smelting characteristics of northern California chromite, have shown that resources of the Seiad Creek area can be concentrated to 53 percent Cr_2O_3 (73 percent recovery) by a combination of gravity and electrostatic processing; flotation will yield a 45-percent chromic oxide concentrate with a 75-percent recovery. Magnetic processing alone yielded only 62 percent recovery in a 41- to 42-percent Cr_2O_3 concentrate. Electrostatic separation by itself gave even lower recovery (59 percent), but provided about a 53-percent Cr_2O_3 concentrate.

These examples are cited to illustrate the general feasibility of processing many of the domestic low-grade chromites and the situation that is presented if such recovery is undertaken. A high Cr_2O_3 content in concentrate is obtained either by sacrificing recovery and/or involves a complex and likely costly to operate process.

An important factor in how successful any beneficiation procedure can be is determined by the previously mentioned mineralogical character of the chromite. When magnesium oxide (MgO), aluminum oxide (Al_2O_3), and ferric oxide

(Fe_2O_3) are chemically combined with chromic oxide (Cr_2O_3), which is the case with low-grade resources of less than 20 percent Cr_2O_3, the mineral character of the chromium contained can be such that upgrading to a commercial concentrate (48 percent or more Cr_2O_3) is impossible by gravity, magnetic, flotation, or electrostatic processes.

Another factor to consider is the relationship of chromium to iron in the concentrate. The preferred market relationship is three parts chromium to one part iron, a condition that generally is attainable, by physical beneficiation, only with resources of high initial Cr_2O_3 content. Concentrates having less than three parts chromium per unit of iron normally are at a disadvantage because such a material, with some exceptions, will produce a lower value product through subsequent processing stages.

Alternative systems to physical beneficiation of chromium ores include chemical and pyrometallurgical processes. Physical methods of beneficiation separate the chromite from gangue material in the ore, whereas chemical and pyrometallurgical processes can be developed and used to improve the chromium-to-iron ratio. Such a process, using a pyrochemical technique, has been investigated and reported by Town and coworkers (36). The basic idea is to develop conditions whereby the chemical condition of the ore-mineral is reconstituted, that is, the mineral is reformed (recrystallized) into a new, improved crystal having more ideal characteristics; in the above investigation, Montana chromite from the Mouat mine was upgraded from a 1.5 to 1 chromium-to-iron ratio to a ratio of 8 to 1.

Recrystallization would follow mining and precede physical beneficiation. The reformed crystals would be beneficiated out of the matrix in which they are grown, providing a very high-grade product for further processing. Reforming may or may not be an expensive process. The development of a pilot operation and cost estimates remain to be accomplished. In any case, reduced costs that would be expected from having a high-quality product to smelt would at least offset some portion of the mineral-reforming-process cost.

AVAILABILITY OF U.S. CHROMIUM RESOURCES

Recoverable domestic chromium resources, estimated at approximately 1.8 million tons of chromium, are considered available at a cost of 2 to 64 cents per pound of chromium (Cr) in ore or concentrate, based on approximate mining and milling costs. Figure 2 illustrates the chromium supply curve described by the supply-cost estimates given in table 2.

At a price of 7 cents per pound chromium, about 106,000 tons of chromium could be available; at 8 cents, a total of 669,000 tons; and at 13 cents, nearly 1.6 million tons. Foreign chromite sells for about $0.03 to $0.05 per pound of contained chromium delivered on the eastern seaboard (1967).

Most domestic ores and concentrates would have a low chromium-to-iron ratio and would be of low chromic oxide (Cr_2O_3) grade compared with imported ores.

TABLE 2. - *Estimated U.S. chromium resource recovery costs*

(Tons)

Production costs Cr[1] (cents/pound)	Montana		Oregon		Washington		California		Alaska		Total	
	Ore	Available chromium	Ore	Available chromium	Ore	Available chromium	Ore	Available chromium	Ore	Available chromium	Ore	Available chromium
1.0- 1.9....	-	-	42,100	11,423	-	-	-	-	-	-	42,100	11,423
2.0- 2.9....	-	-	5,100	1,033	30,000	4,017	-	-	-	-	35,100	5,050
3.0- 3.9....	800	140	129,800	29,034	7,400	1,773	11,400	3,752	-	-	149,400	34,699
4.0- 4.9....	65,200	9,124	25,400	3,639	800	143	9,000	2,586	-	-	100,400	15,492
5.0- 5.9....	1,200	139	25,200	4,110	400	63	12,600	3,096	-	-	39,400	7,408
6.0- 6.9....	21,200	2,285	46,100	6,353	1,100	177	58,700	19,281	13,500	3,990	140,600	32,086
7.0- 7.9....	5,345,000	503,750	33,000	4,262	88,400	3,868	57,800	16,622	112,600	33,888	5,636,800	562,390
8.0- 8.9....	42,000	3,261	55,700	6,750	1,000	105	30,000	7,789	85,600	24,604	214,300	42,509
9.0- 9.9....	1,027,000	92,270	4,600	493	28,300	2,903	25,800	6,367	-	-	1,085,700	102,033
10.0-10.9....	3,280,000	266,275	235,500	21,921	-	-	23,500	5,140	-	-	3,539,000	293,336
11.0-11.9....	2,033,000	153,313	21,600	1,712	-	-	-	-	1,800	327	2,056,400	155,352
12.0-12.9....	3,906,000	295,947	4,200	226	300	15	-	-	55,100	9,054	3,965,600	305,242
13.0-63.9....	22,000	1,126	4,041,300	57,851	360,800	7,869	108,900	6,055	976,700	117,719	5,509,700	190,620
Total...	15,743,400	1,327,630	4,669,600	148,807	518,500	20,933	337,700	70,688	1,245,300	189,582	22,514,500	1,757,640

[1]Excludes all costs beyond producing ore or concentrate f.o.b. mine or mill.

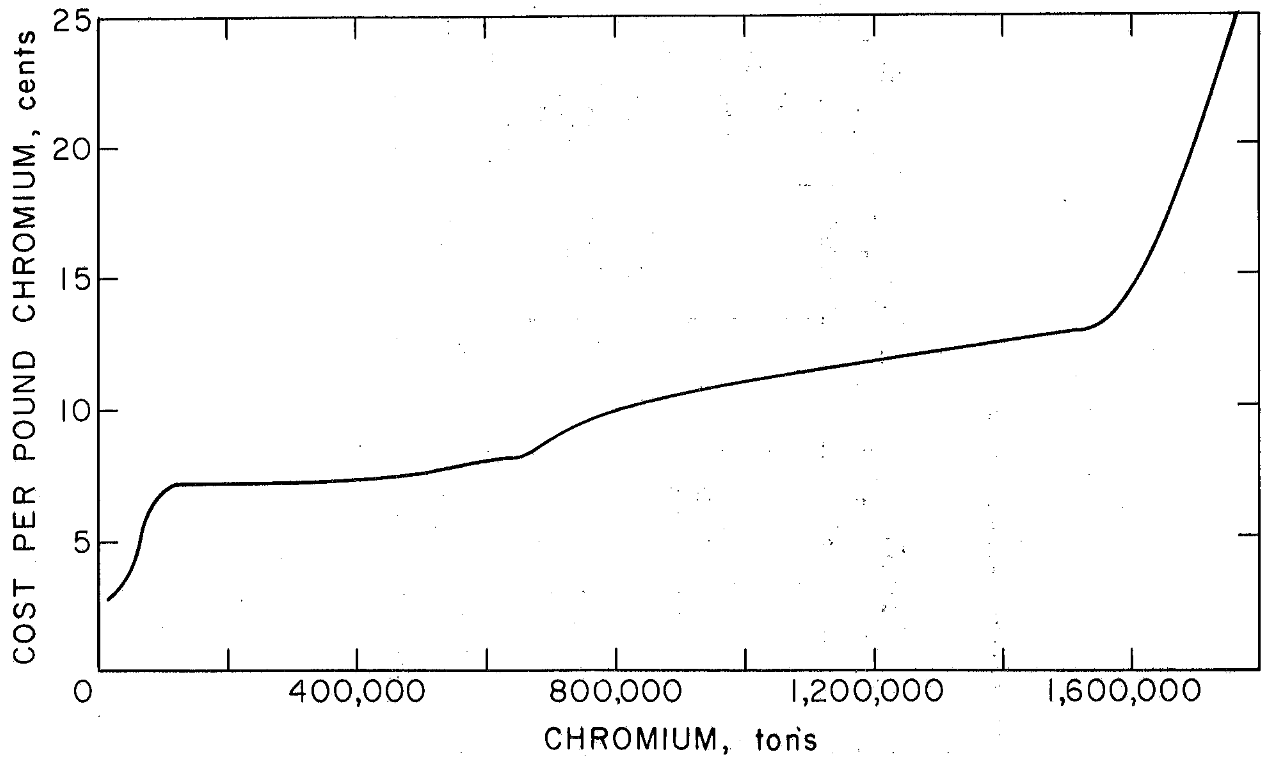

FIGURE 2. - Cumulative Tons of Chromium Available at Various Costs From Resources in Montana, Oregon, Washington, California, and Alaska.

The average ore recovery rate for underground mining is estimated at 85 percent. When the Mouat chromite deposit in Montana was worked, the average loss of ore was 10 percent due to pillars and wing raises (24, p. 14). It is estimated that smaller underground mines, in the Oregon and Washington peridotites, would lose as much as 20 percent of the ore.

For estimates in this report, an average 80-percent mill recovery of the chromic oxide in lode ores is used. Previous milling experience on domestic ores indicates a range of 63 to 86 percent Cr_2O_3 recovery (25, pp. 102, 151). Chromite recovery experienced at the Mouat mill, Nye, Mont., averaged approximately 85 percent when the ore was concentrated to 38 to 40 percent Cr_2O_3.

When the Oregon beach sands were mined and milled, only 37 percent of the original Cr_2O_3 was recovered (3, p. 15). This recovery is exceptionally low and probably could be improved. For estimation purposes, the recovery rate on the beach sands was increased to 50 percent.

The results of investigations (33, p. 1) on recovering chromite by various methods from low-grade ores of Montana were as follows, in percent Cr_2O_3:

Sample grade	Concentrate grade	Chromium recovery
9.95	42.8	85
9.95	42.0	86
9.95	40.7	84
7.75	39.5	69
7.75	40.1	69
8.04	40.0	71
8.04	38.5	69

All recoveries were based on concentrating ores of less than 38 percent Cr_2O_3 to a minimum of 38 percent Cr_2O_3, which was the minimum grade required by the Government for concentrate produced from the Mouat mine, Montana, for stockpile purchase. It is recognized that an efficient mill would be able to concentrate some chromite ores to more than 38 percent Cr_2O_3, as well as obtain better than 80 percent recovery of the chromic oxide.

Chromium recovery rates used for mining methods and milling are as follows, in percent:

General mining method	Mining recovery	Milling recovery	Total recovery
Open pit............	100	80	80
Beach sands.........	100	50	50
Underground.........	85	80	68

Costs assigned to the various types of mining varied according to mine accessibility, mining method, depth of ore (underground), and the amount of mine exploration and development needed. The range of mining costs per ton is as follows:

Open pit............	\$4 to \$10
Underground.........	\$12 to \$22

All ore milled was assigned a milling cost of \$2 per ton. It was assumed that in most areas, particularly Oregon, the mill or mills would be located at a central point in the producing areas and would serve as custom mills. Estimates include a shipping cost for a maximum of 40 miles to the mills. Many mining districts in Oregon and Washington are inaccessible. It has been assumed that roads would be constructed to these areas by someone other than the mining companies or miners.

The estimated costs for mining and milling range from \$6 to \$24 per ton of ore mined. The metal costs in this report (table 2) were not calculated through an estimate of capital requirements and operating costs at various rates of mine and mill output. Judgment costs were accepted from experience documented during the Federal chromium stockpiling programs conducted since World War II. Judgments were made in the assignment of those earlier costs, updated to present-day costs with an economic index, to the estimated available resources. The metal cost estimates in table 2 do not include profit since no capital estimates were made to provide a basis for doing so.

No shipping charges for delivering concentrates or ore to consumers have been included in the costs. While the cost estimate results in some ore that is seemingly competitive at the present price of chromite ore, it is because the costs do not include profit or shipping charges to the markets. Inclusion of shipping costs to the consuming areas of the United States (dominantly in the eastern portion of the country) increases the tabulated costs by an estimated 4.8 cents per pound of chromium. This assumes a 38-percent Cr_2O_3 ore or concentrate shipped at a cost of $25 per ton (520 pounds of contained chromium per ton).

SUMMARY AND CONCLUSIONS

The known available chromium resources of the United States are largely in the low-grade massive chromite deposits of the Montana Stillwater complex. This resource exceeds 15 million tons of potential ore containing over 75 percent of the domestic chromium estimated to be available. These resources are not presently competitive with foreign sources supplying U.S. requirements, and the known domestic resources represent but a small fraction of the sizable world resources situated principally in Africa. Some small, high-grade (metallurgical-grade) deposits occur in Oregon, Alaska, and California. In these same areas a potential exists for development of large tonnages of very low-grade resource containing about 5 percent Cr_2O_3. A significant quantity of low-grade resource is available in southern Oregon and northern California beach sands, but recovery losses are high in beneficiation. Generally, adequate means of metallurgical recovery have been developed for the major portion of the known U.S. resources. The potentially large and yet to be delineated disseminated chromite resources, containing 5 percent Cr_2O_3 (plus or minus 3 percent), would present difficulty in metallurgical recovery. If an effort is made to determine this possible resource, additional metallurgical studies would be required to develop means to improve the percent of chromium recovery and to improve extraction economics.

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