Information Circular 8977

Chromium Availability—Market Economy Countries

A Minerals Availability Program Appraisal

By P. R. Thomas and E. H. Boyle, Jr.

UNITED STATES DEPARTMENT OF THE INTERIOR
William P. Clark, Secretary

BUREAU OF MINES
Robert C. Horton, Director

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. administration.

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PREFACE

The purpose of the Bureau of Mines Minerals Availability Program is to assess the worldwide availability of nonfuel minerals. The program identifies, collects, compiles, and evaluates information on active, developed, and explored mines and deposits, and mineral processing plants worldwide. Objectives are to classify domestic and foreign resources, to identify by cost evaluation resources that are reserves, and to prepare analyses of mineral availabilities.

This report is part of a continuing series of Minerals Availability Program reports to analyze the availability of minerals from domestic and foreign sources and the factors that affect availability. Questions about the program should be addressed to: Chief, Division of Minerals Availability, Bureau of Mines, 2401 E Street, N.W., Washington, D.C. 20241.

CONTENTS

ILLUSTRATIONS

CONTENTS — Continued

ILLUSTRATIONS—Continued

Page

TABLES

CONTENTS — Continued

TABLES—Continued

Page

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	m/yr	meter per year
cm	centimeter	mm	millimeter
d/yr	day per year	pct	percent
DWT	deadweight ton	ppm	part per million
°F	degree Fahrenheit	sq km	square kilometer
ha	hectare	10^3 t	thousand metric tons
km	kilometer	t	metric ton
kW	kilowatt	t/cu m	metric ton per cubic meter
kW-h	kilowatt hour	tpd	metric ton per day
MVA	megavolt ampere	tpy	metric ton per year
m	meter	yr	year

CHROMIUM AVAILABILITY - MARKET ECONOMY COUNTRIES

A MINERALS AVAILABILITY PROGRAM APPRAISAL

By P. R. Thomas[1] and E. H. Boyle, Jr.[2]

ABSTRACT

The Bureau of Mines determined the costs associated with the production of chromium, in the form of chromite and high-carbon ferrochomium, from the demonstated resources of 10 market economy nations. The analyses evaluated the relative geologic and economic position of these chromite resources contained within 80 producing or potential mining operations.

This report presents cost evaluations of a demonstrated resource of chromite, contained within the nations studied, of appoximately 1.2 billion metric tons (t). Of this total, 70 pct is contained within the southern African nations of Zimbabwe and the Republic of South Africa. The majority of current chromium mining and smelting capacity is contained within these two countries as well. India and the Philippines have recently demonstrated greatly increased chromite resources and hold the most promise for expanding both chomite and ferrochromium production outside southern Africa. Their demonstrated resources represent approximately 7 and 16 pct, respectively, of the cost evaluated total tonnage.

Chromite resources, on an identified or hypothetical basis worldwide, are highly concentrated within Zimbabwe and South Africa, with these two nations containing in excess of 95 pct of the total.

Given the present market structure, a majority of chromium contained within the demonstrated chromite resources of the nations studied is economically recoverable; but from a long-term resource and economic perspective, South Africa should inceasingly dominate the markets for both chromite and high-carbon ferrochromium. In addition, it is anticipated that an increasing percentage of chromium traded on the world market in the future will be in the form of high-carbon ferrochromium as opposed to chromite, as this additional processing stage continues to relocate from the industrial nations that account for a majority of chromium consumption to those nations that mine chromite.

[1] Economist.
[2] Geologist.
Minerals Availability Field Office, Bureau of Mines, Denver, CO.

INTRODUCTION

This study addresses the international availability of the element chromium (Cr) contained in chromite products and in the refined form of its most significant primary metallurgical product, high-carbon ferrochromium. The study evaluates the geologic, engineering, and economic determinants of 80 significant deposits, operating properties, or districts, within 10 market economy countries, that contain chromite of a quality[3] sufficient for the manufacture of at least 52 pct (contained chromium) ferrochromium or chromite sufficient for use in the refractory industry.[4] The 10 countries included in the engineering and economic cost analyses are Brazil, Finland, Greece, India, Madagascar, New Caledonia, the Philippines, South Africa, Turkey, and Zimbabwe.

The major engineering and geologic factors affecting the availability of chromium in each country are addressed, including quality and quantity of chromite reserves and resources, mining and beneficiation methods and costs, ferrochromium production methods and costs, and modes and costs of transportation.

The major economic and policy issues surrounding this industry are also addressed. These issues are centered on the relative quantity and quality of resources, comparative costs of production and transportation, capacity and location of downstream processing stages, developmental constraints upon the industry, and governmental policies that impact upon it. The following section presents an overview of the mineral and commodities in question in order to define and sharpen the perspective of the analysis.

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[3] Chromite with at least a 1.3 Cr:Fe ratio and less than 52 pct contained Al_2O_3.
[4] Chromite with at least 20 pct contained Al_2O_3 and 60 pct combined $Al_2O_3 + Cr_2O_3$.

COMMODITY OVERVIEW

Chromium is a commodity of critical importance that imparts unique qualities to the material to which it is added. It is essential in the production of stainless steel and high-temperature-resistant superalloys having numerous and essential industrial and defense-related applications. There is currently no element that can act as a total substitute for chromium in the manufacture of stainless steel. Certain elements are partial substitutes for chromium in the production of some steels, with certain acceptable quality reductions. These partial substitutes, however, such as cobalt, molybdenum, nickel, niobium, and vanadium, are all priced 3 to 10 times as high as chromium. In addition, although the known-world resources of chromium exceed those of its partial substitutes, these resources are geographically concentrated in a very limited number of countries.

The only known commercial source of chromium (Cr) is in ores in which the mineral chromite occurs with other gangue minerals, usually silicates and ferruginous oxide minerals. The ore containing the chromite and gangue minerals is commonly referred to as "chromitite." The mineral chromite is a member of the spinel group and has a chemical composition of $FeCr_2O_4$. In its purest natural form, in situ chromite contains 68 Cr_2O_3 (chromic oxide), although seldom does it contain more than 55 pct. The grade of an in situ chromite resource and the products resulting from its extraction (ore and concentrates) are most often quantified in terms of this Cr_2O_3 content, with most products ranging from 38 to 55 pct Cr_2O_3 to be acceptable for marketing. However, once these products are further smelted to produce ferroalloy products, the grading system is based on the chromium content of the ferroalloy. Thus, where the availability of ferrochromium alloy production is addressed, a standard of 68 pct contained chromium (Cr) in Cr_2O_3 was utilized to determine the content of chromium in chromite products.

Chromium in the form of ore and concentrate (chromite) is classified as either high-chromium chromite or high-iron chromite, depending upon the percentage of contained chromium relative to contained iron (i.e., Cr:Fe ratio), or as high-alumina chromite depending upon the percentage of contained alumina (Al_2O_3). The standard applied throughout this report is to define high-chromium chromite (hereafter referred to as high-Cr) as that which has a Cr:Fe of $\geq$2:1, high-iron (hereafter referred to as high-Fe) chromite as having a Cr:Fe ratio of <2:1, and high-alumina chromite as containing >20 pct Al_2O_3.

Chromite products are employed in many uses, the markets for which were traditionally defined as metallurgical, chemical, and refractory. By far the most significant market for chromite is the metallurgical industry, which consumes both high-Cr and high-Fe chromite. The products produced by this industry are high-carbon and low-carbon (hereafter referred as to high-C and low-C) ferrochromium of varying types and specifications (i.e., amount of contained chromium, carbon, etc.), ferrosilicon chromium, and chromium metal, all of which are primarily consumed as intermediate products in the manufacture of stainless and superalloy steels. The chemical market, utilizing high-Fe chromite, produces sodium dichromate (a chemical base product), from which a wide range of other products and applications are derived. High-alumina chromite is primarily consumed in the manufacture of refractory bricks for use in the steel industry.

Both high-Cr and high-Fe chromite are acceptable for the production of ferrochromium. The most significant difference is that high-Cr chromite produces a ferroalloy product that contains more chromium than does high-Fe chromite. This basic relationship is shown in figure 1; the curve represents a "generalized" functional relationship between the Cr:Fe ratio of chromite, the classification of chromite, and the amount of contained chromium present in a refined ferrochromium product. This generalized relationship is used in this study to define three ferrochromium product grades. Thus, all grade-C (also called "charge") ferrochromium is defined as containing approximately 50 to 55 pct Cr and is produced from high-Fe chromite with a Cr:Fe ratio of <1.8. Grade-B ferrochromium, defined as containing 56 to 64 pct Cr, is generally produced from chromite with Cr:Fe ratios ranging from 1.8 to 2.5. Grade-A ferrochromium, defined as containing in excess of 64 pct Cr, is produced from high-Cr chromite with Cr:Fe ratios >2.5.

During the course of the last decade the composition of ferrochromium production has changed dramatically. In the stainless steel industry, the widespread adoption of the argon-oxygen-decarburization (AOD) process for the manufacture of stainless steel has resulted in a very significant shift away from the production of low-C, high-Cr ferrochromium in favor of high-C, low-Cr ferrochromium since the AOD steelmaking process allows for the addition of ferrochromium with a lower chromium and higher carbon content.

This has blurred the traditional distinction between chemical- and metallurgical-grade chromite that was based in part upon whether the Cr:Fe ratio was $\geq$2 or <2. Furthermore, because the production of low-C ferrochromium requires further processing to reduce the carbon content, the high-C product is always less costly. Of particular importance to this study, however, is the fact that in either case the high-C form is always the first stage product from chromite ore or concentrate, except in limited cases where chromite ore is smelted directly with ferrosilicon chromium for the production of low-C ferrochromium.

During the last 15 yr, the shift to high-C ferrochromium as a percentage of total ferrochromium production and consumption has been large, rapid, and increasing through time. In the United States, for example, of all chromium ferroalloys consumed in the manufacture of stainless steel in 1968, 47 pct were low-C and 28 pct high-C; by 1980 low-C ferrochromium had decreased to 6 pct of this total, while high-C had increased to a predominant 80 pct (*1*, p. 276; *2*, p. 192).

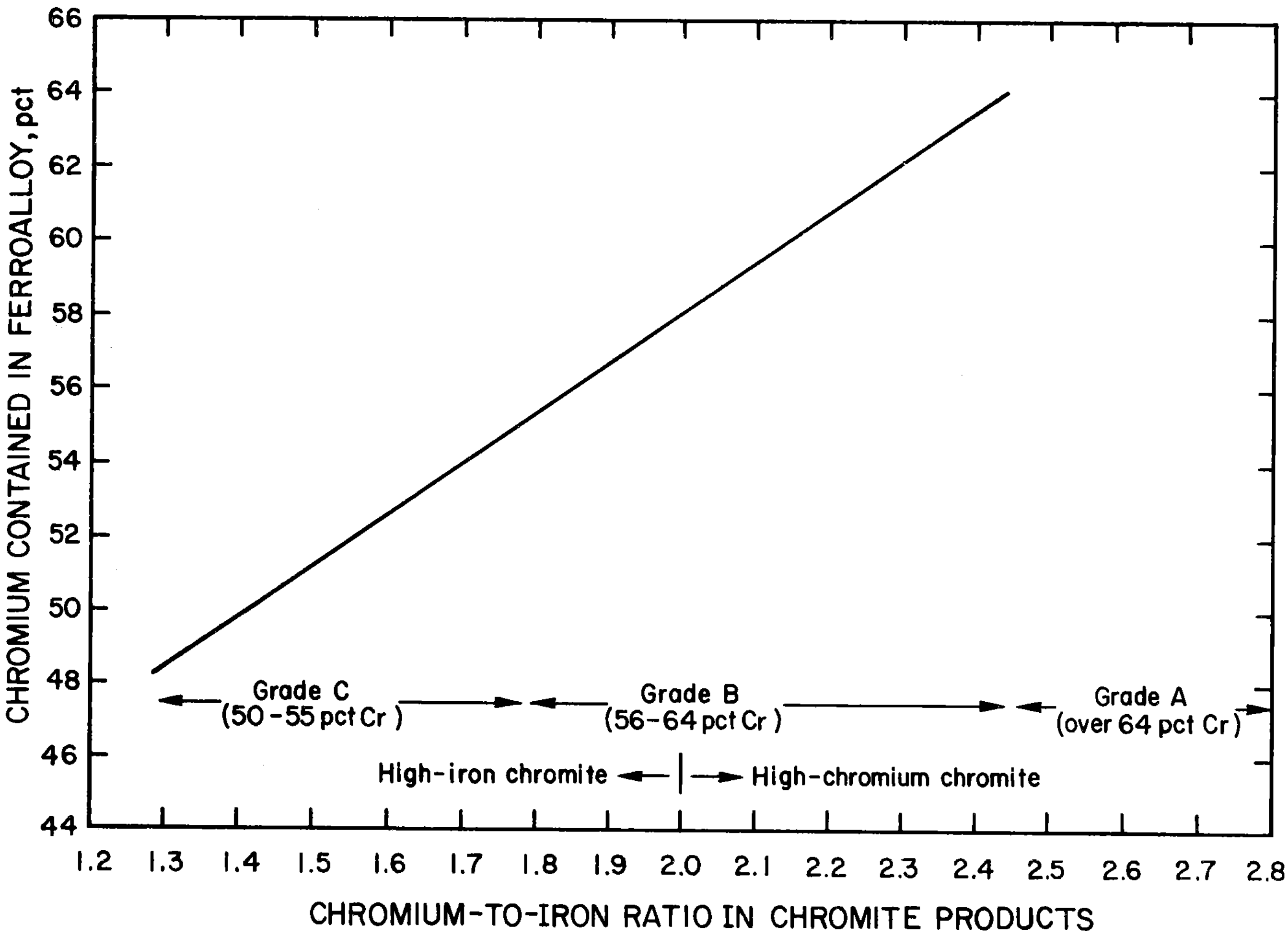


Figure 1. — Relationship between Cr:Fe ratio of chromite ores and chromium contained within a ferroalloy product.

This technological change has resulted in a massive locational restructuring of the international ferrochromium industry. Within the context of mineral availability, this can best be expressed by an examination of the installed ferrochromium smelting capacities of the major producing countries. In 1972, it was reported that the Republic of South Africa had an installed capacity of 290,000 tpy (*3*, p. 10). By 1982, this had increased dramatically to 800,000 tpy (*4*, p. 94). By contrast, the United States was estimated to have had an installed capacity in 1972 of 390,000 tpy (*3*, p. 10), which has subsequently declined to 145,000 tpy by 1982 (*4*, p. 97).

Other major ferrochromium-producing areas are Japan and western Europe, both of which import almost all chromite raw material requirements. Japan's capacity in 1980 was around 700,000 tpy and is primarily dependent upon South Africa for its chromite supply. Other import sources are the Philippines and India. Western Europe's capacity (with the exception of Sweden and Finland), like that of the United States, has been declining. Great Britain and France basically have no ferrochromium smelting capacity; Spain, Norway, and Italy are only small producers. West Germany now maintains most of the capacity within the European Economic Community (EEC). Western Europe also primarily obtains its chromite imports from South Africa, with the U.S.S.R., Turkey, Finland, and recently Albania as secondary sources.

The cycles of the world chromium industry are inextricably tied to the level of world economic activity in general and the world steel industry in particular. Chromium is an intermediate-product industry and as such its growth and contraction are dependent upon the demand for those products that employ it as a raw material input. Although the percentages fluctuate somewhat, the metallurgical industry remains by far the largest and most important consumer of chromite, and high-C ferrochromium has become its most important product. The purpose of this study, within this context, is to ascertain the relative economics of the chromium-commodity-availability base, within the countries analyzed, in the form of chromite products and high-C ferrochromium products.

METHODOLOGY OF ANALYSIS

The analyses performed for the purposes of this study involved geologic, engineering, and economic evaluations.

The geologic aspects particular to each current or proposed chromite operation included in the study were determined in order to develop estimates of the demonstrated and identified resource levels (see fig. 2) and in situ grades. In situ resource tonnages are reported in metric tons,[5] in situ grades in percent Cr_2O_3. The geologic discussion in each section of the report includes a description of the physical criteria and assumptions made in the determination of the resource estimates. A tabular summarization of the demonstrated and identified resource tonnages, in situ chromite grades, and the amount of contained chromium at the demonstrated level, on a property by property basis, is presented for each country. All resource estimates are as of January 1980.

It is recognized that the chromium industry is very diverse. It is not uncommon, for example, for a single mining operation to produce a mix of high-Cr, high-Fe, or refractory-grade chromite products of differing Cr_2O_3 grades and product sizes. In addition, this product mix can change according to changing market circumstances under which the firm is operating. For this reason, certain simplifying assumptions were necessary in order to address the world chromium industry in comparative terms with a long-run perspective. In order to ascertain the relative cost and availability of chromite by mining operations and countries, the resources were classified according to predominant types of chromite present, either high-Fe, high-Cr, or high-alumina. The high-alumina (refractory-grade) chromite was not further evaluated for the production of high-C ferrochromium because of technological processing problems in smelting such products. High-C ferrochromium was chosen as a ferroalloy product for comparative purposes because of its aforementioned predominance in the metallurgical industry.

The demonstrated resource level was employed for costing purposes in order to determine the relative economic position of each operation and each country studied. For cost analysis, all cost and resource estimates were updated to January 1981. In order to ascertain the cost and availability of chromium in the form of ore and concentrate (chromite availability), mining and beneficiation methods and costs were developed according to actual or proposed development plans and associated production capacities, including all announced capacity expansions. The estimates of mining and beneficiation operating costs are composed of three components:

- direct and indirect labor costs
- equipment operation costs
- material and supplies cost

The operating cost estimates do not include:

- allowances for capital recovery (depreciation)
- taxes
- royalties
- interest charges or
- reinvestments in plant and equipment

These costs are calculated and entered into the analyses separately.

The engineering evaluation outlines these major mining and beneficiation production methods and operating parameters, as well as the percentage con-

[5] In this report, "ton" refers to the metric ton (2,204.8 lb), except where otherwise indicated.

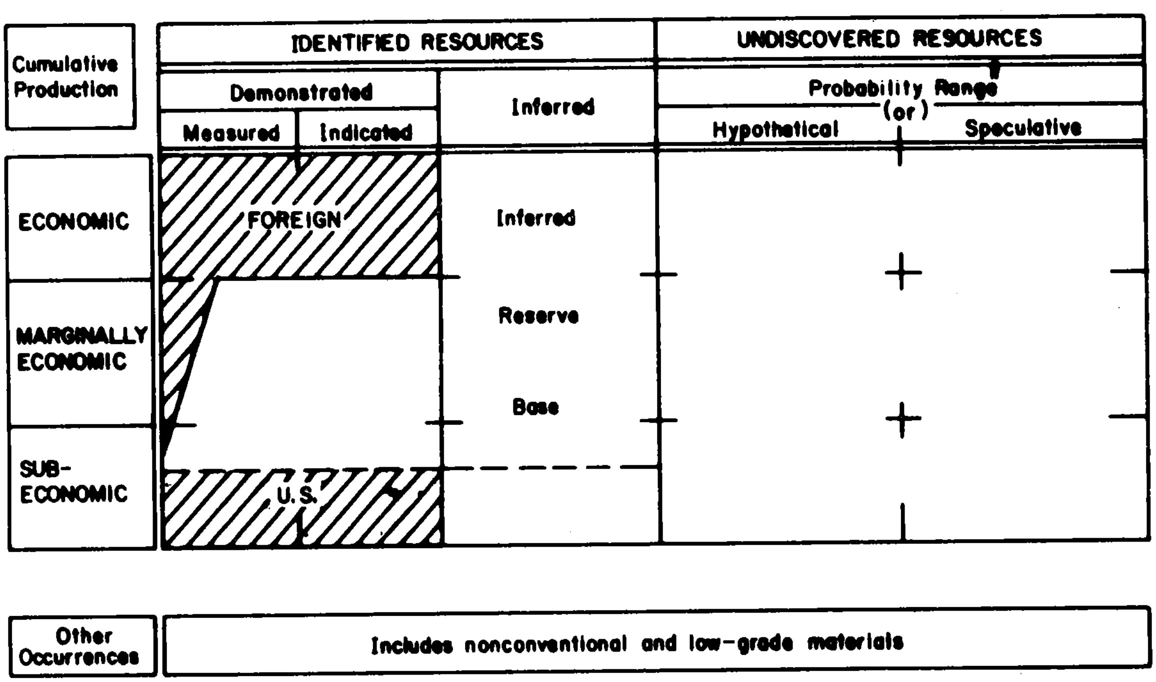


Figure 2. — Classification of mineral resources.

tribution of each of the three components to operating cost. In addition, mining and milling capital costs, and any exploitation problems which are significant in affecting the availability of chromite from the demonstrated resource tonnages that were determined, are also addressed.

In order to rank the operations and countries by resource level and degree of economic competitiveness, all mining and beneficiation operating costs and chromite transportation costs were recalculated for each operation *on a per-ton-of-mill-product basis* and aggregated as weighted averages, by country, along with each country's total potential availability of chromite in tons.

Also calculated is a measure of the amount of crude ore that must be mined in order to produce 1 ton of salable chromite product. This measure is defined as the "concentration ratio" and addresses the quality of the host country's chromite resources from a mining-efficiency point of view.

To determine the cost and quantity of high-C ferrochromium potentially available from these demonstrated chromite resources, by ferrochromium product grade (i.e., grade A, B, or C), the analyses were expanded to include:

- ferrochromium smelting methods
- smelter operating and capital costs
- chromite and ferrochromium transportation and handling costs
- smelting capacities and
- all announced expansions to existing capacity or construction of new facilities

In addition, interest on debt and all existing foreign country tax structures that relate to capital recovery and taxation of income were also incorporated into the analyses in order to perform a complete economic evaluation.

The economic evaluation of each operation was performed using discounted cash flow rate of return (DCFROR) techniques. This evaluation determines the long-run average total cost of producing high-C ferrochromium from each operation over its producing life. The average total cost is equal to the constant-dollar long-run price at which the commodity must be sold, so that the present value of revenues equals the present value of all costs including a prespecified rate of return.

For this study, rates of return of 0 and 15 pct were specified when determining the average total cost of production over the life[6] of a property. The first rate (0 pct) is used to determine the breakeven point, where revenues are sufficient to cover total investment and production costs over the operation's life but provide no positive rate of return. This rate would reflect the investment parameters of a project given only market share or developmental concerns, where potential multiplier effects (i.e., social benefits) would offset company-operation-specific profitability. For privately owned enterprises or those not strictly developmental in nature, a more reasonable economic decisionmaking parameter is that represented by the 15-pct DCFROR. This rate was considered the minimum sufficient to maintain adequate long-term profitability and attract new capital to the industry. Within these two economic horizons lies the cost structure of the operations and countries in question.

The availability of *the commodity* (chromite or ferrochromium) from an operation is presented in this study as a function of the average total costs associated with it. Availability curves are constructed as aggregations of all evaluated operations ordered from those having the lowest average total costs to those having the highest. The potential availability of *the commodity* can be seen by comparing the expected long-run constant dollar market price to the average total cost values shown on the availability curves.

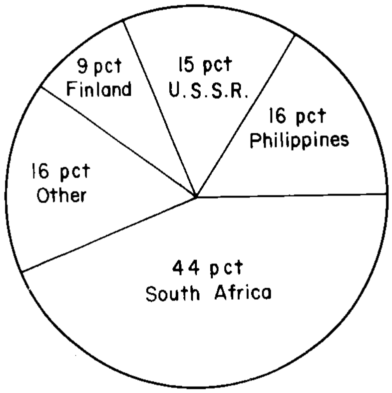
This report is presented in country sections to allow for a complete discussion of the costs, commodity availabilities, and future production and export potential for each of the nations under study. An executive summary has been prepared which summarizes each country section, presents cross-country comparative discussions of chromite and ferrochromium product costs and availabilities, and addresses the relative resource and economic position of each nation. The relative position of the United States and its perspective from the point of view of a major importer of both chromite and ferrochromium, and the mineral policy issues this presents, are addressed in the following section.

THE U.S. PERSPECTIVE

In general, U.S. import reliance for the element chromium is 91 pct, with secondary recovery accounting for the remaining 9 pct. The United States has produced chromite in the past, most notably during the Korean War period, but is currently dependent entirely upon imports for its chromite consumption requirements. A recent Bureau of Mines report (*5*) evaluated the potential of domestic chromium-bearing resources and determined that if these resources were fully developed (an unlikely event) the production potential would be small and of short duration. In addition, market prices for chromite concentrates and ferrochromium products would have to increase substantially in order for any domestic-resource-based production to become economic.

The major suppliers of chromite to the United States (fig. 3) are South Africa (predominantly high-Fe chromite), Turkey and the Soviet Union (high-Cr chromite), and the Philippines (refractory-grade chromite). During the period 1977-80, South Africa

[6] The project life of each property evaluated was determined by assuming that the property would be operated at 100 pct of designed mine capacity for producing operations, or for nonproducing operations, as determined according to the engineering development plan that was derived. The mine life covers only the demonstrated resource level.



1977 - 80, average

Figure 3. — Chromite import market shares by country.

alone accounted for 44 pct of all U.S. chromite imports (*6*, p. 32). The Philippines has accounted for roughly 16 pct of U.S. imports, almost entirely refractory grade (*6*, p. 32). The Soviet Union has averaged around 15 pct of total U.S. chromite imports during the 1977-80 period, declining through time as a major supplier of chromite relative to South Africa (*6*, p. 32). This trend is expected to continue. The other communist bloc country with a significant share of U.S. chromite imports is Albania, which accounted for 10 pct of U.S. chromite imports in 1979 (*2*, p. 195).

Reliance upon imported chromite has been the case in the United States for decades, the major concern being diversification of supply sources. Of much greater importance and concern, however, is the ever-increasing shift to reliance upon ferrochromium imports as opposed to domestic production of ferrochromium from imported chromite (*7*, pp. 173-4). Table 1 presents data on ferrochromium, reported in terms of contained chromium, for domestic shipments, imports, exports, inventory adjustments, reported and apparent consumption, and a measure of import reliance. As the data indicate, there has been a noticeable upward trend in reliance upon chromium imported in the form of ferrochromium. Prior to 1975, ferrochromium imports from all countries averaged 28 pct of apparent chromium consumption. Since 1975, import reliance has doubled, averaging 61 pct of apparent consumption, with 1981 posting an import reliance figure of 76 pct.

This trend is also expected to continue. As a result, domestic ferrochromium capacity has continued to close and utilization of existing capacity has remained at low levels since 1980. It is estimated that capacity utilization in 1982 could be as low as 30 pct. A number of measures have recently been taken by the ferroalloys industry to counteract this trend, including successful petitions filed with the International Trade Commission (ITC) (covering the period from November 15, 1978, to November 15, 1982) imposing a minimum floor price of $0.38/lb contained Cr on high-C ferrochromium imports and a $0.04/lb penalty duty on imports entering the United States below the floor price. This penalty duty has expired.

One of the most important issues as regards tariff levels (duties, minimum prices, etc.) is the determination of production cost differentials between ferrochromium produced in the United States from imported South African chromite, and the cost of ferrochromium produced in South Africa and exported to the United States. A recent ITC study (*8*, p. A-53) determined a $0.034/contained-Cr cost advantage, as of 1981, for high-C ferrochromium produced in South Africa and delivered to the United States as opposed to the same chromite processed to the same product in the United States. The importance of this issue is easily illustrated by the fact that for the years 1977-81, South African high-C ferrochromium imports have accounted for 73 pct of the U.S. total. This trend of reliance upon South Africa has been steadily increasing. As shown in figure 4, South Africa's market share has effectively doubled during the 1970's. Zimbabwe's import market share has fluctuated noticeably (from a high of 40 pct in 1973 to essentially zero in 1978 and 1979), due to civil war and trade embargos that disrupted normal trading patterns. Yugoslavia and Brazil have maintained relatively constant market shares, while Japan and Finland no longer account for noticeable percentages.

Imposing import quotas is another possible action to help maintain an adequate level of ferrochromium capacity, but this could require, among other things, that the ferroalloy industry be deemed essential to the

Table 1. — U.S. ferrochromium market data,[1] high- and low-C ferrochromium, 1970–82
(Thousand metric tons of contained chromium)

Year	Domestic shipments	Imports	Exports	Inventory adjustments	Consumption		Import reliance,[2] pct
					Apparent	Reported	
1970	187	24	17	− 1	195	165	12
1971	155	49	5	+10	189	153	26
1972	148	82	8	+ 5	217	187	38
1973	220	95	9	− 9	315	246	30
1974	199	93	4	− 8	296	283	31
1975	101	180	8	+38	235	158	76
1976	119	136	8	+ 5	242	194	56
1977	122	122	7	− 8	245	218	50
1978	112	165	11	− 9	275	248	60
1979	137	123	9	− 9	260	273	47
1980	112	158	19	− 4	255	213	62
1981	81	224	8	+ 4	293	216	76
1982	45	77	3	−14	134	133	58

[1] All data subject to conversion and rounding.
[2] Imports as a percentage of apparent consumption.

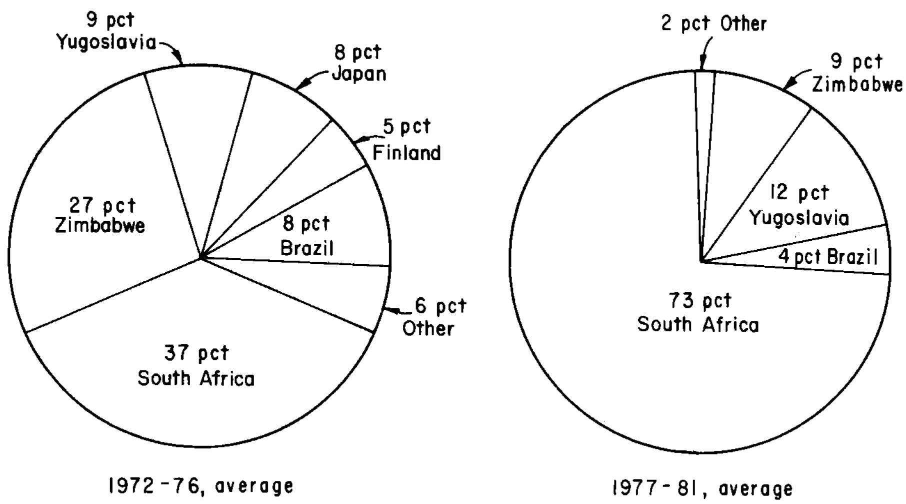


Figure 4. — Ferrochromium import market shares by country.

national security. Also, the idea has been advanced that the chromite stockpile be converted to ferrochromium by the domestic ferroalloy industry as a way to increase capacity utilization. However, current stockpile inventories of high-and low-C ferrochromium are in excess of the stated objectives, and there is the added concern for stockpile obsolescence if the chromite is converted to ferrochromium.

The major mineral policy issues and questions for the United States, then, are (1) to ascertain the cost and availability of chromite from current and potential international sources, (2) to determine the cost and availability of high-C ferrochromium from current and potential sources, (3) to attempt to diversify both sources of chromite and ferrochromium imports, and (4) to maintain an adequate level of domestic ferrochromium capacity. This study specifically addresses these issues and questions.

SUMMARY

CHROMIUM RESOURCES

Chromium contained within chromite ore occurs primarily in podiform, stratiform, and eluvial deposits. Podiform deposits occur as irregular pods or lenses and have relatively similar sizes in all three dimensions; i.e., length, thickness, and extension to depth. Stratiform or seam-type deposits occur as layers. They are commonly traceable over many kilometers (i.e., large strike lengths) and have large extensions to depth (along the dip of the seam) but very small thicknesses of the seam relative to the length and depth extension. Eluvial, alluvial, lateritic, and "soil" deposits are all loose definitions of various types of chromium-rich soils derived from the weathering of podiform or seam-type deposits with reconcentration either in situ (eluvial) or transported and reworked (alluvial). Podiform and stratiform are primary deposits, whereas eluvial deposits are secondary.

Table 2 lists the names, producing status, and predominant type of resource occurrence of all 80 operations comprising the cost-evaluated demonstrated resource that was estimated for the availability study. An in situ demonstrated resource of approximately 1.2 billion t was estimated to be contained within these 80 operations in the 10 nations under study. The relationship of this 1.2 billion t of cost-evaluated resource to estimates of the total demonstrated and identified resource levels for these 10 countries is illustrated in figure 5. This 1.2 billion t, although a small percentage (17 pct) of the total demonstrated resource available in these nations, still represents over 60 yr of total world consumption of chromite for all end-use applications. As indicated in figure 5, effectively 100 pct of the remaining non cost-evaluated tonnage is contained within Zimbabwe and the Republic of South Africa. Figure 6 and supporting data in table 3 provide a percentage breakdown, by country, of the cost-evaluated tonnage.

Two nations, Zimbabwe and South Africa, contain approximately 70 pct of this total. The estimates for these two nations are but a small subset of their potential, with total in situ estimates for South Africa ranging from 3.096 billion t (*9*, p. 55) to as high as 16 billion t (*10*, p. 120); for Zimbabwe, estimates run as high as 10 billion t.[7] For the purpose of cost evaluation, these subsets were calculated according to specific property information and geologic criteria as detailed in the text. However, just these small subsets themselves represent over 50 yr of potential total world consumption. If the analysis were expanded to include a *complete geologic estimate* of world chromium re-

[7] Confidential source.

Table 2. — Name, status, and resource type of the 80 operations comprising the cost-evaluated demonstrated resource level, as of January 1981[1]

Name	Type of occurrence	Status[2]
South Africa:		
Zwartkop	Stratiform	P/S
Consolidated Chrome	do	P/S
Ruighoek	do	P/S
Ntuane	do	P/S
Waterkloof	do	P/S
Millsell	do	P/S
Kroondal	do	P/S
Rustenburg (Chrome Chemicals)	do	P/S
Henry Gould	do	P/S
Mooinooi	do	P/S
Ucar Chrome	do	P/S
Winterveld (TCL)–North Section	do	P/S
Groothoek	do	P/S
Dilokong	do	P/S
Montrose (Hendriksplaats)	do	P/S
Winterveld (TCL)–South Section	do	P/S
Lavino (Grootboom)	do	P/S
Grasvally	do	P/S
Marico (Nietverdiend)	do	P/S
Zeerust	do	P/S
Zimbabwe:		
Glenapp-Ivo	do	P/S
Impinge	do	P/S
Sutton-Rodcamp	do	P/S
Vanad	do	P/S
Caesar	do	P/S
Crown-Divide North	do	P/S
Glenapp-Hay-Noro	do	P/S
Umvukwes	do	P/S
Ore Recovery Tribute	do	P/S
Greenvale	do	P/S
Maryland	do	P/S
McGowan	do	P/S
Divide	do	P/S
Rutala	do	P/S
Umsweswe	do	P/S
Umsweswe-Bee	do	P/S
Windsor-York-York West	do	P/S
Bat Claims	do	P/S
Cambrai	do	P/S
Netherburn	do	P/S
York	do	P/S
Railway Block	Podiform	P/S
Selukwe Peak	do	P/S
Zimbabwe — Continued:		
Valley Chrome	Podiform	P/S
Magazine Hill	do	P/S
Iron Sides	do	P/S
Iron Ton	do	P/S
Belingwe District	do	P/S
Impinge (eluvial)	Eluvial	P/S
Turkey:		
Kefdag	Podiform	P/S
Soridag	Stratiform	P/S
Kavak	Podiform	P/S
Kopdag West-North Zone	do	P/S
Uckopru	do	P/S
Kandak	do	P/S
Philippines:		
Masdang	do	E
Narra	do	P/S
Acoje (Santa Cruz)	do	P/S
Candelaria	do	E
Lagonoy	do	P/S
Llorente	Eluvial-alluvial	E
Bicobian	Lateritic-eluvial	E
Batang-Batang	Alluvial	E
Bacungan	Podiform-eluvial	P/S
Irahuan	do	E
Coto-Masinloc	Podiform	P/S
Kinmalgin	do	P/S
India:		
Byrapur	do	P/S
Jambur-Tagadur	Stratiform	E
Cuttack District:		
Low grade	Stratiform-podiform	E
High grade	do	P/S
Keonjhar District:		
Low grade	do	E
High grade	do	P/S
Brazil:		
Pedrinhas (Campo Formoso)	Stratiform	P/S
Limoeira (Campo Formoso)	do	P/S
Finland: Kemi	do	P/S
New Caledonia: Tiebaghi	Podiform	P/S
Greece: Xerolivado	do	P/S
Madagascar:		
Andriamena	do	P/S
Ranomena	do	P/S

[1] The term "operation" refers to either an individual mine or group of mines, or an area, section, or district, depending upon the criteria of each individual nation under study.

[2] The status is listed as either P/S or E. If listed as P/S, the operation is either a current or past producer. If listed as E, *no* production had occurred as of January 1981.

sources on an identified basis (demonstrated *plus* inferred resources) these two southern African nations would represent over 95 pct of the total, which could be as high as 27 billion t or more.

Six nations constitute the "others" category, which comprises only 6 pct of the total cost-evaluated resource estimate. The remaining two nations, India and the Philippines, have recently increased their level of resources and represent 7 and 16 pct of the total, respectively. India's demonstrated resource level has been increased primarily by lowering the cutoff grade of the Cuttack and Keonjhar districts, used for defining the resource estimate, to 30 pct Cr_2O_3. The resource estimate for the Philippines includes recently investigated large tonnages of very low grade eluvial deposits. These deposits contain smaller amounts of recoverable Cr_2O_3 relative to their in situ tonnage estimates than do podiform-type deposits in countries, such as Turkey and New Caledonia, which have smaller in situ tonnage estimates but much higher Cr_2O_3 grades.

The world chromium industry developed historically around the exploitation of these high-grade, podiform-type resources of limited tonnage. As they are depleted, the trend in production toward dominance by very large tonnage, seam-type resources will continue. These seam-type resources are located almost entirely in Zimbabwe and the Republic of South Africa.

In addition to the operations and nations extensively evaluated in this report, there exist other deposits and/or countries that may produce chromite in the future. These deposits, listed in table 4, were not evaluated at the time of this study because insufficient information existed concerning the geologic, engineering, and economic determinants to allow for a complete cost evaluation. Future research concerning the availability of chromium in the market economy countries should also concentrate on these deposits.

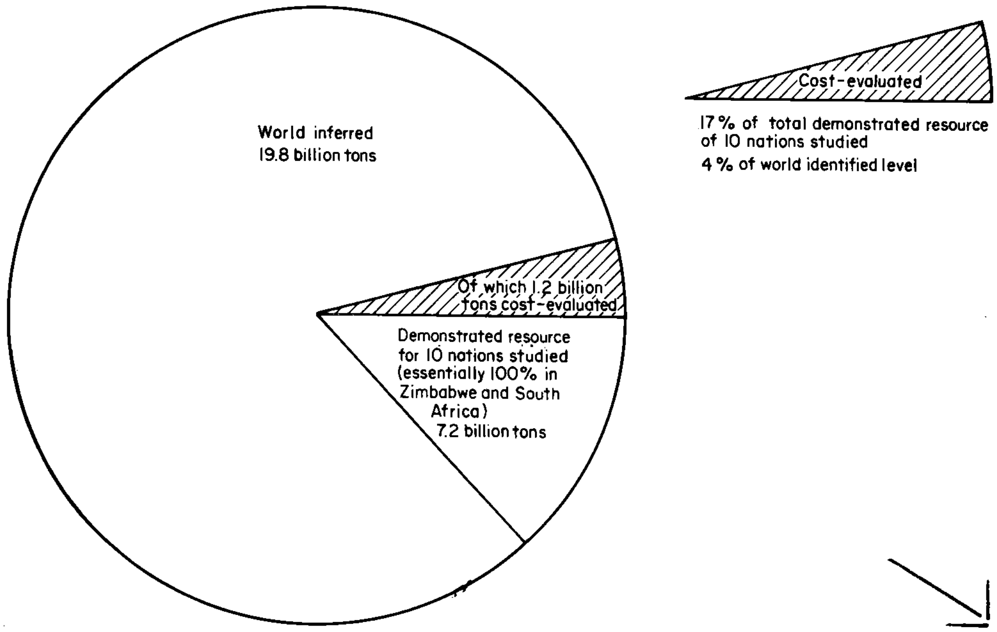


Figure 5. — Relationship of cost-evaluated tonnage to an estimate of the total demonstrated and identified resource levels within the 10 nations under study.

Table 3. — Summary of cost-evaluated in situ chromium-bearing resources

Country	Demonstrated resource, 10^3 t	Percent of total tonnage	Weighted-average grade, pct Cr_2O_3	Contained Cr_2O_3, 10^3 t
South Africa	637,876	53.0	41.0	370,227
Zimbabwe:				
Seam type	175,000	NAp	49.0	NAp
Podiform type	16,900	NAp	46.5	NAp
Eluvial soil	4,700	NAp	20.0	NAp
Total or average	196,000	16.5	49.0	94,329
Turkey	[1] 11,630	1.0	38.0	4,500
Philippines:				
Low grade	178,495	NAp	2.0	NAp
High grade	[2] 12,301	NAp	30.3	NAp
Refractory	[3] 16,960	NAp	26.0	NAp
Total or average	207,756	17.5	5.6	11,716
India	81,230	7.0	32.0	26,000
Brazil	[4] 17,000	1.4	21.0	2,900
Finland	29,200	2.4	27.0	7,884
New Caledonia	2,300	.2	44.0	1,012
Greece	2,200	.2	18.0	396
Madagascar	10,250	.8	31.6	3,270
Grand total	1,196,000	100.0	NAp	522,234

NAp Not applicable.

[1] Does not include the many small deposits and operations, representing 20 to 30 pct of Turkey's overall total production of chromite products, which are too small or sporadic to evaluate for costs.

[2] Does not include 21 deposits containing about 1.8 million t of in situ resources; 18 are very small (average 40,000 t reserve); 3 are fairly large (average 360,000 t). Small size or lack of data precludes estimation of costs.

[3] Does not include 12 deposits containing about 1.1 million t of in situ resource; 10 are very small (average 50,000 t); 2 are fairly large (average 300,000 t).

[4] Represents resource in the Campo Formoso District only.

COMPARATIVE CHROMITE AVAILABILITY

This section presents a brief cross-country comparative summary of chromite production costs and availability. Table 5 and figure 6 provide an overview of relevant chromite product cost and availability data for the 10 countries studied in the cost evaluations. As illustrated in figure 6, there are approximately 632 million t of chromite products potentially recoverable from the 1.2 billion t of chromium-bearing material contained within the 80 operations, deposits, and districts of these 10 nations. Over 85 pct of the total recoverable chromite is contained within just two nations, Zimbabwe and South Africa, with South Africa alone accounting for 65 pct of total chromite availability.

All other country product tonnages are quite small by comparison. This concentration of chromite resources in South Africa, in and of itself, should ensure that the world chromite industry will be increasingly dominated by the cost and production levels of this country.

The great majority (82 pct) of the total cost-evaluated chromite tonnage is potentially recoverable at a combined long-run mining, beneficiation, and transportation cost level, FOB the port of exportation, of \$100/t. Of this overall total, 80 pct is contained within the South African operations. At a long-run cost level of \$65/t of product, about 37 pct of the total tonnage is potentially recoverable, and of this total, 80 pct is also contained within the South African operations. Therefore, it can be expected that the South African mines will increasingly establish the long-run average cost level for the world chromite industry as a whole. This infers that in periods of weak demand and low or falling prices for chromite, the South African producers will dominate a very large part of the market since they represent by far the greatest availability of low cost products. In addition, in periods of high demand and rising prices, the South African industry, with its ability to expand mining capacity relatively quickly with scale economies, will provide a moderating effect upon prices, thereby ensuring long run dominance of the market.

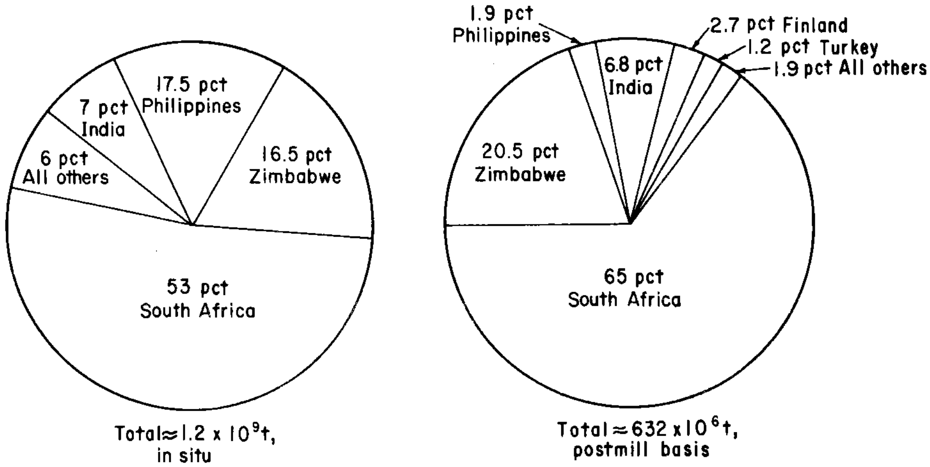


Figure 6. — Percentage distribution, by country, of total cost-evaluated in situ tonnage and total chromite product availability.

Table 4. — Other chromite resources, market economy countries[1]

Country	Deposit	Type of resource	Estimated in situ tonnage, 10^3 t	Grade, pct Cr_2O_3	Cr:Fe ratio	Problems and status
Australia	Coobina	High-grade, podiform-type deposits.	2,100	28–49	1.5	Remote location, refractory-grade material.
Canada	Winnepeg District	...do	18,600	8.7	1.0–1.48	Very low Cr:Fe ratios.
Greenland	Fiskenaesset	Low-grade, seam-type deposits.	2,500	20–26	1.0–1.2	Remote location, very low Cr:Fe ratio.
Indonesia	None announced	Residual deposits and laterites.	NA	NA	NA	Exploration being conducted for low-grade eluvial chromite deposits. Also chromite in Ni-Co laterites.
Papua New Guinea	Ramu River	...do	100,000	5–10	NA	Remote location, low-grade, some of economics will depend on Ni-Co laterite technology and economics.
South Africa	East and West Bushveld Complex.	UG2 seam	630,000	5.5	1.2–1.3	Extractable at certain operations on the Complex, but economic and marketing aspects questionable. Low Cr:Fe ratio of concentrate product. More promising for platinum values.

NA Not available.
[1] Not evaluated in this study for product availability or costs. Major questions of geology, economics, technology of extraction, or marketability raise doubts about production for the near term. In addition to these nondeveloped resources, other countries such as Cyprus, Iran, Japan, Pakistan, and Sudan do produce very small amounts of chromite (140,000 t combined production for 1980) and, of this total, 82,000 t represents Iranian production.

Table 5. — Total chromite product availability and weighted-average mining, beneficiation, and transportation costs, by country
(1981 U.S. dollars)

Country	Total chromite potential, 10^3 t	Pct of total estimate	Weighted-average shipping grade, pct Cr_2O_3	Concentration ratio, crude ore to chromite product	Weighted average cost per metric ton concentrate			
					Mining	Beneficiation	Transportation[1]	Total cost[2] (FOB port)
South Africa	412,000	65.0	43.0	1.2	$35.00	$4.00	$26.00	$65.00
Zimbabwe:								
Seam type	116,660	18.5	NAp	1.1	84.50	2.25	27.50	114.25
Podiform type	12,682	2.0	NAp	1.2	29.50	6.00	28.00	63.50
Total or average	129,342	20.5	50.0	1.1	79.00	2.50	27.50	109.00
India	43,000	6.8	46.0	1.5	42.50	5.00	17.00	64.50
Finland	17,112	2.7	31.0	1.6	9.50	6.5	9.00	25.00
Philippines:								
High grade	6,200	1.0	NAp	1.8	22.50	5.50	7.50	35.50
Low grade	5,912	.9	NAp	30.0	33.50	55.50	12.00	101.00
Total or average	12,112	1.9	47.0	15.3	28.00	29.50	10.00	67.50
Turkey	7,600	1.2	46.0	1.3	35.00	5.00	59.50	99.50
Brazil	4,618	.7	44.0	3.5	65.50	11.50	31.50	108.50
Madagascar	3,877	.6	49.0	2.5	31.00	16.00	19.50	66.50
New Caledonia	1,700	.2	51.0	1.3	42.50	7.00	7.00	56.50
Greece	500	.09	51.0	3.5	57.50	18.00	35.00	110.50
Grand total	631,946	100.0	NAp	NAp	NAp	NAp	NAp	NAp

NAp Not applicable.
[1] Includes handling charges.
[2] Total mining plus milling plus transportation cost per metric ton of concentrate. Does not include taxes, depreciation, interest, or allowance for profit.

At the 1979 world production rate of 10.5 million tpy of chromite products, there is approximately 60 yr of recoverable chromite available for consumption from just the 1.2 billion t of demonstrated resource (632 million t of chromite products) herein evaluated. The obvious conclusion is that there is no shortage of chromite resources nor serious (quantitative) supply problems, given the ability of South Africa (and to a lesser extent Zimbabwe) to expand their productive capacities, as well as the emergence of potentially significant tonnages available from India and the Philippines. The major issue of concern is the current concentration of productive capacity in southern Africa.

The level of chromite demand depends upon the level of steel and chemical market demand, which in turn is based upon the level of general economic activity. The question of which mining operations and countries will provide the supply that fulfills the demand will depend primarily upon production costs (including transportation) and the resource base; the lowest cost producers with the largest resource base should increasingly serve as world industry suppliers. However, other factors such as risk, bilateral agreements, political changes, etc., will also impact upon which mines and/or countries will provide future supply.

From a long-term point of view, it can be expected that an increasing percentage of chromite supply will come from seam-type deposits, such as South Africa and Zimbabwe, as the relatively finite podiform-type resources (historically the major supply sources) are depleted. Chromite output from the major producing nations that have podiform-type resources, such as Turkey, the Philippines, Albania, and the Soviet Union, should decline relative to seam-type producers.

A cross-country comparison of mining costs per ton of product (table 5) demonstrates the advantage of chromite resources that are amenable to surface mining, such as in Finland, and also demonstrates the importance of stripping ratios and concentration ratios. Thus, Finland, with low stripping and concentration ratios, has much lower surface mining costs than Brazil, which is expected to encounter increasingly higher stripping ratios as the Campo Formoso surface resource is mined out, and which faces a higher overall concentration ratio.

The advantage of greater scale economies and thicker chromite seams is apparent in the lower South African mining cost estimate compared with that of Zimbabwe. The estimates derived for Turkey and the Selukwe and Belingwe (Podiform) districts of Zimbabwe demonstrate the cost advantages apparent from mining large, high grade, underground podiform resources.

A similar comparison of beneficiation costs shows a direct correlation between the two factors, in situ grade and beneficiation method, and the cost per ton of chromite product. Thus, Zimbabwe, with high in situ grades and mostly simple beneficiation methods, has a very low milling cost per ton of salable product relative to, for instance, the low-grade eluvial deposits of the Philippines, which have very low in situ grades and relatively complicated heavy-media, magnetic-separation methods of beneficiation.

Transportation is of special concern, since it involves both the actual cost of transportation and the availability of a sufficient transportation network. The total cost of transportation is determined by distance, the mix of transport mode employed (i.e., truck, rail, and ocean freight), the cost of each mode in the different countries, and the product (chromite or ferroalloy) that is being transported. The capital and operating expense of truck transport is borne entirely by the mining concern; rail capital costs, with the exception of connecting spurs to a main line, are generally an infrastructural given, with the rail freight charge to the point of sale borne by the mining concern. Transport costs for barging and international ocean freight to the point of sale are a major operating expense for the world chromium industry and combined with other internal transport costs help to determine regional competitive advantage.

In the case of chromite, transportation includes the cost of moving the ore from the mine or mill site to the port of exportation, including all handling and loading charges. For ferrochromium, transportation includes the cost of moving the ore from the mine or mill site to the appropriate smelter (either in-country or to Europe, Japan, or the United States) plus the cost of moving the ferroalloy itself to the point of sale or port of exportation, also including all handling and loading expenses. A major difference in total expense between transporting chromite and ferrochromium lies in the increased handling charges of the latter. These handling costs are generally twice the cost of handling chromite products and this relationship has been adopted as a standard here.

Table 6 provides a detailed breakdown of (chromite) transportation costs for the countries studied. A cross-country comparison of internal chromite transportation costs demonstrates the obvious advantage of close proximity of mining operations to ports of exportation. It is clear that mines in such countries as the

Table 6. — Chromite transportation cost estimates from mines to ports within various countries
(1981 U.S. dollars)

Country of origin	Port city	Cost per metric ton concentrate: Range	Weighted-average
South Africa	Durban, South Africa	$20.00-$32.00	$26.00
	Maputo, Mozambique	12.00- 24.00	16.50
	Port Elizabeth, South Africa.	29.00- 41.00	34.00
Zimbabwe	Beira, Mozambique	20.00- 40.00	27.50
	Durban, South Africa	30.00- 46.00	38.00
	Maputo, Mozambique	33.00- 50.00	41.00
	Port Elizabeth, South Africa.	56.00- 73.00	64.00
Turkey	Fethiye	10.00- 17.00	13.50
	Iskenderun	60.00- 70.00	65.00
	Ismit	NAp	55.00
	Trabzon	NAp	41.00
Philippines	Numerous	5.00- 18.00	10.50
India	Mangalore	10.00- 12.00	11.00
	Paradip	17.00- 22.00	19.50
Brazil	Salvador	31.50- 32.50	32.00
Finland	Ajo	NAp	9.00
New Caledonia	Tiebaghi	NAp	7.00
Greece	Volos	NAp	35.00
Madagascar	Tamatave	14.00- 20.00	17.00

NAp Not applicable.

Table 7. — Projected utilization of chromite products at highest annual expected production level
(Thousand metric tons)

Country	Capacity[1] of chromite products for metallurgical use	Ferrochromium smelting capacity		In-country smelter requirements[4] of chromite as raw material feed	Chromite products available for export
		Current[2]	Proposed[3]		
South Africa	4,500	820	500	3,000	1,500
Zimbabwe	1,000	320	150	1,000	0
Turkey	460	50	50	250	210
Philippines	580	0	50	110	470
India	543	29	156	400	143
Brazil	190	90	0	225	0
Finland	475	50	0	125	350
New Caledonia	85	0	0	0	85
Greece	40	0	30	60	0
Madagascar	113	0	0	0	113

[1] Capacity levels utilized in this study assuming that the highest level of proposed expansions of the late 1970's and early 1980's is attained.
[2] Current estimated smelting capacity based upon information from 1979-80. Includes capacity for the production of both high- and low-C ferrochromium as well as small tonnages for the production of ferrosilicon-chromium, where applicable.
[3] Includes all announced plans of the late 1970's and early 1980's.
[4] Chromite raw material requirements are based upon tonnage factors ranging from 2.0 to 2.5 t of chromite per ton of annual smelting capacity.

Philippines, New Caledonia, and Finland are low cost internal transporters of chromite products, primarily because the distances are much less than those encountered in all the other countries. The issues of internal transportation capacity and its availability for the transportation of chromium products are dealt with in the individual country sections.

In order to determine both the current and near-term tonnage of high-C ferrochromium potentially available from the chromite resources of the nations studied, the analyses incorporated each country's current ferrochromium smelting capacity and announced expansion plans of the late 1970's or early 1980's. Table 7 contains data on the projected level of chromite utilization for in-country ferrochromium production and the potential amount of chromite available for export. The data presented are *approximations* intended to convey the relative resource and product position of each nation in terms of the availability of chromium in the form of ferrochromium versus the availability of chromium in the form of chromite.

The data of table 7 indicate three trends of importance. First, there is a noticeable trend toward increased ferrochromium smelting capacity being located in those nations which possess chromite resources; those nations that contain the largest resource levels—such as South Africa, Zimbabwe, and India—show the largest proposed increases. Second, countries such as the Philippines and Greece, which currently do not (effectively) produce any ferrochromium, are now constructing new smelting facilities. Third, the net result is an increasing trend away from the international trading of chromium in the form of chromite and toward the trading of chromium in the form of (mostly high-C) ferrochromium.

COMPARATIVE HIGH-CARBON FERROCHROMIUM AVAILABILITY

This section presents a brief cross-country, comparative analysis of the cost structure and availability of chromium in the form of high-C ferrochromium. In this discussion, three product grades are identified for comparison; grade-A (>64 pct contained Cr); grade-B (56 to 64 pct contained Cr); and grade-C (52 to 55 pct contained Cr). These product grade groupings recognize the real difference in the selling price of ferrochromium, which is dependent upon the amount of chromium contained in the ferroalloy product. The long-term average total production cost and availability of each product grade from each producing and potential operation are shown graphically on availability curves. Weighted-average total production costs (by ferrochromium product grade) are then derived for each country in order to rank individual countries. Lastly, these production costs are compared with U.S. import prices in an attempt to determine the relative long-term competitive position of the ferrochromium industry in each country vis-a-vis the U.S. market.

Grade-A, High-Carbon Ferrochromium

The cost and availability of grade-A, high-C ferrochromium is depicted graphically in figure 7, with respective country percentage contributions to total availability shown in figure 8. Generally, in the absence of ore blending, chromite with a Cr:Fe ratio 2.5 or greater is required for the production of grade-A

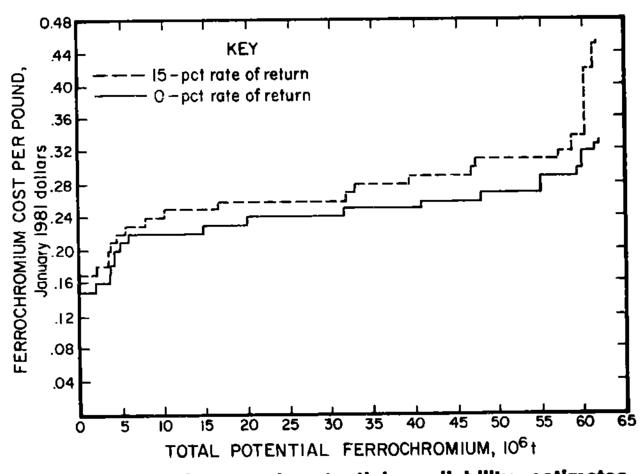


Figure 7. — Cost and potential availability estimates of grade-A, high-carbon ferrochromium.

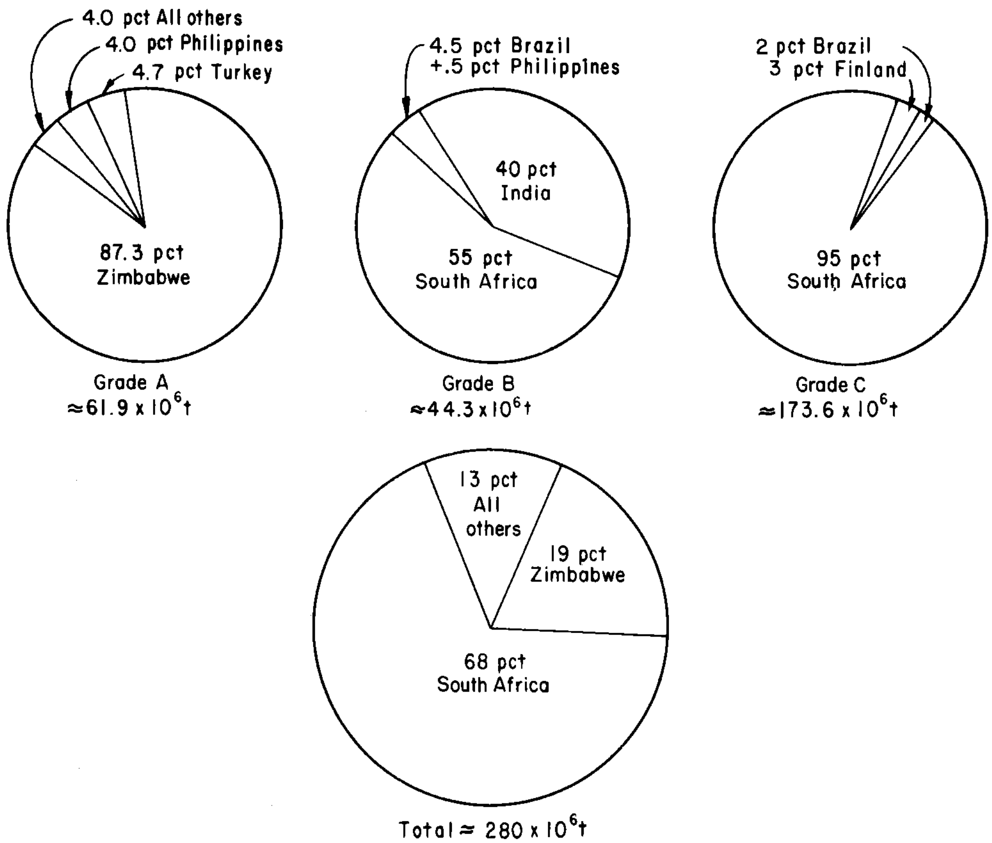


Figure 8. — Percentage contribution, by country, to total high-carbon ferrochromium availability estimates by product grades A, B, and C.

high-C ferrochromium. Six of the ten countries evaluated have at least some chromite resources of a quality sufficient for producing this product, the great majority of which is contained within currently producing operations. Of these countries, Zimbabwe alone contains 87.3 pct (54.1 million t) of the potential availability estimate of 61.9 million t of grade-A, high-C ferrochromium.

Table 8 ranks the countries according to tonnage potential and weighted average cost per pound of

Table 8. — High-carbon ferrochromium; cost ranges per pound of contained chromium, availability estimates, and percentage distribution, by country

(1981 U.S. dollars)

Country	Percent of total ferrochromium availability estimate	Availability estimate, 10^3 t	Breakeven cost level	15-pct profitability cost level
GRADE A				
Zimbabwe	87.3	54,097	$0.22–$0.43	$0.25–$0.50
Turkey	4.7	2,892	.33– .46	.36– .46
Philippines	4.0	2,439	.32– .41	.34– .64
Madagascar	2.5	1,535	.47	.48
New Caledonia	1.2	726	.25	.29
Greece	.3	241	.49	.67
Total or weighted-average	100.0	61,930	.37	.40
GRADE B				
South Africa	55	24,412	$0.31–$0.34	$0.36–$0.50
India	40	17,798	.36– .50	.56– .79
Brazil	4.5	1,899	.41– .53	.50– .59
Philippines	.5	244	.38– .43	.44– .46
Total or weighted-average[1]	100	44,353	.32	.44
GRADE C				
South Africa	95	165,411	$0.26–$0.51	$0.30–$0.55
Finland	3	5,332	.29	.29
Philippines	2	2,850	.40– .56	.43– .70
Total or weighted-average	100	173,593	.38	.43

[1] The overall average is calculated without factoring in the Indian cost determinations in order to reflect existing conditions.

contained chromium. The cost estimates for Greece are higher than the other countries because this country is just now developing its own ferrochromium industry. The cost estimate derived for Madagascar represents the cost to produce ferrochromium in Japan from Madagascar chromite resources, since that country has no local ferrochromium smelting industry. The cost estimates for New Caledonia and the Philippines (with the exception of one operation) are also on a Japan-market basis. For Zimbabwe and Turkey, the estimates represent the cost to locally manufacture ferrochromium (including the cost of new smelting capacity).

In order to evaluate these costs relative to a common base, they are compared with import sales prices for chromium delivered to the United States. On this basis, weighted-average cost for all grade-A ferrochromium ranges from $0.37/lb contained Cr at the breakeven level to $0.40/lb at the 15-pct profitability level. As of the first quarter of 1981, imported grade-A ferrochromium was selling in the United States at prices between $0.46/lb and $0.49/lb contained Cr; a difference of between $0.06/lb and $0.12/lb. However, it is estimated that ferrochromium transportation costs to the United States can average anywhere from $0.04/lb to $0.12/lb contained Cr. Thus, the difference of between $0.06/lb and $0.12/lb is similar to the range of transportation costs to the United States from the different countries involved. It must be stressed that the actual cost of any individual ferrochromium shipment is dependent upon such factors as the point of origin, the market conditions at the time of shipment, the size of shipment, the point of delivery, the number and length of stops (demurrage charges), etc. Given these factors, it is felt that international shipping costs for ferrochromium should fall within this $0.04 to $0.12 range, but these costs are highly variable.

According to this criterion, at least two-thirds of the total grade-A ferrochromium availability estimate can be considered internationally competitive at the 1981 cost and price levels. In particular, grade-A ferrochromium produced in Zimbabwe and Turkey, and Japanese production from high-grade Philippine and New Caledonian chromite, are the most cost competitive. These three countries are major world producers of this product. Ferrochromium produced in Greece appears to be the least cost competitive. The Greek government's development of a domestic ferrochromium industry would appear to be based more upon developmental concerns or EEC trading arrangements than international cost competitiveness.

Grade-B, High-Carbon Ferrochromium

The cost and availability of grade-B, high-C ferrochromium is presented in figure 9 with supporting data aggregated by country given in table 8. Percentage contributions by country are shown in figure 8. A total of 44.3 million t is potentially available at breakeven costs of up to $0.53/lb contained Cr. The cost estimates for Brazil, India, and South Africa represent total domestic manufacture of ferrochromium from local chromite resources. The cost estimates for the Philippines represent the cost to produce this grade of ferrochromium in Japan from Philippine chromite resources.

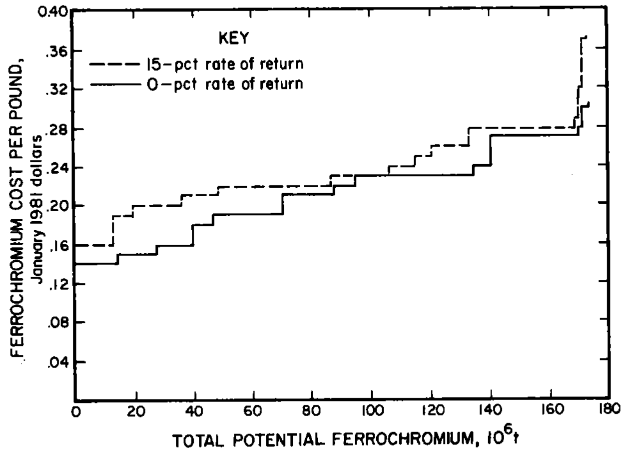


Figure 9. — Cost and potential availability estimates of grade-B, high-carbon ferrochromium.

Although 40 pct of the total potential tonnage is available from India, it must be remembered that the Indian ferrochromium industry is only beginning to be developed, and it is uncertain, at this point in time, whether all proposed capacity will in fact be constructed. Thus, the 24.4 million t available from producing South African operations really represents the great majority of total available tonnage from current smelting capacity. It is primarily this South African long-run production cost level that the ferrochromium industry of India will potentially compete against.

In terms of cost, South Africa is approximately 25 pct lower than the Indian operations, evaluated at the breakeven level, and approximately 35 pct less at the 15-pct profitability level. The cost estimates for India, at the 15-pct level, are markedly higher than the other nations because of the large capital investments that would be required to fully develop India's domestic ferrochromium industry while obtaining this long-run level of profitability.

Of greater significance is the fact that of the total tonnage of grade-B ferrochromium potentially available at or below the average breakeven cost level, approximately 100 pct originates from South Africa. Of the total tonnage potentially available at the average 15-pct profitability cost level, over 98 pct originates from South Africa. This means that in this product category (and indeed in all lower grade chromite ore and ferrochromium categories) as prices increase, an increasing percentage of the market is filled with South African products (since almost all mining operations that were analyzed in South Africa are producers, the ferrochromium smelting capacity is in place, and the ability to expand mining and smelting capacity relatively quickly with scale economies is also present). Also, as prices decline, South Africa virtually becomes the market since 98 to 100 pct of all grade-B ferrochromium potentially available at or below the average cost points is a South African product.

Comparing these cost estimates on a contained-chromium basis, delivered to the United States, with average selling prices of imported grade-B ferrochromium, again shows that the long-run production costs herein estimated are similar to the first quarter 1981 market prices when transportation costs are included. The costs determined, range from $0.32/lb to $0.44/lb contained Cr, which are similar to the first quarter 1981 U.S. import selling prices of $0.46/lb to $0.47/lb.

Grade-C, High-Carbon Ferrochromium

The cost structure and availability situation for grade-C ferrochromium is also entirely based upon cost conditions in South Africa. As figure 8 indicates, 95 pct of all potential grade-C ferrochromium is derived from South African-based chromite resources. This is of particular importance, since this grade of ferrochromium has been capturing the largest share of the world ferrochromium market, with the widespread adoption of the AOD steelmaking process during the last decade.

The cost estimates, at both profitability levels, for South Africa (see figure 10 and table 8) are average cost ranges for the production of grade-C ferrochromium from South African chromite resources. The ranges are composites of the cost of producing this product in South Africa, the United States, Europe, and Japan. South African production costs are at the lower end of the range (the weighted average South African cost is $0.32/lb Cr) with production in Japan and western Europe occupying the upper end of the range. The United States is estimated to have a weighted average of $0.43/lb. These cost ranges illustrate the predominant position of South Africa as either the source of chromite for the production of ferrochromium or, increasingly, the source of this ferrochromium product itself as South Africa continues to increase its smelting capacity. It is important to note again that neither Western Europe nor the United States produce any chromite products. Japan's production of chromite is very insignificant relative to its consumption. Thus, these nations are heavily dependent upon South Africa for their chromite raw material inputs to the ferrochromium production process.

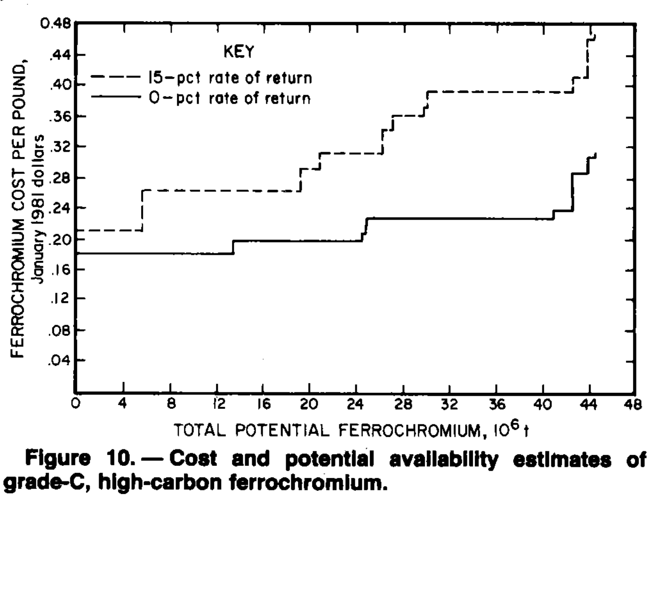


Figure 10. — Cost and potential availability estimates of grade-C, high-carbon ferrochromium.

The Philippines (as a source of chromite for Japanese ferrochromium smelting) and Finland (an exporter of ferrochromium) are significant because of their location vis-a-vis major markets.

In this regard, special attention is paid to the potential for exploiting the very low grade "alluvial" and "eluvial" deposits of the Philippines and their potential use by the ferrochromium and steel industries of Japan. It appears at this point in time that the economic position of this resource is submarginal, and since the potential tonnage of ferrochromium available from these very low grade chromite resources is limited, the Philippines source will probably never attain the significance of South Africa as a raw materials supplier to Japan.

The country-wide average breakeven and 15-pct profitability level cost estimates range from approximately $0.38/lb to $0.43/lb contained Cr, respectively. Imported grade-C ferrochromium was selling in the United States in the first quarter of 1981 for $0.44/lb to $0.46/lb contained Cr, which again indicates that these derived costs, after factoring in transportation charges to the United States, are very similar to import market prices. By this criterion, virtually all of the 165.4 million t of grade-C ferrochromium potentially availabile from the chromite resources of the (mostly) active mines in South Africa, as well as the potential 5.3 million t in Finland, can be considered as economic.

In general, it can be concluded that constraints to the further expansion of the international ferrochromium industry are not resource based (there is no shortage of chromite), nor in most cases studied, economic. Rather, the industry is directly tied to the level of demand and highly concentrated in those nations that possess the vast majority of chromite resources, productive smelting capacity, and currently hold a dominate market share for the products in question. Clearly, South Africa has a long-term advantage for the production of high-C ferrochromium, for as figure 8 clearly indicates, 68 pct of the total 280 million t of high-C ferrochromium of all grades potentially available from the total demonstrated in situ resource that was cost-evaluated, is either produced in South Africa or represents smelting capacity dependent upon South African chromite resources.

On an individual country basis, the major implications as a result of the information and analyses of this study are as follows:

South Africa

- Both chromite and ferrochromium production should increase in the future, both in absolute terms and as a percentage of the world total.
- South Africa should increasingly set the long-run minimum cost (and price) levels for both chromite and high-C ferrochromium as a result of an enormous chromium resource base, large mining and processing capacity, and the attendant scale economies.
- The increase in high-C ferrochromium smelting capacity should come at the expense of declining U.S., European, and Japanese capacity.

Zimbabwe

- Chromite and ferrochromium production costs should rise through time as the podiform resources are depleted and a greater percentage of production comes from the seam-type operations.
- Large capital investments will be required to alleviate transportation and energy supply bottlenecks in order to realize the full potential of the industry.
- The availability of chromite products for export should decline as the country's stated goal of utilizing 100 pct of its chromite for ferrochromium production is instituted.

Turkey

- Full capacity production of ferrochromium (including expansion plans) would exhaust the demonstrated resource estimate in 26 yr; the potential for proving additional chromite resources is considered good; and ferrochromium production and export should increase as chromite exports decrease.

Philippines

- The construction of the Philippines' first commercial-scale ferrochromium smelter and the resultant ferrochromium production will reduce the amount of high-grade metallurgical chromite available for export and represents a continuation of the trend toward ferrochromium production in those countries that mine chromite.
- The vast majority of the low-grade eluvial and alluvial resources currently appear to be subeconomic both in terms of chromite and ferrochromium production costs.

India

- Major implications are that chromite export controls and increased domestic production of high-C ferrochromium in the future will reduce chromite products available for export. This also represents a continuation of the trend toward ferrochromium production in those countries that mine chromite.

Brazil

- Should be able to meet its projected domestic ferrochromium consumption needs and continue to export relatively small quantities of ferrochromium products, but does not hold any promise as a major available source of imported chromite for the United States at this time.

Finland

- Should remain a major exporter of both chromite and ferrochromium for the rest of this century.

New Caledonia

- All chromite output should most likely go to Japan as raw material feed for the production of high-C ferrochromium. Will probably play only a minor role in the overall world production of chromite in the future.

Greece

- All chromite production will be processed locally into high-C ferrochromium at the newly constructed smelter with the output being exported, most likely to the EEC.

Madagascar

- No major change in trading patterns is expected, and the construction of a domestic ferrochromium smelter remains doubtful.

THE REPUBLIC OF SOUTH AFRICA

GEOLOGY AND RESOURCES

South Africa's chromite resources are predominantly contained within four basic geographic-geologic areas (fig. 11): (1) the eastern (Lydenburg) belt of the Bushveld Complex, (2) the western (Rustenburg) belt of the Bushveld Complex, (3) the Potgietersrust-Grasvally District located in the northern part of the Bushveld Complex, and (4) the Zeerust-Marico District, an extension of the Bushveld Complex to the west of the western belt.

Much has been published in the past on the origin, geology, and mineralogy of the Bushveld Complex (*10-19*). The following chromite resource discussion focuses mainly on the specific geologic data and assumptions pertinent to this analysis rather than attempting a comprehensive overview of the myriad of information published on the Bushveld Complex.

As a whole, the Bushveld Complex covers a total of 67,000 sq km and consists of three major rock formations: a granite-granophyre unit, the Rooiberg felsite, and a gabbro-norite fraction. In terms of economic minerals, the gabbro-norite unit is the most important since it contains a magnetic-vanadium horizon, a platinum-bearing horizon (the Merensky Reef), and a section of numerous chromite seams. The gabbro-norite unit can be more specifically broken down into country rock units of pyroxenite, norite, and anorthosite which contain the chromite and platinum seams as individual layers that are generally concordant to the igneous layering. Further subdivision of the chromite seams within the Complex is possible into three major groups—(1) the upper group, (2) the middle group, and (3) the lower group—but this is as far as a general subdivision or correlation can go. The number and type of chromite seams present varies from one mining property to another. Table 9 summarizes the general

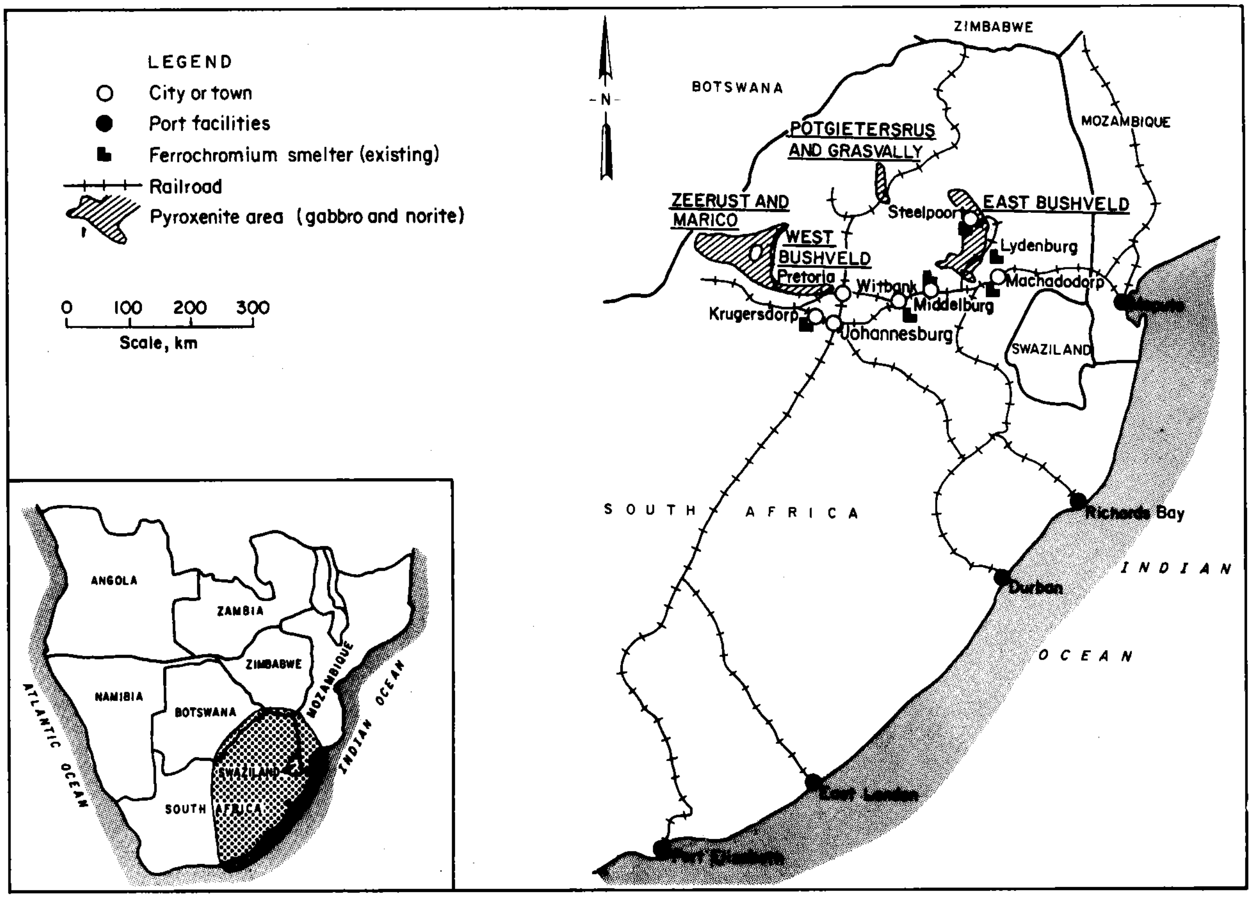


Figure 11. — Location of South African chromite mining areas, smelting facilities, railway network, and ports of exportation.

Table 9. — General characteristics of upper, middle, and lower group chromite seams in South Africa

Group	Geological characteristics	Important seams	Economic significance	Best locations
Upper	Anorthosite country rock, same marker bed as for platiniferous Merensky Reef. Lowest Cr_2O_3 grade, thinnest seams, fewest seams (2) of all the groups. Inconsistent outcrops.	UG2	The UG2 seam is to be processed by Western Platinum for production of platinum-group metals, copper, and nickel. Could produce chromite concentrates of low Cr_2O_3 grade (35 to 40 pct) with a low Cr:Fe ratio (1.35), but processing and economics are still relatively unknown. The lowest grade group in terms of Cr_2O_3.	Boschoek to Brits section in West Bushveld. Section north of Pilanesberg in West Bushveld.
Middle	Norite and anorthosite country rock. In idealized geologic section, this group is stratigraphically closer to lower group than to upper group.	MG1, MG2, MG4	The MG1, MG2, and MG4 seams are presently being mined in West Bushveld. Predominantly medium-grade, high-Fe chromite ores and concentrates (43 to 47 pct Cr_2O_3; 1.5 to 1 Cr:Fe ratio).	Rustenburg to Marikana sector in West Bushveld. Sector east of Marikana in West Bushveld. Section in area north of Steelpoort River in East Bushveld.
Lower	Mostly pyroxenite country rock. As many as 25 or more individual, uncorrelated seams have been identified. Most consistent outcrops of the 3 groups.	Main seam (also known as LG6, main, Steelpoort, and Magazine seam at various localities), leader seam, LG2, LG3, LG4, H, F	The vast majority of past and present production has been from seams classified as lower group seams. The main and leader seams together comprise the "main horizon" and are most important from a chromite production standpoint. Predominantly high-Fe chromite ores and concentrates. (43 to 47 pct Cr_2O_3; 1.5 to 2.0 Cr:Fe ratio).	Nearly ubiquitous in all areas. Basically absent only in four areas: (1) 20-km section north of Rustenburg. (2) 15-km section from Brits westward. (3) Most of the 35-km section from the Consolidated Chrome mine northeast to the Zwartkop mine. (4) 15-km section north of Steelpoort River.

characteristics of each of the three groups of chromite seams. As shown, only 11 seams have had or could have economic importance to the chromite industry in South Africa.

A major portion (60 to 75 pct) of chromite ore in South Africa is friable, which means that it occurs as loose grains or in fragments that readily disintegrate into "fines" when handled. Products from mining and milling are basically in five forms: (1) friable run-of-mine ore, (2) hard, lumpy run-of-mine ore, (3) ore concentrates, (4) refractory-grade ore, and (5) foundry sand.

Because the majority of Bushveld chromite is rich in iron content and low in Al_2O_3 content, it has limited use as a refractory material. However, the seams in the Marico-Zeerust District and those of the Grasvally District are of better refractory quality (more Al_2O_3, less FeO) than the main Bushveld ores. This overall "less-refractory" quality of South African ores is claimed to give them an advantage over Zimbabwean ores in terms of ferrochromium smelting because they can be smelted at a faster rate with slightly less flux addition (*16*, p. 34). For example, a normal medium-grade South African chromite ore contains only 28 pct slag-forming materials versus 37 pct for a typical Zimbabwean ore (*16*, p. 34).

Because of the large strike lengths (horizontal surface distance) and generally continuous nature of the seams (particularly for the lower group), both horizontally and to depth, any projection for resource estimation purposes will result in enormous chromite tonnage estimates for the entire Bushveld Complex. The official Bureau of Mines reserve estimate as of 1980 was 2.5 billion t (*6*, p. 33), while the official South African Minerals Bureau estimate was as high as 3.096 billion t (*9*, p. 55). At 1980 crude ore (full capacity) production levels, these tonnages, if proven to be extractable, would last 370 and 507 years, respectively. Other resource estimates run as high as 16 billion t (*10*, p. 120), which at 1980 crude ore (full capacity) production levels would last for over 2,600 yr. The above estimates do not include chromite concentrates that possibly could be produced from the platiniferous UG2 seam, which has been estimated to contain 630 million t of chromium-bearing material to a vertical depth of 1,200 m (*19*). Assuming that roughly 10 pct of this material is comprised of the mineral chromite and assuming a milling recovery of 80 pct to produce a 35-pct-Cr_2O_3 concentrate, this 630 million t of material in the UG2 would contain about 50 million t of chromite concentrates.

The most recent and detailed estimate of chromite resources in South Africa is that of Von Gruenewaldt (*19*). His calculation in 1981 separated the resource into an "identified reserve" category, defined as exploitable material down to a vertical depth of 150 m, and an "identified resource" category, defined as exploitable material from 150 m down to 1,200 m, which he considers the depth to which the prevailing geothermal gradient would allow mining operations in the Bushveld Complex. The "identified reserve" category is estimated at 718 million tons, of which 12 pct is considered high-Cr material and 88 pct high-Fe material. The "identified resource" category is estimated to contain an additional 8.535 billion t composed of 7 pct high-Cr material and 55 pct high-Fe material in seams presently being mined, and 38 pct high-Fe material in seams not presently being mined. Thus, his estimate to 1,200 m vertical depth totals 9.253 billion t.

In contrast to the huge estimates reported above, this study analyzes the economics of extracting only about 638 million t of in situ material at the demonstrated level. Table 10 presents these data on a proper-

Table 10. — Estimated in situ chromite resource data for selected South African operations as of 1980

Operation	Average in situ grade, pct Cr_2O_3	In situ tonnage[1], 10^3: Demonstrated resource	Contained Cr_2O_3	Identified resource[2]
West Bushveld:				
Zwartkop	44.5	59,317	26,396	178,269
Consolidated Chrome	40.0	4,275	1,710	16,291
Ruighoek	41.0	16,227	6,653	60,873
Ntuane	38.0	14,898	5,661	49,370
Waterkloof	42.0	19,212	8,069	73,575
Millsell	42.0	4,836	2,031	26,297
Kroondal	42.0	33,708	14,157	123,830
Rustenburg (Chrome Chemicals)	39.0	24,920	9,719	88,981
Henry Gould	40.0	21,957	8,783	78,370
Mooinooi	38.5	21,294	8,198	127,656
East Bushveld:				
Ucar Chrome	44.0	29,075	12,793	67,978
Winterveld (TCL)-N. Section	41.0	43,815	17,964	150,757
Groothoek	41.0	29,004	11,892	66,335
Dilokong	42.0	42,179	17,715	81,573
Montrose (Hendriksplaats)	43.0	36,130	15,536	60,216
Winterveld (TCL)-S. Section	40.5	112,946	45,743	195,442
Lavino (Grootboom)	41.5	21,321	8,848	21,321
Potgietersrust-Grasvally District:				
Grasvally	30.0	21,471	6,441	44,336
Zeerust-Marico District:				
Marico (Nietverdiend)	43.0	60,971	26,217	376,891
Zeerust	43.0	20,320	13,038	20,320
Total or average	[3]41.0	[4]637,876	[5]267,564	2,785,768

[1] Data may not add to totals shown because of averaging and independent rounding.
[2] Identified resource tonnage calculated to 1,000 m vertical depth; equals demonstrated plus inferred tonnage; where equal, there was insufficient information to support an inference beyond the demonstrated level.
[3] Country grade is the in situ weighted average over all operations at the demonstrated level.
[4] Covers all seams for which there is current production or for which there was production in the late 1970's calculated according to the specific geologic and engineering criteria outlined in the text for the purpose of cost analysis.
[5] Total in situ contained Cr_2O_3, at the demonstrated level for all operations included in this study, summed over all individual operations. Does not equal weighted-average grade times total demonstrated resource level.

Table 11. — Criteria for determination of demonstrated chromite resource estimates for selected South African operations

Operation and farm[1]	District and seam	Demonstrated resources, 10^3 t: In situ	Demonstrated resources, 10^3 t: Recoverable	Evaluated mine capacity level, 10^3 tpy	Estimated life of recoverable resources, yr	Cr:Fe ratio	Depth, m: Vertical	Depth, m: Incline	Strike length, m
Zwartkop: Zwartkop 369, Schildpadnest 385, Vlakpoort 388, Middellaagte 382, Haakdoorn 374.	West Bushveld—Magazine (LG6), Intermediate, New.	59,317	53,385	350	152	1.5–2.2	300	1,000	13,000
Consolidated Chrome: Groenfontein 302.	West Bushveld—Main (LG6)	4,275	3,634	25	145	1.5	300	1,579	1,200
Ruighoek: Ruighoek 169JP	..do	16,227	13,793	250	55	1.5	300	1,442	4,000
Ntuane: Ruighoek 169JP, Vogelstruisfontein 173JP	..do	14,898	14,071	60	234	1.6	300	1,917	2,400
Waterkloof:									
Waterkloof 305JQ	..do	4,028	NA	NA	NA	1.5	200	1,000	1,600
Waterkloof 306JQ	..do	15,184	NA	NA	NA	1.5	300	1,442	3,000
Total or average		19,212	15,369	175	88	NAp	NAp	NAp	NAp
Millsell:									
Waterkloof 305JQ	..do	2,613	NA	NA	NA	1.5	200	1,230	1,900
Do	West Bushveld—Leader	2,223	NA	NA	NA	1.5	200	1,000	1,900
Total or average		4,836	4,352	250	17	NAp	NAp	NAp	NAp
Kroondal:									
Kroondal 304JQ	West Bushveld—Main (LG6)	23,354	NA	NA	NA	1.5	300	1,570	4,500
Do	West Bushveld—Leader	10,354	NA	NA	NA	1.5	300	1,570	4,500
Total or average		33,708	30,337	350	87	NAp	NAp	NAp	NAp
Rustenberg (Chrome Chemicals): Rietfontein 338JQ.	West Bushveld—Main (LG6)	24,920	21,182	225	94	1.5	300	1,333	4,800
Henry Gould:									
Buffelsfontein 467JQ	..do	17,121	NA	NA	NA	1.5	300	1,240	4,000
Elandsdrift 465JQ	..do	4,836	NA	NA	NA	1.5	300	1,240	1,000
Total or average		21,957	18,373	288	64	NAp	NAp	NAp	NAp
Mooinooi: Elandskraal 469JQ.	West Bushveld (MG1)	21,294	19,165	240	80	1.5	300	1,400	3,000
Ucar Chrome: Jagdlust 418KS, Winterveld 417KS.	East Bushveld—Steelpoort (LG6).	29,075	26,168	220	119	1.5	300	710	10,500
Winterveld (TCL)—N. Section: Waterkop 113KT, Zwartkopies 413KS, Paschaskraal 466KS.	..do	43,815	39,434	200	197	1.6	300	1,040	12,000
Groothoek: Groothoek 256KT, Twyfelaar 119KT, Driekop 253KT.	..do	29,004	24,653	400	62	1.6	600	2,050	4,000
Dilokong: Maandagshoek 254KT, Mooihoek 255KT.	..do	42,179	35,852	240	149	1.6	300	1,442	7,500
Montrose (Hendriksplaats): Hendriksplaats 281KT.	..do	36,130	32,517	600	54	1.6	600	2,316	4,000
Winterveld (TCL)—S. Section: Doornbosch 294KT, Winterveld 293KT, Onverwacht 330, Goudmyn 337KT.	..do	112,946	101,651	1,300	78	1.7	600	1,442	11,000
Lavino (Grootboom): Grootboom 336KT, Annex Grootboom.	East Bushveld—F	21,321	19,189	400	48	1.5	400	1,553	3,000
Grasvally:									
Grasvally 293KR	Potgietersrust	5,035	NA	NA	NA	2.4	500	708	1,600
Zoetveld 294KR	..do	16,436	NA	NA	NA	2.4	500	872	3,400
Total or average		21,471	19,293	385	53	NAp	NAp	NAp	NAp
Marico (Nietverdiend):	Marico-Zeerust—LG2	NA	NA	NA	NA	2.0	200	780	850
Goudini 30JP, Allenyspoort 29JP,	Marico-Zeerust—LG3	NA	NA	NA	NA	2.0	194	2,085	1,200
Driekop 14JP, Strydfontein 12JP.	Marico-Zeerust—LG4	NA	NA	NA	NA	2.0	194	1,640	13,900
	Total or average	60,971	44,674	85	525	NAp	NAp	NAp	NAp
Zeerust: Turfbult 10JP	Marico-Zeerust—LG3	NA	NA	NA	NA	2.0	36	602	3,750
	Marico-Zeerust—LG4	NA	NA	NA	NA	2.0	204	2,011	12,560
	Total or average	20,320	16,015	85	188	NAp	NAp	NAp	NAp
Grand total		637,876	553,110	NAp	NAp	NAp	NAp	NAp	NAp

[1] The number assigned to Farm names is current as of 1980 and is an integral part of the Farm name.

ty basis for the demonstrated and identified resource levels, as well as in situ Cr_2O_3 grades and contained Cr_2O_3 at the demonstrated level. Table 11 provides greater detail as to the farms,[8] districts, seams, recoverable resource tonnages, vertical and inclined depths, strike lengths, and estimated life at capacity operation, for the 20 properties evaluated. To determine the demonstrated resource level, the seams have been projected to a vertical depth of 300 m in the majority of cases. Where the projection is <300 m, the operating company does not own the lease area (farm) in

[8] A mining property can consist of anywhere from one to as many as five or six farms or leases, depending upon the individual holdings by companies.

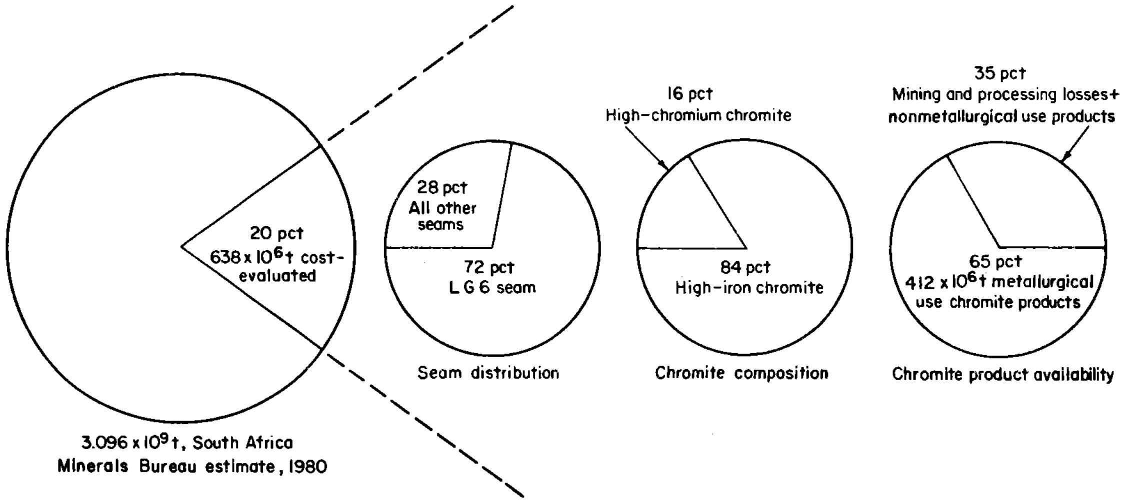


Figure 12. — Summary of South African cost-evaluated in situ tonnage; percent of total potential, seam distribution, chromite composition, and chromite product availability.

the direction of the projection. Where the projection is >300 m, the size of the operation was such that the rate of mining indicated the need for greater projection to reflect a reasonable life for the operation. This estimate of demonstrated resources (see figure 12) represents roughly 20 pct of the South African Minerals Bureau estimate and consists of approximately 16 pct high-Cr chromite (Cr:Fe ≧2) and 84 pct high-Fe chromite (Cr:Fe <2). Of this total tonnage, over 99 pct is material that will have to be mined by underground methods. In terms of individual seams, fully 72 pct (457 million t) is contained in the LG6 seam (also called Magazine, Main, and Steelpoort seam), while the remaining 28 pct is split among nine different seams. Of the demonstrated 638 million t, it is estimated that 533 million t should be recoverable through mining, and this in turn should produce about 412 million t of lump ore, fines ore, and ore concentrates for metallurgical use.

The operations and seams listed in tables 10 and 11 constitute the demonstrated resource level evaluated for cost and availability purposes in this study. They only represent the operations and/or seams that are presently producing, are temporarily shut down, or have produced in the recent past. There are two reasons for this limited choice of demonstrated resource for analysis:

1. The operations analyzed include all planned expansions of the present operations. In the South African chromite industry, expansion of existing operations seems to be preferred over developing new ones in undeveloped areas. As stated in the South African Mining and Engineering Journal of January 1980, "it is unlikely that new mines will be developed in the near future unless they form part of an integrated operation" (*20*, p. 59).

2. The average life of the demonstrated resources for the 20 operations analyzed, at full capacity operation, is 124 yr. Even this relatively small amount of resource is enormous in comparison to the other nations evaluated.

In a discussion of tonnages beyond the demonstrated resource analyzed, a few points should be made. First, if all of the seams shown in table 11 are projected to a further vertical depth of 1,000 m, the extension adds about 2.1 billion t of in situ inferred material to the 638 million t at the demonstrated level, for a total identified tonnage of around 2.7 billion t of material. When it is considered that this is only for seams presently being mined on producing lease (farm) areas, it is easy to see how Von Gruenewaldt's "identified resource" for all seams to 1,200 m on producing plus nonproducing farms could be calculated at 8.535 billion t. Second, it should be realized that many engineering and cost details are unknown about mining at vertical depths of 1,000 to 1,200 m on the Bushveld Complex for a relatively low-cost commodity like chromite. The geothermal gradient at Rustenburg Platinum's operation is about 21° C (70° F) per 1,000 m. This would indicate that at a vertical depth of 1,200 m the temperature would most likely be over 50° C (120° F) and refrigeration would definitely be required, as is the case at Rustenberg Platinum. By contrast, at 600 m vertical depth (the maximum limit of this study), ambient rock temperatures would be only about 30° C (86° F), and no refrigeration would be necessary. Third, at a dip of 15°, a vertical depth of 1,200 m would indicate the need for a 4,500-m haulage distance underground if the present inclined shaft method is used. This is at least four times greater than what some of the deepest operations are experiencing at present and indicates that a different method of access would be chosen to mine at this depth. Be that as it may, the demonstrated resource of 638 million t herein evaluated is sufficient for South Africa to produce at a rate at least one-third above 1979's production level through the 21st century and can be attained simply by slight expansion and/or extension to operations and seams presently in production.

MINING AND BENEFICIATION

Except for less than 0.5 pct, all of the demonstrated resource will have to be mined by underground methods. In general, the mining method in use on the Bushveld Complex, breast stoping, does not vary a great deal from operation to operation since the seams all dip gently (5° to 25°) and have similar structural and mineralogical characteristics. The most significant difference in terms of effect on mine operating cost lies with the thickness of the chromite seam in relation to the stoping height.

In the majority of operations, the seam thickness is 0.9 m or greater and usually represents 90 pct of the stope height, which means that relatively little waste is produced in stoping operations and can be packed back with little trouble. However, some seams are as thin as 0.4 m, in which case fully half of the material blasted will be waste material. In this case, it is very difficult to pack all of the waste back and as much as 50 pct has to be transported to the surface. This can add as much as 60 pct to the mine operating cost on a crude ore basis, everything else being equal. In general, one stoping section is set up to produce anywhere from 60,000 to 120,000 tpy of ore. Stoping heights vary from as little as 0.9 m to as great as 1.8 m, depending upon the seam thickness. As far as is known, only one operation stopes out two seams from one stope, the remainder are mining only one seam at a time.

Access is almost exclusively by means of inclined shaft systems that parallel the dip of the seam, although topographic characteristics can make adit access feasible, as at the Lavino operation south of the Steelpoort River on the East Bushveld. These inclined shaft systems are usually designed to serve about 1 to 1.5 km of strike length over the life of the shaft and can have individual hoisting capacities of 20,000 to 200,000 tpy of ore, although most are in the 100,000 to 120,000 tpy range. Older shafts use drum hoisting of ore and waste, but most of the newer shafts utilize conveyor belt hoisting, especially where the dip is 15° or less.

Mine operating costs estimated for the 20 operations were determined to reflect the long-run average cost in constant dollar terms to mine out all of the associated resource for that operation. On a crude ore basis, they range from as low as \$17/t to as high as \$43/t. In terms of a percent of total mine operating cost, labor costs are estimated to constitute anywhere from 38 to 45 pct, materials and supplies compose 33 to 38 pct, and equipment operation 20 to 25 pct. Productivities in underground chromite operations in South Africa are estimated to range from 0.5 to 1.5 t per worker-shift, with the majority of operations estimated to have productivities around 1 t per worker-shift.

Since all operations analyzed are either producers or on standby status, the initial capital investments have been recouped. Mining capital costs, then, are primarily composed of ongoing development work and replacement of mining equipment. Replacement of typical mine equipment at the properties analyzed would range from about \$5/t to \$14/t of annual crude ore capacity, while development costs for all work other than actual stoping would range from \$1/t to \$7/t of annual capacity. It is roughly estimated that to bring a 200,000-t capacity, underground operation into production from scratch in South Africa would cost \$4 to \$6 million. It is important to note that at one recently developed South African mine in this size range, it took only 15 months to develop the mine and construct the mill, with ore being stockpiled only 5 months after the start of shaft development (*21*, p. 87). The importance of this is to underscore the tremendous flexibility of the South African chromite industry. In general, production can be doubled or halved, in light of changing market circumstances, in the course of less than a year. Thus, as prices for chromite products increase, the South African chromite industry can quickly expand production, thus moderating prices and ensuring their dominant position in the international market for chromite products. For this reason, it is not likely that countries with submarginal chromite resources, such as the United States, will be able to economically develop a domestic chromite industry on a world market basis. Similarly, as prices decline, the South African mines can reduce production or temporarily shut down, which also tends to moderate prices. A period of declining or low market prices for chromite products can place some South African mines in a position where revenues are not sufficient to cover variable costs of production and where these variable costs are greater than the fixed costs incurred from not producing. When the market again turns up, these mines have the ability to reopen and expand quickly with scale economies and change the product mix if required.

All of the material analyzed in South Africa goes through at least rudimentary beneficiation. A variety of methods are in use at the 20 operations, depending upon the types of products desired. The methods range from a simple screen, hand-sort operation to a complex heavy-media, magnetic, gravity-separation plant. In the former, examples of products would be a minus 23-cm, plus 2-cm lump product and a minus 2-cm, run-of-mine fines product. In the latter, examples of products would be a plus 1-cm lump product from heavy-media separation and two different-sized concentrate (fines) fractions from gravity and magnetic separation. The majority of the operations utilize methods between these two extremes, consisting of either crushing-washing-screening-hand sorting or crushing-washing-grinding-gravity separation. In general, where gravity separation is utilized, the preferred method is with spirals, even though some properties utilize Wifley tables or diamond pans. Overall recoveries of Cr_2O_3 range from 75 to 90 pct, with the vast majority around 82 to 85 pct. With the simple methods, the Cr_2O_3 grade can be raised only a small amount, estimated to range between 1 and 4 pct. However, with the more complex method, some material is being increased from as low as 30 to 33 pct Cr_2O_3 in the ore feed to 50 pct in the concentrate product.

Beneficiation operating costs are insignificant relative to the overall cost of chromite products FOB the port. The estimated operating costs for the beneficiation plants analyzed range from \$1.75/t to \$6/t of crude ore feed. The labor portion of these costs is estimated to range from 40 to 50 pct, while equipment operation accounts for roughly 20 to 25 pct, and maintenance-supplies costs contribute 30 to 35 pct.

Mill plant and equipment costs vary considerably in terms of the estimated replacement cost. They range, roughly, from an inexpensive \$2 per annual ton of crude ore feed for the simplest screen-sort operation to as high as \$12.50 per annual ton of crude ore feed for the most complex methods. The more common gravity mills cost about \$6 per annual ton of crude ore feed capacity. Thus, for a 200,000 tpy gravity milling operation, the estimated plant and equipment capital investment would be approximately \$1.25 million. Infrastructure reinvestments should represent a minor portion of future investments by the operations since all are either producers or on standby status, and most infrastructural items are in place.

It should be noted that in the mid-1970's concern was raised that the operating companies were generally restricting investments in their beneficiation plants and that this policy had resulted in bottlenecks and inadequate capacity at some operations.[9] It is believed that this problem has been partially addressed as evidenced by production levels and expansion plans of the late 1970's. This study has incorporated into the economic analysis all necessary mill capacity expansions to accommodate the mining capacity expansions that were assumed. Bottlenecks at the milling production stage, in terms of cost and time, would seem to pose no serious problem for the South African chromite industry under the relatively small increases assumed for this study.

CHROMITE AVAILABILITY

Mining of chromite began in South Africa in 1924 and has been continuous since that time. It is estimated that approximately 40 million t of chromite products have been produced in South Africa through 1980. Annual output has been steadily increasing. Production in 1979 totaled 3.3 million t of chromite products, a 37-pct increase over 1976 production (*22*, p. 33). In 1980, production was up slightly to 3.4 million t of products (*6*, p. 33). South Africa now accounts for roughly one-third of total world chromite production and around 60 pct of market economy country production.

It is estimated in this study that to produce 3.3 million t of products per year would require about 4.3 million t of crude ore and would represent the extraction of about 4.8 million t of in situ resource. If market conditions warrant and all planned expansions of the late 1970's were instituted in 3 yr, the 20 operations analyzed could produce a total of about 4.5 million t of products from about 6.1 milion t of crude ore, an increase of 36 pct over 1979's production. At this production level, individual mine capacities would range from 25,000 to 1.3 million tpy of crude ore, with an average of 300,000 tpy. Chromite product output would range from 19,000 to 877,000 tpy, with an average of 225,000 tpy.

Almost all of the chromite products produced in South Africa are either high-Cr chromite or high-Fe chromite, with the great majority being high-Fe chromite suitable for the production of grade-C, high-C ferrochromium.

Three major cost items determine the FOB operating cost per ton of chromite product; mining and beneficiation costs per ton of chromite product, plus transportation, handling, and loading costs to the closest port of exportation (excluding capital costs and taxes). These costs were determined for each operation and are related to cumulative chromite availability in figure 13. These operating costs are long run average costs of extracting, processing, and transporting all of the chromite products potentially recoverable from the demonstrated resources herein evaluated. The estimated productive lives vary from 17 to 525 yr, depending upon each operation's resource and production level, with an average mine life of 124 yr. Because the time frame is so long, these mining and milling operating costs take into account such factors as increasing underground haulage distance and additional underground development needed, as well as expansions to mining and processing capacity planned for the near term as they affect operating costs. As such, they reflect general trends through time (which is the purpose of this study) but do not necessarily represent current costs of operation. Transportation costs do represent current costs (in 1981 dollar terms) and reflect the general infrastructural network in place as of the study date.

Given that mine operating costs per ton of crude ore range from \$17 to \$43, and a weighted average ore-to-concentrate product ratio of 1.2, then mine operating costs per ton of chromite product vary from approximately \$20 to \$52, as shown in figure 13. A weighted average over all tonnage yields an estimate of \$35, which represents around 54 pct of the total combined operating costs. For 19 of the 20 operations, mill operating costs per ton of crude ore range from \$1.75 to \$4.00, which results in a range of from \$2/t to \$5/t of chromite product. This low cost and narrow range is a result of similar and relatively constant mill feed grades, mill recoveries, and beneficiation methods used. The weighted average of \$4 over all chromite product tonnage represents approximately 6 pct of the combined operating costs.

Table 12 presents a breakdown of the most common routes, transport modes, general distances, and transportation costs from the four chromite producing regions of South Africa to the two closest ports of exportation, and to the Witbank area (see figure 11 for details), which was selected as a centrally located ferrochromium smelting center in order to ascertain an average chromite transportation distance to smelting facilities.

For all four regions, there is a distant cost savings to utilizing the port of Maputo in Mozambique, with the operations of the East Bushveld able to reduce chromite transport costs by one-half, overall, when

[9] Confidential source.

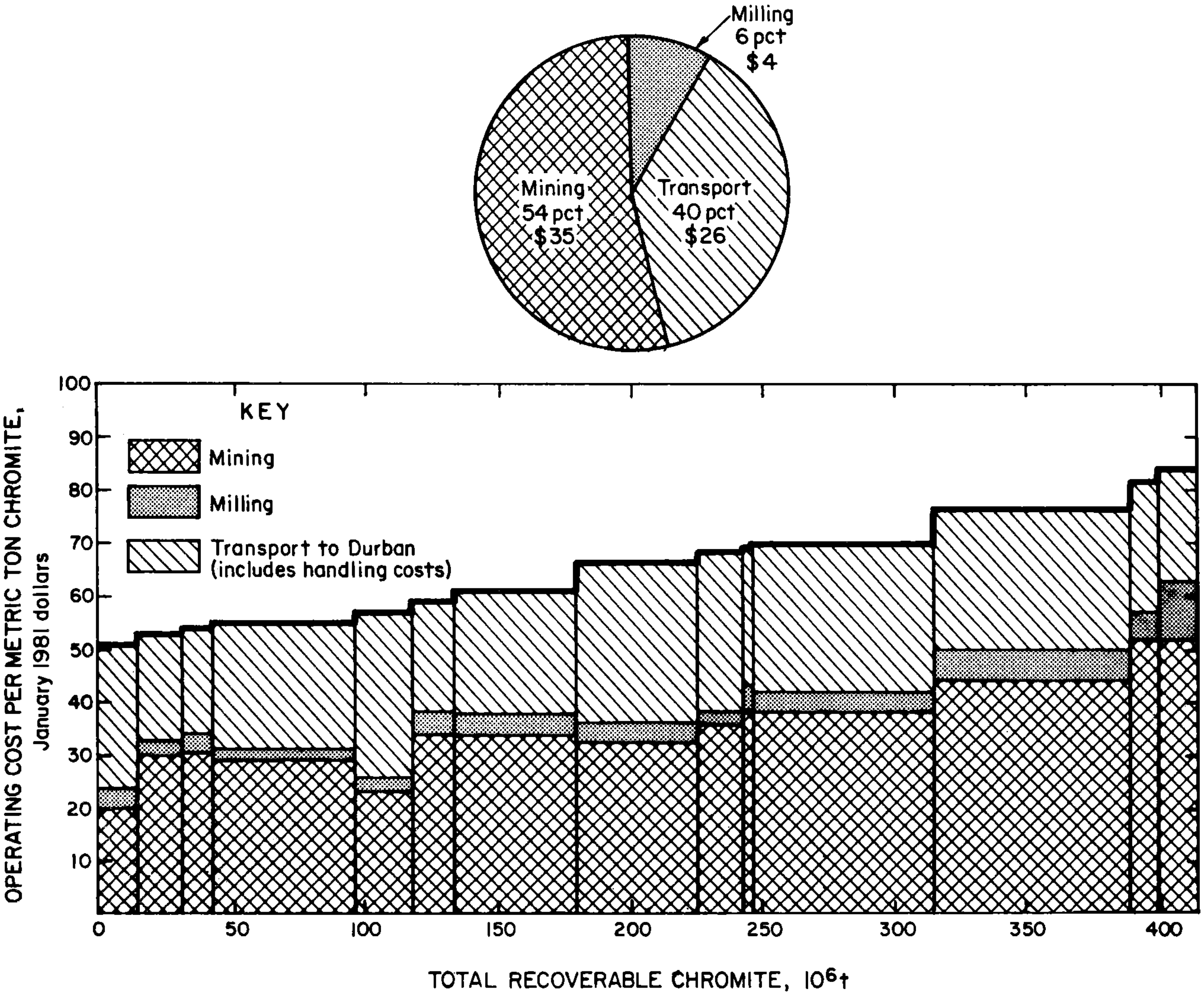


Figure 13. — Mining, milling, and transportation costs, FOB Durban, and availability of chromite from selected South African operations.

Table 12. — Most common routes, transport modes, approximate distances, and costs from the four chromite-producing areas in South Africa

(January 1981 dollars)

Originating district or area and destination	Approximate distance, km		Cost per metric ton chromite	
	Truck to railhead	Rail	Range	Weighted average
East Bushveld:				
Port–Maputo, Mozambique......	5–60	450	$12–$17	$14.00
Port–Durban, South Africa	5–60	1,025	27– 32	29.00
Smelter–Witbank[1]	5–60	275	7– 15	11.00
West Bushveld:				
Port–Maputo, Mozambique......	5–20	600	15– 20	16.50
Port–Durban, South Africa	5–20	800	20– 25	22.00
Smelter–Witbank[1]	5–20	225	6– 9	7.50
Potgietersrust:				
Port–Maputo, Mozambique......	NAp	650	NAp	17.00
Port–Durban, South Africa	NAp	900	NAp	25.00
Smelter–Witbank[1]	NAp	300	NAp	8.00
Marico-Zeerust:				
Port–Maputo, Mozambique......	60	700	NAp	23.50
Port–Durban, South Africa	60	900	NAp	28.00
Smelter–Witbank[1]	60	350	NAp	17.00

NAp Not applicable.

[1] Refers to the Witbank area as the point of common reference.

utilizing this port. However, Maputo has declined noticeably in terms of the amount of cargo handled since the latter half of the 1970's. The most recent estimates show Maputo handling only about 500,000 tpy (*23*, p. 330) and currently can only berth vessels up to 65,000 t (*24*, p. 53). The inland distances from mine sites to ports range from approximately 450 to 750 km to Maputo and from approximately 800 to 1,100 km to Durban. All mines are in close proximity to railheads and with the exception of the Steelpoort-Belfast Branch line and Zeerust to Krugersdorp, all South African railroads handling chromite or ferrochromium are fully electrified. Transportation costs average $14/t to $23.50/t of chromite to Maputo and $22/t to $29/t to Durban. If all South African chromite production was exported through Durban (the closest *South African* port), a weighted average cost of $26/t of product is estimated; when combined with long-run, weighted-average estimates of mining and milling costs, this gives a total FOB cost of $65/t of chromite product, with transportation representing 40 pct of the total. Thus, at a long-run FOB Durban (operating) cost level of $65/t, approximately 220 million t of chromite products are potentially available. At an operating cost level of $85/t, all 412 million t of chromite products are recoverable. It is important to note, as figure 13 indicates, that the total FOB Durban operating cost per operation ranges from approximately $50/t to $85/t. This relatively narrow (and low) range reflects the fact that these operations are similar in geology, production methods, and hence costs.

The total chromite product availability estimate from the demonstrated resources of the South African operations is a huge 412 million t of chromite, with an average grade of 43 pct Cr_2O_3. The tremendous size of this availability estimate and the scale of the South African chromite industry in relation to the other countries discussed in this study can be emphasized by taking South Africa's 1979 production of around 3.3 million t of chromite products and dividing it into the chromite product availability estimates derived for the other nations. At this production level, South Africa would have at least 124 yr of easily attainable production, whereas Finland would have only 5.2 yr, New Caledonia and Greece <1 yr, the Philippines 3.7 yr, India 13 yr, Madagascar 1.2 yr, Zimbabwe 39 yr, Turkey 2.3 yr, and Brazil 1.4 yr. Clearly, South Africa should increasingly dominate the chromite industry in general throughout the 21st century, as long as there remains a market for primary (mined) chromium. It is expected that the long-run minimum cost level, which determines long run prices, will increasingly be set by the South African industry, thus ensuring that particularly high cost, potential producers of chromite, such as the United States, will probaby never achieve production on an economic basis.

HIGH-CARBON FERROCHROMIUM AVAILABILITY

Currently, there are six ferrochromium smelters in South Africa, with a combined capacity of approximately 750,000 tpy of high-C ferrochromium, 46,000 tpy of low-C ferrochromium, and 24,500 tpy of ferrosilicon chromium. The great majority of productive capacity is devoted to high-C ferrochromium, which is reflective of world demand for high-C relative to low-C ferrochromium. South Africa roughly accounts for about 20 pct of world production of high-C ferrochromium. It is important to note that the invention of the AOD steelmaking process by Union Carbide created the large markets for high-Fe chromite for metallurgical use and high-C ferrochromium as an additive to the manufacture of stainless steel. These markets came to be heavily dominated by the South African chromium industry. This development was the result of many factors, such as the Rhodesian trade embargo, but most of all represents aggressive South African development and marketing of their tremendous chromite resources. Figure 11 shows the locations of South African ferrochromium smelting facilities that are all ideally situated with respect to energy sources (coal and electric power), raw material sources (dolomite, silica, etc.), labor supply, transportation networks, and, most importantly, the chromite operations themselves. Table 13 provides respective smelter capacities.

There are basically four chromite input feeds in use at the six smelters, with the differences due to the type of feed material used and the preparation required prior to smelting:

1. The conventional feed, using 100 pct lumpy ore—in use at the Machadodorp and Krugersdorp smelters. A briquetting plant has recently been installed at Krugersdorp, which allows them to use either run-of-mine lump or fines and concentrates.
2. The combination of run-of-mine ore (30 to 40 pct) and fines and concentrates (60 to 70 pct) as feed—in use at the Tubatse (Steelpoort) smelter.
3. Feed consisting entirely of fines and concentrates which must be converted to partially reduced pellets because of the use of the Showa-Denko process—in use at the Lydenburg smelter.
4. A combination of lumpy ore and briquets made from fines and concentrates—in use at the Middelburg and Witbank smelters.

Smelting recoveries at older smelters were assumed to be 80 pct, while at newer smelters a 90-pct recovery was utilized for evaluation.

At current capacity levels, the domestic ferrochromium industry requires roughly 2 million t of chromite to operate at full capacity utilization. If future develop-

Table 13. — Current South African ferrochromium smelters and estimated 1980 capacity for the production of high- and low-C ferrochromium and ferrosilicon chromium
(Thousand metric tons)

Smelter location	Ferrochromium		Ferrosilicon chromium
	High-carbon	Low-carbon	
Machadodorp	80	26	20
Middelburg	100	20	4
Krugersdorp	80	0	0
Witbank (Samancor)	200	0	0
Lydenburg	120	0	0
Tubatse	170	0	0
Total	750	46	24

ments in the South African chromite industry proceed as assumed in this report and chromite production were to increase to 4.5 million t of ore and concentrate products, then either additional chromite exports or ferrochromium production and export would ensue, market conditions warranting. In order to determine the long-run average cost, availability, and relative economic position of South African ferrochromium producers, this study determined average production costs from a number of perspectives.

First, South African chromite export levels and patterns of the late 1970's were maintained and the entire ferrochromium smelting capacity was utilized with domestic chromite resources. The additional tonnage of chromite production left over after accounting for chromite exports and for current South African ferrochromium production capacity was assumed to be sent to new ferrochromium facilities in order to factor in the cost of expanding the local industry. This extra tonnage would represent about 500,000 tpy of additional ferrochromium production capacity.

This assumes that each furnace will operate at its rated capacity. However, a technique for handling run of mine ore and concentrates has been developed at Tubatse which allows their furnaces to operate at 25 pct above rated capacity. The continuation of such developments would have the double effect of lowering the estimated amount of capacity that needs to be added while also making South African ferrochromium that much more competitive.

In terms of construction time and costs, this addition would not be difficult since the present smelters, especially the newer ones, are designed to make low-capital-cost extensions possible by the fairly simple addition of a furnace module. As stated in the South African Mining and Engineering Journal (*20*, p. 55), "certain plants could, for instance, add a module and thus produce an additional 100,000 t of ferrochromium per year for less than a $40 million investment." It is estimated that total capital investments of approximately $400 to $500 million would be required to achieve this 500,000 tpy increase in capacity. It is felt that this level of expansion is well within the capabilities of the South African ferrochromium industry.

The average total cost of producing ferrochromium in South Africa was then calculated on an FOB smelter basis and compared to the average cost of ferrochromium FOB the port of Durban in order to isolate the cost contribution resulting from inland transportation of ferrochromium to this port, including all handling and loading expenses.

The results of these analyses are given in table 14. It is estimated that inland ferrochromium transportation costs from the smelters located near the Bushveld Complex to the port of Durban average approximately $0.03/lb of contained Cr. This is the difference between the weighted average total cost estimate of $0.32/lb of Cr calculated FOB Durban as opposed to the $0.29/lb Cr estimated FOB the smelter.

An additional analysis was performed in order to determine the cost differential between ferrochromium manufactured in the United States from imported South African chromite and the same product manufactured in South Africa and then shipped to the United States. To determine the cost differential, the same mining operations that formed the basis of the long-run average cost estimate for South Africa were assumed to have all chromite output shipped to the United States for the manufacture of high-C ferrochromium. The result (see table 14) was a weighted-average, long-run, breakeven cost level estimate of $0.43/lb of contained Cr as compared to $0.32/lb determined FOB the port of Durban. However, it is estimated that ferrochromium transportation costs to the United States can average anywhere from $0.04/lb to $0.12/lb contained Cr. Thus, the difference of $0.11/lb is not considered to represent a large competitive advantage for the South African producers, since ferrochromium transportation costs to the consuming centers within the United States (in this case Pittsburgh via Baltimore or New Orleans, including barge and rail transport) can easily offset this differential. Within the context of this analysis, there would appear to be a South African advantage of only a few cents per pound of contained chromium.

Table 14. — Weighted-average cost estimates per pound of contained chromium for the production of high-C ferrochromium from South African chromite resources, the United States versus South Africa

	Breakeven cost	15-pct DCFROR
FOB smelter, South Africa	$0.29	$0.38
FOB Durban, South Africa	.32	.41
Smelted in the United States, FOB Pittsburgh	.43	.51

Two caveats are in order. First, the actual transportation cost of any individual shipment is dependent upon such factors as market conditions at the time of shipment, size of the shipment (ranging from a few t up to complete shiploads or 15,000 t or more), point of delivery, number and length of stops (demurrage charges), etc. Given these factors, it is felt that international shipping costs for ferrochromium should fall somewhere within this $0.04 to $0.12 range, but the variability of these costs must be stressed. Second, it must also be stressed that the variability of international shipping costs also affects not only the delivered cost of chromite concentrates but also the delivered cost of other raw material inputs that U.S. ferroalloy producers, located in areas such as South Carolina or Ohio, would incur.

What does represent a long-term advantage for South African producers is the fact that all raw material inputs into the smelting process are readily available within close proximity. This fact, and the desire to increase domestic product value added, represent the primary rationale behind the trend of locating downstream processing stages close to the sources of raw material inputs. In the case of South Africa, this fact, coupled with the long-run momentum of large installed capacity and the attendant scale economies, as well as the advantages from vertical integration, should ensure that South African smelting capacity will increase while U.S. and European capacity declines. The issue the United States should address on a governmental policy level is how much domestic

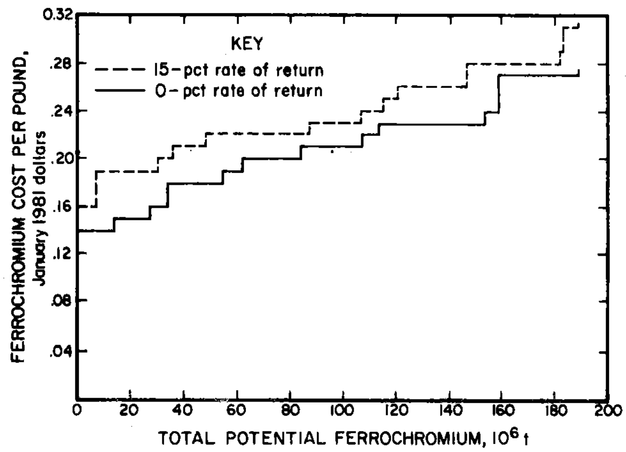


Figure 14. — Cost and potential availability estimates of high-carbon ferrochromium from selected South African chromite operations.

ferroalloy capacity, if any, should be maintained and at what cost.

Lastly, an analysis was performed to determine the total amount of ferrochromium production potentially available from South Africa's demonstrated chromite resources. This total South African chromite-resource-based, high-C ferrochromium availability estimate is approximately 190 million t, which represents 68 pct of the total ferrochromium tonnage potentially available from *all* of the demonstrated chromite resources evaluated in *all 10* of the nations studied. Of this total, fully 87 pct is grade-C and 13 pct grade-B ferrochromium. Figure 14 relates the cost per pound of ferrochromium to cumulative potential ferrochromium availability from the 20 South African chromite operations evaluated. These cost estimates were purposely derived to run the gamut from those representing South African ferrochromium production from domestic chromite resources, to those representing production in the United States, Europe, and Japan from imported South African chromite. The purpose is to demonstrate the long-run average total cost of South African chromite resource-based ferrochromium availability on a major ferrochromium-producing-country basis; and in order to emphasize the predominance of South Africa as a world supplier of chromite for metallurgical uses. The cost estimates (table 15) range from $0.14/lb to $0.27/lb of grade-C ferrochromium at the breakeven level (with a weighted average cost of $0.40/lb of contained Cr) and represent the minimum, long-run, constant dollar cost level of world grade-C ferrochromium production utilizing South African chromite. The cost estimates for grade-B ferrochromium (if assumed to be processed entirely within South Africa) would range from

Table 15. — Breakeven cost level estimates of ferrochromium production from South African-based chromite resources

	Grade C	Grade B	Total
Cost range per pound ferrochromium	$0.14-$0.27	$0.18-$0.21	NAp
Weighted-average cost per pound contained Cr	$0.40	$0.29	NAp
Availability estimate-10^3 t	165,000	25,000	190,000
Pct of total availability estimate	87	13	100

NAp Not applicable.

$0.18/lb to $0.21/lb ferrochromium (with a weighted-average cost estimate of $0.29/lb contained Cr).

This total ferrochromium availability estimate, like the one for South African chromite products, is enormous. To illustrate, if all current South African ferrochromium smelting capacity (820,500 tpy) were devoted exclusively to the production of high-C ferrochromium from just the 638 million t of South African chromite resource that was cost evaluated, this total tonnage estimate would represent 231 yr of ferrochromium production. If all planned capacity expansions were constructed, this tonnage estimate would still represent over 143 yr of full-capacity production. Basically, there are no "life" limits to either the South African chromite or ferrochromium industries. The amount, product mix, and duration of production will depend solely upon the demand for chromium products.

In terms of long run cost and availability, it is expected that South Africa will increasingly dominate the ferrochromium industry conceivably throughout the 21st century, and that the long-run minimum cost level for high-C ferrochromium will be set by the South African industry. Even including the cost of expanding ferrochromium smelting capacity by almost two-thirds results in a weighted average, breakeven domestic cost level of $0.32/lb contained Cr, FOB Durban; and even the analytical requirements of a 15-pct long-run rate of return on this increased level of productive capacity results in an average total cost estimate lower than that determined at the breakeven level for the United States (i.e., $0.41/lb as compared to $0.43/lb contained Cr). And again, it must be stressed that the in situ demonstrated resource level from which this ferrochromium availability estimate is derived is itself a very conservative estimate, representing only 20 pct of the official South African Minerals Bureau estimate. In short, the world's high-C ferrochromium industry for grades B and C is dominated in terms of cost and quantity by South Africa.

SUMMARY

- A cost evaluation was made of 638 million t of chromium-bearing resource contained within 20 operations.
- This resource is estimated to contain 412 million t of recoverable chromite products suitable for metallurgical use, with a weighted average grade of 43 pct Cr_2O_3.
- Total high-C ferrochromium potentially producible from this chromite resource is estimated at 190 million tons.
- Chromite production costs, as defined, were estimated at $65, FOB Durban, South Africa, with mining cost per ton of product accounting for 54 pct, milling 6 pct, and transportation 40 pct.
- High-C ferrochromium production costs, as defined, were estimated for South African producers at $0.32/lb contained Cr at the breakeven level, FOB Durban, South Africa. The same chromite resource smelted to the same grade of ferrochromium in the United States was estimated to cost $0.43/lb contained Cr, FOB Pittsburgh.

Ferrochromium transportation costs to the consuming centers of the United States were estimated to range from $0.04/lb to $0.12/lb of contained Cr.

- South Africa currently accounts for approximately 33 pct of world chromite production and 20 pct of world high-C ferrochromium production.
- Major implications are that both chromite and ferrochromium production should increase in the future, both in absolute terms and as a percentage of the world total. South Africa should increasingly set the long-run minimum cost (and price) levels for both chromite and high-C ferrochromium as a result of an enormous chromium resource base, large mining and processing capacity, and the attendent scale economies. The increase in high-C ferrochromium smelting capacity should come at the expense of declining U.S., European, and Japanese capacity.

ZIMBABWE

GEOLOGY AND RESOURCES

Zimbabwe's chromite resources may be categorized into six different types of occurrences : (1) the seam-type deposits of the Great Dyke, (2) the podiform-type deposits of the Selukwe area, (3) the podiform-type deposits of the Belingwe area, (4) eluvial (residual) deposits scattered over the Great Dyke, (5) the podiform deposits of the Mashaba area, and (6) the so-called "chromite inclusion" deposits of various areas off the Great Dyke proper. Only the first four types of deposits have been of any economic or production significance over the years and, as such, are the only types discussed in detail in this section.

Great Dyke Seam Deposits

The Great Dyke is one of the most striking geologic features in the world. Covering nearly 7,500 sq. km, it is an igneous rock complex with a north-northeast, south-southwest trend of about 535 km and an average width of 5 to 6 km, with its maximum width measured at 11 km in the vicinity of the town of Selous. As shown in figure 15, the Great Dyke begins about 145 km north of Harare (Salisbury) and extends to a point about 150 km southwest of Fort Victoria. Also, as shown in figure 15, the Great Dyke is geologically compartmentalized from north to south into four different complexes—Muzengezi, Hartley, Selukwe, and Wedza—which correspond to four separate basic-ultrabasic intrusions. However, the sequence of rock types from complex to complex is remarkably similar and can be divided into four major zones as follows: (1) quartz gabbro, (2) norite and gabbro, (3) anorthosite gabbro, and (4) lower ultramafic zone (serpentinite, dunite, and pyroxenite).

The lower ultramafic zone comprises a basal dunite zone, a central, olivine-rich, dunite-peridotite (harzburgite) zone, and a very thick upper zone composed almost entirely of enstatite (a pyroxene mineral). The chromite seams occur within the central harzburgite zone and the upper pyroxenite zone. Worst (*25*) identified 11 chromite seams within the Great Dyke Complex. These chromite seams are usually quite distinct and persistent.

There has been no mining of any chromite seams in the Muzengezi Complex, with only six seams outcropping at isolated localities.

The Hartley Complex has contributed the most production from the seam-type deposits because the seams are generally thicker here and extend over greater distances along strike. All 11 of the chromite seams have been identified in this complex.

The Selukwe Complex has provided the second largest amount of production from the seam deposits. However, relative to that from the Hartley Complex, total production has not been very large. Although 7 of the 11 chromite seams are known in this complex, the vast majority of production has come from only seams 1, 2, and 5, and most was from shallow, labor intensive surface excavations ("pig-rooting").

The Wedza Complex is the least explored of all of the complexes and has contributed very little production, all from limited, small scale, open pit operations. Six seams (1-6) are known in the Wedza Complex either from outcrops or from the Wedza borehole.

Each of the four complexes has a synclinal form in cross section, with the synclinal axis plunging gently north and south from its respective south and north ends towards the center of the complex. Where they outcrop, both limbs (east and west) show dips ranging from 26° near the margins to only 4° near the axis with an overall average of around 16°. Work in the Mtoroshangu area has proven that dips decrease to horizontal at the center of the Dyke, in effect connecting the two limbs across the width of the Dyke. Persistence of the seams along strike has also been well documented by prior mining operations and locations of outcrops. In the area of the Dyke south of Mtoroshangu Pass (south of south latitude 17°, 6′), tectonic effects, mainly in the form of faulting, are minor. The area north of Mtoroshangu Pass has undergone somewhat more faulting and intrusion and, as such, the continuity of chromite seams cannot be assured. However, this increased tectonic activity has actually caused the area north of Mtoroshangu Pass to account for the largest portion of past production from the seam deposits because outcrops are more numerous, access by adits and shallow incline shafts is possible, and it is also possible to mine more than one seam from one access system in certain cases.

B. G. Worst (*25*) defined the 11 chromite seams of the Great Dyke in terms of the marketing characteristics prevalent at the time (1960). Thus, he characterized seams 1, 2, and 3 as "chemical-grade" chromite ore, and seams 4 through 11 as "metallurgical-grade"

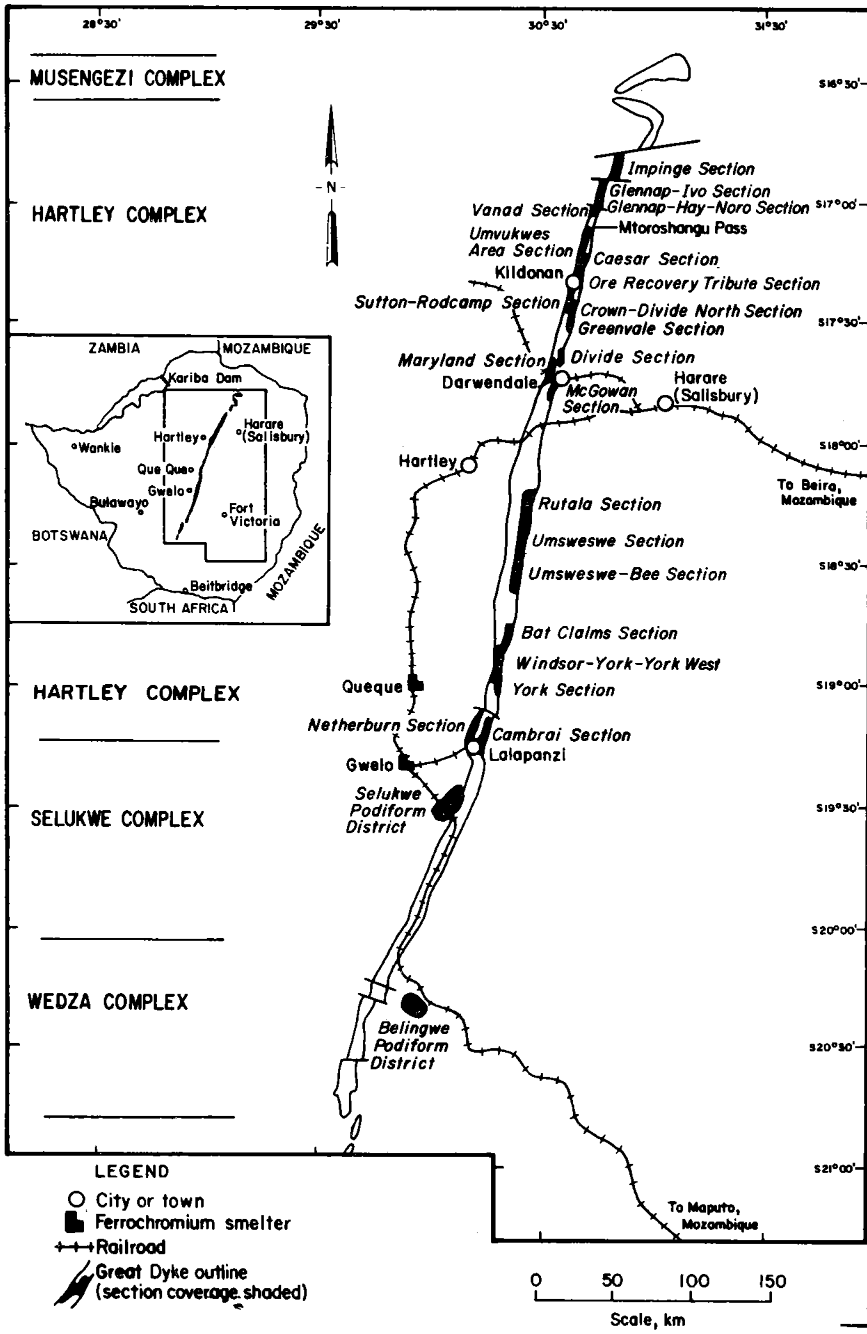


Figure 15. — Location of chromite mining areas, smelting facilities, and transportation network, Zimbabwe.

ores. Worst chose this characterization simply because the Cr:Fe ratios in seams 1, 2, and 3 are commonly in the 1.8 to 2.3 range while those in the other seams are very high, ranging from 2.5 to as much as 3.4. Changes within the ferrochromium industry would now place all of this material in the metallurgical category, since chromite with Cr:Fe ratios as low as 1.3 can be used in producing grade-C charge ferrochromium and ores with low and high Cr:Fe ratios can be blended to produce intermediate grade ferrochromium.

Owing to the high Al_2O_3 and MgO contents (typically 11 to 13 pct Al_2O_3 and 14 to 17 pct MgO), much of the Zimbabwe seam chromite is suitable for refractory use and does have negative aspects in the smelting process because it forms more slag material and results in a slower smelting process. However, for this study it was assumed that *all* of the seam chromite material analyzed could be utilized for ferrochromium production, simply because the market for refractory-grade chromite in and from Zimbabwe is very limited and is provided, at present, almost entirely from Selukwe podiform operations.

Table 16 characterizes all 11 seams in terms of Cr_2O_3 content, Cr:Fe ratio, thickness, and ore-quality type. Obviously, when trying to generalize occurrences

Table 16. — Great Dyke chromite seam characteristics

Seam	Thickness, m		Cr_2O_3 average, pct	Cr:Fe ratio	Ore type	Occurrence
	Range	Average				
1	0.15–0.40	0.22	46	1.6–2.3	Hard lumpy along outcrop, friable down-dip; Cr_2O_3 content can be very variable.	All 4 complexes, more important south of Mtoroshangu Pass.
2	.15– .40	.35	46	1.4–2.3	Hard lumpy along outcrop, friable down-dip.	Do.
3	.08– .20	.12	48	2.6–2.9	Hard lumpy along outcrop, semi-friable to friable down-dip, limited data.	Selukwe and Hartley complexes most important.
4	.04– .20	.15	49	2.4–3.3	Coarse-grained and hard on outcrop and to depth-a preferred metallurgical ore.	Do.
5	.05– .20	.12	50	2.8–3.0	Description only of basal portion-friable to semi-friable ore.	Most important in Hartley complex.
6	.08– .15	.12	50	3.0	Bulk of material is friable, 50 pct hard lumpy in outcrop.	Do.
7	.10– .15	.15	52	3.0	Bulk of material is friable, 30 pct hard lumpy along outcrop.	Do.
8	NA	.15	51	2.8–3.1	20 pct hard lumpy along outcrop, friable at depth.	Most known in Hartley complex, mined by pits but not effectively by underground methods.
9	NA	.10	50	2.8–3.3	Hard lumpy along outcrop, friable at depth.	Has only been mined north of Mtoroshangu Pass.
10	NA	.12	50	3.2	Hard lumpy along outcrop, friable at depth, limited data.	Do.
11	NA	.10	50	2.6	....do	Outcrops few, knowledge very scant.

NA Not available.

over a 500 km strike length, there will be differences from any tabulation that results. Individual economic evaluations have attempted to take these differences into account. As an example of these differences, seam 5 is thin in the Selukwe and Wedza complexes (<0.07 m of solid ore) but has at least 0.10 m of solid ore in the Hartley Complex. The Cr_2O_3 grades shown in table 16 are estimates of weighted averages that were used in the economic evaluations.

In terms of ore type, hard lump material in the chromium seams only occurs locally under two basic conditions: 1) in the immediate vicinity of thrust faults and 2) where groundwater circulation has modified the matrix material (related to past and present water tables.)[10] It appears that below a vertical depth of 125 m or so, the only hard, lumpy ore to be encountered will be found in the immediate vicinity of faults. For this study, it is estimated that only about 10 pct of the total Great Dyke seam material analyzed will be of the hard, lumpy type (>1-mm size grains) while the remainder is considered as friable (fines) with average grain sizes of about 0.2 mm.

There have been many estimates of Great Dyke seam chromite resources. The first and foremost was by B. G. Worst (*25*), who included nine separate geological maps covering the entire Great Dyke, along with cross sections at intervals of approximately every 3.2 km and longitudinal sections along the axes. As part of his study, he estimated the chromite resource to total about 296 million t of extractable material or 370 million t of in situ material, 65 pct being chemical-grade (seams 1, 2, and 3) and 35 pct being metallurgical-grade (seams 4-11). Only 9.5 pct of the total tonnage was located in the Wedza Complex, with nearly 25 pct in the Selukwe Complex, and 65.5 pct in the Hartley Complex. His estimate was based on the outcrops of seams, projected to about 183 m on dip (only about 80 m vertical depth) except where seam thicknesses were less than 0.076 m, in which case projection was only to 3 m on dip (open cast mining only). Worst noted at the time that the total in situ chromite resource probably would be more like 10 times his original estimate (nearly 3.7 billion t). Other published estimates of Zimbabwe's chromite resources in the Great Dyke seam deposits over the years have ranged from 50 million t of economically minable high-Fe chromite resources (*26*, p. 25), to 10 billion t of total in situ resources.[11] Regardless of criteria, it is obvious that the tonnage present in the Great Dyke is enormous.

It is estimated that maximum crude ore production in the late 1970's from seam deposits on the Great Dyke was only around 450,000 tpy. This would mean that 3.7 billion t of in situ resource would last for over 8,000 yr at late 1970's production levels. Since analysis of such a large tonnage would necessitate unrealistic assumptions as to development schedules and production levels, it was decided that analysis of availability would consist only of what were mentioned as producing areas (sections) in the late 1970's or areas that were recent past producers and held promise for production in the near future.

The sections comprising the demonstrated resource tonnage used in this study are shown in figure 15 as shaded areas over the Great Dyke outline. Table 17 lists these sections, the seams that outcrop, the demonstrated resource tonnage, weighted average grades, and amount of contained Cr_2O_3 for each of these seams along that section. Each seam has been projected downdip for a length of 300 m (approximately 100 m vertical) and an in situ tonnage factor of 4 t/cu m was utilized. The resulting (cost evaluated) demonstrated resource of 175 million t of in situ material is located entirely within the bounds of the Hartley Complex. The relationship of this tonnage to Worst's estimate and the composition of the seam material is shown on figure 16. Although the cost evaluated tonnage represents but a small fraction of this potential

[10] Confidential source.

[11] Confidential source.

Table 17. — Estimated in situ chromite resource data for selected Great Dyke, Zimbabwe, seam deposits as of 1980

Section name and description	Seams present (outcropping)	Strike length, km	Seam thickness, m	Demonstrated resource, 10^3 t	Weighted-average grade, pct Cr_2O_3	Contained Cr_2O_3, 10^3 t	Identified resources,[1] 10^3 t
Glenapp- Ivo:							
Both limbs of Dyke, 10-km sec. from S. 16°55′ to S. 17°0′.	9–11	8–20	0.10–0.125	6,480	50	3,240	16,880
Impinge:							
Both limbs of Dyke, 12-km sec. from S. 16°48′ to S. 16°55′.	9–11	6–24	.10– .12	6,144	50	3,072	18,240
Sutton-Rodcamp:							
West limb; 18-km sec., from Kildonan to S. 17°30′.	4–10	15	.10– .15	15,480	50	7,740	76,440
Vanad:							
Both limbs; 3-km sec. from Ethel fault southwards.	6–10	2–6	.10– .15	4,032	51	2,056	12,984
Caesar:							
East limb; 4-km sec. from Caledonian northwards.	4–9	4	.10– .15	3,552	51	1,811	22,848
Crown-Divide North:							
East limb; 4-km sec. from S. 17°30′ to 1 km south of Maquadzi.	4–9	4	.10– .15	3,552	51	1,811	21,088
Glenapp-Hay-Noro:							
Both limbs; 7-km sec. from Ethel fault northwards to S. 17°0′.	7–11	10–14	.10– .15	8,976	51	4,578	25,120
Umvukwes Area:							
West limb; 12-km sec. from Mtoroshangu Pass southwards to Caledonian.	5–10	12	.10– .15	10,944	51	5,581	53,856
Ore Recovery Tribute:							
West limb; 10-km sec. from Caledonian southwards to Kildonan.	5–10	10	.10– .15	9,120	50.5	4,606	36,960
Greenvale:							
East limb; 8-km sec. from S. 17°30′ to Brinsham.	5–9	8	.10– .15	6,144	51	3,133	36,672
Maryland:							
West limb; from 1-km south of Maryland siding to point 8-km north.	4–9	5–8	.10– .15	6,384	51	3,256	38,768
McGowan:							
East limb; 8-km sec. from Hunyani River northwards to Darwendale.	1, 2, and 5	8	.12– .35	6,720	46.5	3,125	130,372
Divide:							
East limb; 8-km sec. from Divide mine northwards to Brinsham.	4–10	8	.10– .15	8,256	50	4,128	45,696
Rutala:							
East limb; 25-km sec. from Umfuli River southwards to point 3.5-km north of Umsweswe River.	1 and 2	18	0.25	10,800	46	4,968	283,680
Umsweswe:							
East limb; 3.5-km sec. from Umsweswe River northwards.	1 and 2	3	0.20– .27	1,974	46	908	37,940
Umsweswe-Bee:							
East limb; 25-km sec. from Ngezi River northwards to S. 18°30′.	1, 2, 5, 6, and 7	14–24	.10– .28	20,808	47.5	9,884	228,960
Windsor-York-York West:							
Both limbs; 20-km sec. from Umniati River southwards to S. 19°0′.	5, 7, 8, and 9	14–40	.10– .15	14,040	51	7,160	33,840
Bat Claims:							
East limb; 8-km sec. from Umniati River northwards.	1, 2, 5, and 7	8	.10– .28	6,912	47.5	3,283	28,800
Cambrai:							
East limb; 14-km sec. from Lalapanzi to Bembezaan River.	1, 2, and 5	14	.15– .23	9,391	47	4,414	17,663
Netherburn:							
West limb; 21-km sec. from opposite Lalapanzi to S. 19°10′.	1, 2, 5	21	.15– .23	14,087	47	6,621	26,493
York:							
East limb; 4-km sec. from Sebakwe dam to S. 19°0′.	5	4	.15	734	50	367	1,224
Sections costed	NAp	NAp	NAp	174,530	49	85,520	1,195,000
Sections not costed[2]	NAp	NAp	NAp	543,083	49	266,111	3,228,000
Total or average	NAp	NAp	NAp	718,000	49	352,000	4,423,000

NAp Not applicable.

[1] Identified tonnage equals demonstrated plus inferred tonnage.

[2] This area includes the properties of Aver, Boots, Bridge, Chrome Interests, Frances, Great Dyke, Magundi, Maquadzi, Mdindi-Rose, Mount Chrome Claims, Otto, Pons, Rhochrome, Seymore, Yani, and Nyamenetsi.

NOTE: Data may not add to totals shown because of averaging and independent rounding.

tonnage estimate, it is important to note that this tonnage itself would last for over 300 yr assuming a mining rate of 500,000 t of crude ore per year and a mining recovery of 90 pct.

It must be remembered that not all of the seams shown in table 17 are presently being mined. In actual operations on the Great Dyke, when mining operations on the seam being exploited reach a point 300 m downdip along the entire strike length of the section, a decision could be made to proceed farther downdip on

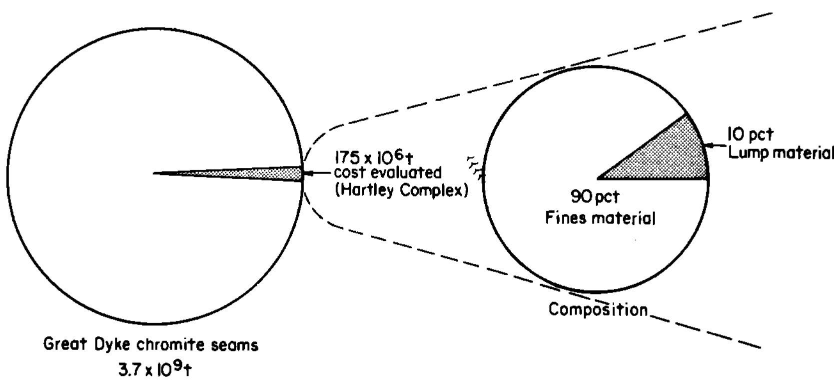


Figure 16. — Composition of cost-evaluated Great Dyke seam material and its relationship to total potential in situ tonnage.

that seam rather than develop the other unexploited seams. However, for this economic analysis, it was assumed that when the tonnage to a down-dip depth of 300 m is exhausted, new development will proceed to the next most attractive seam(s) or along strike on the same seam rather than extending the current operation to greater depths.

An identified resource has been estimated for this study by extending the projections to downdip depths ranging from 300 to 2,000 m for (1) all seams contained within those sections (operations) analyzed at the demonstrated resource level, plus, (2) seams not outcropping but inferred to occur at depth on the sections cost analyzed, plus, (3) those sections of the Great Dyke not cost evaluated as demonstrated resources (nonshaded areas of figure 15). These results give estimates of about 1.2 billion t contained within the cost evaluated sections and a total of 3.2 billion t contained in the noncovered areas, which results in a total in situ identified resource level of approximately 4.4 billion t, or 3.96 billion t of recoverable resource, slightly more than the 3.7 billion in situ tonnage Worst expected. However, numbers this large lose their relevance in light of the fact that, as already noted, a 3.7-billion-t resource would last on the order of at least 8,000 yr at present mining rates and recoveries.

Selukwe Podiform Deposits

The podiform-type deposits of the Selukwe area have historically provided at least 40 pct of Zimbabwe's annual production since 1906. It is estimated that through 1979 total production from the District has been about 11.5 million t of chromite products.

The Selukwe District abuts and is transsected by the western margin of the Great Dyke, as shown in figure 17. The total district covers a 30-km length (north-south) and a 7- to 10-km width (east-west). Within this area are 15 to 20 subordinate complexes comprising outcrops of ultramafic rock referred to as "slices." Only about eight of these complexes are of sufficient size and are proven to contain chromite bodies. These eight complexes are estimated to cover only about 40 sq km of the total 240 sq km comprising the entire District. Of these eight complexes, only three, Selukwe Peak, Railway Block, and Valley Chrome, have produced the vast majority of output over the years.

The original peridotite sheets and lenses containing chromite were emplaced in the early Precambrian period nearly 800 million yr prior to emplacement of the Great Dyke. The geology of the district is very complex owing to multiple stages of folding, faulting, metamorphism, metasomatism, and intrusion (*27*). Regionally, the Selukwe District rocks and formations belong to the Selukwe Schist Belt, which consists of eight formations. The important chromite ore deposits occur only in the talc carbonate, silicified talc carbonate, and silicified serpentine units in the Selukwe Ultramafic Formation.

An early study of the area (*28*) stated that homogenous chromite ore bodies are irregularly distributed throughout the talc-carbonate and serpentine rocks and that the homogenous ore bodies took two forms: (1) irregular, rounded lenses up to 137 m in length and (2) long, narrow bodies with a veinlike outcrop and shallow downward extension. Since that time, much geologic investigation has been done in the District, including extensive surface and underground mapping and diamond drilling, especially during the years 1957-66. Following are short geologic discussions of what have been the most important chromite mining operations in the District over the years—Selukwe Peak and Railway Block.

At Selukwe Peak, five ore zones occur over a stratigraphic thickness of 245 m (*29*). The lowest two zones (in relation to the ultramafic sheet) contain chromite of very low Cr_2O_3 content (<36 pct) and low Cr:Fe ratio (1.7). Zones 3, 4, and 5 contain high-grade material of >40 pct Cr_2O_3 and Cr:Fe ratios >2. Zone 3 covers the main ore zone at Selukwe Peak. As of 1969, at least 25 ore bodies had been mined or were delineated at Selukwe Peak. These ore bodies occur sporadically over a strike length of approximately 2,500 m. The grade of material at Selukwe Peak is somewhat lower in terms of Cr_2O_3 and Cr:Fe ratio than at Railway Block. Supposedly, the main ore zone (zone 3) has been traced over the entire 5 km length of the Selukwe peridotitic-tectonic "slice", essentially double the length that had been worked as of 1969.

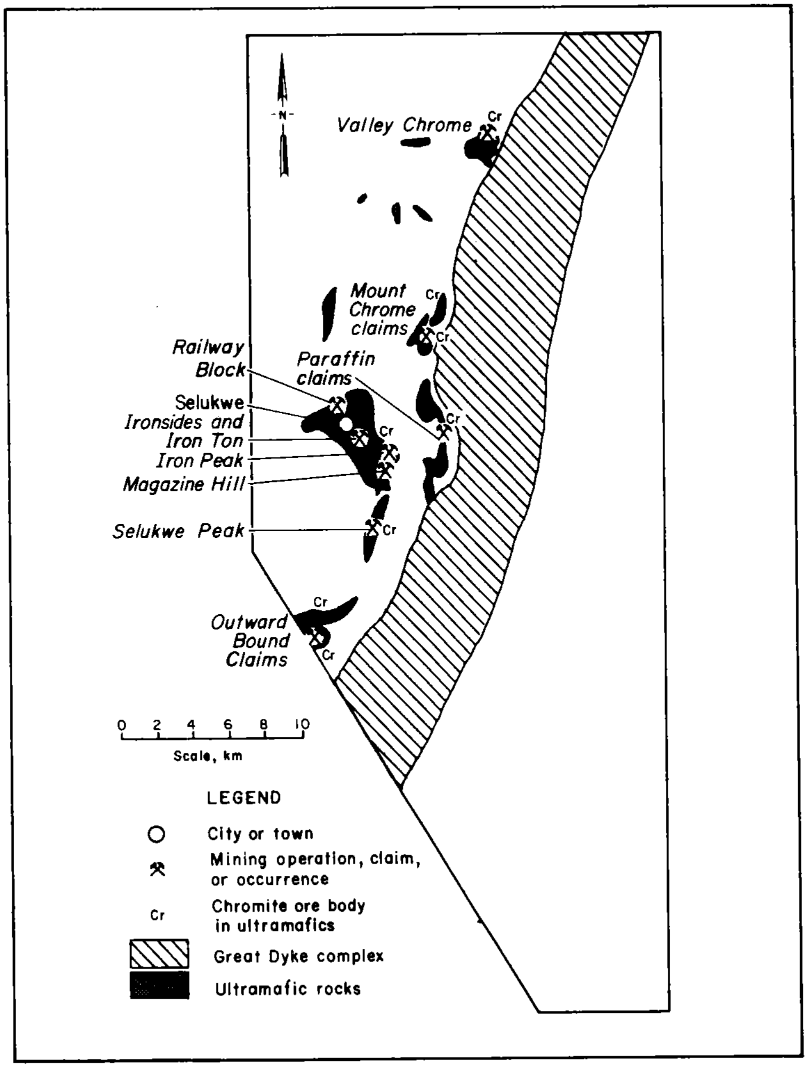


Figure 17. — Location of chromite ore bodies and mining operations, Selukwe Podiform District in Zimbabwe.

According to Cotterill (*29*), the Railway Block property as of 1969 consisted of five separate zones: (1) the Friable Zone, (2) the Railway Block West Zone, (3) the Priority Zone, (4) the Central Zone, and (5) the Kinraids and Barbadoes Zone. Of all of the zones, the most important as of 1969 was the Priority Zone, where two large ore bodies plus several smaller ore bodies had been found and proved from the 116 m to the 305 m levels. The larger ore bodies were said to occur along 300 m of strike, with average thicknesses of 12 m and extensions to depth of nearly 50 m. Descriptions of other operations analyzed in the Selukwe District are shown in table 18.

Generally, 80 pct of a lens deposit in the Selukwe District will consist of chromite grains ranging in size from 0.5 to 4 mm and is considered as lump ore. The other 20 pct will consist of disseminated, chromite grains ranging in size from 0.01 to 0.5 mm and is considered as fines ore. The Valley Chrome deposit, which is a large low-grade deposit, consists entirely of the disseminated fines-type of ore.

An unpublished report of 1980,[12] estimated that there were 3 million t of high-grade, hard, lumpy ore and 1.5 million t of low-grade, hard, lumpy material available from the Selukwe District podiform deposits. Von Gruenewaldt (*19*) estimates that there is 1 million t available to a vertical depth of 150 m and a hypothetical resource of 76 million t available to a vertical depth of 1,200 m. The disparities arise because of the erratic nature of podiform chromite deposits (ore bodies). In essence, as in all podiform occurrences (e.g., Turkey, the Philippines, etc.), it is virtually impossible to predict from surface occurrences what will eventually be found at depth. However, when it is noted that Zimbabwe Mining and Smelting Co. announced plans in 1981 to bring three new mines—Magazine Hill, Iron Ton, and Railway Block East—into production and to expand capacity at the Valley Chrome, Selukwe Peak, and Railway

[12] Confidential source.

Table 18. — Ore bodies, ore type, and analysis of crude ore composition, Selukwe District operations-properties, Zimbabwe

Operation-property and ore bodies-zones	Ore type	Analysis, uncleaned ore: Cr_2O_3	SiO_2	Al_2O_3	MgO	Cr:Fe ratio	Comments
Railway Block:							
Priority	Majority lump	49.25	5.02	12.58	15.58	3.8	Two large ore bodies and several smaller ore bodies proved from 116-m level to below 305-m level.
Central	do	45.30	5.96	11.92	20.70	3.4	Concentration of ore bodies along 60-m of strike, starts at 160-m depth.
Friable	do	49.80	3.22	12.41	18.17	3.5	Bodies being mined are small and irregularly shaped (average less than 12,000 t).
Railway Block West	do	49.20	3.60	12.00	18.05	3.5	Do.
Kinraids-Barbadoes	NA	NA	NA	NA	NA	NA	No substantial reserves proven as of 1969.
Selukwe Peak:							
4A	Majority lump	45.80	5.40	10.80	13.80	2.7	A "central" concentration of ore bodies occurring over 2,500 m strike length. At least 25 ore bodies mined up to 1969.
2A	do	49.45	5.60	12.60	14.05	2.9	
Valley Chrome:							
Black Ore	Disseminated, fines	39.70	8.70	14.10	17.00	2.3	Large chromite bodies totaling several million t of disseminated, high-magnesia chromite grains.
Blue Ore	do	42.20	7.00	15.20	16.80	2.7	
Magazine Hill:							
Borehole M.H. 50 219.3 to 219.75 m.	Majority lump	49.55	7.60	12.40	14.85	3.4	Zone 305 m long and 60 m wide, contains lenses 6 m thick.
Iron Sides:							
Borehole I 64:							
84.2 to 85.7 m	Majority lump	43.60	7.10	13.80	16.34	3.0	Zone 610 m long and 30 m wide, contains lenses up to 10 m thick.
90.3 to 91.5 m.	do	46.10	6.70	13.60	16.89	3.2	
Iron Peak	do	NA	NA	NA	NA	NA	No available information. Not cost-evaluated.
Iron Ton	do	NA	NA	NA	NA	NA	Do.

NA Not available.

Block operations, then estimates of 1 million and 3 million t for the Selukwe District appear much too low (*30*, p. 40).

Table 19 shows this study's estimate of demonstrated resource tonnages and grades for the Seluke District operations that are expected to make significant contributions to near-term production from the District. Also shown in this table are the geologic criteria used as the basis for the estimates. Because of the lack of up-to-date geologic information, especially in the cases of Magazine Hill, Ironsides, and Iron Ton, approximations of geologic occurrence had to be made in order to estimate costs of production. It is probable that the estimated in situ demonstrated resource of 14.88 million t of chromite (table 19), will eventually prove to be a somewhat conservative tonnage for the Selukwe District. However, since the demonstrated resource tonnage already utilized a high degree of inference, it was impossible to estimate an inferred-level resource on a property-by-property basis based upon the available information. As was the case for the Great Dyke, there are many different estimates of chromite resources in the Selukwe District podiform deposits.

It is reasonable to expect at least as many ore bodies of sizes used in developing table 19 to be present throughout the District. Nevertheless, the question of depleting podiform resources in the Selukwe District is an important one to the Zimbabwe chromite industry. Ore from these deposits has consistently accounted for 40 pct or more of Zimbabwe's production because it is the cheapest material to produce, it is mostly lumpy material (slightly cheaper and easier to smelt), and it is generally higher grade (higher Cr:Fe ratio) than the Great Dyke seam deposits. On average, the demonstrated resource of 14.88 million t would last about 21 yr assuming a 90-pct mining recovery and the capacities shown in the mining section of this report. For comparison, the 76 million t of hypothetical resource would last about 129 yr using the same assumptions. The importance of the Selukwe podiform deposits to Zimbabwe's chromium industry lies with the added cost per ton of ferrochromium that would

Table 19. — Estimated in situ chromite resource data for selected Selukwe District podiform deposits of Zimbabwe, as of 1980

Operation-property	Demonstrated resource, 10^3 t	Weighted-average grade, pct Cr_2O_3	Contained Cr_2O_3, 10^3 t	Criteria for tonnage estimates
Railway Block	4,600	49.0	2,254	Two ore bodies with strike lengths of 310 m each, thicknesses of 13 m each and extensions downdip of 215 m.
Selukwe Peak	6,900	46.5	3,208	Three ore bodies with strike lengths of 120 m, 320 m, and 200 m, thicknesses of 20 m, 10 m, and 15 m, respectively, downdip extensions of 200 m.
Valley Chrome	1,400	40.5	567	Published estimate of "several million tons" at start, minus estimated production from 1970 through 1979.
Magazine Hill	660	49.0	326	Geologic "model" is 1 ore body 300 m on strike, 7 m thick, extending 80 m on dip.
Iron Sides	660	45.0	300	Do.
Iron Ton	660	45.0	300	Do.
Total or average	14,880	[1]46.5	6,955	NAp

NAp Not applicable.
[1] Weighted-average in situ grade at the demonstrated level.

result from replacing Selukwe podiform output with Great Dyke seam material, as will be shown in subsequent sections.

Belingwe Podiform Deposits

The Belingwe podiform deposits are located about 60 km south of the city of Belingwe. They were discovered sometime in the early to mid-1950's, and first production began in 1957 (*31*). By 1959, the District was producing 3 pct of Zimbabwe's chromite production. Because of its minor position in the Zimbabwe chromite industry and the generally sparse amount of information published during the last 20 yr on Zimbabwe, very few data are available on the geology, mining, production, or any other aspect of this District. It is known that, as of 1978, at least two mines, Inyala and Rhonda, were in operation in the District (*32*) and that in the early 1970's a third operation, the Mlimo mine, was producing.

The District is part of the Limpopo Schist Belt, also known as the Limpopo Mobile Belt or the Limpopo Metamorphic Belt. One description from 1959 (*31*) states that the chromium ore bodies occur within isolated, steeply dipping ultramafic "inclusions" in a granite country rock and that the ore bodies are separated within the ultramafic inclusions like "plums in a plum pudding." A second, more recent unpublished source[13] describes the occurrences only as small chromite lenses in a granulite gneiss environment. The vast majority of the chromitite available is of the hard, lumpy type although bodies of friable material are known. Indications are that the grade of Belingwe chromite ranges from 40 to 50 pct Cr_2O_3 with Cr:Fe ratios mostly <2.5. The Chamber of Mines article of 1959 (*31*) listed two grades of products: a high-grade, hard, lumpy ore of 47 to 50 pct Cr_2O_3, 14.7 pct FeO, 12.5 pct Al_2O_3, and a Cr:Fe ratio of 2.7 to 3.0, and a low-grade, hard, lumpy ore of 45 to 50 pct Cr_2O_3, 20 pct FeO, 15.2 pct Al_2O_3, and Cr:Fe ratios of 2 to 2.3.

Rough estimates of podiform resources in the Belingwe District are only available from two sources. An unpublished source[14] estimated the tonnage at 1 million tons, including 40 pct high-grade, lumpy material and 60 pct low-grade, lumpy material. Von Gruenewaldt (*19*) recently estimated a "hypothetical" resource figure of 13 million t for the Belingwe District. As already stated in the discussion of Selukwe District podiform deposits, it is very difficult to estimate reserves and resources for podiform chromite deposits since ore at depth is only found in the course of underground development and exploration. Thus, there will be wide discrepancies in any estimate of chromite resources for a district containing podiform chromite deposits.

Because of the lack of any detailed geologic data on the Belingwe District chromite deposits, it was necessary to construct models to analyze costs. For this study, it was assumed that there are at least three ore bodies present in the District, with dimensions comparable to an average-sized ore body in the Selukwe District. Thus, the model consists of three separate ore bodies, each with strike lengths of 300 m, thicknesses of 7 m, and extensions downdip for 80 m. The total in situ tonnage contained in the three model ore bodies would be about 2 million t (double the unpublished source's estimate but only 15 pct of Von Gruenewaldt's hypothetical resource estimate) at an average grade of 48 pct containing approximately 904,000 t of Cr_2O_3. It is assumed for analysis that this demonstrated, in situ resource of 2 million t would consist of 50 pct hard, lumpy ore and 50 pct of fines or lower grade material that should be beneficiated by gravity methods.

At the total estimated production capacity for all operations in the District of about 30,000 t of ore, the demonstrated resource of 2 million t should last for 60 yr. However, this result is based on rough estimates and should be further enhanced by future data collection.

Eluvial Chromite Deposits

For years in Zimbabwe, residual deposits of chromite grains in soil were viewed as a possible source of chromite production. The first attempts at production from soils were begun in the early 1950's, and for a 5-yr period (1952-56) declared output of chromite concentrate from eluvial deposits was 103,000 t (*25*). By the late 1950's three plants in operation in the area north of Mtoroshangu Pass were treating chromite soils using a magnetic separation-flotation process. However, by 1976 only one plant was still in operation, Zimbabwe Mining and Smelting Co.'s Impinge plant, and the flotation process had been abandoned.

The eluvial deposits are residual concentrations of chromite grains in soils resulting from the weathering of the chromite seams and surrounding rocks. The residual concentrations tend to be best in flat, poorly drained areas in the most mountainous (elevated) areas along the Great Dyke. The soils consist mostly of chromite, magnetite, and hematite with average chromite grain sizes of 0.2 to 0.3 mm. The process of residual concentration results in overall lower Cr:Fe ratios than would be found in the parent chromite seams. This occurs because the overall iron content in the soil is higher and it is difficult in processing to completely eliminate the additional iron. Because of this, the best chromite soils deposits from a resource grade standpoint will be those derived from seams with Cr:Fe ratios >2.8 (essentially seams 4-11 on the Great Dyke).

All of the producing operations so far have been located within the section of the Great Dyke from Mtoroshangu Pass northwards to the Gurungwe Fault in the Hartley Complex, which Worst (*25*) considered the best area.

The sole operating mine in 1976 reported that the soil thickness at their operation varied from 0.12 to 1.8 m thick with an average of 0.45 (*33*) and that 95 pct of the recoverable chromite was in the minus 0.5-mm soil fraction with the remainder in the form of pebbles in coarser material near the parent seams. Based on published production rates and assumed grades of concentrates and mill recovery, it is esti-

[13] Confidential source.
[14] Confidential source.

mated that the average feed grade of soil to the plant was 20 pct Cr_2O_3 with ranges probably from 10 pct to 40 pct.

Only one estimate of eluvial chromite resources in Zimbabwe is available—that made by Von Gruenewaldt in 1981 (*19*). He estimates a total of 54 million tons, which presumably is the tonnage of soil available. The criteria behind the estimate are not known. A comprehensive, detailed survey of suitable eluvial deposits along the entire Great Dyke is not known to have ever been conducted. Thus, the 54 million ton resource estimate is not "locatable." Because of that, it was decided that the demonstrated resource of eluvial chromite soil in Zimbabwe to be cost evaluated in this study, should consist solely of those operations known to be recently in production. Hence, the Zimbabwe Mining and Smelting Co.'s Impinge operation is the only eluvial operation evaluated in this study as constituting a "demonstrated resource."

The demonstrated resource of eluvial soil remaining as of 1980 for this property is estimated to be around 4.7 million t at an average grade of 20 pct Cr_2O_3 with a Cr:Fe ratio of 2.2 and containing approximately 950,000 t of Cr_2O_3. The resource tonnage was estimated based on the assumption that mineralization of appropriate thickness (average of 0.45 m) is found over 800 ha of area, utilizing a tonnage factor of 2.3 t/cu m and includes subtractions of an estimated 3.6 million t of soil extracted from 1968 through 1979. The demonstrated resource tonnage would have an approximate production life of nearly 16 yr at a production rate of 300,000 tpy of soil treated (50,000 tpy of concentrate produced) and would result in approximate total production of 830,000 t of concentrates.

It is highly probable that as much as 54 million t of eluvial chromite soil exists throughout the 300,000-ha area covered by the Great Dyke. However, even this large a tonnage would only produce about 9.5 million t of concentrates, and the economics of this total tonnage are impossible to analyze without the ability to specify the exact areas where it occurs or details of occurrence specific to that location.

In summarizing the eluvial chromite resources in Zimbabwe, three points should be stressed. First, the technology for extraction and production of marketable concentrates does exist. Second, there are too many operational unknowns to determine whether economic production of concentrates from the hypothetical 54-million-t resource is possible. Third, a comprehensive and detailed survey of the Great Dyke area must be accomplished before attempting to estimate the total chromite resources that would be available from eluvial chromite soils in Zimbabwe.

Table 20 and figure 18 summarize the in situ demonstrated and identified resources of chromite-bearing material in Zimbabwe estimated according to the criteria of this study. The in situ demonstrated resource tonnage of 740 million t is comprised of 97 pct from seam deposits on the Great Dyke, 2.3 pct from podiform deposits in the Belingwe, Mashaba, and Selukwe districts, and 0.7 pct from eluvial chromite soils. Of the total in situ identified resource tonnage of 4.574 billion t, fully 97 pct is also from the seam deposits on the Great Dyke.

Table 20. — Summary: In situ demonstrated and identified resources of chromite in Zimbabwe, by type of deposit

Type of deposit	Demonstrated resource, 10^3 t	Weighted-average grade, pct CR_2O_3	Contained Cr_2O_3, 10^3 t	Identified resource,[1] 10^3 t
Seam deposits, Great Dyke:				
Costed	[2]175,000	49.0	85,520	[3]1,195,000
Not costed	[4]543,000	49.0	266,111	[5]3,228,000
Total	718,000	49.0	351,631	4,423,000
Podiform deposits:				
Selukwe	14,900	46.5	6,955	[6]76,000
Belingwe	2,000	48.0	904	[6]13,000
Mashaba	[7]400	45.0	180	[6]8,000
Total	17,300	46.5	8,039	97,000
Eluvial chromite soils	[8]4,700	20.0	950	[6]54,000
Total, or average, all deposit types	740,000	49.0	360,620	4,574,000

[1] Identified tonnage equals demonstrated plus inferred tonnage.
[2] Calculated for producers or recent producing sections only to a downdip extension of 300 m.
[3] Calculated for producers or recent producing sections to downdip extensions of between 300 and 2,000 m.
[4] Calculated for all other sections not in recent production to a downdip extension of 300 m. Not cost evaluated.
[5] Calculated for all other sections not in recent production to downdip extensions of between 300 and 2,000 m.
[6] Von Gruenewaldt (*19*).
[7] Unpublished (confidential source) — not cost evaluated in the study; production effect basically nil.
[8] Estimated for the study; see text for description.

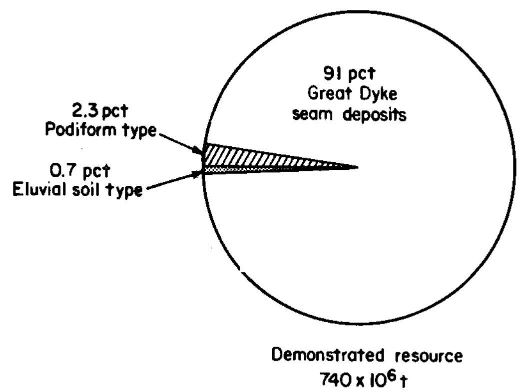


Figure 18. — Distribution of demonstrated resource level, by type of occurrence, in Zimbabwe.

MINING

Mining of chromite ore in Zimbabwe consists of three major types—underground resue mining of seam deposits on the Great Dyke, underground sublevel stoping of podiform deposits, and surface mining of the eluvial-type deposits. Each type is discussed separately in the following sections.

Great Dyke Seam Deposit Mining—Resue Mining

By the mid to late 1940's, mining of chromium seams on the Great Dyke had progressed, by necessity, from "pig-rooting" (surface mining of seams along outcrop to shallow depths) to underground methods. The basic underground mining method now in use is called "resuing". In this method, a stoping width (vertical height) of 0.9 m is usually established. From 0.1 to 0.30 m of this width will consist of the chromite seam, with the remainder pyroxenite or serpentinite waste rock. Blast holes are usually drilled with electric "coal" drills (less often with jackhammers). The blast holes are put into the relatively soft waste rock at sufficient distances from the chromite seam so that the seam will not be disturbed by blasting. After blasting, the waste rock is removed from the stope by hand-lashing. As much of the waste as possible is packed into stoped-out areas for support, and the remainder is wheeled or scraped, then railed and hoisted to the surface. After all of the waste has been removed from above the chromite seam, crowbars, hammers and chisels, pneumatic drills, or even light blasting are used to remove the chromite seam. Where the ore is friable and the seam is not "frozen" to the footwall, the chromite seam can be lifted out using only crowbars, hammers and chisels, or even by hand. This type of occurrence is the case in the majority of seams. The ore is next transferred to footwall drives, either by box-type winch scrapers or by wheelbarrow, while haulage in footwall drives to the shafts is usually by small electric or diesel locomotives hauling 3- to 4-t cars. It should be noted that modifications to the basic resue mining system are constantly being made and vary from mine to mine.

This study assumes no dilution and mining recoveries in the range of 85 to 90 pct. In actual operations, great care is taken throughout the mining process to minimize the effect of dilution from serpentinite or pyroxenite waste rock. Scrapers, railcars, and skips are carefully cleaned after use in transporting waste, and scraper paths are swept clean after waste scraping and prior to ore scraping. Reported mine recoveries have ranged from 75 to 95 pct. Losses occur mostly through ore left in support pillars that are not reclaimed. The highest recoveries are attained with methods that include reclaiming of support pillars with consequent total filling with waste rock.

As of 1975, a rule-of-thumb estimate for resue mining was that in order to produce 1 t of salable chromium ore, about 3.7 t of waste and 1 t of ore would have to be hoisted to the surface (*34*). In addition, 1.9 t of waste would have to be packed back into the stopes if standards of the 1950's (*35*), in terms of the percentage of waste hoisted versus the percentage of waste packed, still applied. With the trend being to improve support by completely filling stoped-out areas with waste, it is not unreasonable to expect that at least 50 pct of the total waste rock broken now goes into support, with the remainder needing to be hoisted to the surface. This analysis assumes that in operations where the chromite seam thickness is 0.10 to 0.15 m, 50 pct of waste is packed and 50 pct is hoisted, changing to 60 pct packed and 40 pct hoisted for mining of seams with thicknesses in the 0.20 to 0.25-m range. It should be noted that at no time in the history of chromite mining on the Great Dyke have seams with thicknesses of 0.05 m or less been mined underground for a significant length of time and that none of the seams herein analyzed are that thin.

In areas of high relief, generally north of Mtoroshangu Pass, access is mostly by adits in combination with internal inclined shafts (*36*), while mines in low relief areas, generally south of Mtoroshangu Pass, must utilize inclined shafts for access. Adit entry has several advantages over inclined shaft entry in addition to the initial development costs being less. Adits provide self-drainage for the workings during the wet season, whereas inclined shaft systems generally require pumping. Ventilation is also less costly and less complex with adits, and it is also possible at some operations north of Mtoroshangu Pass to mine more than one seam from one basic access, although this is the exception rather than the rule along the Great Dyke.

Although there have been a few small vertical shafts sunk for operations on the Great Dyke, generally, vertical shafts are not chosen for initial mining (less than 200 to 300 m on dip) because there is a lead time before obtaining production, while an inclined shaft system can provide immediate production, essentially simultaneous with development.

Capacities of individual inclined shaft systems range from about 10,000 to 30,000 tpy of crude ore, while individual adit systems are estimated to have capacities of 10,000 to 20,000 tpy of crude ore. Capacities higher than 30,000 tpy of ore are not utilized for two reasons. Chromium ore is a product that suffers from markets that are often unfavorable, so that high capital cost layouts are not recommended unless there is a sure market at all times (*34*); and an operation producing 60,000 tpy of ore will mine out a block of nearly 12 ha in a year, which equates to an advance downdip of about 130 m/yr for one inclined shaft system, and is an excessively high extraction rate.

Because of the many variations possible, it was necessary to construct several mining models to estimate costs for economic analysis. The models used, and associated capital and operating cost estimates for the mining units, are shown in table 21. Six inclined shaft models with capacities ranging from 10,000 to 30,000 tpy of crude ore and two adit models with capacities of 10,000 to 20,000 tpy of crude ore were utilized. Each unit is intended to service 1,000 m of strike length to a downdip depth of 300 m. The assumption was made that at no point can two seams be mined from a single access unit. Thus, when the 300 m limit is reached, a totally new access system must be developed to mine another seam or to mine the same seam for a second 1,000 m strike length. Exploration costs prior to development are not shown in table 21 because they were assumed to be negligible, consisting of examination and sampling of "pig-rooted" outcrops to determine if the width of the seam is consistent over at least 650 m of strike length.

As shown in table 21, capital cost requirements are very low. Mine equipment costs range from $200,000 to $600,000, while mine plant costs range from $500,000 to $1.1 million in 1981 U.S. dollars. The total cost for development of a 300,000 sq m block is estimated to range from $1.4 million to $1.8 million. In general,

Table 21. — Capital and operating cost estimates; generic mining models of Great Dyke seam mines

Mining model description[1]		Capital costs (thousand 1981 U.S. dollars)			Mine operating cost (per metric ton of ore) by seam thickness		
Access method	Capacity, 10^3 tpy	Development cost for 30-ha area	Mine equipment	Mine plant	0.10 m	0.15 m	0.25 m
Inclined shaft:							
Dip > 23°	10	$1,800	$200	$500	$91.0	$68.0	$56.0
Dip < 23°	10	1,600	200	500	91.0	68.0	56.0
Dip > 23°	20	1,800	400	700	96.0	72.0	59.0
Dip < 23°	20	1,600	400	700	96.0	72.0	59.0
Dip > 23°	30	1,800	600	1,100	78.0	59.0	48.0
Dip < 23°	30	1,600	600	1,100	78.0	59.0	48.0
Adit	10	1,400	200	500	86.0	65.0	52.0
Adit	20	1,500	400	500	77.0	58.0	51.0

[1] Mining method: advance-retreat resuing (scrapers).

Table 22. — Comparison of mining cost differences due to changes in seam thickness

Seam thickness ... m	0.10	0.125	0.15	0.20	0.25	0.30
Ore hoisted ... 10^3 tpy	12	12	12	12	12	12
Waste packed ... 10^3 tpy	46	36	29	24	20	15
Waste hoisted ... 10^3 tpy	46	36	29	16	13	10
Advance or retreat ... m/yr	140	110	95	70	60	50
Underground laborers	105	84	70	52	45	38
Supervisory personnel	4	4	4	4	4	4
Productivity, t per worker-shift:						
Underground	0.38	0.47	0.57	0.76	0.89	1.00
Overall	0.24	0.31	0.37	0.49	0.57	0.68
Labor ... pct total cost	41	41	40	37	37	39
Estimated mining cost (1981 U.S. dollars) ... $/t ore	$91.00	$79.00	$68.00	$62.00	$56.00	$48.00

bringing a 20,000-tpy inclined shaft system into full production should cost about $2.5 million and it should have a mining life of 7 to 10 yr, depending upon the thickness of the seam.

Assuming that the operations are mining the same thickness of seam (0.10 m for example), operating costs for resue mining vary about 20 pct depending upon capacity and access method. The cheapest operations would be high-capacity (30,000 tpy) inclined shaft systems and high-capacity (20,000 tpy) adit-access systems estimated at $78/t and $77/t, respectively. The most expensive operation, with an estimated mine operating cost of $96/t, is a 20,000-tpy inclined-shaft system mining a 0.10-m seam. The same relationship applies for mining of 0.15- and 0.25-m-thick seams, although the overall mine operating costs are significantly less, averaging 25 pct less expensive for a 0.15-m thick seam and about 40 pct less expensive for mining a 0.25-m-thick seam.

The indication then, is that crude ore mine operating costs (including on-seam development) are most sensitive to the thickness of the seam being mined. This is demonstrated by the data shown in table 22, which compares technical and cost differences based on hypothetical operations of the same 12,000-tpy capacity, mining seams with thicknesses of 0.10, 0.125, 0.15, 0.20, 0.25, and 0.30 m. Assuming that all other factors are the same, an increase in seam thickness from 0.10 to 0.15 m for example, will decrease the required stope face advance-retreat by 32 pct/yr, while maintaining the same amount of production. Underground stoping productivity would increase 50 pct, while overall productivity (surface plus underground employees) would increase 55 pct. However, since labor constitutes only 40 pct of the total, mine operating cost would decrease by only 25 pct. An increase in seam thickness to 0.30 m on the other hand, would result in a 48-pct decrease in mine operating cost.

As a percentage of total crude ore mine operating cost, labor costs (direct and indirect) account for 40 to 45 pct, materials and supplies for 30 to 35 pct, and equipment operation for 20 to 30 pct for the resuing method.

Podiform Deposits—Sublevel Stoping

In the Selukwe District, mining of podiform deposits has involved many different methods over the years, including surface pitting, top-slicing, shrinkage stoping, cut-and-fill stoping, modified square-set stoping, and sublevel stoping. Presently, smaller lenses (assumed to be any lens with <100,000 t of in situ resource) are mined using shrinkage or cut-and-fill methods, while larger lenses (>100,000 t of in situ resource) employ the larger scale, lower cost sublevel stoping method. Since all of the Selukwe and Belingwe podiform demonstrated resources evaluated in this study are assumed to be contained in lenses (ore bodies) with >100,000 t of ore the only mining method utilized in this analysis is the large scale, sublevel stoping method.

Over the years, access methods in the Selukwe District have involved many combinations of adits, vertical shafts, and inclined shafts. In general, deeper levels are accessed with high-capacity vertical shafts, while near-surface levels utilize numerous adits if the topography allows it. Each of these main access systems also uses internal inclined shafts (winzes) for subsequent development, depending upon the circumstances encountered.

The sublevel stoping method is basically a caving method. It requires driving of a main haulageway from the adit or shaft connecting with subordinate haulage drives running parallel to the long axis of the ore body (lens) to be mined. Main haulage levels are usually established at 50- to 60-m vertical intervals, while sublevels are established approximately every 12 m. Haulage cross cuts are driven along the short axis of the ore body at about 10-m intervals and ore pass raises with cone shapes of 10 m diameters are established from the haulage cross cuts to a sill level 7.5 m above the cross cut. Long-hole drilling proceeds from benches cut on each sub-level, with the lower level stope in advance of the next highest. Broken ore is loaded directly from ore pass chutes into rail cars pulled by battery locomotives. The ore is delivered to underground grizzleys which at Selukwe Peak are set at 150 mm. Little support is required and mine recoveries are high, estimated to average 90 pct; however, there is little control over the grade of ore being mined. Underground mining productivities are high relative to many other chromite mining operations around the world, estimated to be about 2 t of ore per underground workershift. Overall productivity (surface plus underground laborers) is somewhat lower, at 1.33 t per workershift. These productivities are more than 3 times higher than those attained in Great Dyke seam mining, and the advantage shows up in much lower crude ore mine operating costs, around 66 pct lower on average.

Estimated crude ore mine operating costs for the Selukwe podiform operations range from \$18.70/t to \$28/t of ore. Of these costs, about 30 to 35 pct represents labor costs, 50 to 55 pct is composed of materials and supplies, and only 15 pct is attributable to equipment operation.

Mine equipment replacement costs are estimated to range from \$10/t to \$17/t of annual crude ore capacity. Mine plant replacement costs are estimated to range from \$29/t to \$55/t of annual crude ore capacity. In general, a 30,000-tpy, sublevel stoping, podiform mining operation in Zimbabwe should cost about \$2.5 million to bring into production, assuming that the ore body is at a depth of 100 to 150 m below the surface and is accessed by vertical shaft.

Eluvial Soil Deposit—Level and Hillside Stripping

The most recent description of the Impinge eluvial soil operation was given by Kimble (*33*) in 1976. The mining practice at that time consisted of pit sampling on a grid system to determine the quantity of soil and recoverable chromite content available in future barrow pits. A mining schedule for various combinations of pits was then drawn up, based on keeping the grade of feed to the mill constant and the haulage distance from the various pits as consistent as possible on a ton-kilometer basis. The pits to be mined are delineated by surveying, and perimeters are scored by a road-grader. Drainage ditches are cut with a bulldozer, and the vegetation is either burned off or stripped with the grader. The soil, ranging in thickness from 0.12 to 1.8 m thick (averaging 0.45 m), is bulldozed into windrows laid out on contours to prevent runoff of silt during the rainy season. The soil is then loaded by front-end loaders into 15-t-capacity dump trucks for haulage to the mill. It appears that the maximum haul distance involved is 4 km, with an average of 2 km. The soil is excavated until rubble or bedrock begins to show, at which time mining is halted. Rehabilitation consists of ripping the pit floor on contour to a depth of 0.3 m at 1-m intervals, constructing mounds of soil at 30 m intervals and reseeding. In 1976, all mining and transport of soil was done by contractors at the Impinge operation. The capacity of the operation was very flexible since the mill could handle anywhere from 180,000 to 400,000 tpy of soil feed without any effect on costs or operations. This study's evaluation was made assuming a capacity of 300,000 tpy of soil feed, essentially halfway between the two extremes. Also, the analysis has been made as if the company had to make all capital investments and conducted its own mining rather than on a contractor basis.

The estimated mine operating cost for the eluvial soil operation is \$4.78 per ton of soil delivered to the mill. It is estimated that direct and indirect labor costs comprise 30 pct of the total cost, 64 pct is for equipment operation, and 6 pct for materials and supplies. Assuming a concentration ratio of 5.7 t of soil to produce 1 t of concentrate, the above mining cost represents a cost of \$27.24/t of concentrate produced.

Capital items for mining consist of exploration, mine equipment, and mine plant. It is estimated that a 25-ha block of soil would require about \$450,000 for exploration and that a 300,000-tpy (of soil) operation would require about \$2.3 million in mine plant and equipment capital costs.

BENEFICIATION

Great Dyke Seam Deposits

Prior to 1950, the only beneficiation, other than hand-sorting, done on Zimbabwe chromite ores was gravity concentration at those few operations mining disseminated ore (*35*). By 1960, nearly half of the 34 major operations described by Worst (*25*) had installed gravity concentration plants to upgrade their products.

Generally, high-grade ores (>50 pct Cr_2O_3 Cr:Fe = 3) do not need to be upgraded except for hand-sorting. This is the case for ores of either the hard, lumpy type or of the friable type. Gravity concentration is used solely to improve Cr_2O_3 contents and, if possible, Cr:Fe ratios. For hard, lumpy ores of coarse chromite grain sizes (>8 mesh or 2.38 mm) hand-picking of waste or heavy-media separation are all that are required. However, heavy-media separation is very uncommon in Great Dyke seam operations. Friable chromite ores of fine chromite grain sizes (<8 mesh or 2.38 mm) most often will be beneficiated by gravity methods because the material is already in a "fines" form and increasing the grade is not expensive or complex but could significantly improve marketability. However, as noted, if the grade of Cr_2O_3 and Cr:Fe ratio are high enough, it is not really necessary to beneficiate the friable material.

The hand-sorting process is self-explanatory and the heavy-media process will be described in the discussion of beneficiation methods for podiform deposits. The gravity-separation methods in use on the Great Dyke comprise various combinations of the following major operation: grizzly screening, crushing with jaw crushers or hammer mills, screening with vibratory or trommel screens, recrushing with small rod mills, classification and reclassification by hydraulic methods, gravity separation with jigs, spirals, and tables, and dewatering and desliming. All flowsheets include at least two stages of gravity separation, either jigging followed by tabling or spiral separation followed by tabling. For friable, fines material, liberation of chromite grains occurs at minus 8 mesh; however, strict control of sizes is needed throughout the process because most of the chromite losses occur in slimes, hence the need for multiple-stage screening and classification.

Recoveries of Cr_2O_3 in gravity concentration are estimated to be in the range of 75 to 85 pct, while recoveries in hand-sorting should run to 100 pct. This study assumes 75 pct recovery of Cr_2O_3 for any material going through gravity separation and 100 pct where it is considered that only hand-sorting would be required.

As noted in the geology and resources section, it is estimated that only about 10 pct of the total in situ, demonstrated resource analyzed for the Great Dyke sections-operations consists of hard, lumpy ore with the remainder as friable, fines material; and that seam 4 constitutes the greatest possible source for hard, lumpy material at depth. Because seams 1 and 2 have the lowest Cr_2O_3 grades (46 pct) and Cr:Fe ratios (1.4 to 2.3) of all seams on the Great Dyke (table 23), it was assumed that all sections-operations analyzed where those seams constituted the majority of the resource would have to send 100 pct of their mined material through gravity concentration. Since seams 9 and 10 have the highest Cr:Fe ratios, those properties where seams 9 and 10 predominate were assumed to require beneficiation only by hand-sorting. Seams 3 through 8 are intermediate to high in Cr_2O_3 content and Cr:Fe ratio, thus section-operations containing these seams predominantly were assumed to require a combination of hand-sorting and gravity separation.

Table 23 summarizes estimated recoveries and beneficiation operating costs for these three categories. The entire output of chromite products (lump, fines, and concentrates) estimated to come from the 21 properties cost evaluated for the Great Dyke have >50 pct Cr_2O_3 and should have Cr:Fe ratios ranging from 2.5 to 3.3. This is because all in situ ore below 50 pct Cr_2O_3 has been assumed to undergo beneficiation by gravity methods. Of the total Zimbabwe chromite product output, it is estimated that roughly 10 pct would be in the form of lump ore and the remainder in the form of friable-fines ore or as concentrates.

Table 23. — Estimated beneficiation methods, recoveries, and operating costs, by category of Great Dyke seam

Predominant seam	Beneficiation method	Cr_2O_3 recovery, pct	Operating cost, $/t ore feed
1 and 2	Gravity	75	2.50
3 through 8	Gravity and hand sort.	80–90	1.25–2.00
9 through 11	Hand sort	100	1.00

For purposes of analysis, a cost of $1 per ton of feed has been estimated for hand-sorting and includes the costs of screening, sorting of ore, and transport of waste. It is composed predominantly of labor costs, estimated to comprise 85 pct of the total cost, while materials and supplies account for only 5 pct, and equipment operation 10 pct of the total cost. Personnel requirements for hand-sorting are difficult to determine. For this study it is estimated that a 12,000-tpy operation would require about 30 laborers for hand sorting of crude ore.

The operating costs for a typical gravity-separation plant are estimated to be $2.50/t of ore feed. This typical gravity-separation plant requires crushing, grinding, screening and classification, and two-stage gravity separation with jigs and tables. It is composed of 45 pct labor costs, 28 pct materials and supplies costs, and 27 pct equipment operations costs.

Capital costs for both extremes are relatively small. It is estimated that capital costs for a hand-sort operation plant should range from $10/t to $15/t of annual feed capacity and a typical gravity-separation plant should range from $14/t to $20/t of annual feed capacity.

The technical assumptions of this study result in an overall concentration ratio for the 21 Great Dyke seam operations evaluated of 1.2 t of feed to product 1 t of chromite product (lump, fines, and concentrate). The overall weighted-average milling cost for all 21 operations is $1.60/t of ore feed or $1.92/t of chromite product. The mill operating cost is an insignificant portion of the total mining plus milling cost since, on a chromite product basis, it represents only about 2 to 4 pct of the total mining plus milling cost.

Podiform Deposits

According to the Chamber of Mines Journal of July 1959 (*31*), three basic products were being produced from Selukwe podiform deposits in the late 1950's: (1) a high-grade, hard-lump ore of 47 to 48 pct Cr_2O_3 and a Cr:Fe ratio of 3 to 3.2; (2) a refractory-grade, hard-lump ore of 38 to 40 pct Cr_2O_3 and a Cr:Fe ratio of 2.1 to 2.4; and (3) a low-grade, hard-lump ore of 45 to 46 pct Cr_2O_3 and a Cr:Fe ratio of 3 to 3.2. The same source listed two products from Belingwe podiform deposits: (1) a high-grade, hard-lump ore at 47 to 50 pct Cr_2O_3 and a Cr:Fe ratio of 2.7 to 3.0 and (2) a "chemical-grade" ore of 45 to 50 pct Cr_2O_3 and a Cr:Fe ratio of 2.0 to 2.3.

Referring back to the discussion of Selukwe podiform resources shows that of the six properties evaluated, five (Selukwe Peak, Railway Block, Magazine Hill, Ironsides, and Iron Ton) are estimated to have resources composed 80 pct of lumpy material with grain sizes ranging from 0.5 to 4 mm, and 20 pct of fines material with grain sizes ranging from 0.01 to 0.5 mm, while one (Valley Chrome) is composed entirely of the fines material. Reference back to the discussion of Belingwe resources shows that this study assumes that 50 pct of the demonstrated resource at Belingwe is hard, high-grade lump material and the other 50 pct is low-grade ore that would probably require beneficiation by gravity methods. For properties in the Selukwe District with 80 pct lump and 20 pct fines material, the beneficiation methods are hand-sorting and heavy-media separation for lump material, and gravity separation with spirals and tables for the fines material <0.5 mm in grain size. The Valley Chrome operation utilizes gravity separation with spirals and tables for all of its feed, while the Belingwe operations require only hand-sorting for 50 pct of their material and gravity separation with spirals and tables for the other 50 pct.

It is not known exactly how many mills are present in each district, where they are located, or what the capacities are. There has been a mill situated near the Valley Chrome operation since the late 1950's and a heavy-media separation, gravity-separation process milling complex is located in the Selukwe District. The description of methods used at the Selukwe mill is that a minus 150-mm, plus 60-mm fraction is hand-sorted; a minus 60-mm, plus 6-mm fraction goes to a heavy-media separation plant (sink-float process); a minus 6-mm, plus 0.5-mm fraction goes to a heavy-media separation plant using cyclones, and the minus 0.5-mm fraction goes to a gravity-separation section using spirals and tables to produce concentrates. The hand-sorting and heavy-media separation processes produce lump ore. The Magazine Hill, Iron Ton, and Ironsides operations that are proposed for production are assumed to require hand-sorting and screening of 50 pct of the feed and two-stage gravity separation for the other 50 pct of feed.

Estimated recoveries used for analysis are 100 pct for hand-sorting, 95 pct for heavy-media separation, and 80 pct for gravity separation.

Mill operating costs are estimated at $3/t of ore feed for hand-sorting plus heavy-media separation, $2.50/t of ore feed for gravity separation with spirals and tables, and $1/t of ore feed for a simple hand-sort. For heavy-media separation plus hand-sorting, labor costs are estimated to make up 55 pct of the total cost, while 25 pct is for materials and supplies, and 20 pct is for equipment operation.

The above recoveries and operating costs have been weight-averaged according to the proportions appropriate for the property being evaluated.

For economic analysis, the mill operating costs include estimated costs for transport to what are assumed to be centralized mill complexes. The estimated transport costs for the seven podiform operations analyzed ranged from $2/t to $3.25/t of ore feed. Thus, the costs for transport to the mills plus milling itself ranged from $4.95/t to $5.47/t of ore feed or $5.57/t to $6.19/t of chromite product. On a product basis, this cost represents about 16 pct of the total mining plus milling cost for the podiform deposits.

Estimated capital costs for a combination hand-sort heavy-media plant are estimated to be about $18/t of annual ore feed.

Eluvial Deposits

As of 1976, milling practice at the Impinge eluvial operation consisted of washing and screening (2 mm), classification, screening, magnetic separation (wet), and gravity separation with jigs and spirals. There were five different stages of classification in the flowsheet. The oversize material from initial screening (plus 2 mm "pebbles") was hand-sorted on a waste conveyor to produce about 5 pct of the recoverable chromite. No concentrate grades or recovery values were given in the 1976 description (*36*). It was mentioned, however, that when operating on a 3-shift-per-day, 30-days-per-month basis (maximum capacity) that the mill could produce 6,000 t per month of concentrates and, if required, could operate on a one-shift-per-day, 30-days-per-month basis (minimum capacity) to produce 2,500 t per month of concentrates.

It is probable that the concentrate grade was at least 50 pct Cr_2O_3 and could have exceeded 52 pct or more. This study assumed a concentrate grade of 52 pct Cr_2O_3 for evaluation. Recovery for economic analysis was estimated to be very low at only 45 pct of the contained Cr_2O_3. This low recovery was assumed for three reasons. First, concentration ratios for other soil operations of the 1960's were greater than 5 t of soil per ton of concentrate. Second, the process has as its overall aim the improvement of Cr:Fe ratios (through magnetic separation), which would probably result in greater loss of chromium along with iron. Third, the amount of slimes waste will be much larger than usual, resulting in more chances for loss of chromium.

The operating cost for the eluvial soil operation is estimated to be $2.78/t of soil feed. Labor costs are estimated to comprise 45 pct of the total cost, while materials and supplies account for 30 pct, and equipment operation for 25 pct. Since no crushing or grinding is required, the operating cost is slightly less than would normally be expected for a magnetic-separation, gravity-separation plant. In 1976, Kimble (*33*) noted that the total operating cost remained static no matter at what capacity the mill was operaing.

Because of the rather complex flowsheet, the estimated capital cost for a plant of this size (300,000 to 400,000 tpy of soil) would be in the vicinity of $5 million, relatively expensive for a chromite beneficiation plant.

CHROMITE AVAILABILITY

There are two major issues to be addressed when evaluating the availability of chromium from Zimbabwe. First, there is the issue of chromite production from the podiform resources versus chromite production from the seams of the Great Dyke. Secondly, there is the general issue of chromium available in the form of chromite products versus chromium available in the form of ferrochromium products. This latter issue, dealt with in the section on ferrochromium availability, is of particular importance since it is the stated objective of the government to use all of its domestic chromite resources for the production of ferrochromium. This section discusses the relative cost and availability of chromite from the podiform and Great Dyke seam deposits.

In 1980, Zimbabwe's total prodution of chromite ore and concentrates was about 550,000 t (*37*, p. 1147). Of this, it is estimated that 50 pct came from operations in the Selukwe Podiform District, 45 pct from operations working seams on the Great Dyke, and 5 pct from other operations. The 1980 production level represented a 36-pct decrease from 1976 production of about 860,000 (*37*, p. 1147). Aggregate production figures for 1981 show a further decline to around 500,000 t (*38*, p. 466).

The two major producers of chromite and ferrochromium are Zimbabwe Mining and Smelting Co. (formerly African Chrome Mines and a subsidiary of Union Carbide of the United States) and Zimalloys (formerly Zimbabwe Alloys and before that Rhodall Ltd.). These two companies represent ownership of a majority of the operating chromite mines in Zimbabwe. During the past few years, there have been numerous, often contradictory, claims concerning current mining capacity and future expansion plans. However, as is the case with the mines of South Africa, actual mining capacity is not the issue; the operating mines or those temporarily closed can relatively easily and quite significantly increase mining and milling capacity. The issue is one of demand for Zimbabwean chromite and the availability of sufficient factor inputs such as labor, transportation, and (for chromite smelted in-country) energy supplies.

With this in mind, this study assumed that within a 3- to 4-yr period the mining operations evaluated could attain a crude ore production level of approximately 1.4 million tpy, yielding a mill output of chromite products totaling approximately 1 million tpy. It must be stressed that these figures are similar to those given in the various informational sources addressing the issue of chromite mining capacity expansion, are easily attainable given the extraordinary flexibility of the chromite industry, and are in keeping with announced ferrochromium smelting capacity expansions.

Table 24 lists the names, deposit types, annual crude ore and chromite product capacities, and estimates of the productive life of the recoverable demonstrated resources. Figure 15 shows the location of the operations evaluated, railroad lines and transportation routes, and ferrochromium smelters. A few points concerning table 24 are evident. First, the major producing podiform operations, Selukwe Peak and Railway Block, have very large capacities relative to the Great Dyke seam operations. These latter operations typically range from 15,000 to 30,000 tpy of crude ore, with only 5 of the 21 operations in the 40,000- to 60,000-tpy range. These seam-mining capacities are quite small relative to the operations in South Africa, primarily because in Zimbabwe the chromium seams are much thinner than those of the Bushveld Complex.

Given the relatively small capacities of the seam operations and the enormous availability of in situ chromite resources of the Great Dyke, the estimated mine lives are very large indeed, with an average seam resource operation life of 272 yr. This compares to an average podiform resource life of only 28 yr and points to a very significant long-term change in store for the chromium industry of Zimbabwe. As mining progresses into the next century, an increasing percentage of chromite output will have to come from the Great Dyke seam operations.

Table 24. — Estimated annual capacities of crude ore and chromite products from selected Zimbabwe chromite operations

Operation-section	Crude ore capacity, 10^3 t	Chromite production capacity, 10^3 t	Estimated life of recoverable resources, yr (1981 on)
Great Dyke seam:			
Glenapp-Ivo	10	10	517
Impinge	20	20	245
Sutton-Rodcamp	36	34	343
Vanad	42	39	76
Caesar	42	39	67
Crown-Divide North	20	18	141
Glenapp-Hay-Noro	30	28	238
Umvukwes area	60	46	145
Ore Recovery Tribute	40	37	181
Greenvale	20	18	245
Maryland	20	18	254
McGowan	15	13	357
Divide	15	13	439
Rutala	20	13	431
Umsweswe	25	17	62
Umsweswe-Bee	30	17	554
Windsor-York-York West	20	18	561
Bat Claims	15	10	368
Cambrai	36	24	208
Netherburn	48	32	234
York	15	14	38
Selukwe podiforms:			
Railway Block	160	139	25
Selukwe Peak	190	169	32
Valley Chrome	60	48	20
Magazine Hill	30	27	19
Iron Sides	30	27	19
Iron Ton	30	27	19
Belingwe Podiform:	27	23	62
Eluvial: Impinge	300	53	15
Total	1,406	991	(1)

[1] Average life of Great Dyke seam mining operations: 272 yr; average life of podiform mining operations: 28 yr.

Table 25 addresses the differences in mining, processing, and transportation costs for the two resource types, as well as total chromite availability. As is evident, mining costs for the podiform resources on a per-ton-of-chromite-product basis are markedly lower, by $55, or 65 pct on average, than for the Great Dyke seam operations. Milling costs are greater, but milling costs overall are an insignificant cost relative to mining and transportation expenses. As is expected, transportation costs are not significantly different. What is most striking in this cost comparison is the total delivered cost to the port of Beira, Mozambique, where the podiform operations can deliver a ton of product for less than just the weighted average mining cost of the Great Dyke seam operations. The podiform resource operations are very cost competitive relative to other high-grade chromite producers, such as Turkey, and are also competitive relative to the producers in South Africa. However, it is evident that Zimbabwe chromite production costs, overall, should increase with time as an increasing percentage of

Table 25. — Weighted-average mining, beneficiation, and transportation cost estimates, per ton of product, for selected chromite operations in Zimbabwe

(1981 U.S. dollars)

	Podiform operations	Great Dyke seam operations	Average
Cost per metric ton:			
Mining	$29.50	$84.50	$79.00
Processing	6.00	2.25	2.50
Transportation:			
FOB Beira, Mozambique	28.00	27.50	27.50
FOB Maputo, Mozambique	NA	NA	41.00
FOB Durban, South Africa	NA	NA	38.00
FOB Port Elizabeth, South Africa	NA	NA	64.00
Total:			
FOB Beira, Mozambique	63.50	114.25	109.00
FOB Maputo, Mozambique	NA	NA	122.50
FOB Durban, South Africa	NA	NA	119.50
FOB Port Elizabeth, South Africa	NA	NA	145.50
Chromite potential[1] ... 10^3 t	12,683	111,467	NAp
Shipping grade ... pct Cr_2O_3	49.0	50.0	50.0

NA Not available.
NAp Not applicable.
[1] Total chromite potential is 124,150,000 t.

production comes from the Great Dyke. As shown in figure 19, mining cost of product for the podiform operations at $29.50/t represents 46.5 pct of the total delivered cost to Beira, Mozambique. For the Great Dyke seam operations, the weighted-average mining cost of $84.50/t of product represents 74 pct of the total delivered cost. Therefore, as depleting podiform resource production is replaced with Great Dyke seam production, total chromite production costs will rise towards the level of the Great Dyke operations. In addition, since transportation costs for the seam operations represent only 24 pct of the total (as opposed to 44 pct for the podiform operations), cost reductions in this area will have less of an effect on overall production costs as an increasing percentage of production comes from the Great Dyke.

Also shown in table 25 are estimates of average transportation costs to other ports in Mozambique and South Africa (Zimbabwe is a land-locked country). These other ports are located at greater distance than Beira, hence their utilization is more costly. As will be discussed later, however, rail transportation and port facilities represent a major constraining factor on the further development of the chromium industry in Zimbabwe.

The estimated costs (mining, processing, and transportation) and corresponding cumulative chromite availability estimates for the individual operations are shown graphically in figure 20. The very significant difference in production cost between the two resource types is again evident above a mining cost of $50/t of product, where the podiform resources stop and those of the Great Dyke seams begin.

Total chromite product availability, from just the demonstrated resources that were evaluated, is on the order of 12.6 million t for the podiform resources, the majority of which is contained within the Selukwe Peak and Railway Block operations, and approximately 111.5 million t for the operations of the Great Dyke, for a total of 124.1 million t overall. This figure is both very large and very conservative, given that the demonstrated resource estimate used to derive this chromite product estimate was only on the order of 175 million t. At a world consumption rate of 10.5 million tpy, this resource would satisfy all world requirements for 17 yr. The life of the podiform resource is limited most likely to at least 30 yr, assuming current capacity-production rates, but further exploration and development could extend this resource life beyond the year 2015, although probably not on the same scale as today. There is basically no life limit to the Great Dyke seam resource; the Great Dyke is similar in this respect to the Bushveld Complex in that production will continue as long as there is a demand for mined chromium.

HIGH-CARBON FERROCHROMIUM AVAILABILITY

Zimbabwe currently has two ferrochromium smelting facilities. The largest is located at Que Que and is owned by Zimbabwe Mining and Smelting Co. The

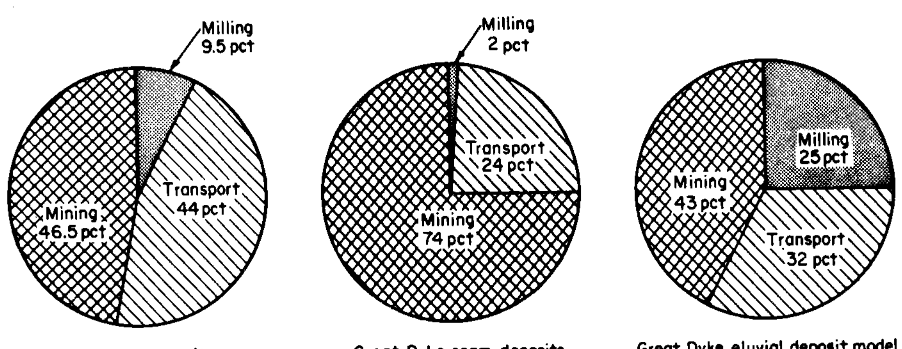


Figure 19. — Percentage distribution between mining, milling, and transportation cost estimates (FOB Beira, Mozambique) for podiform, seam-type, and eluvial chromite deposits, respectively, in Zimbabwe.

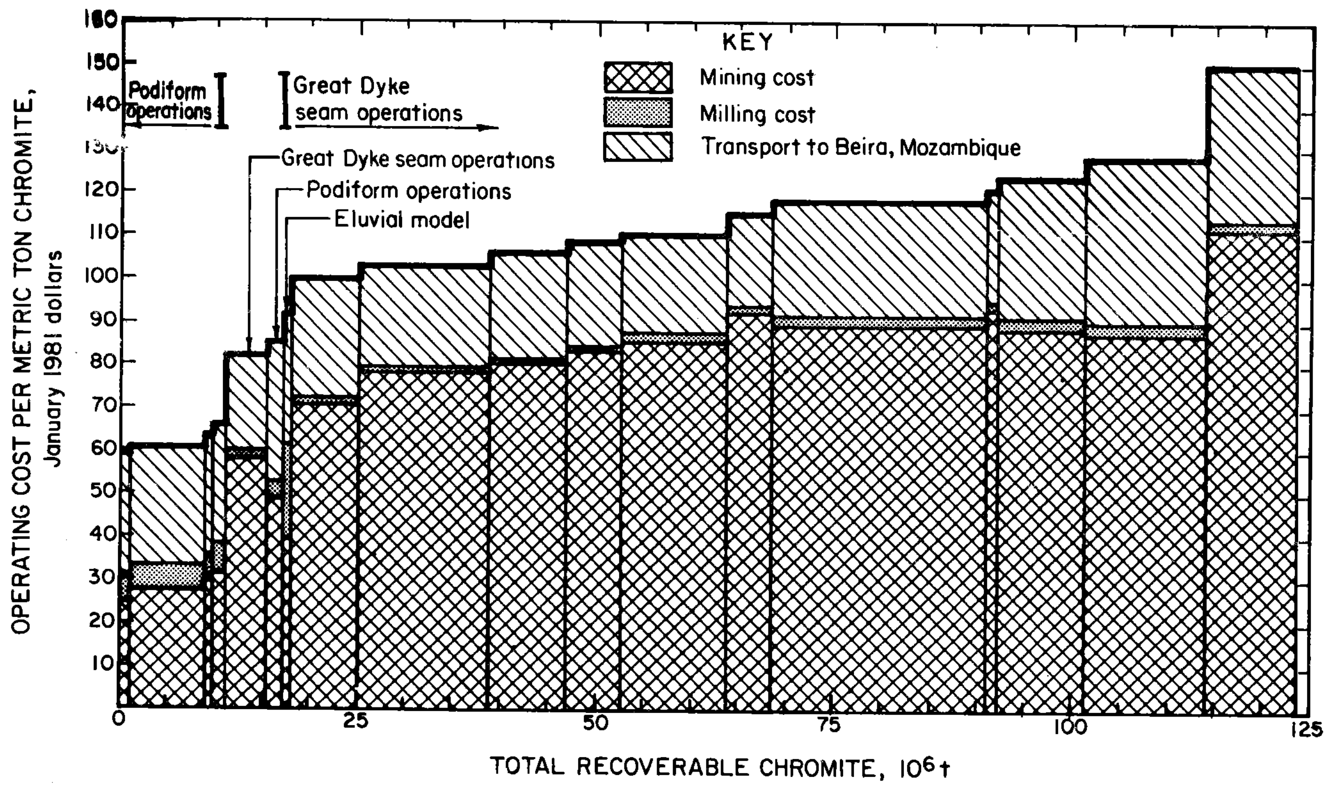


Figure 20. — Mining, milling, and transportation cost estimates (FOB Beira, Mozambique), and potential availability of chromite from selected operations in Zimbabwe.

second, smaller facility is located at Gwelo, approximately 50 km from the Que Que plant and is owned by Zimalloys. Both smelters are located on a main rail line and are in close proximity to the chromite mining operations. Table 26 provides pertinent data concerning current and proposed capacity and smelter products.

As was the case with mining capacity, plans for increasing smelting capacity have been announced, cancelled, and reannounced with regularity over the last few yr since independence. Although one cannot

Table 26. — Ferrochromium smelters, capacities, and products, Zimbabwe

Furnaces, MVA	Furnace capacity, 10^3 t/yr	Furnace product
	GWELO (160 × 10^3 t/yr)[1]	
7.5	8	Low-C ferrochromium.
8.5	9	Do.
8.5	9	Do.
17.5	18	Ferrosilicon chromium.
17.5	18	Do.
30.0	50	High-C ferrochromium.
[2] 30.0	50	Do.
	QUE QUE (310 × 10^3 t/yr)[1]	
15.0	22	High-C ferrochromium.
24.0	37	Do.
24.0	37	Do.
24.0	37	Do.
24.0	37	Do.
24.0	37	Do.
[2] 30.0	50	Do.
[2] 30.0	50	Do.

[1] Expected capacity.
[2] Proposed for analysis.

be certain as to the actual future capacity of the smelting industry, it is certain that expansion will take place given (1) the government's stated objective of smelting all chromite locally to ferrochromium products, (2) the trend observed elsewhere for downstream processing stages (in this case ferrochromium) to be increasingly located near raw material sources, (3) the obvious advantage of utilizing scarce transportation and port facilities for the movement of a higher valued product (ferrochromium versus chromite), and (4) the positive developmental and foreign exchange benefits to be derived from further developing and marketing greater value-added ferrochromium products as opposed to chromite products. With these factors in mind, this study assumed that smelting capacity at the two plants would be expanded to the proposed 160,000 tpy at Gwelo and to 310,000 tpy at Que Que. This represents something on the order of a 50-pct expansion over current capacity. For the economic analysis, all chromite output was assumed to be smelted to a grade-A (>64 pct contained Cr), high-C ferrochromium product.

All capital costs for the smelter expansions were prorated back to the company's chromite mines. It is estimated that the expansions should cost around $1,000/t of annual capacity. Because of the very high Cr:Fe ratios of Zimbabwe chromite, the grade of ferrochromium products is very high, possibly the highest in the world, with typical grades ranging from 64 to 72 pct contained Cr. Using a smelting recovery of 80 pct gives an indicated consumption factor of 2.3 t of a 52-pct Cr_2O_3 chromite concentrate to produce 1 t of high-C ferrochromium. Thus, the indicated total chromite consumption requirements at these expected smelting capacities by year N+2 or N+3 (1983 or 1984 in this analysis) would be roughly on the order of 1 million t. Given that the estimated chromite product output by this time is estimated at approximately 1 million t as well, it is obvious that there is little room for chromite exports from Zimbabwe in the near future. But this is in keeping with the basic plan of the government.

In the smelting process, all fines material must be agglomerated either to briquets or pellets at the smelter to ensure efficient smelting. This practice is particularly prudent at the Gwelo smelter, which utilizes 100 pct Great Dyke material. The cost of briquetting is around $10/t to $15/t of ferrochromium. The Que Que smelter, even though much of its feed material does not require briquetting, nonetheless faces its own problems in that its feed comes from a variety of sources. In 1980, the company was experimenting with blending five different chromite ores-concentrates and their power consumption increased from 3,900 to 4,400 kWt/t of high-C ferrochromium. Of the raw materials needed for ferrochromium smelting, only coal and coke for the Gwelo smelter are indicated as being imported from South Africa. Smelting costs are composed of about 28 pct for power costs, 12 pct for labor, 29 pct for raw materials (reductants, fluxes, electrodes, etc.), 17 pct for supplies and maintenance,

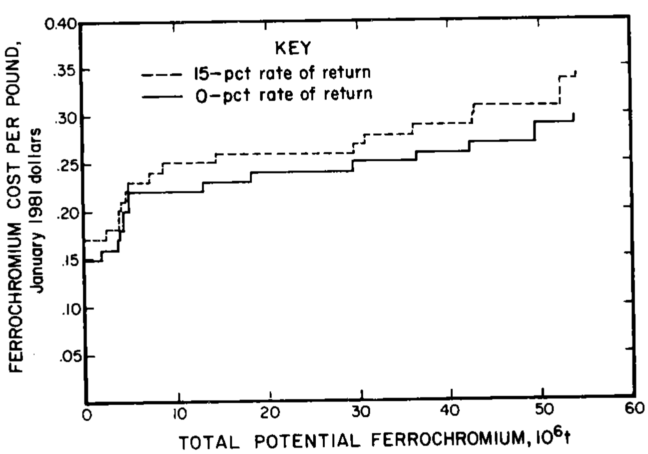


Figure 21. — Cost and potential availability estimates of high-carbon ferrochromium from selected chromite operations in Zimbabwe.

and 14 pct for overhead and indirect costs. These figures should be interpreted as averages.

Figure 21 and supporting data in table 27 present the long-run average total cost estimates and corresponding cumulative high-C ferrochromium tonnage potentially available from the demonstrated resources of the 29 operations evaluated in Zimbabwe. All cost estimates are on an FOB smelter basis. (Since ferrochromium exports utilize numerous ports in Mozambique and South Africa, these costs were calculated on this basis to ensure comparability of operations). Transportation costs per pound of contained chromium to the ports of Mozambique and South Africa are estimated to range from $0.03 to $0.04 to Durban, South Africa, and $0.01 to $0.02 to Beira, Mozambique. The cost of transportation to the port of Durban compares favorably with that for the South African produers, on a per pound contained chromium basis. because a typical ton of ferrochromium produced in Zimbabwe contains 68 pct Cr whereas a typical ton of South African ferrochromium contains around 53 pct Cr or 22 pct less Cr per ton of ferrochromium transported. This helps to offset the greater transportation distances faced by Zimbabwean producers.

The costs for all operations at the breakeven level range from $0.15/lb to $0.30/lb ferrochromium, averaging $0.25/lb, which equates to $0.37/lb contained Cr for a 68-pct ferroalloy product. At the 15-pct profitability level the costs range from $0.17/lb to $0.34/lb ferrochromium, averaging $0.27/lb, which equate to $0.40/lb contained Cr. The narrow range between the two average chromium cost estimates (i.e., $0.37/lb and $0.40/lb) indicates that the chromium industry of Zimbabwe is a mature industry that has already recouped its major, historical capital investments. Further, it can absorb the additional capital costs for mining, milling, and smelting expansions herein assumed and attain a 15-pt long-run profitability level with only a $0.03/lb Cr increase in selling price.

The well established, large-scale podiform operations in the Selukwe District are the least expensive sources for ferrochromium in the country. The other nonproducing podiform operations also represent an available low cost resource. Together the podiform resources have an estimated long-run average cost of $0.25/lb Cr at the break-even level, which is 35 pct less than that estimated for all Great Dyke seam operations.

The Great Dyke material also represents an eco-

Table 27. — Average total cost ranges per pound of contained chromium and corresponding ferrochromium availability, by resource type, for Zimbabwe

(1981 U.S. dollars)

	Breakeven level		15-pct profitability level	Total ferrochromium availability, 10^3 t
	Range	Weighted average		
Great Dyke seam operations	$0.32–$0.43	$0.38	$0.34–$0.50	48,789
Podiform operations	.22– .29	.25	.25– .34	5,068
Eluvial soil model	.34	.34	.35	240
Total or weighted average	[1].37	NAp	[1].40	54,097

NAp Not applicable.
[1] Weighted averages over all operations evaluated.

nomic resource but at a higher cost relative to the podiform resoures. The long-run average cost estimate for all Great Dyke seam operations, at the breakeven level, is estimated to be $0.38/lb Cr. Thus, as the podiform resources are depleted, ferrichromium production costs should begin to increase to the level of the Great Dyke resources. In constant 1981 dollars, this increase through time should approach 35 pct, overall.

The eluvial soil operation model was estimated at $0.34/lb Cr. This seems to indicate that the estimated 54 million t of eluvial soil material could provide a source of increased production in the future as the podiform resources are further exploited. However, this would require much additional exploration and delineation of reserves by location. The problem with the eluvial soil operations seems to be attaining a high enough level of reserves to give a reasonable life to a specific mill.

The total high-C ferrochromium estimate of 54.1 million t, not surprisingly, is enormous and a resource product of high quality. The figure represents 115 yr of full, expanded capacity production and itself represents only a fraction of the ultimate potential for chromium-resource-based products available from Zimbabwe. The podiform operations account for 5.068 million t or 9.3 pct of the total. The remaining 91 pct is available from the Great Dyke operations.

CONSTRAINTS TO DEVELOPMENT

Transportation and Porting Facilities

In order to realize the very great potential discussed above, two major bottlenecks need to be addressed. The first is the availability of a sufficient transportation network and porting facilities.

The greatest distances from mine and mill sites to ports for the countries studied are from the chromium mines of Zimbabwe. The greatest individual distances are encountered when shipping through the ports of Durban and Port Elizabeth in the Republic of South Africa. The distances range from approximately 1,500 to 2,000 km to Durban and 1,700 to 2,200 km to Port Elizabeth. This includes both trucking and rail transport, with rail representing most of the distance.

There is a distinct cost advantage when shipping from Zimbabwe through the port of Beira in Mozambique. The average cost of transporting chromite from all mines in Zimbabwe to this port is approximately $11/t (29 pct less) than the average cost to Durban and about $37/t (58 pct less) than the average cost to Port Elizabeth. However, Beira does not have sufficient capacity to handle all chromium exports in addition to other goods. Currently, Beira can only berth vessels up to 25,000 t. In addition, this analysis indicates that the cost to transport chromite to Maputo, Mozambique's other major port, averages slightly more (even though the distances are less) than the cost to transport chromite to Durban, South Africa. The difference of $3/t results from lower official rail costs within South Africa as opposed to those of Zimbabwe and Mozambique. The actual cost, of course, can vary from operation to operation and is certainly influenced by governmental trade policy (subsidies and/or tariffs) on the part of Mozambique, Zimbabwe, or South Africa.

Although both Beira and Maputo were relatively major ports prior to the latter half of the 1970's, they have both declined noticeably in terms of the amount of cargo handled. This was mainly precipitated by the closure of the rail lines from Zimbabwe during the civil war in 1976. In 1979, Maputo reportedly handled only 1.5 million t of cargo as compared to 13 million t in 1969 and currently can only berth vessels up to 65,000 t (*24*, p. 53). More recent estimates (*23*, p. 330) show Maputo handling only about 500,000 tpy with plans to raise this in the future to 3.3 million tpy. Since the lifting of sanctions in 1980, the port of Beira has reportedly been handling around 550,000 tpy (*23*, p. 330). In any event, given that the rail system of Zimbabwe handled somewhere around 12.5 million net tons in 1981 (*23*, p. 330), it is clear that South Africa remains the major route of exportation and importation.

It has been reported that the government of Mozambique plans to spend $320 million to upgrade and improve the ports and rail lines in the country (*24*, p. 53). The timeframe and availability of the necessary funds are in doubt, however, and until these improvements are made the ports of Beira and Maputo will continue to play a minor role, relative to the ports of South Africa, in Zimbabwe's export trade. Meanwhile, the government of Zimbabwe has earmarked approximately $140 million for equipment and electrification of the railways. It has also undertaken a project, backed by the World Bank, worth approximately $130 million for upgrading the rail system in general (*23*, p. 330). The government's overall plan is to make Zimbabwe the transport hub for the black-ruled states of southern Africa, and it intends to switch its exports to the ports of Mozambique from South Africa as soon as such a switch becomes technically feasible.

Power Supplies

The ferrochromium smelters are the largest consumers of electricity in the country, consuming at least 10 pct of total electric power generation. Currently, 90 pct of electricity generation is hydroelectric-based, with around one-third imported from Zambia (*24*, p. 51). This import level should decrease in the future as Zambia's growth requirements consume a larger share of its total electric generation. When the smelting capacity expansions outlined above are in place (N+3 or N+4 yr) then ferrochromium's share of total electric generation would represent around 20 to 25 pct of total country requirements assuming 1980-81 consumption for uses other than ferrochromium smelting remain constant. According to Shekarchi, it took approximately 600 to 750 million kWh of electricity in 1980 to produce 150,000 t of ferrochromium (*24*, p. 51). At a capacity level of 470,000 tpy, a rough estimate indicates a need for 1.8 to 2.3 billion kWh. Thus the availability of sufficient electric supplies would be strained, and the expansions discussed above would depend heavily on expanding power supplies.

The Wankie I coal-fired generating plant, due to start up in 1983, and the Wankie II, due to start up in 1986, will add about 1.3 billion kWh of electric power generation between them. Given Zimbabwe's large coal reserves, coal powered generators are a logical primary source of future power for the country. Additional hydroelectric power is another source, with the possibility of adding two generators to the Kariba South power station on the Zambezi River. Shekarchi (*24*, p. 52) further estimates that, assuming a 10-pct growth rate for electricity demand and imports from Zambia declining to zero, by 1990 Zimbabwe could still face a consumption requirement shortfall of 5 billion kWh. The resources for expanding electric supply are there but the enormous cost and the time requirement pose the problems to overcome.

THE MINERALS MARKETING CORPORATION OF ZIMBABWE

In 1982, the government of Zimbabwe enacted legislation establishing a Minerals Marketing Corp. (MMC) (*39*, p. 61). Although the full intent of the agency will only be ascertained through examination of its future performance, it would appear that the intent is twofold. First, the MMC is granted authority to assume the function of marketing the products of the country's mining industry, with the exception of gold. This would mean either purchasing all mineral product output directly from the operating companies for resale to world markets or for internal consumption, or review and endorse or reject the privately arranged sales contracts. The companies will therefore probably have to make the agency privy to production and sales details. Seond, the agency has the authority to impose a sales commission.

Among the reasons for establishment of the MMC is the concern within the government over alleged abuses of "transfer pricing", which is a means of overinvoicing or underinvoicing between local and foreign parent companies to avoid taxation and to transfer capital. There is also an element of governmental revenue raising involved, as well as the desire to more closely control and coordinate the mining industry within the context of the overall economic goals of the government, which, later on, should begin to seek to acquire an equity position within the industry.

The long-term effect of governmental intervention in the mining industry of Zimbabwe via such functions as marketing, production control, or equity participation, for example, is beyond the scope of this report. However, one can address the long-term impact upon average production cost from imposition of a sales commission.

The direct impact from imposition of any "add-on" cost, such as a sales tax (commission), is to either raise average production costs and therefore sales price, or lower company profits, or both. These costs are particularly burdensome in periods of oversupply or weak demand such as has been the case in recent years in the world chromium industry.

The methodological approach taken in this analysis is to impose a 15-pct pretax sales commission on the total revenues generated per operation per year from the production of high-C ferrochromium.

The current sales commission is probably not in excess of a few percent; however, the sales commission was set at this potentially high level in order to address the maximum impact that such an add-on cost (or costs) might have on determining the ability of Zimbabwe's ferrochromium producers to remain competitive. It is not at all unlikely that this type of cost will increase in the future.

It is assumed that all properties operate at full capacity throughout the productive life of the demonstrated resource tonnages identified for each property, and that all output is sold at that price (FOB the smelter), which will maintain a specified profitability level after covering total investment costs. The profitability level selected was the breakeven level. The results obtained from this analysis are then compared with those of the base case analysis presented earlier in order to isolate the total (cost = sales price) increase necessary to maintain a given level of profitability, and further, to show what the reduction in ferrochromium availability would be at any given price-cost level. Of course, in times of falling world prices for ferrochromium, when it is not possible for all producers to obtain the prices necessary to absorb the tax-cost increase, rates of return would fall. The purpose here is to identify only the increase in production cost and thus determine the effect upon the long-term competitiveness of Zimbabwe's ferrochromium industry relative to other producing nations. It bears mentioning that since the sales commission is applied in this analysis as a pretax cost, its effect upon the determination of necessary price is less than if it were applied as an after-tax cost.

The results of this analysis indicate clearly that the full imposition of a 15-pct sales commission would result in significant increases in necessary long-run sales prices for the industry to maintain a breakeven level of profitability. The difference between the cost increase for operations mining the seams on the Great Dyke as opposed to the podiform-type operations is illustrative. Table 28 provides cost estimates for the two resource types with and without the imposition of the MMC tax, herein assumed. This differential effect can also be seen in figure 22, which shows a greater upward shift in cost for the seam-type operations of the Great Dyke. As shown, the imposition of the sales tax results in an average increase of $0.05 per pound contained chromium for the operations mining Great Dyke seam deposits as opposed to an average $0.03/lb contained Cr increase (40 pct less) for those mining the podiform-type deposits in the Selukwe and Belingwe Districts.

Table 28. — Weighted average breakeven cost estimates per pound of contained chromium in Zimbabwe, with and without a 15-pct MMC sales commission

	All properties	Great Dyke seams	Off-Dyke podiform type
Base case	$0.37	$0.38	$0.25
MMC	.42	.43	.28
Difference	.05	.05	.03

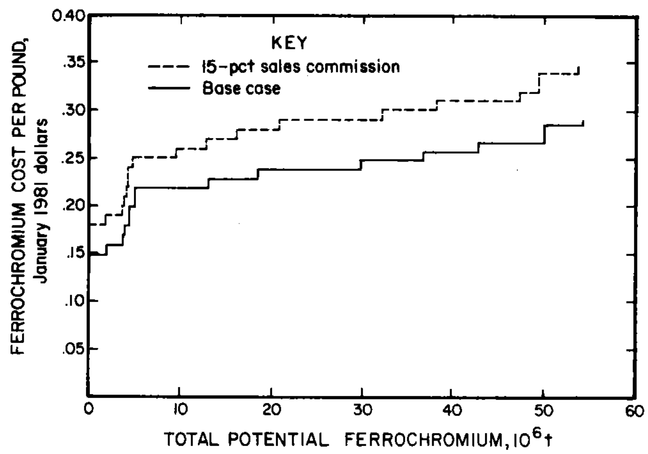


Figure 22. — The effect of a 15-pct MMC sales commission upon the breakeven cost level estimates of high-carbon ferrochromium production in Zimbabwe.

The podiform-type deposits currently account for a large majority of Zimbabwe's chromium production. These properties are already very competitive and could conceivably absorb the total tax burden and still remain so. However, the total production life of these properties is very limited relative to the seams of the Great Dyke. It is this latter resource that will provide the long-term (beyond 30 yr) production potential for Zimbabwe; and these properties, because they are more costly to develop and operate, would require significantly higher selling prices to absorb the additional tax burden. The differential effect upon the two types of operations should cause an increase in the competitive advantage of the podiform type over the Great Dyke seams and could result in more capital resources being devoted to their exploitation relative to the seams. Assuming that the podiform resource will last well into the next century, however, there would not appear to be any immediate, overall detrimental effect upon Zimbabwe's competitiveness in the world chromium industry.

A comparison with the properties of South Africa indicates that the advantage enjoyed by the South African ferrochromium producers would be enhanced by the imposition of this tax. A comparison of breakeven weighted average total costs, on a per pound of contained chromium basis (in order to compare the two properly), shows a South African advantage relative to all Zimbabwean producers (FOB the smelter) of \$0.08/lb without the imposition of the sales commission. This advantage increases to \$0.14/lb contained chromium with the tax imposed. The producing podiform operations in Zimbabwe, with imposition of the tax, have their \$0.04/lb advantage effectively eliminated. These results are shown in table 29.

A few caveats are in order. First, the overall advantage of South African producers is understated here because of the added transportation cost incurred by the Zimbabwe producers versus the South African. Some of the ferrochromium produced in Zimbabwe must be routed through South African ports at a higher cost because of the inability of the ports of Mozambique to accommodate all output. Second, the producing podiform operations in Zimbabwe, even with the long-term increase in production costs from the imposition of this tax, are still lower cost producers than those in Turkey, which directly competes with Zimbabwe for the sale of grade-A ferrochromium. Finally, what is perhaps more significant for the long-term potential of the chromium industry in Zimbabwe is not the actual imposition of a sales tax but rather the existence of a government agency involved in the decisionmaking process of production, stockpiling, sales, and ownership of the industry—which could result in reduced private investment in the country. This effect, of course, is difficult to quantify but uncertainly in business is a major consideration.

SUMMARY

- A total of 175 million t of in situ demonstrated chromium-bearing resource was cost-evaluated.
- This resource is estimated to contain approximately 124.2 million t of 50 pct Cr_2O_3 high-Cr chromite products in the form of lump and fines material.
- Of the total chromite tonnage analyzed, 12.7 million t (10 pct) is contained within the podiform operations and 111.5 million t (90 pct) is contained within the Great Dyke seam operations.
- Total high-C ferrochromium potential is estimated at 54.1 million t, also split 10 pct to the podiform operations and 90 pct to the Great Dyke seam operations.
- Chromite production costs, as defined, were estimated at \$63.50/lb and \$114.25/lb, delivered to Beira, Mozambique, for the podiform and seam-type operations, respectively.
- High-C ferrochromium production costs (as defined) were estimated (FOB the smelter) at \$0.25/lb and \$0.38/lb Cr at the breakeven cost level for the podiform and seam-type operations, respectively.

Table 29. — Comparison of weighted-average production costs per pound of contained chromium at the breakeven level in South Africa versus Zimbabwe with the imposition of a 15-pct sales commission

(1981 U.S. dollars)

	Zimbabwe weighted-average production cost		South African advantage or disadvantage[1]	
	Base case	Sales commission	Base case	Sales commission
All properties	\$0.37	\$0.43	(−) \$0.08	(−) \$0.14
Great Dyke seams	.38	.44	(−) .09	(−) .15
Podiform type	.25	.29	(+) .04	0

[1] The negative sign (−) or positive sign (+) means that South African production is *less than* (−) or *greater than* (+) the cost determinations for Zimbabwe.

- Major implications are that chromite and ferrochromium production costs should rise through time as the podiform resources are depleted and a greater percentage of production comes from the seam-type operations. In addition, large capital investments will be required to alleviate transportation and energy supply bottlenecks in order to realize the industry potential outlined above.
- Availability of chromite products for export should decline as the country's stated goal of utilizing 100 pct of its chromite for ferrochromium production is instituted.

TURKEY

GEOLOGY AND RESOURCES

As shown in figure 23, ultramafic rock complexes in Turkey that have served, or could serve, as host rock for chromite deposits are widespread and numerous. Since approximately 23,000 sq km of area consist of ultramafic outcrops, it follows that the number of individual deposits and occurrences could be very large as well. Ethem (*40*) states that chromite occurrences

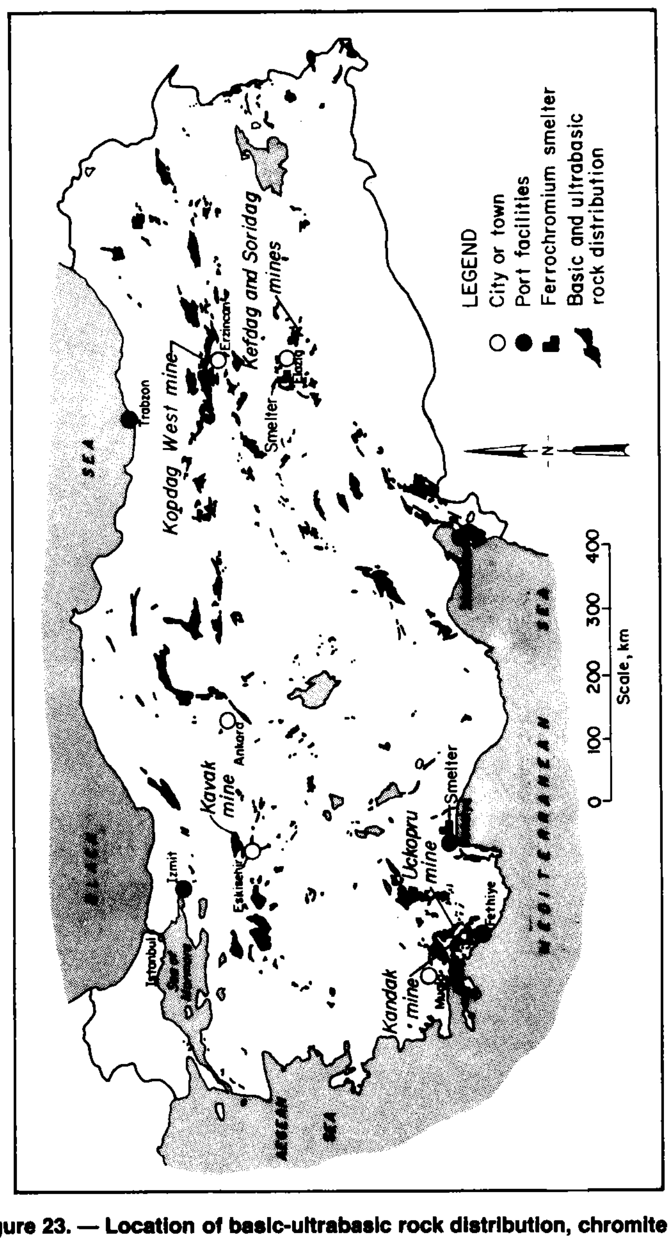


Figure 23. — Location of basic-ultrabasic rock distribution, chromite mines, ferrochromium smelters, and ports of exportation in Turkey.

Table 30. — Chromite reserves of Turkey, 1972 Turkish government estimates

Deposit[1]-Operation	District	Province	Reserve tonnage, 10^3 t			
			Proven	Probable	Possible	Total
Kefdag*	Maden	Elazig	3,767	1,126	15,000	19,893
Soridag-Guleman*	do	do	5,949	552	NA	6,501
Kavak*	Mihaliccik	Eskisehir	950	1,050	NA	2,000
Kopdag*	Tercan	Erzincan	652	876	NA	1,528
Uckopru*	Fethiye	Mugla	605	411	383	1,400
Kandak*	Ula	do	NA	NA	800	800
Akcabuk	Orhaneli	Bursa	NA	NA	640	640
Karaismailler	Acipayam	Denizli	NA	NA	556	556
Yoruceler	Orhaneli	Bursa	NA	NA	410	410
Sariova-Uzunoluk	Tavas	Denizli	105	185	40	330
Beydemir	Orhaneli	Bursa	202	NA	NA	202
Mevlutler	Acipayam	Denizli	34	61	42	139
Mesebuku-Otmanlar	Koycegiz	Mugla	60	40	NA	100
Others	NA	NA	NA	NA	NA	1,817
Total			12,325	4,302	17,871	36,317

NA Not available.
[1] Asterisk indicates those operations subject to cost evaluation.
Source: Kocaefe (*42*).

can be found in 40 of the nation's 67 provinces. He lists 90 separate regions or districts as having chromite deposits or occurrences.

In 1966 MTA, the government exploration agency, in an attempt to describe all known chromite deposits or occurrences, reported on over 330 deposits or deposit groups (*41*). This report stated that, "information on most of these deposits is incomplete and only in a few cases could a detailed description be given." In 1972, MTA released estimates of chromite reserves in Turkey (*42*). As shown in table 30, six individual operations—the Kefdag, Soridag, and Uckopru operations of Etibank and the Kandak, Kavak, and Kopdag operations of various private owners—accounted for 96 pct of the proven plus probable resource tonnage of 16.6 million t (roughly equivalent to the demonstrated level) and 89 pct of the proven plus probable plus possible resource tonnage of 36.3 million t (roughly equivalent to the identified level).

For this study, the Bureau of Mines has concentrated on determining the demonstrated resources of these six operations as of 1980. A seventh operation, Mesebuku-Otmanlar, was also investigated but was determined to have an insignificant resource level and therefore not subjected to complete cost analysis. The results are shown in table 31. The total demonstrated resource level, as of 1980, for these six operations is estimated to be approximately 11.7 million t of in situ material with an average grade of 38 pct Cr_2O_3 that represents 4.5 million t of contained Cr_2O_3. These six operations represent the tonnage contained in only 25 deposits or deposit groups out of the more than 300 referenced by MTA nationwide. The identified resource level for these properties is the same as the demonstrated level precisely because of the lack of confidence in inferences based upon the sketchy data that is available on Turkish chromite deposits. The following discussion deals with each of the six properties subjected to complete cost evaluation.

The Soridag group consists of 10 deposits, all within a 10.5-sq km area. The demonstrated resource of 2.7 million t at a weighted average grade of 46 pct Cr_2O_3 represents the combined in situ tonnage of three major deposits within the group; the Ayi Damar, Kapin, and Uzun Damar deposits. An estimated 1.25 million t of Cr_2O_3 is contained within this tonnage. The three deposits are all of the planar--banded type with ore body thicknesses averaging about 3 m. The ore grades vary from 42 to 51 pct Cr_2O_3 with a weighted average of 46 pct and a Cr:Fe ratio of 2.9. In general, the deposits can be followed for long strike lengths, although interruptions by faults are common.

Table 31. — Estimated in situ chromite resource data for selected Turkish operations as of 1980

Deposit-operation	Demonstrated resource,[1] 10^3 t	Weighted-average grade, pct Cr_2O_3	Contained[2] Cr_2O_3, 10^3 t
Kefdag	5,100	36.0	1,836
Soridag	2,727	46.0	1,254
Kavak	1,600	29.0	464
Kopdag West-North Zone	1,000	43.0	430
Uckopru	850	40.0	340
Kandak	353	46.0	162
Mesebuku-Otmanlar	[3] 46	40.0	18
Total or average	11,676	[4] 38.0	4,500

[1] Identified tonnage equals demonstrated plus inferred tonnage; in this case, there was insufficient information to support an inference beyond the demonstrated level.
[2] Data may not add to totals shown due to averaging and independent rounding.
[3] Not cost evaluated.
[4] Country grade is the in situ weighted average over all deposits at the demonstrated level.

The Kefdag group of deposits is located about 5 km southwest of the Soridag group. It consists of two deposits, Kefdag East and Kefdag West. They are also of the planar-banded type with two types of ore; disseminated, low-grade material, and massive, high-grade material. The low-grade, disseminated ore grades in the range of 30 to 38 pct Cr_2O_3, averaging 36 pct, and the massive, high-grade material averages about 38 pct Cr_2O_3. The demonstrated resource of the Kefdag group is estimated at 5.1 million t, approximately 65 pct of which is disseminated, low-grade ore and 35 pct of which is massive, high-grade ore. This resource contains approximately 1.8 million t of contained Cr_2O_3 with a Cr:Fe ratio of 2.9. The ore bodies strike northeast and dip to the south at Kefdag West and to the north at Kefdag East. Dip is almost vertical at depth.

The Kavak-Mihalliccik District is located on the crest and south flank of the Tastepe mountain range. This district consists of 21 separate ore bodies all located within a 1,000- by 500-m area. Three different structural types of ore bodies are present: pipelike or chimneylike ore bodies (Camasirlik I through V, Orta, and Yazlik); flow-type ore bodies (Ernler I through VI), and planar-banded ore bodies (numbers 12-17). The greatest potential lies in the chimneylike ore bodies Camasirlik II and III, which are presently being mined, and Camasirlik V. The ore itself is of the schlieren type, grading 32 to 37 pct Cr_2O_3 when not diluted. Below the 150 m level in the present underground mine, the contact between the dunite and chromite is not distinct so dilution of about 15 pct dunite is unavoidable. The demonstrated resource of 1.6 million t represents ore at Camasirlik II and III above the 360-m level and assumes a dilution of 15 pct. The diluted grade averages 29 pct Cr_2O_3, and the two ore bodies combined contain an estimated 464,000 t of Cr_2O_3 in situ at a Cr:Fe ratio of 3.

The Kopdag-Askale chromite region is centered about 120 km south of the Black Sea port of Trabzon. It consists of three basic chromite districts, the most important of which appears to be the Kopdag West group located about 30 km northwest of the town of Tercan. Within the Kopdag West group, the north zone of occurrences is by far the more important of the two zones with at least 25 separate occurrences or deposits found along a 13-km east-northeast trend. Supposedly, the ore bodies are large, and it has been conjectured that some could extend to depths of 100 m. In 1965, a rough estimate was that the north zone could contain at least 1 million t of ore (*41*). As shown in table 30, MTA's 1972 reserve estimate for Kopdag was 652,000 t of proven and 876,000 t of probable ore. For this study, the 1980 demonstrated resource estimate for the 25 deposits in the Kopdag West north-zone area is set at 1 million t grading 43 pct and containing 430,000 t of Cr_2O_3. The Cr:Fe ratio ranges from 2.1 to 3.

The Uuckopru operations and the Kandak mine are located within a large peridotite complex covering about 3,000 sq km in southwestern Turkey; extending 130 km from the Datca Peninsula to a point about 20 km southeast of the port city of Fethiye. The Uckopru operations consist of two deposits; Uckopru and Zimparalik, located within 5 km of one another in an area about 40 km due north of Fethiye. The Kandak mine is located about 30 km east-southeast of the town of Mugla and 23 km due north of the town of Koycegiz.

As mentioned, the demonstrated resource for the Uckopru operation consists of ore from two disparate ore bodies: Uckopru and Zimparalik. The Uckopru material is relatively high-grade, massive-type ore averaging 46 pct Cr_2O_3. The Zimparalik ore is low-grade, dissiminated-type ore averaging 34 pct Cr_2O_3. The two ore bodies contain an estimated 850,000 t of in situ resource at the demonstrated level, with a weighted-average grade of 40 pct, containing about 340,000 t of Cr_2O_3. The Cr:Fe ratio runs about 3.

The Kandak deposit occurs as an antiform plunging 50° to 70° to the west. The north limb of the antiform is the important portion of the deposit as the south limb has been shown to die out at a down-limb depth of 40 to 50 m. Demonstrated resources are herein estimated to be about 353,000 t of ore, grading 44 to 48 pct, containing approximately 162,000 t of Cr_2O_3 at a Cr:Fe ratio of 3.

A summarization of two points is in order. First, the demonstrated resource of 11.7 million t that was cost evaluated represents the tonnage available from only 25 individual deposits being mined by just six operations. This is about 5 to 8 pct of the total chromite deposits, occurrences, or deposit groups that have been described in past literature. Second, the operations in this study represent only about 70 to 80 pct of the country's total production; the remaining 20 to 30 pct is supplied by numerous small mines which are impossible to cost evaluate. There are still many possibilities for discovery of new podiform deposits or rediscovery of old deposits, given that the country is covered by more than 23,000 sq km of ultramafic complexes. However, it is questionable whether enough of these discoveries could ever leave Turkey in the position of being able to significantly and rapidly increase production. Most operations mining a reasonably sized ore body of 50,000 to 100,000 t are very small capacity operations (probably averaging 12,000 tpy of mine output) and very labor intensive (around 0.5 to 0.75 t of ore mined per worker-shift).

To double estimated 1980 production of chromite products from 440,000 to 880,000 t would require about 600,000 additional t of run-of-mine crude ore, which would entail 50 separate 12,000-tpy mining operations and approximately 3,000 to 4,000 additional mine laborers. Seemingly in recognition of this small-size-deposit problem, it is understood that MTA is investigating the possibility of mining and beneficiating large, very low-grade chromite bodies in the 5- to 10-pct chromite range. The geologic potential in Turkey for such ore bodies is unknown at this time but is probably high considering the size of complexes available as hosts. However, much exploration and study remain to be done.

MINING AND BENEFICIATION

Except for a few small surface operations, the largest of which is probably the Mesebuku operation, all of the major chromite mining operations in Turkey utilize underground mining methods. The six major mines evaluated here are all underground operations. The three basic types of underground-mining technology employed in Turkey are horizontal cut-and-fill, inclined cut-and-fill, and shrinkage stoping. The choice of method depends upon the strengths of the rock types and the thickness and inclination of the ore body. Labor productivity estimates for the various methods range from lows of 0.5 to 1 t per worker-shift in inclined cut-and-fill operations, to 1.2 in horizontal cut-and-fill operations, to the highest productivity of 1.6 for the shrinkage stoping method.

The percentage of mine operation costs per ton of crude ore that is represented by labor, ranges from 30 pct in the highest productivity mines to as much as 65 pct in the lowest productivity mines. The cost of supplies ranges from 20 to 30 pct of the total mine operating cost. Exploration and development costs directly attributable to day-to-day operations range from \$1.50/t to \$2.75/t of ore. Of importance is the fact that as much as 25 pct of total labor costs (5 to 15 pct of the total mine operating cost) can be attributed to the hand sorting of waste and various types of ore either underground or on the surface.

The mine operators in Turkey are constantly looking to further mechanize the mines to improve productivity. An example of possible savings was given by Kromer in 1954 (*43*). He lists "before and after" data for the introduction of mechanization at the old Basoren mine. After mechanization, productivity at this 15,000 tpy crude ore operation increased 83 pct from 0.35 to 0.65 t per worker-shift. The cost of labor, explosives, and other supplies decreased 42, 15, and 83 pct, respectively. The overall effect was a 47-pct decrease in direct mining costs. However, there are limits to mechanization in Turkish chromite mines, mostly due to the need for sorting of ore from waste and the small thicknesses of the ore bodies (3 m or less). Only in ore bodies or ore zones that reach 5 m or more in thickness can the use of high tonnage mechanized methods and equipment be considered. Even then, the probability of excessive dilution of already low-grade ore, or exacerbation of support problems, will most likely offset the advantages.

Transportation costs can average as low as \$1/t or as high as \$4.25/t of ore depending upon the distance from the mine head to the mill site. Mining recoveries are estimated at between 90 and 95 pct, and working days per year range from around 250 to 300. Costs for the reinvestment of mine equipment range from \$15.50/t to \$19.50/t of annual crude ore capacity, whereas replacement costs for mine plant generally average about half of the mine equipment replacement costs. In total, a new underground Turkish chromite mine averaging about 50,000 tpy of crude ore would cost approximately \$2.7 to \$3.2 million to develop.

Beneficiation of chromite in Turkey is highly variable from property to property and even within a particular property. An example of one property utilizing a variety of beneficiation methods is the Kefdag operation in Elazig Province.

At Kefdag, the higher grade, massive ore is hand sorted and screened to produce a lump ore product and a fines feed to a simple gravity plant. The low-grade, disseminated ore provides the feed to a magnetic separation plant. These three basic methods are used in various combinations at the other producing properties.

Operating costs for the different chromite beneficiation methods vary considerably. Component factor contributions to total operating cost vary as well. The percentage contribution of labor cost can range from 90 pct in the case of hand-sorting operations to 30 pct for magnetic separation. Materials and supplies costs can contribute up to 30 pct of the total and equipment operation can range from effectively zero for hand-sorting operations up to 40 pct for heavy-media, gravity processing. Labor is the primary cost item since about half of all chromite ore is beneficiated by hand-sorting methods. Capital replacement costs, as of 1981, are estimated to range from \$14/t of annual ore feed capacity for a basic hand-sort, gravity-separation mill, to \$27/t for a heavy-media, gravity mill, to as much as \$80/t for a magnetic-separation plant.

The weighted-average concentration ratio for all six properties evaluated is 1.3 t of crude ore per ton of salable chromite product. This concentration ratio ranges from 1:1 for run-of-mine marketable ore to as high as 1.7 to 2.3 where either magnetic separation is necessary, or a combination of heavy-media and conventional gravity separation is used to produce an extremely high grade concentrate product. Estimated mill recoveries range from lows of 80 to 84 pct for fairly complicated processes required for low-grade ores to as high as 100 pct for high-grade, run-of-mine lump ores. The weighted average mill recovery for all six operations comes to 94.3 pct, which is fairly high on a worldwide basis, reflecting the large percentage of Turkish resource that is high-grade, basically run-of-mine material.

CHROMITE AVAILABILITY

The demonstrated resources for the six operations evaluated in Turkey have a potential total chromite availability of 7.6 million t of shipping-grade chromite products averaging 46 pct Cr_2O_3. Mine operating capacities range from a low of 15,000 to a high of 236,000 tpy of crude ore. Mine lives for the six operations at full capacity utilization would range from 7 to 33 yr. Of the total estimated analyzed capacity of approximately 621,000 tpy of crude ore, 46 pct requires only hand sorting and/or screening to produce a marketable product, 34 pct is sent to various gravity-separation mills, and 20 pct goes through a magnetic-separation process. This mine output, after accounting for the various recoveries at the mill sites, produces approximately 460,000 tpy of chromite products. Of the estimated total available products from these properties, about 59 pct is produced from simple hand sorting and/or screening, 25 pct is produced from gravity-separation processes, and 16 pct comes from magnetic separation. Cr:Fe ratios for Turkish chromite products are generally $\geqq$2.8.

With a weighted average concentration ratio of 1.3 and weighted-average crude ore mining cost of \$27/t, the mine operating cost of salable product is estimated to average a relatively low \$35/t. Since beneficiation is primarily by hand sorting and gravity concentration, processing costs average only about \$5/t of product. Transportation costs at \$59.50/t, however, are by far the highest of all the countries studied. This brings the total cost of product, on an average country basis FOB the various ports of exportation, to an estimated \$99.50/t.

In Turkey, the chromium mines are dispersed throughout the country. The terrain can often be mountainous, and distances from the ports can range as long as 300 to 500 km. These distances are not as great as those faced by the countries of southern Africa, but overall transportation costs are greater owing to the mountainous terrain through which some chromite must be shipped, the greater dependence on long-haul trucking, smaller tonnage shipments, competition from higher valued commodities, and increased maintenance costs.

The mines in Mugla Province (including the Uckopru deposits and the Kondak mine) are approximately 40 to 100 km, respectively, from the port of Fethiye, and with weighted-average transport costs to this port of $13.50/t, are the least expensive in the country. However, in terms of total potential tonnage nationwide that needs to be transported, only about 10 pct is located sufficiently close to utilize this port. Most tonnage is moved through the port of Iskenderun from the Guleman chromite district in southeastern Turkey and is estimated to average approximately $65/t in transport costs from the mines to the port. The other major producing area (Eskisehir) utilizes the port of Izmit on the sea of Marmara and faces inland shipping distances of up to 350 km. The Kavak mine in the Eskisehir area utilizes an aerial tram, truck, and rail to transport chromite ore to this port.

HIGH-CARBON FERROCHROMIUM AVAILABILITY

At present, Turkey has two ferrochromium smelters, both owned and operated by Etibank, itself a 100-pct government-owned company. The Antalya plant, located in the port city of the same name on the southwest coast, produces only low-C ferrochromium. Its present production capacity is 10,000 tpy. The plant was built in the 1960's and was the only ferrochromium smelter in the country until 1976. The Elazig smelter, located in the provincial capital city of Elazig, about 40 km northwest of the Soridag-Kefdag deposits, produces only high-C ferrochromium. As of 1980, the plant's design capacity was 50,000 tpy of high-C ferrochromium, although it has never produced more than half of that tonnage in any year since the start of production in 1976.

Etibank has announced plans to increase high-C ferrochromium capacity to 100,000 tpy with the addition of two submersible electric-arc furnaces which would require an additional 275,000 tpy of ore and concentrate feed. This tonnage requirement represents approximately 100 pct of Etibank's current production capacity in the Elazig District, according to this study. This would leave very little additional tonnage available for export; but such a development would be advantageous because the output of ore and concentrate from Etibank's Elazig operations suffers from having the longest and most inefficient transportation route to the nearest port of exportation of all the major Turkish chromite operations. Production of ferrochromium not only increases the product value-added but in this case serves to more effectively compete with other high value commodities for the limited rail capacity. Smelter operating costs in Turkey are composed, on average, of about 40 pct electric power, 28 pct labor, and 32 pct raw materials.

Turkish chromite is high in chromium content, averaging 46 pct Cr_2O_3, and produces a high-Cr (grade-A) ferrochromium containing at least 65 pct Cr. In order to ascertain the total potential availability of domestically produced ferrochromium, the smelters at Antalya and Elazig were assumed to operate at full capacity for the production of only high-C ferrochromium. Etibank's plans to expand capacity at the Elazig smelter to 100,000 tpy were incorporated, and the estimated capital cost of this expansion was prorated to the Etibank properties that feed it. Cost determinations included all processing and transportation costs to produce and deliver ferrochromium FOB the ports of Antalya and, in the case of the Elazig smelter, Iskenderun.

The results underscore the basic competitiveness of the Turkish ferrochromium industry. The cost determinations ranged at the breakeven point from $0.22/lb to $0.30/lb ferrochromium, averaging $0.25/lb on a weighted-average country basis. This equates to an average of $0.39/lb of contained Cr. At the 15-pct profitability level, the range and weighted-average cost of ferrochromium are $0.24/lb to $0.31/lb and $0.27/lb, respectively. In terms of contained chromium this equates to about $0.41/lb. The narrow range of these two profitability level cost estimates is indicative of a mature industry whose major historical cost investments have been recovered and whose further expansion is economically viable.

The resources of the six operations analyzed could potentially provide the feed for an estimated 2,892,000 t of 65 pct high-C ferrochromium production. At capacity utilization of both smelters this would represent about 26 yr of production. The mining operations of Etibank, if devoted exclusively to the production of ferrochromium, would account for 75 pct of this total. Currently, since Etibank owns both smelting facilities, it is the only producer and exporter of ferrochromium.

It can be expected that Etibank, for the foreseeable future, will remain the dominant operating company in the Turkish chromium industry from mine output through ferrochromium production. It can further be expected that Turkey will continue to expand its ferrochromium smelting capacity given its competitive position and the developmental and national income value-added benefits to be derived from increasing the capacity of downstream processing stages. It has been estimated (*44*, p. 100) that the value-added in Turkey from production of ferrochromium is approximately six times the value-added of salable (run-of-mine) ore and 4.7 times the value-added of salable chromite concentrate. In addition, the "charge on external trade balance" is 4.9 times greater and the estimated "effect on activity and employment in other sectors" (i.e., multiplier effect) is 30 pct for ferrochromium production versus 5 pct for the production of chromite ore and concentrate products.

Turkey's main export markets are Europe and the United States. Given that this country is the main world source of high-grade metallurgical chromite outside of Zimbabwe, Albania, and the U.S.S.R., demand for its chromium products should continue. However, the demonstrated resource herein evaluated will last, at most, up to 33 yr at this study's assumed mining capacity of 621,000 tpy of crude ore. The resource tonnages at some individual mines will last only 7 yr without additional tonnages being proven out. In contrast to southern Africa, where conservatively estimated resources will last for hundreds of years, there would appear to be a trend, albeit a long-term one, for the Turkish chromium industry to decline relative to these producing nations. But the potential for proving further resources is there; the question is more one of importance as a major international supplier of chromite and ferrochromium rather than one of the continued existence of a domestic Turkish industry, for as this analysis shows, Turkey is cost competitive at this point in time.

SUMMARY

- A total of 11 million t of in situ demonstrated chromium-bearing resource was cost evaluated.
- This resource is estimated to contain 7.6 million t of recoverable high-Cr chromite products with a weighted average grade of 46 pct Cr_2O_3.
- Total grade-A, high-C ferrochromium potentially available from this demonstrated resource is estimated at 2,892,000 t.
- Chromite production cost (as defined) was estimated at $99.50/t of product on a country-wide, FOB port basis with mine operating cost accounting for 35 pct, mill operating cost 5 pct, and transportation cost 60 pct of the total.
- High-C ferrochromium production cost (as defined) was estimated at $0.39/lb of contained Cr at the breakeven level and $0.41/lb at the 15-pct profitability level.
- Major implications are that full capacity production of ferrochromium (including expansion plans) would exhaust this static resource estimate in 26 yr; the potential for proving additional chromite resources is considered good; and ferrochromium production and export should increase as chromite exports decrease.

THE PHILIPPINES

GEOLOLGY AND RESOURCES

It is estimated that 3.8 pct of the land area of the Philippines is covered by ultramafic complexes and serpentine rock, which are typical host rocks for chromite deposits. This equates to about 11,500 sq km of area. With such a large distribution of host rocks it is not surprising that the Philippines has a large number of chromite occurrences and/or deposits (see fig. 24). Table 32 gives the geographic distribution of chromite deposits and occurrences as of 1976, according to Bacuta (*45*, p. 1).

Of the total deposits-occurrences shown in table 32, 84 pct are located in the five provinces of Dinagat, Mindoro, Palawan, Samar, and Zambales; and Zambales Province contains approximately 50 pct of all occurrences. To show the inordinate importance that a few individual chromite operations can have, Bacuta estimated (*45*) that during the period 1946-76, 40 pct of total metallurgical-grade chromite production came from the Acoje mining operations and 94 pct of refractory-chromite production came from the Coto mining operations, both in Zambales province. Figure 25 shows the location of the current and proposed operations analyzed in this study.

Table 32. — Distribution of chromite deposits or occurrences in the Philippines

Region and province or island	*Number of deposits or occurrences*
Luzon Island:	
Zambales	62
Pangasinan	3
Tarlac	1
Quezon	1
Camarines Sur	3
Central Philippine Islands:	
Palawan	14
Mindoro	13
Samar	8
Homohon	4
Dinagat	8
Mindinao Island:	
Misamis Oriental	3
Bukidnon	1
Davao Oriental	4
Total	125

Source: Bacuta (*45*, p. 1).

In 1976, reserve estimates for the Philippines were set at 4 million t of metallurgical-grade chromite and 7.8 million t of refractory-grade chromite (*45*, p. 2). At the time these estimates were published, it was pointed out that at current (1976) production rates these tonnages would be depleted within 20 to 30 yr. Because of this, the Philippines Bureau of Mines instituted a program during the late 1970's with three major aims: (1) reconnaissance geologic mapping of the country's ultramafic complexes; (2) canvassing and inventory of all chromite occurrences; and (3) geologic, mining, and beneficiation investigations of low-grade alluvial, eluvial, and lateritic chromite deposits. The emphasis on low-grade chromite resources was intended to alleviate the chronic mining reserve problems caused by the relatively small sizes of high-grade, metallurgical-grade, podiform-type deposits.

Indeed, the current results of the program indicate that the potential for large, low-grade chromite deposits is great. As table 33 indicates, approximately 178.5 million t of low-grade resource, at the demonstrated level, is available for exploitation in the Philippines. On a crude-ore basis, this represents about 86 pct of the total demonstrated resource level. However,

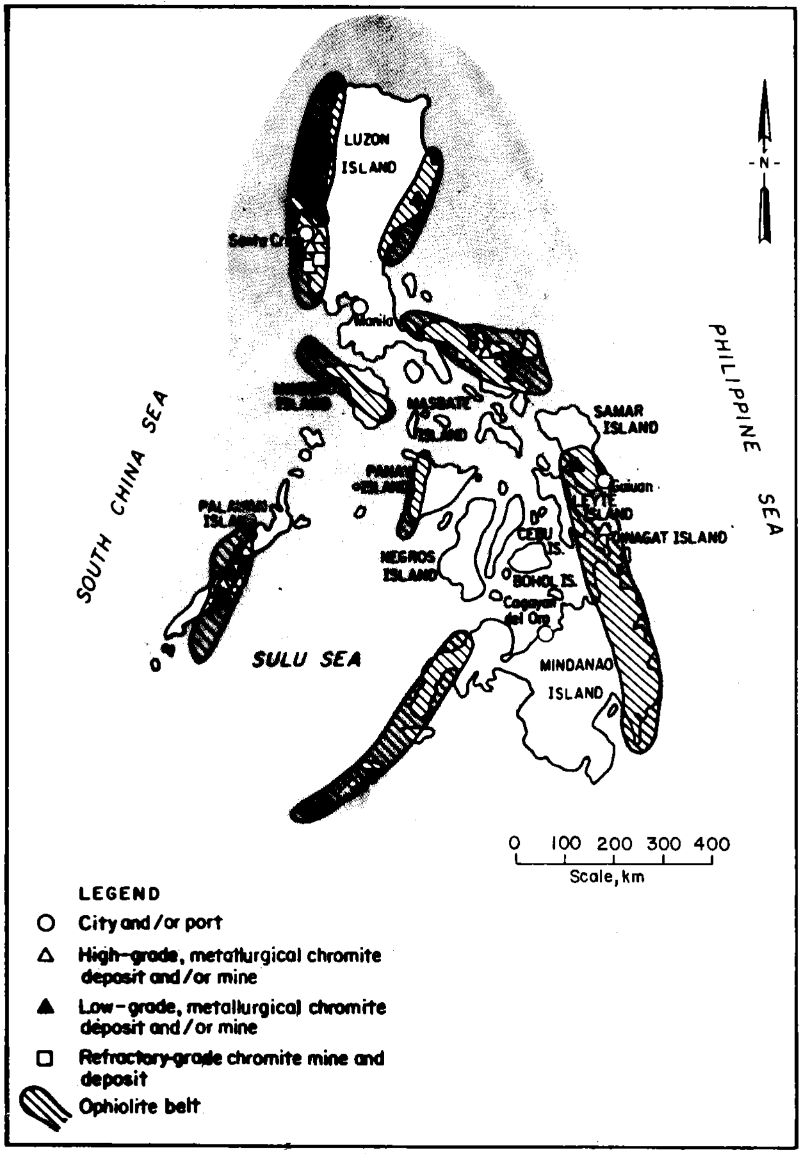


Figure 24. — Ophiolite belts and low- and high-grade, metallurgical- and refractory-grade chromite deposits-operations in the Philippines.

because the grade of these deposits averages a very low 2 pct, the amount of contained Cr_2O_3 represents less than one-third of the country total. This study estimates the demonstrated resource level for high-grade, metallurgical and refractory-grade chromite at, 12.3 and 16.9 million t, respectively. The in situ grades for these resources are markedly higher, but when included with the low-grade material on a total, country-wide basis, the Philippine resource grade averages a low 5.6 pct Cr_2O_3, owing to the large tonnage of low-grade material. However, the operations listed in table 33 do not represent all of the operations and deposits that the Philippine Bureau of Mines officially carries as its own resource base. Their base also includes another 21 high-grade metallurgical deposits containing a total of 1.8 million t of ore and 12 refractory-grade deposits containing a total of 1.1 million t of ore. The average-sized resource for operations and deposits not evaluated in this study is 86,000 t for metallurgical-grade operations and deposits and 92,000 t for refractory grade operations and deposits. Because of the small sizes and/or lack of information, these operations and deposits were not evaluated for this study.

The chromite resource specifications of the Philippines vary considerably. Cr:Fe ratios range from a low of 1.3 at Llorente to a high of 3.2 to 1 at Acoje and Narra. Cr_2O_3 grades range from a low of 1.3 pct, also at Llorente, to a high of 44.6 pct at Lagonoy.

Refractory-grade chromite resources are almost en-

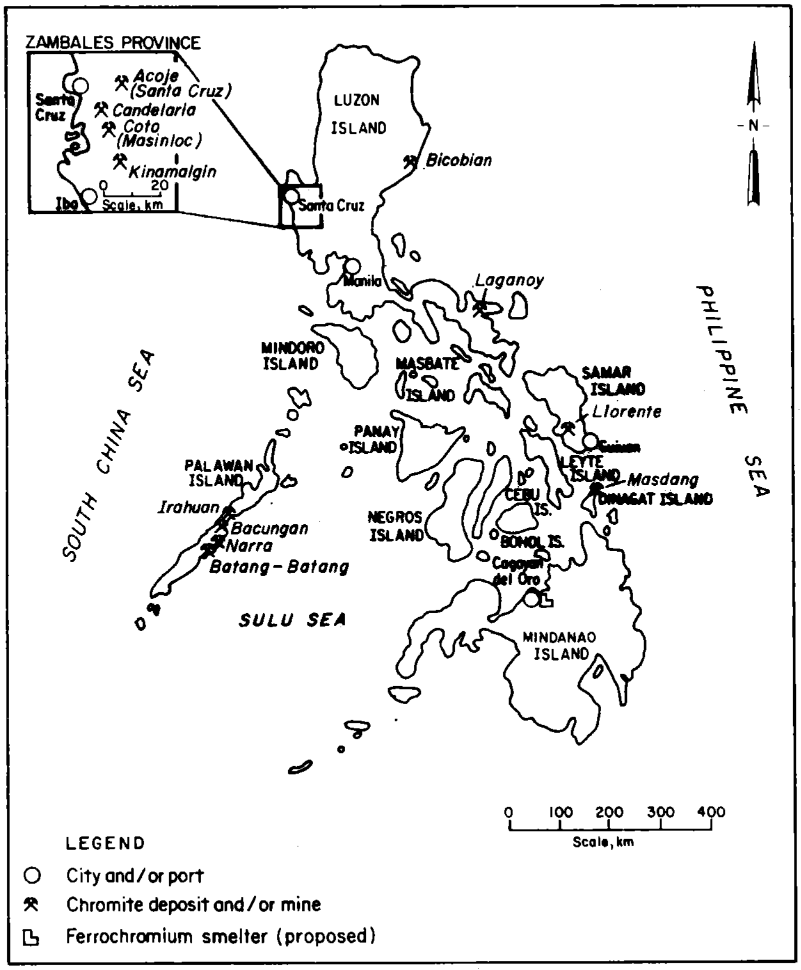


Figure 25. — Location of chromite deposits-operations and the proposed ferrochromium smelter in the Philippines.

tirely located in the Coto-Masinloc mining properties in Zambales province. The Masinloc property is located about 10 km south of the Coto operations, and when in production, its ore is sold to and processed through the Coto mill. For this reason, its demonstrated resource of approximately 0.5 million t of 34 pct Cr_2O_3 is reported along with the Coto operation. In addition, the total demonstrated resource figure includes a major, new, underground, low-silica deposit, within the area of Government Mineral Reservation Number 1 (*46*). This mineral reservation has historically been included in the Coto reserve-resource estimates because the chromite is mined on a royalty basis by the operating company at Coto. The total tonnage at the main Coto operation is contained within approximately 17 separate ore bodies or lenses with over 80 pct contained within only 6 of the ore bodies.

A summary of resources and future prospects indicates that if no major technological or economic problems arise in mining or beneficiating the low-grade material, then the near-term prospects for the Philippine chromite industry are bright. The tonnages this study has identified are very large and show that by intense geological investigation of only five deposits of low-grade eluvials, placers, and beach sands, the Philippines has greatly increased its demonstrated chromite resource level over the last 6 yr. However, the product from these low-grade ores is invariably of a low Cr:Fe ratio suitable only for the production of grade-C charge ferrochromium. The outlook for additional discoveries is excellent, given the large proportion of land mass that contains favorable host rocks for chromite. However, for the metallurgical portion of the country's chromite industry it is apparent that the problem of small-sized, high-grade deposits will remain and that no vast increase in this type of chromite resource should be anticipated.

As for refractory chromite resources, the prospects for the next 10 yr are directly tied to the prospects of the Coto operation, which has been the single largest refractory-grade chromite producer in the world for the last 36 yr. Prospects for additional discoveries of refractory-grade chromite are better than for metallurgical-grade because refractory predominates over metallurgical-grade ore bodies in the primary chromite occurrences of the Philippines. However, the same problem of small-sized ore bodies also affects refractory-grade operations. The exceptions are the few large

Table 33. — Estimated in situ chromite resource data for selected Philippine deposits and operations as of 1980

Deposit-operation name	Status[1]	Demonstrated resource, 10^3 t	Weighted-average grade, pct Cr_2O_3	Contained[2] Cr_2O_3, 10^3 t	Identified resource[3], 10^3 t
High grade:[4]					
Masdang	Exp	4,500	32.5	1,462	4,500
Narra	P/S	4,130	35.5	1,466	4,130
Acoje (Santa Cruz)	P/S	2,850	18.4	524	2,850
Candelaria	Exp	650	35.0	227	710
Lagonoy	P/S	109	45.0	49	109
Silangin	P/S	[5]62	19.5	12	80
Total or average		12,301	[7]30.3	3,740	12,379
Low grade:[6]					
Llorente	Exp	124,700	1.3	1,621	124,700
Bicobian	Exp	48,220	3.3	1,591	48,220
Batang-Batang	Exp	2,627	5.5	144	5,940
Bacungan	Exp	1,671	7.0	117	3,840
Irahuan	Exp	1,277	6.6	84	1,277
Total or average		178,495	[7]2.0	3,557	183,977
Refractory grade:[7]					
Coto-Masinloc	P/S	16,785	26.0	4,364	16,785
Kinmalgin	P/S	175	31.2	55	175
Total or average		16,960	[8]26.0	4,419	16,960
Grand total or average		207,756	[9]5.6	11,716	213,316

[1] Status as of January 1981: P/S-producing or on standby status; Exp-explored prospect.
[2] Data may not add to totals shown because of averaging and independent rounding.
[3] Identified tonnage equals demonstrated plus inferred tonnage; where equal, there was insufficient information to support an inference beyond the demonstrated level.
[4] Cr_2O_3, > 15.0 pct; Al_2O_3, < 20.0 pct.
[5] Not cost evaluated.
[6] Cr_2O_3, < 15.0 pct; Al_2O_3, < 20.0 pct.
[7] Al_2O_3, > 20.0 pct.
[8] Grade is the in situ weighted average, within group at the demonstrated level.
[9] Country grade is the in situ weighted average over all deposits at the demonstrated level.

ore bodies that have been found in the vicinity of the Coto operations.

MINING AND BENEFICIATION

Chromite mining in the Philippines ranges from entirely surface methods, to combinations of surface and underground methods, to entirely underground methods. Table 34 summarizes pertinent data and assumptions used in the analysis of the Philippine properties included in this study. As shown, nine properties were costed as utilizing surface mining only, two (Acoje and Coto-Masinloc) were costed using a combination of surface and underground methods over the mine lives, and only one small operation (Lagonoy) was evaluated based on utilizing only underground mining methods.

Of the entire 207,756,000 t of chromite-bearing material estimated to comprise the demonstrated resource for the Philippines, 93.3 pct is considered to be minable by surface methods, while only 6.7 pct is estimated to require underground methods for extraction. However, in terms of contained Cr_2O_3, the percentages change slightly to 87 and 13 pct, respectively.

There are many reasons for the preponderance of surface mining in the Philippine chromite industry. First, 86 pct of the evaluated chromite-bearing material occurs as low-grade beach sand, eluvial, alluvial,

Table 34. — Surface mining data for selected Philippine chromite operations

Type of resource material and deposit-operation[1]	Surface minable resource tonnage, 10^3 t	Percent of recoverable resource mined by surface methods	Yearly capacity, 10^3 t mined	Concentration ratio	Yearly capacity, 10^3 t product
High-grade, metallurgical:					
Masdang	4,500	100	180	1.7	104
Narra	4,130	100	259	1.5	170
Acoje (Santa Cruz)	1,600	56	200	6.6	30
Candelaria	650	100	65	1.8	36
Low-grade, metallurgical:					
Llorente	124,700	100	4,500	45.0	99
Bicobian	48,220	100	1,371	19.0	73
Batang-Batang	2,627	100	252	10.0	26
Bacungan	1,671	100	300	8.0	39
Irahuan	1,277	100	115	8.0	14
High-grade, refractory:					
Coto-Masinloc	4,196	25	348	3.5	100
Kinmalgin	175	100	18	1.0	18
Total	193,746	NAp	7,608	NAp	709

NAp Not applicable.
[1] Silangin deposit-operation (listed in table 33) not analyzed for costs, owing to small resource tonnage.

or lateritic deposits, occurring on the surface with little or no overburden. Second, the vast majority of the known high-grade (metallurgical) podiform deposits in the Philippines outcrop but do not extend to great depths. Third, surface mining methods make it easier to follow the erratic trend of typical Philippine podiform deposits. In fact, surface mining is considered to be an important exploration method in the Philippines due to the variable shapes, attitudes, and mineralization of chromite occurrences (*47*). Fourth, in many cases the color of the dunite host rock is difficult to distinguish from the chromite ore, and surface mining helps to allevite this problem.

In general, it appears that an effective economic limit to surface mining of chromite ore bodies in the Philippines is around 4 t of waste to 1 t of ore. At this stripping ratio and beyond, it is probably more economic, in terms of the mine operating cost, to select an underground method although other considerations such as reserves, volume, and production requirements should also be considered.

Surface Mining

Ten of the 11 surface mining properties selected for complete engineering cost evaluation in this study are, or are proposed to be, relatively large operations on a crude-ore basis by world chromite industry standards. Capacities for 10 of the 11 properties range from 65,000 to 4.5 million tpy of crude ore. Only one of the properties, Kinmalgin, with a capacity of 18,000 tpy of run-of-mine ore, has been analyzed as a labor intensive "camote-type" mine. The others have been analyzed as mechanized surface mines with some manual activities incidental to the major operation. These operations fall into two categories—those that mine high-grade, podiform-type deposits with relatively small lateral dimensions but extensions to depths >5 m, and those that will mine low-grade beach-sand, alluvial, or eluvial deposits with large lateral dimensions and shallow depths (<5 m). The Acoje (Santa Cruz), Candelaria, Coto-Masinloc, Masdang, and Narra properties are in the first category while Bacungan, Batang-Batang, Bicobian, Irahuan, and Llorente are of the second type.

"Camote-type" mining is a local term used to describe any small-scale, labor-intensive, unsystematic method of mining. It can be used to describe both surface and underground operations. This method developed due to the nature, size, erratic mineralization, and remoteness of chromite deposits in the Philippines. Common hand tools such as wheelbarrows, shovels, picks, and pris-bars are used in camote-type mining and mechanization is minimal, usually consisting of a bulldozer for major cleaning or stripping and small trucks for transport of product. Where the material is amenable, no drilling or blasting is done. Instead, bulldozers or, more commonly, hand tools, are used for breaking the rock.

The camote-type method is only suitable for small-scale mining of high-grade, shallow occurrences with an erratic trend to mineralization. It is usually chosen by a company with little or no capitalization. The advantage, at least in terms of the operating cost to produce a final product, is evident at the Kinmalgin operation where the mine operating cost per ton of salable product is only 16.5 pct of that estimated for the other properties on a weighted-average basis. Productivity with this mining method is very low, estimated to be 0.5 to 1 t per worker-shift. The Kinmalgin property is one of the largest camote-type mining operations possible, and as such, has been assumed to be at the upper end of the productivity range. It is estimated that with camote-type mining, 75 to 85 pct of the mine operating cost consists of direct labor. As expected, capital costs are very low. Exploration and development costs are usually part of the normal mining cost. It is roughly estimated that the cost of mine equipment, mine plant, and infrastructure capital costs should be about $7/t of annual capacity for an average small-scale, camote-type surface operation.

Nine of the remaining 10 mechanized operations are hillside or level strip-bench operations. Clearing of vegetation and initial stripping for development and exploration purposes is accomplished with bulldozers. Waste and ore extraction is most often done by front-end loaders, back-hoes, or "traxcavators" of 0.5- to 3-cu m capacity, which load into small rear-dump trucks of about 10- to 15-t capacity. Exceptions to this description are the Coto-Masinloc property where 0.5-cu m shovels have been used for excavation and loading, and the proposed Bicobian and Llorente operations, where 30-t trucks are proposed for handling ore and waste. Waste material from stripping and mining operations is either pushed aside or transported short distances from the pits.

Because the mining will follow the trends of the ore bodies, a variety of pit shapes occur, resulting in oval, semioval, circular, tunnel, or U-shaped plan views (*47*). The number of benches will vary depending upon the number of chromite exposures and the trends of the ore bodies. Usually two to six benches are required. According to Bacani (*47*), bench widths range from 3 to 5 m in smaller operations and 5 to 8 m in larger operations. Bench heights range from 3 to 6 m in the small mines and 5 to 12 m in the larger pits. Bench slopes range from 48° to 65°, and haul roads grade 1 to 5 pct. Water drainage generally poses no problem, being handled by digging canals or ditches at the sides and/or toes of the benches. Productivities of these operations are estimated to range from 1 to 1.5 t of crude ore per workershift.

The Batang-Batang property is proposed to be a hydraulic operation. The engineering evaluation is based on a preliminary study done in 1978, which proposed a hydraulic operation because the chromite is disseminated in fine sands and clays. Hydraulic monitors will direct a slurry to a prepared sump pit for pumping to a mobile screening plant, which will in turn feed a stationary gravity-magnetic separation plant.

Table 35 shows the percentage breakdown of capital cost estimates for nonoperating surface mines in the Philippines. The total investment required to bring the proposed operations into production is apportioned between three categories; exploration-development-infrastructure capital costs; mine equipment capital

Table 35. — Percentage breakdown of total estimated surface mining capital investment required for developing Philippine chromite deposits

Type of material and deposit-operation name[1]	Capital investment to develop, pct of total[2]		
	E-D-I[3]	Mine equipment	Mine plant
High grade:			
Masdang	63.0	32.0	5.0
Candelaria	52.0	46.0	2.0
Low grade:			
Llorente	27.0	69.0	4.0
Bicobian	21.0	66.0	13.0
Batang-Batang	29.0	57.0	14.0
Bancugan	39.0	58.0	3.0
Irahuan	51.0	40.0	9.0

[1] Explored.
[2] 1981 U.S. dollars.
[3] Exploration, development, and infrastructure.

costs; and mine plant capital costs. As the data indicate, there are significant differences in total investment required to initiate production for the proposed low-grade and high-grade operations. In general, the low-grade eluvial deposits require a smaller percentage of exploration-development-infrastructure investments (an average of 33 pct) than the high-grade deposits (58 pct). Mine equipment accounts for the bulk of mine capital investments for the low-grade deposits, with an average of 58 pct versus only 39 pct of total investment attributable to mine equipment for the high-grade deposits. On average, mine plant investment requirements constitute a very small proportion of the total investment for both types of deposits, averaging 9 pct for the low-grade and 3.5 pct for the high-grade deposits, respectively.

Of particular note is the relatively small total capital investment required to develop a world-class-size surface chromite mine. The average estimated output, in terms of final product, for the seven currently non-producing operations evaluated in this study is 56,000 tpy of concentrate, which can be brought into production for an average of around $8 million in total mine investments.

Underground Mining

Only three of the operations evaluated for this study have been costed on the basis of partial or complete production by underground mining methods. Pertinent data resulting from the study for the three operations is listed in table 36. Of total recoverable demonstrated resources, approximately 6.7 pct is minable by underground methods. This tonnage represents 13 pct of the total contained Cr_2O_3.

Table 36. — Underground mining data for selected Philippine chromite operations (high grade)

	Metallurgical		Refractory: Coto-Masinloc
	Acoje (Santa Cruz)	Lagonoy	
Minable resource ...... 10^3 t	1,250	109	12,589
Recoverable resource[1] ... pct	44.0	100.0	75.0
Annual capacity, 10^3 t:			
Mine production	160	5	1,044
Recoverable product[2]	87	5	297

[1] Pct of total demonstrated resource recoverable by underground mining methods.
[2] Output of upgraded ore in the form of concentrates.

The Lagonoy property has been, and probably will continue to be, mined as a very small-scale, camote-type underground operation of around 5,000 tpy of crude ore. The Acoje (Santa Cruz) underground operations are large scale by Philippine standards, although the resource tonnage estimated to be minable by underground methods is only 44 pct of the total for the property. The Coto-Masinloc operations are the largest underground chromite mining operations in the country, estimated to have an underground mining capacity of 1.044 million tpy of crude ore. Production from the underground resource tonnage analyzed at Coto-Masinloc comes from five or more ore bodies and is highly mechanized. It is estimated that 75 pct of the total resource available at the Coto-Masinloc properties will have to be mined by underground methods.

According to Bacani (*47*), prior operations at Lagonoy consisted of scattered adits and some shafts to allow access for the miners to follow the "veins" (ore bodies), extracting ore as they proceeded. Timbering, drilling, and blasting were necessary, but mucking was done with wheelbarrows. This camote-type, underground mining method is very labor intensive, with very low estimated productivities of 0.25 to 0.5 t per worker-shift.

The mining methods at Acoje (Santa Cruz) and Coto-Masinloc are basically very similar; the method is officially referred to as "top slicing." Horizontal slices of ore, 2.5 to 3 m thick, are extracted after blocking out by development drifts and raises. At Acoje (Santa Cruz), successive slices are taken from the top to the bottom (underhand slicing) while at Coto-Masinloc the slices proceed from bottom to top (overhand slicing). The first system develops into what essentially is a "caving" operation while the second system (at Coto-Masinloc) requires sand filling with mill tailings as mining progresses upward. Scrapers and hand-tramming seem to be the preferred methods of haulage in the stoping areas while main haulage is by diesel locomotives. At present, the most common access method for the large scale mining of large ore bodies is by vertical shaft. Productivities for these large-scale operations are estimated at 5.5 t per worker- shift and are very high in comparison with other chromite operations throughout the world.

Mine operating costs at these three underground operations are not significantly different. The mine operating cost at Lagonoy is slightly less than the other two due to the lack of need for a significant amount of stope development. The small difference in mine operating costs between Acoje (Santa Cruz) and Coto-Masinloc is due to better scale economies at the latter. For the camote-type mining (at Lagonoy), it is estimated that labor accounts for 75 pct of the total mine operating cost, with 15 pct comprised of materials and supplies, and 10 pct representing equipment costs. For the large-scale underground operations, the relevant percentages are labor, 20 pct; materials and supplies, 30 pct; and equipment operation, 50 pct. Of this latter 50 pct, half is attributable to energy costs.

General Operational Problems

A number of operation problems need to be mentioned in relation to the chromite mining industry in the Philippines because of the major impact they could have at any time on production capabilities. First, adverse weather conditions, particularly very heavy rains, not only affect normal surface mining operations but can also seriously affect negotiation of haul roads from the mine to mills or stockpiles and to port facilities. Road washouts and high water levels at associated river crossings could also halt haulage operations, especially to port facilities. Second hand or old equipment is commonly used at the mines (most often at the smaller mines), and availability of mechanized equipment is sometimes a constraining factor. In addition, remoteness of the mines and the associated lack of good facilities in the mining camps makes recruiting of technical and skilled workers difficult. This remoteness also creates communication difficulties as well. The above points and related issues are covered in greater detail in Bacani (*47*).

BENEFICIATION

Table 37 lists pertinent technical data on beneficiation of chromite ore in the Philippines for the 10 metallurgical-grade properties evaluated for potential production of high-C ferrochromium. The resources of the first five properties listed are considered to be high-grade at 18.6 to 45 pct Cr_2O_3 in the mill feed, while the resources for the last five are considered to be low-grade at 1.3 to 7 pct Cr_2O_3 in the mill feed.

The five high-grade resource operations represent a total mill-feed capacity of 920,000 tpy of crude ore to produce 432,000 tpy of concentrate products. The concentration ratio for these high-grade resources averages 1.8, on a weighted basis. Methods used to beneficiate the high-grade ores range from a simple, labor-intensive, wash-handsort operation at Lagonoy, to gravity separation with a combination of spirals and tables at Acoje (Santa Cruz) and Candelaria, to gravity separation with spirals, tables, and jigs at Narra and Masdang. Estimated mill recoveries range from 75 to 100 pct of the contained Cr_2O_3, and concentrate grades range from 45 to 48 pct Cr_2O_3. Of the total estimated actual or proposed production from these five operations, only about 17 pct could be considered as lump product, with the remaining 83 pct in the form of concentrates.

The five low-grade-resource operations represent a total mill-feed capacity of 6.537 million tpy of crude ore to produce a potential product of only 250,000 tpy of concentrate, which results in a very high ratio of ore mined to concentrate output of approximately 30 to 1. Proposed beneficiation methods for the low-grade ores do not vary significantly. All involve a combination of gravity separation with spirals and tables followed by high-intensity magnetic separation. The only significant difference is the preparation of ore prior to gravity separation where methods range from a slurry-screen-classify operation at Batang-Batang to full crush-grind-screen-classify preparation for the lateritic material at Bicobian. Estimated Cr_2O_3 recoveries for the low-grade ores range from 80 to 90 pct, with concentrate-product grades ranging from 45 to 50 pct Cr_2O_3. All product output will be in the form of concentrates.

The weighted-average mill operating cost on a crude-ore-feed basis for the low-grade deposits is 42 pct lower than for the high grade. However, on a per-ton-of-product basis the weighted-average mill operating cost for the low-grade resource operations is estimated to be very high, approximately 10 times greater than the corresponding figure for the high-grade resource operations. This is the single most negative factor mitigating against production of chromite concentrates from these low-grade resources. If, for example, a deposit requires 25 t of material mined to produce 1 t of beneficiated product at an estimated $1.00/t of feed, and this cost were to increase by only $0.25/t, then the cost of product would increase by $6.25/t, or 25 times the increase/t of material mined. In what is normally a stable market for chromite concentrates, this increase could seriously affect the profitability of the operation and certainly represents an additional risk that high-grade resource operations are not as seriously exposed to. This economic difference between the high-grade and low-grade chromite resources of the Philippines is graphically demonstrated in figure 26 and fully explained in the following availability discussion.

Table 37. — Technical data on beneficiation of Philippine chromite

Deposit-operation	Type of ore	Mill: Recovery, pct	Mill: Grade, pct Cr_2O_3: Feed	Mill: Grade, pct Cr_2O_3: Concentrate product	Mill: Capacity, 10^3 tpy: Feed	Mill: Capacity, 10^3 tpy: Product	Type of product output
Masdang	High grade (44 pct), low grade (56 pct).	85.0	32.5	48.0	180	103	100 pct concentrate.
Narra	do	85.0	35.5	46.0	260	171	40 pct lump, 60 pct concentrate.
Acoje	do	85.0	18.4	48.0	360	117	100 pct concentrate.
Candelaria	do	75.0	35.0	48.0	65	35	Do.
Lagonoy	do	100.0	45.0	45.0	5	5	100 pct lump.
Llorente	Low-grade eluvial, sandy	80.0	1.3	45.0	4,500	98	100 pct concentrate.
Bicobian	Low-grade eluvial, lateritic.	85.0	3.3	50.0	1,372	73	Do.
Batang-Batang	Low-grade eluvial, (100 pct sand, clay, gravel).	83.0	6.0	44.0	250	25	Do.
Bancungan	Low-grade soil (93 pct), rock (7 pct).	90.0	7.0	49.0	300	39	Do.
Irahuan	Low-grade sand (85 pct), banded (15 pct).	83.0	6.6	44.0	115	13	Do.

CHROMITE AVAILABILITY

There are very distinct economic differences between the operations evaluated. Most apparent are the wide-ranging operating and transportation costs per ton of salable product. Figure 26 and the data in table 38 detail the differences in mining, processing, and transportation costs for the high- and low-grade metallurgical resources. For the high-grade (nonrefractory) resource operations, actual or proposed mine operating costs/t of product lie in a range of from approximately $15/t to $53/t, with a weighted average of $22.50/t. For the low-grade resource operations, all of which are either nonproducing or in the initial exploitation stages, mine operating costs per ton of product are estimated to be 50 pct higher on a weighted-average basis even though all are surface mining operations. This is due primarily to very high concentration ratios, estimated to average 30:1 for the low-grade resources and only 1.8:1 for the high-grade resources.

As mentioned previously, mill operating costs on a per-ton-of-concentrate-product basis are 10 times greater for the low-grade as opposed to the high-grade resources, again primarily as a result of very high concentration ratios. Transportation costs, when put on the same basis, are 60 pct greater for the low-grade resources, entirely because of greater transportation distances. The total estimated cost per ton of chromite product, FOB ocean transport, stands at $35.50/t for the high-grade resources and $101/t for the low-grade resources, or 284 pct greater. Clearly, the high-grade resources of the Philippines are very competitive on a worldwide basis and are vastly superior economically to the low-grade resources. Factoring all of this information into a single country statistic would place the Philippines at a total weighted-average cost (FOB) of approximately $67.50/t of chromite product. If a cutoff point of $65/t of product (FOB) were chosen to determine overall export competiveness, then approximately 50 pct of the total estimated potential 12.1 million t of chromite products would meet this criterion. Of this total, 90 pct would be from high-grade resources and 10 pct would come from the low-grade resources.

Table 38. — Estimated mining, milling, and transportation costs per ton of chromite product, and total chromite product availability, by resource type, for the Philippines
(1981 U.S. dollars)

	High-grade	Low-grade	Total
Ore-concentrate ratio	1.8	30.0	15.3
Weighted-average cost per metric ton of concentrate:			
Mining	$22.50	$ 33.50	$28.00
Beneficiation	5.50	55.50	29.50
Transportation[1]	7.50	12.00	10.00
Total cost, f.o.b. port	35.50	101.00	67.50
Total chromite potential .... 10^3 t	6,200	5,912	12,112
Weighted-average grade Cr_2O_3 ... pct	47	48	47

[1] Includes handling charges.

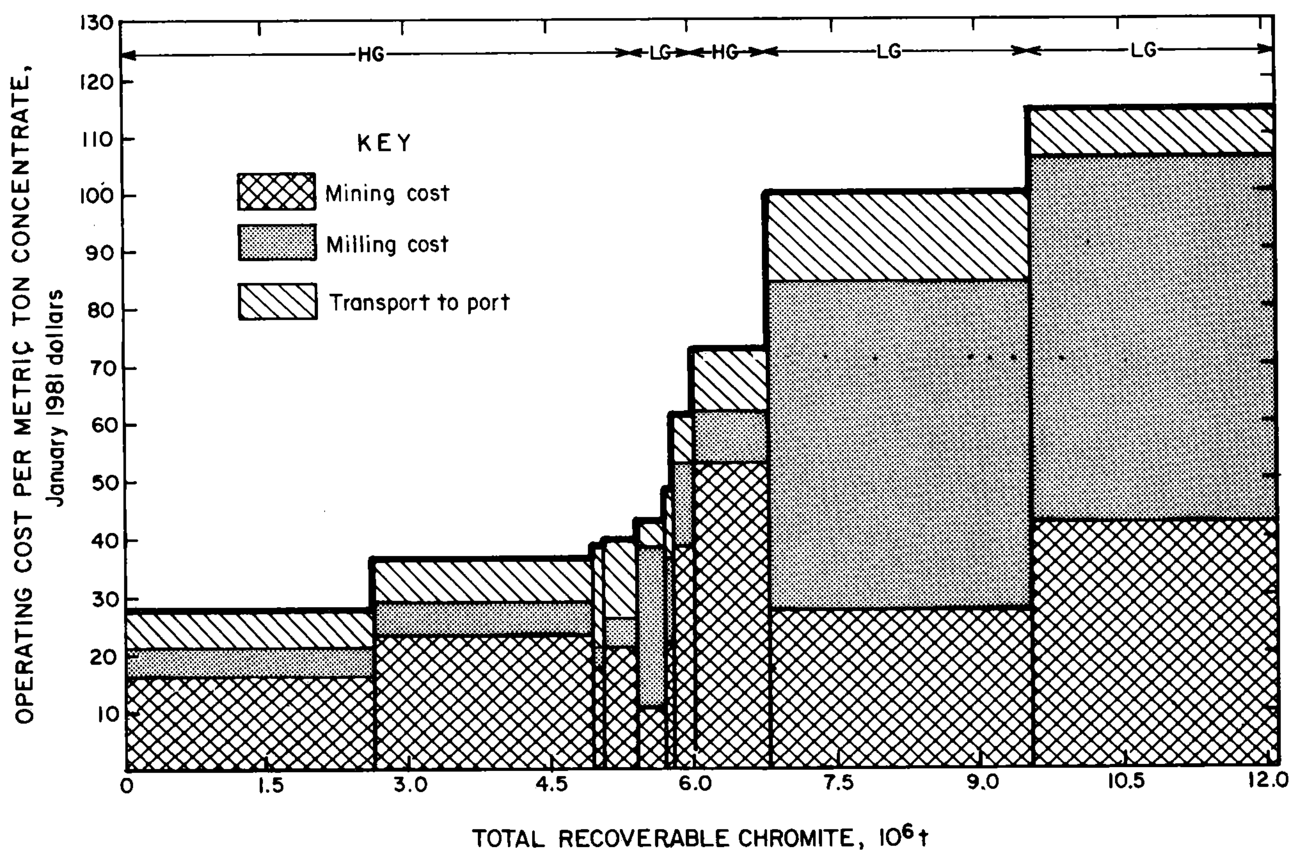


Figure 26. — Estimated mining, milling, and transportation costs per ton of chromite product, and availability of chromite from selected operations in the Philippines.

If all (non-refractory-grade) deposits and properties evaluated were developed and operated at estimated full capacity, they would represent a total combined mine output of 7.4 million tpy of chromium-bearing resource yielding approximately 682,000 tpy of chromite products. On a weighted-average basis, this represents an overall concentration ratio of material mined to product output of 15.3, which is extremely high because the majority of potential resources are of a very low grade. The beneficiated-product grades range from 44 to 53 pct Cr_2O_3 with a countrywide average of about 47 pct. For the combined high- and low-grade (nonrefractory) demonstrated resource level of 190.8 million t, it is estimated that a potential 12.1 million t of 47 pct Cr_2O_3 products could be produced. Using the 1980 reported and estimated mine capacity production estimates this would represent productive mine lives of from 6 to 36 yr.

The refractory-grade properties contain an estimated 3.95 million t of recoverable chromite concentrate, 99 pct of which is contained within the Coto-Masinloc operation. This equates to approximately 396,000 tpy at capacity operation, with the demonstrated resources at Coto-Masinloc sufficient for about 10 yr of production at current capacity.

The Philippines has the shortest inland transportation distances, and with countrywide average transport costs of $10/t, is the least expensive of the major producing countries. The chromite operations currently producing or proposed are located on several different islands and generally truck the chromite to a nearby portage for either direct loading or barging to the ocean freighter. With the exception of the 50,000-tpy proposed ferrochromium smelter in Cagayan de Oro, the great majority of chromite will continue to be exported. Given the reliance upon short-haul trucking, the cost and availability of which is borne by the mining concern, no major transportation infrastructural problems are evident in terms of cost, but the overall capacity of the transportation system is quite limited.

Currently, the major export markets for Philippine chromite are the United States, Western Europe, China, and Japan. At this time, a number of factors point to an increase in sales to the Japanese ferrochromium industry. Among these factors are, the geographical proximity of the Philippines to Japan and the lower transport costs this implies, the cost competitiveness of its high-grade resources vis-a-vis other competing suppliers, and the need on the part of the Japanese ferrochromium manufacturers to conserve electric power consumption and costs; this favors Philippine high-grade material because the high Cr:Fe ratio of this resource helps reduce power consumption and cost, since less material is required to be smelted/t of product.

There are real constraints, however, on the absolute size of potential Philippine chromite sales to Japan (or its other markets) given the problems of limited high-grade reserves and its relatively limited shiploading facilities. It is doubtful, given present circumstances, that the Philippines could ever replace South Africa, quantitatively, as a major chromite supplier to either the United States or Japan. The major significant factors to monitor in this regard are the quantity, quality, and cost competitiveness of the relatively large low-grade resources herein evaluated. But again, even these somewhat optimistic resource estimates pale in comparison to the known reserves of South African chromite.

HIGH-CARBON FERROCHROMIUM AVAILABILITY

Historically, the chromium marketing situation in the Philippines has been centered entirely around the export of chromite ore and concentrate products. Refractory-grade chromite has held a majority position in total chromite exports, while the smaller tonnage exports of metallurgical-grade chromite have primarily gone to the Japanese ferrochromium industry. In 1976, Ferro-Chemicals Inc. began producing high-carbon ferrochromium from its small, 12,000-tpy plant in Misamis Oriental Province on the island of Mindanao. The raw material is obtained from most of the country's high-grade producers. Because the plant's output is very limited, primarily for domestic consumption, and it was unclear where the smelter's ore-concentrate feed sources were, this plant was not evaluated here.

There has been recent advanced planning on the part of Acoje Mining Co. of the Philippines and Voest Alpine (Austria) to construct a 50,000-tpy ferrochromium plant to produce (65 pct contained Cr, grade A) high-C ferrochromium using local chromite concentrates (*48*, p. 209). This will doubtless reduce the amount of metallurgical-grade chromite available for export and will add to the chromite import problems of Japanese ferrochromium smelters, while providing direct competition to their ferrochromium products.

In order to ascertain the economic potential of this endeavor the total cost estimate of the ferrochromium plant was incorporated into a cost determination evaluation based upon one currently nonproducing mining operation supplying all concentrate feed requirements. The results (table 39) point favorably to the development of this facility. To cover total investment costs from mine development through the construction and operation of the ferrochromium plant

Table 39. — Per pound of contained chromium cost and potential availability estimates, by ferrochromium product grade, for the Philippines
(1981 U.S. dollars)

Type	Weighted average cost		Total potential ferrochromium, 10^3 t	Pct of total
	Breakeven level	15-pct level		
Grade A[1]	$0.37	$0.49	2,439	44.0
Philippine smelter model[2]	.40	.64	(1,172)	(21.0)
Grade B[1]	.40	.45	244	4.5
Grade C[1]	.54	.64	2,850	51.5
Total[3]	NAp	NAp	5,500	100.0

NAp Not applicable.
[1] FOB-Japan-market basis, includes all chromite and ferrochromium transportation and handling costs.
[2] FOB export point, includes all chromite and ferrochromium handling and transportation costs.
[3] Items in parentheses not included in "Total".

(and obtain a 15-pct rate of return on the investments) would require a 1981 U.S. dollar price (FOB) of approximately $0.42/lb ferrochromium or $0.64/lb contained Cr.

Assuming all chromite ore and concentrates suitable for the manufacture of high-carbon ferrochromium were to be carried through to this processing stage either in-country or in Japan, this ferrochromium facility would represent about 21 pct of the ferrochromium production potentially available from Philippine demonstrated chromite resources. Its construction would represent a major structural change in the Philippine chromium industry, yet another step towards greater reliance by the steel industries of the major industrial countries on the supply of ferrochromium from less industrialized nations and a concomitant reduction in industrialized-nation ferrochromium production capacity. It is thought at this time that the output of this plant will primarily be exported to China, which somewhat reduces the impact of direct competition to ferrochromium manufacturers in Japan alluded to previously, but still represents a reduction in available chromite supply to their ferrochromium industry.

The remaining nine actual or proposed (non-refractory-grade) operations were assumed to transport total mine and mill product output to Japan for processing to high-C ferrochromium. These results underscore the attractiveness of Philippine chromite as a source of raw material supply to Japanese ferrochromium manufacturers.

Given the general relationship between the Cr:Fe ratio of chromite and the grade of ferrochromium produced, the Philippine resources were apportioned 44 pct to the manfacture of grade-A, 4.5 pct to grade-B, and 51.5 pct to grade-C ferrochromium. The cost determinations at the breakeven level for the grade-A product averaged $0.24/lb ferrochromium, grade-B averaged $0.23/lb, and grade-C averaged $0.28/lb. On a per-pound-contained-Cr basis the weighted-average costs are $0.37, $0.40, and $0.54, respectively. The 15-pct profitability level analysis determined ferrochromium costs of $0.32/lb for grade-A, $0.26/lb for grade-B, and $0.34/lb for grade-C, which equates to per-pound-contained-Cr costs of $0.49, $0.45, and $0.64, respectively. These costs are all on a delivered-to-market-in-Japan basis (except for grade-A product category, which includes the operation feeding the Philippine smelter) and represent a general measure of the competitiveness of both the Philippine raw material and the Japanese and Philippine manufactured ferrochromium products. The grade-C product is that which is estimated to be available from the low-grade resources; its relatively higher cost is basically due to the higher cost of delivered low-grade chromite concentrates.

The results of the analysis indicate that 5.5 million t of ferrochromium products are potentially recoverable from the demonstrated resources evaluated. Applying the assumption of full capacity operation from mine through ferrochromium manufacture for all operations yields an average yearly availability estimate of 299,000 tpy.

It needs to be emphasized that the issues discussed previously concerning production and shipping capacity, limited high-grade reserves, and the ability to expand supply significantly, as they related to the availability of chromite products, hold at this further processing stage as well. At this point in time, the outlook for the future is more one of structural change (i.e., ferrochromium production versus chromite exports) rather than one of significantly expanding the scale of the industry itself.

SUMMARY

- A total in situ demonstrated resource estimate of 207.8 million t was cost evaluated. As shown in figure 27 the total resource tonnage is apportioned 86 pct to low-grade, nonrefractory resource; 6 pct to high-grade, nonrefractory resource; and 8 pct to the high-grade refractory resource type.
- The total (nonrefractory grade) demonstrated resource is estimated to contain a potential 12.1 million t of chromite products suitable for further processing to high-C ferrochromium. The product tonnages are as apportioned in figure 27.

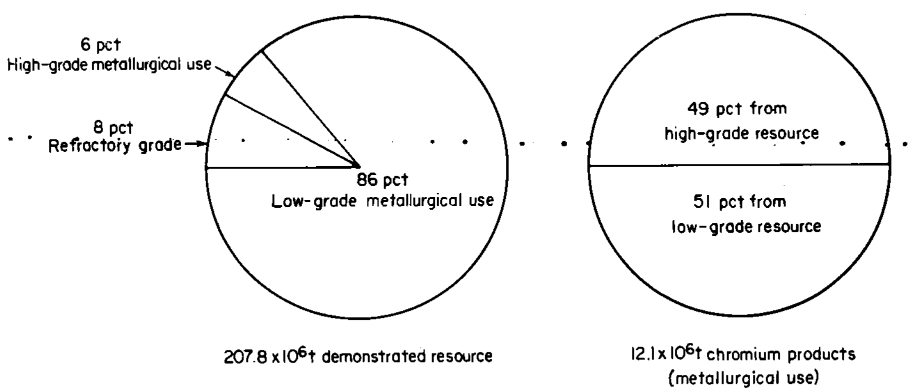


Figure 27. — Composition of cost-evaluated in situ demonstrated resource and percentage of total chromite potential attributable to low- and high-grade metallurgical resources in the Philippines.

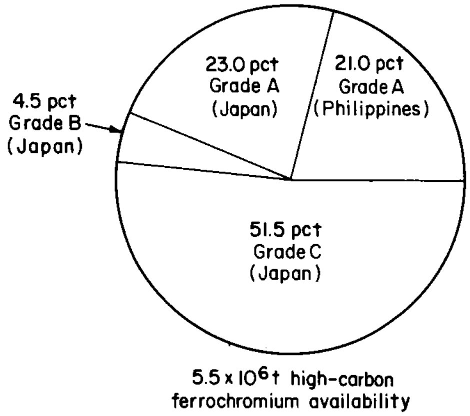


Figure 28. — Distribution of potential high-carbon ferrochromium availability estimates, by ferrochromium product grade, from the Philippines.

- Total high-C ferrochromium potentially available from this demonstrated resource is estimated at 5.5 million t, apportioned between product grade as shown in figure 28.
- Chromite production costs (as defined) are estimated to total \$35.50/t for the high-grade resources, \$101/t for the low-grade resource, and \$67.50/t on a countrywide basis. The percentage contributions of mining, milling, and transportation costs to the total operating cost for the high- and low-grade resources are given in figure 29.
- High-C ferrochromium production costs (as defined) are estimated for the breakeven level at \$0.37/lb contained Cr for all grade-A ferrochromium products, \$0.40/lb for grade B, and \$0.54/lb for grade C. The planned ferrochromium smelter in the Philippines was estimated to break even at \$0.40/lb contained Cr for the production of grade-A, high-C ferrochromium.

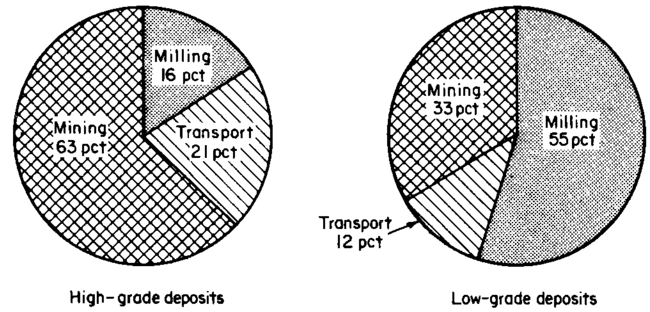


Figure 29. — Percentage distribution between mining, milling, and transportation cost estimates (FOB port) for high- and low-grade metallurgical resources, respectively, in the Philippines.

- Major implications are that, ferrochromium production in the Philippines will reduce the amount of high-grade metallurgical chromite available for export and represents a continuation of the trend toward ferrochromium production in those countries that mine chromite; secondly, the low-grade resources currently appear to be subeconomic both in terms of chromite and ferrochromium production costs.

INDIA

GEOLOLGY AND RESOURCES

In 1975, India's total in situ demonstrated chromite resource was estimated at 17 million t. Recent work by the Geological Survey of India and the government's Mineral Exploration Co. has resulted in very large upward revisions of the total chromite resource tonnage in India. The work involved reevaluation of resources at a cutoff grade of around 30 pct rather than the old standard of 40 pct Cr_2O_3, which was the basis for the total in situ estimate of 17 million t reported in 1975. The results of this program have only recently been announced and then only in general terms. Total Indian chromite resources are now estimated to be 112 million t (*49*), 60 million of which is considered as "proven" (*50*, p. 454). It has been stated that 100 pct of the "new" additional resource is located in Orissa State—with 80 pct of this tonnage in the Cuttack District, 10 pct in the Dhenkenal District, and 10 pct in the Keonjhar District (*50*, p. 459). These chromite resources represent about 98 pct of India's total known chromite resource with 96 pct located in Orissa State, and another 2 pct in Karnataka State. The resource in Orissa is essentially contained within two mining districts, Cuttack (Sukinda Valley) and Keonjhar. A third district, called the Dhenkenal, is located at the extreme southwestern end of the Sukinda Valley and is considered as part of the Cuttack District for this study. A fourth district, Hassan, contains the resource of Karnataka State.

For this study, the Bureau of Mines has estimated demonstrated in situ chromite resources at approximately 81 million t with a weighted-average grade of 32 pct Cr_2O_3 (table 40). Of this total, 16 pct is high-grade material averaging 43 pct Cr_2O_3, and 84 pct is low-grade material averaging 30 pct Cr_2O_3. There is contained within this demonstrated resource approximately 26 million t of Cr_2O_3. Identified resources are estimated at 108.5 million t, the additional 24.4 million t being entirely of low-grade material.

On a district basis, the total demonstrated resource tonnage is distributed 85 pct to Cuttack and 12 pct to Keonjhar district of Orissa State, and 3 pct to Hassan District in Karnataka State. On a property-by-property basis, this total tonnage represents the estimated resource contained in about 43 different ore bodies-deposits—30 in Cuttack, 10 in Keonjhar, and 3 in the Hassan districts.

The general indication now is that the majority of

Table 40. — Estimated in situ chromite resource data for selected Indian deposits, operations, and districts as of 1980

Deposit-operation-district name	Demonstrated resource, 10^3 t	Weighted-average grade[1], pct Cr_2O_3	Contained[2] Cr_2O_3, 10^3 t	Identified resource[3], 10^3 t
Karnataka State: Hassan District:				
Byrapur	1,000	47.0	470	1,000
Jambur-Tagadur	1,500	35.0	525	1,500
Total or average	2,500	40.0	1,000	2,500
Orissa State:				
Cuttack District:				
Low grade	59,200	30.0	17,760	83,160
High grade	10,120	43.0	4,352	10,120
Total or average	69,320	32.0	22,180	93,280
Keonjhar District:				
Low grade	7,410	30.0	2,223	10,720
High grade	2,000	40.0	800	2,000
Total or average	9,410	32.0	3,011	12,720
Orissa State total or average	78,730	32.0	25,000	106,000
Grand total or average	81,230	[4]32.0	26,000	108,500

[1] In situ weighted-average at the demonstrated level.
[2] Data may not add to totals shown because of averaging and independent rounding.
[3] Identified tonnage equals demonstrated plus inferred tonnage; where equal, there was insufficient information to support an inference beyond the demonstrated level.
[4] Country grade is the in situ weighted-average over all deposits at the demonstrated level.

India's chromite resource available for future mining consists of medium-grade, medium Cr:Fe ratio material suitable for the production of grade-B ferrochromium. The overwhelming majority of this medium-grade material will have to undergo relatively sophisticated and more costly beneficiation, resulting in the proportion of fines to lump ore production dramatically increasing from the present estimate of 2:1.

The possible potential beyond the tonnages mentioned above is thought to be great. An unpublished report[15] mentions that the total geologic potential in India could be as high as 700 million t of chromite-bearing material. The majority of this potential probably lies in basically two areas: undiscovered deposits on the buried north limb of the Sukinda ultramafic syncline, and reevaluation of resources at an even lower cutoff grade than the present 30 pct Cr_2O_3.

MINING AND BENEFICIATION

According to the Tex Report (*51*, p. 94), over 99 pct of total Indian production of chromite products during the mid- to late-1970's came from the Cuttack-Dhenkenal, Keonjhar, and Hassan districts.

Production amounts for a typical mining unit in India vary greatly from year to year. This is clearly illustrated by the Tex Report (*51*, p. 94), which identified 22 "production units" with each "unit" usually consisting of several different quarries or pits. The mining methods in use are very labor intensive, which makes it easy to increase or decrease production rapidly as market conditions change. This flexibility also extends to the types of chromite products that are available from Indian chromite resources. For simplification, the products can be organized into four basic types: (1) high-grade fines and concentrates (>47 pct Cr_2O_3), (2) medium-grade fines and concentrates (35-47 pct Cr_2O_3), (3) low-grade lump (35-40 pct Cr_2O_3), and (4) high-grade lump (>40 pct (Cr_2O_3).

The purpose of the foregoing discussion is to point out the complexity of the Indian chromite industry both in terms of the consistency of mining plans and in terms of the variety of products available. This complexity requires a certain amount of simplification in order to evaluate overall Cr availability. When dealing with India, any estimate of future mine capacities, types of chromite resource to be exploited, grade of feed material, and final products to be produced, is subject to a very high degree of variation over a time period as short as just 5 yr. The scenario proposed for this study of the Indian chromite industry exists within certain boundaries established by the specific large-scale-exploitation assumptions outlined below. It must be emphasized that this large-scale development scenario could diverge significantly from actual future developments within the chromite industry. The purpose here is to evaluate the maximum potential of chromite and ferrochromium products potentiallly available from a fully developed Indian chromium industry.

Table 41 defines the mining units and summarizes the mining data estimated for this analysis. The mining units shown represent a composite of what will, in reality, be many different individual mining operations. Therefore, all mine capacities, in situ resource grades, operating costs, capital investments, mining and milling recoveries, and product grades, represent weighted averages for the mining unit (district) as a whole.

Only about 6 pct of the total demonstrated chromite-bearing resource is proposed to be extracted using underground methods, while 94 pct is expected to be recoverable by surface methods. Because the additional low-grade resource has been added mostly by decreasing the cutoff grade from 40 to 30 pct, substantial amounts of material previously ignored in prior sur-

[15] Confidential source.

Table 41. — Estimated mining data as evaluated in this study, India

Deposit-operation-district	Type of mining technology	Average stripping ratio, ton waste per ton ore	Labor productivity[1], per worker-shift	Estimated crude ore, 10^3 tpy	Estimated total product capacity, 10^3 tpy
Hassan:					
High grade	100 pct underground (cut and fill).	NAp	0.20	15	15
Low grade	Open pit, semimechanized	6	.25	30	19
Cuttack-Dhenkanal:					
High grade	do	6	.30	110	110
Low grade	do	7	.27	400	229
Keonjhar:					
High grade	50 pct surface, 50 pct underground.	8	.22	70	70
Low grade	Open pit, semimechanized	8	.25	190	100
Total				815	543

NAp Not applicable.
[1] Total mine labor plus staff.

face operations would now be considered as economically recoverable.

The entire resource amenable to surface methods is estimated to have an average stripping ratio of ~7 over the entire life of the demonstrated resource evaluated for costs. In general, surface mining methods are not expected to change significantly from the labor-intensive, semimechanized pitting-quarrying operations in use over the last 30 yr. This method basically involves drilling and blasting of ore and waste, then excavation of waste, usually by front-end loaders, bulldozers, or small 1.5 to 2-cu m diesel shovels loading into very small trucks of about 5 t capacity. Manual labor is used for sorting, handling, and loading of ore and some waste. Ferro Alloys Corp. Ltd., (FACOR) does have plans to increase mechanization at its Bouala mine in the Keonjhar District, but operating costs are not expected to decrease significantly because the company expects the stripping ratio to increase by nearly 50 pct. Because estimated productivities using semimechanized surface mining are very low, 0.25 to 0.30 t per worker-shift, labor costs account for 70 to 75 pct of operating costs; equipment operation comprises an estimated 15 to 20 pct; while materials and supplies contribute only about 10 pct.

Underground mining is presently in use at the Byrapur operation of Mysore Minerals in the Hassan District. At Byrapur, the mining method employed is cut-and-fill, taking overhand slices and using sand fill pumped from the surface; access is thought to be by a series of adits and inclines. Timber support is required and operations are estimated at 300 d/yr, two shifts per day. Ore is hand trammed in small (1-t) cars, and mining is estimated to be not more than 200 m at depth; mining recovery is estimated at 90 pct. This study also assumes that underground mining will be required for about 50 pct of the high-grade resource in the Keonjhar District operations. The Keonjhar underground operations were assumed to be similar to that at Byrapur, except that fill material should consist of waste material rather than sand, and access would probably be via an inclined shaft system. The mining plan is predicated on an assumed mining width of 10 to 15 m.

Labor productivity for underground mining, at 0.2 t per workershift, is estimated to be slightly less than for surface operations. Total underground operating costs are, on average, around 50 pct higher than surface mining operating costs.

Beneficiation of the chromite resource evaluated breaks down into two basic methods. The only beneficiation generally required for high-grade, chromite-bearing material is a hand-sort and screening operation with essentially 100 pct recovery of the contained Cr_2O_3 to produce a lump ore product and a fines ore product. For all the low-grade material it was assumed that the minimum amount of beneficiation required would be two-stage jaw and roll crushing of material to minus 4-mm, screening-washing-classifying, and then two stages of gravity separation with flat and shaking tables. This is the method used at the Mysore Minerals pilot mill in the Hassan District, which has been in operation since 1977 or 1978. Studies of Orissa State's low-grade ores suggest that magnetic separation should probably be added for processing some of the Cuttack District low-grade material (*52*), but it is believed that this should be applied on an individual mine-deposit basis and not applied in an overall evaluation of the district. Overall recovery in treating low-grade material by gravity methods is assumed to be 80 pct. This recovery has been reported for the Hassan District pilot plant and is the expected recovery by FACOR at their Keonjhar District operations. However, lab-scale tests on seven different ores from both the Cuttack and Keonjhar districts had recoveries in the 60 to 85 pct range, hence 80 pct should be viewed as almost as high a recovery as can be reasonably expected.

Estimated mill operating costs are composed of as much as 90 pct labor for the hand-sort-screen method and about 25 pct for the gravity separation method. Equipment operation and materials and supplies each constitute about 10 pct of the costs in the hand-sort, screening method, while for gravity separation these two categories make up 40 and 35 pct, respectively, of the total cost.

CHROMITE AVAILABILITY

The potential availability of chromite ore and concentrate products from the demonstrated resources of India is on the order of 43 million t, with an average grade of 46 pct Cr_2O_3. This equates to a potential chromite availability of 543,000 tpy if all operations were producing at estimated capacity. This figure is only about 9 pct higher than peak production of 500,000 t in 1975 and is considered realistic. Of the potential 43 million t of chromite products, approximately one-third is classified as high grade (>40 pct Cr_2O_3) and two-thirds as low grade (<40 pct Cr_2O_3).

India's production of chromite products has decreased since the mid-1970's and, although ostensibly attributed to reduced demand, this is mostly due to the imposition of controls by the Indian government on the domestic chromite industry as part of its conservation policy. These controls include (1) banning the export of certain lump ores (40-42 + pct Cr_2O_3 with low SiO_2 values) and fines ore (>47 pct Cr_2O_3); (2) export taxes on all other chromite products that are exported; and (3) export tonnage quotas imposed on all individual companies producing chromite products for export. It is interesting to note that since 1975 there has been an almost 1:1 correlation between declining annual production and declining annual exports of chromite products. As of 1979, total country export quotas stood at 57,000 t of lump ore, 50,000 t of low-grade fines, and 10,000 t of concentrates.

On a per-ton-of-product basis, nationwide mining costs average \$41/t of chromite; beneficiation averages \$4.50/t, and transportation \$17.50/t of product, for a total production cost, FOB the port of exportation, of \$63/t. Total (FOB) production costs for the high-grade material currently being produced in the Cuttack and Keonjhar districts average \$41/t and \$58/t, respectively, and is even more competitive in light of the fact that it competes directly with Turkish, Iranian, and Soviet high-grade resources which are either more costly by this report's criteria or unavailable as long term supply sources. It is thus clear that India, overall, possesses cost-competitive chromite ore and concentrate products. The major issues and constraining factors surrounding the availability of chromite from India are not related to resources, technology, or production costs, but rather to governmental policy concerning the conservation of high-grade resources, the further development of a major domestic ferrochromium industry, and transportation-infrastructural problems.

Transportation (fig. 30) of chromite from the Keonjhar District is usually accomplished by trucking the ore and concentrate about 55 km southeast to the Bhadrack railhead on the Cuttack-Calcutta railroad line. From Bhadrack it is about 100 km by rail to the city of Cuttack and 300 km by rail to Calcutta. If chromite products are to be exported via Paradip port to the southeast of Cuttack, it is probably more efficient to truck the chromite all the way from Bhadrack to Paradip, a distance of about 150 km, giving a total trucking distance of about 200 km from the Keonjhar mines. A 1979 proposal to construct an 80-km rail line from Cuttack to Paradip would allow shipments from Bhadrack to be railed to Paradip, but the status of this spur is not known at present.

Chromite from the Cuttack District mines bound for export through Paradip port have to be trucked anywhere from 150 to 170 km, mostly by an express high-

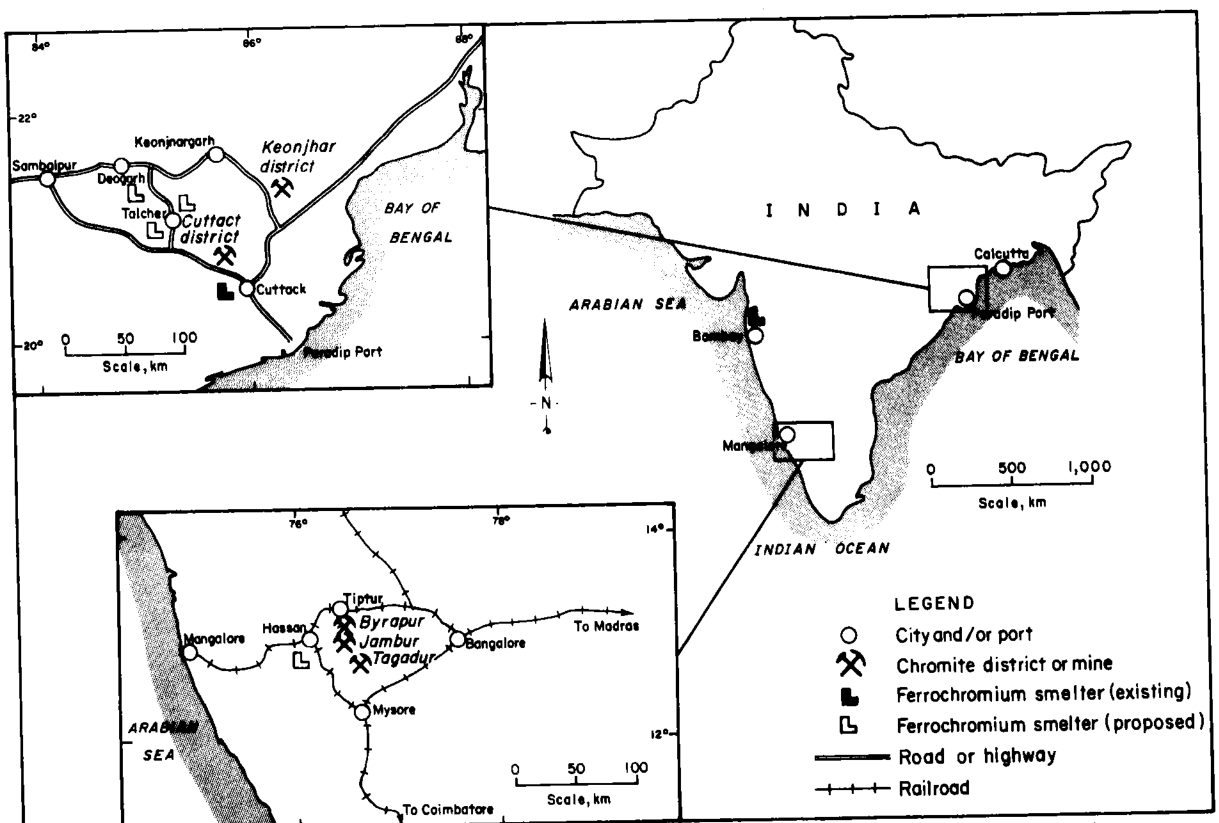


Figure 30. — Location of selected chromite mines and mining districts, current and proposed ferrochromium smelters, transportation network, and ports of exportation in India.

way. If bound for Calcutta, the chromite would probably be trucked 60 to 70 km to the city of Cuttack and railed an additional 400 km.

The Hassan District of Karnataka State in western India currently utilizes the port facilities at Mangalore for transshipment. This port is approximately 225 km from the producing mine at Byrapur and would service the operations planned for the nearby Jambur-Tagadur area as well. Transport is via truck for about 25 km to the Tiptur railhead for transshipment 200 km by rail to the port.

Within India there are no major distance or cost disadvantages to overcome, but the capacity of the railroads is severely strained. It has been estimated (*53*, p. 68) that 80 pct of all rail traffic in India carries coal, which is in great demand given the shortage of domestic oil production. Chromite must then compete for the remaining space against other, higher valued commodities. In addition, India's rail system is not computerized nor electrified. The Indian government has asked the World Bank for a $700 million loan to accomplish this, but the Bank has questioned the old freight rate policies that equalize costs across the subcontinent and is further concerned about the employment effects upon those industries, such as coal, which can employ up to 70,000 women in a single manual coal-rail-loading operation (*53*, p. 68).

In addition, the government of India, in 1979, signed an agreement with the Soviet Union to supply them with 3 million tpy of iron ore from the mines in Orissa State. Since this material is to be exported through Paradip port on a preferred basis, and since Paradip is the major chromite-exporting point, it is anticipated that chromite shipments from India will be adversely affected. There is another major ore and bulk cargo handling facility at Visakhapatnam, which lies approximately 400 km south of Cuttack. It is accessible by highway and rail and can handle ships up to 100,000 DWT. The primary mineral commodities handled, however, are iron ore, coal, and alumina. Also, the additional cost of rail transport to this port could range from $20/t to $25/t of product, and rail capacity availability is uncertain. The potential expansion of the chromium industry in India, particularly as it concerns international trade, therefore depends not only upon the upgrading of the transportation infrastructure but upon the status of other developmental and trading issues as well.

To summarize, India has recently proven very large tonnages of chromite-bearing material, the great majority of which is low-grade material in Orissa State. Historically, India has been a major supplier of chromite products to Japan, which usually purchases most available supply. India's high-grade resources, which compete directly with other high-grade producers such as Turkey and the Philippines and represent about one-third of potential chromite product availability, have been banned from export. The volume of potential exports is further constrained by transportation and portage problems, export quotas, and increasing domestic demand for chromite products for local ferrochromium production. The relative proximity of India to Japan, its historic chromite trading patterns, and the announced plans to further develop a domestic ferrochromium industry all mitigate against India becoming a major supplier of chromite material to the United States.

HIGH-CARBON FERROCHROMIUM AVAILABILITY

At present (1981) there are only two small producers of ferrochromium in India (fig. 30), the FACOR plant at Shreeram Bawar in Maharastra State and the Orissa State Industrial Development Corp's Jaipur Road smelter in the city of Cuttack, Orissa State. FACOR's plant has a design capacity to produce 10,000 tpy of low-C ferrochromium, 5,000 tpy of high-C ferrochromium, and 4,000 tpy of ferrosilicon chromium. The Jaipur Road plant has a capacity to produce 10,000 tpy of high- and low-C ferrochromium and 700 tpy of ferrosilicon chromium. Both plants were commissioned in 1969.

Total country production of ferrochromium products has varied from 17,000 to 21,500 tpy during the mid to late 1970's. At this production rate it is estimated that about 50,000 to 60,000 tpy of chromite ore and concentrate would be consumed in ferrochromium production, roughly about 15 pct of India's total annual production during that period. However, plans have been proposed and, in some cases approved, to construct at least four additional ferrochromium smelters in the country:

- A 50,000-tpy high-C ferrochromium smelter to be built by Orissa Mining Corp. in Orissa State with assistance by Outokumpu Oy of Finland and Voest Alpine of Austria.
- A 50,000-tpy high-C ferrochromium smelter to be built by FACOR based on their own technology derived from the Garividi (Shreeram Bawar) plant in Maharastra State.
- A 50,000-tpy high-C ferrochromium smelter to be constructed by Indian Metals and Ferroalloy's Ltd., also to be built in Orissa State with assistance by Elkem of Norway.
- A 6,000-tpy ferrochromium smelter to be built at Byrapur in Karnataka State by Mysore Minerals Ltd., with Japanese assistance.

If all of this ferrochromium smelting capacity (156,000 tpy) were to be built, it would consume an additional 350,000 tpy of chromite, bringing total internal consumption for metallurgical use to about 400,000 tpy. This means that, provided the country can maintain production of around 540,000 tpy of chromite ore and concentrate (the estimated maximum production capacity as of 1981), fully 75 pct would be consumed to feed the ferrochromium plants already planned. This would leave 25 pct (~140,000 t) of (probably low-grade) chromite product for export. This, of course, is a maximum potential scenario.

Because of the developmental direction indicated by these plans, it was decided to analyze all of the Indian chromite "units" as if, by 1985, all output were being smelted to high-C ferrochromium in-country. It was decided to apply this scenario to all "units" in order to ascertain total potential availability of high-C ferrochromium from the demonstrated resources that have been established, and, because of the impossibility of ascertaining what proportion of output from each of the six mining "units" should go to the planned smelters, what proportion would go to domestic chemical market uses, and what proportion would be exported.

It is also impossible at this time to know for sure which, if any, of the proposed smelters will actually be built. As a result of this decision, all six mining units were burdened, proportionally, with estimated capital costs for ferrochromium production facilities incorporating all announced plans. In addition, the mining units in the Keonjhar and Cuttack districts were burdened with approximately $53 million (1981 dollars) in infrastructure capital investments associated with constructing the ferrochromium facilities.

To utilize total chromite product capacity of 540,000 tpy for the domestic manufacture of high-C ferrochromium would require a total smelting capacity of around 222,000 t, for a total capital plant investment of about $295 million. The majority of this cost is prorated to the low-grade material, since the planned smelters would utilize this resource the most.

The total potential availability of high-C ferrochromium determined as a result of this analysis is 18.3 million t of grade-B ferrochromium (56 to 64 pct contained Cr) or approximately 82 yr of potential full capacity production. The long-run average total cost of production at the breakeven level ranges from $0.21/lb to $0.25/lb ferrochromium, with a weighted-average of $0.23/lb, or about $0.40/lb of contained Cr. In order to attain a 15-pct long-run profitability level, sales prices of $0.33/lb to $0.46/lb ferrochromium with a weighted-average of $0.38/lb, or $0.64/lb of contained Cr would be required. These latter cost estimates are markedly higher because of the large capital investments, which require higher necessary sales prices in order to recover the total investment and attain this 15-pct rate of return.

It would seem that India, which currently is a net importer of ferrochromium, could economically satisfy its domestic demand by the further expansion of its smelting capacity. The competitiveness of its ferrochromium in the international market would be in question, however, given the overall predominance of South Africa, especially in terms of grade-B and grade-C ferrochromium products and the competitiveness of the higher grade ferrochromium producers, such as Turkey, which have a distinct comparative advantage given that their industry is well established. Also, since the major market for Indian chromite products has been Japan it is uncertain if that market would become available for the sale of ferrochromium as opposed to chromite raw material. It is uncertain, at this time, whether all of the proposed ferrochromium smelters will actually be built in the near future. Lastly, the aforementioned constraints concerning the expansion of chromite ore and concentrate production and export hold here as well.

SUMMARY

- Indian chromite resources at the demonstrated level are estimated to be 81.2 million t with a weighted average grade of 32 pct Cr_2O_3, 97 pct of which is contained within Orissa State.
- This cost-evaluated resource is estimated to contain a potential 43 million t of chromite products.
- Total potential grade-B high-C ferrochromium availability is estimated at 18.3 million t.
- Chromite production costs (as defined) are estimated at $63 FOB the port of exportation, apportioned $41/t of product for mining, $4.50/t of product for milling , and $17.50/t of product for transportation.
- Domestic Indian high-C ferrochromium production costs (as defined) are estimated at $0.40/lb of contained Cr for the break-even level, and $0.64/lb of contained Cr for the 15-pct profitability level.
- Major implications are that chromite export controls and increased domestic production of high-C ferrochromium in the future will reduce chromite products available for export. This represents a continuation of the trend toward ferrochromium production in those countries that mine chromite.
- Since the above analysis of high-C ferrochromium availability was completed, two of the four proposed smelters have been constructed, the 50,000-tpy smelter of Orissa Mining Corp. in Orissa State and the 50,000-tpy smelter of FACOR, also in Orissa State, both of which initiated production in 1983. These developments further underscore the trend toward increased Indian high-C ferrochromium production and export.

BRAZIL

GEOLOLGY AND RESOURCES

Brazilian chromite resources at the identified level (measured plus indicated plus inferred) were officially set by the Departmento Nacional do Producao do Minerales (DNPM) in 1977 at approximately 24 million t of ore. Of this, 57 pct was in the Campo Formoso District, 2 pct in the Jacurici River Valley deposits, 4 pct in the Alvarado do Minas area, and 37 pct among about 100 "other" small occurrences nationwide (*54*, p. 24). (See figure 31 for locational details.)

This study estimates total Brazilian chromite resources (table 42) for the in situ demonstrated level, at approximately 18.6 million t, and identified resources at about 39 million t. With a weighted-average demonstrated resource grade of 21 pct, it is estimated that a total of 3.9 million t of Cr_2O_3 is contained within this resource.

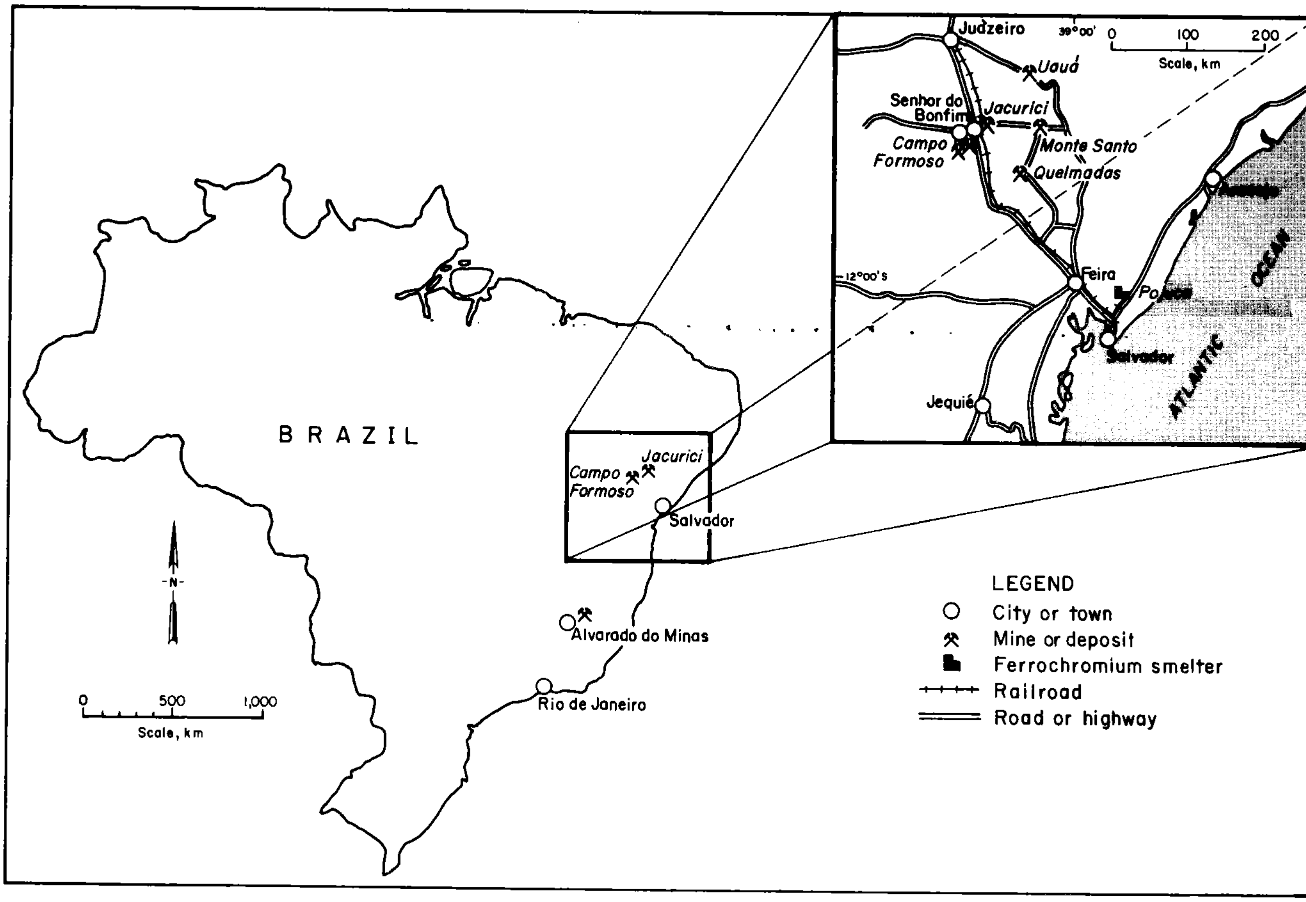


Figure 31. — Location of selected chromite mining operations, transportation network, ferrochromium smelter, and attendant port facility in Brazil.

Table 42. — Estimated in situ chromite resource data for selected Brazilian deposits and operations, as of 1980

Deposit-operation name	Demonstrated resource, 10^3 t	Weighted-average grade, pct Cr_2O_3	Contained Cr_2O_3[1], 10^3 t	Identified resource[2], 10^3 t
Pedrinhas (Campo Formoso)	13,000	21.0	2,730	} 37,000
Limoeira (Campo Formoso)	4,000	17.0	680	
Jacurici Valley[3]	1,110	37.4	415	1,180
Alvorado do Minas[3]	525	26.5	139	850
Total or average	18,635	[4]21.0	3,964	39,030

[1] Data may not add to totals shown because of averaging and independent rounding.
[2] Identified tonnage equals demonstrated plus inferred tonnage.
[3] Not cost evaluated for reasons explained in text.
[4] Country grade is the in situ weighted average over all deposits at the demonstrated level.

For this study, a complete engineering and economic evaluation was performed for the extraction of the estimated 17 million t of demonstrated chromite included in the Campo Formoso District. This area currently produces 87 pct of Brazil's chromite products. The resource is considered to be minable by open pit methods to a vertical depth of 50 m for the entire 14-km trend of the Campo Formoso District. The assumption is made that individual pits will be developed all along the strike and that no pit will go to underground mining until the entire strike length has been mined by surface pitting to a 50-m vertical depth.

The deposits of the Jacurici River Valley and Alvarado do Minas areas, as well as the 100 or so other occurrences in the country, were not subjected to complete cost evaluation. There are three major reasons for this. First and most important, the level of individual deposit data at this point in time is too scant to meaningfully address the economic determinants. Second, reported production from the small individual mines and deposits is too variable to make a meaningful projection of capacity, mining methods, and the attendant costs. Third, the relative importance of these areas to an overall study of Brazil's chromium industry as it presently exists is virtually nonexistent. There is obvious potential for further expansion within these areas, but much more geologic knowledge must be obtained and larger ore bodies found for these areas to provide a significant contribution to the Brazilian chromite industry.

The total resource available from underground mining in the Campo Formoso District could be on the order of 20 million t of 44 pct Cr_2O_3, giving it substantial potential. However, many questions regarding methodology of extraction remain to be answered before the economic potential of this resource can be determined.

The chromite resources in the Campo Formoso area from the Pedrinhas and Limoeira operations are classified as stratiform deposits. The chromite layers have been categorized into two basic ore types: (1) serpentinite containing more than 75 pct chromitite is considered as "high-grade" ore, and (2) serpentinite with 20 to 75 pct chromitite is considered as "low-grade" ore. Generally, the low-grade ores are economically mined only where weathering has been intense enough to yield friable ore. Assuming that there is about 90 pct chromite in the chromitite and 50 pct Cr_2O_3 in chromite, then the low-grade ore would range from 10 to 35 pct Cr_2O_3 and the high-grade ore from 35 to a theoretical 50 pct (where 100 pct of the chromitite is chromite). Because the mechanized open pit operations presently producing cannot practice selective mining of the individual high-chromitite-grade layers, the overall grade of material fed to the mill runs about 21 pct Cr_2O_3 from the Pedrinhas operation and 17 pct from the Limoeira operation, with Cr:Fe ratios ranging between 1.8 and 3.0.

MINING AND BENEFICIATION

The Campo Formoso District consists of three well-defined trends—Pedrinhas, Limoeiro, and Cascabulhos. The Pedrinhas and Cascabulhos trends have been combined into one operation which includes all the open pit operations of FERBASA, as well as the Coitzeiros open pits of COMISA, a subsidiary of the Bayer group of West Germany. The Limoeira trend was evaluated separately.

Pedrinhas Operation

Production from the Pedrinhas and Cascabulhos trends began in the 1960's. Until 1970, production did not exceed 40,000 tpy of crude ore. Major increases in capacity brought crude-ore production up to approximately 250,000 tpy by 1972. As of 1980, capacity of the several open pit operations in the Pedrinhas and Cascabulhos trends was estimated to be 400,000 tpy of crude ore, and was the rate applied throughout the remaining life of the operation. The weighted-average stripping ratio over the life of this demonstrated resource tonnage is estimated to be 5.7. Thus, from 1980 through the remaining life, it is estimated that on average about 2,268,000 tpy of waste and 400,000 tpy of ore will have to be moved in order to produce 120,000 tpy of chromite products.

The mining plan incorporated the assumed necessity to drill and blast all material other than the colluvial overburden which can be simply dozed. No preproduction stripping is required and clearing requirements are minimal. Operations were modeled on a two-shift-per-day, 300-d/yr basis. For this surface mining operation, the mining operating cost/t of crude ore is composed of 15 pct labor, 8.5 pct materials and supplies, and 76.5 pct equipment operation. Exploration and acquisition costs are relatively insignificant.

For this study, it has been estimated that about 10 pct of the resource for the combined Pedrinhas and Cascabulhos trends (to a vertical depth of 50 m) is lump ore with an average Cr:Fe ratio of about 2.0 to 2.5; the remaining 90 pct is friable ore with lower grades and lower Cr:Fe ratios which must be concentrated by gravity and magnetic separation to produce a 45-pct-Cr_2O_3 concentrate with a Cr:Fe ratio of 1.8.

There are two processing mills for this resource, a 1,000-tpd mill owned by FERBASA and a smaller 333-tpd mill owned by COMISA. The FERBASA processing mill was constructed prior to 1965 and has been constantly expanded to its present capacity. The overall grade of crude ore feed to this mill averages a relatively low 21 pct Cr_2O_3, owing to dilution from barren rock and low-grade serpentinite-chromitite ore interspersed among the higher grade chromitite layers. This results from the necessity to practice non-selective mining of the resource. Mill recoveries for lump ores and grains, estimated to constitute 25 pct of salable product, are effectively 100 pct. Recovery of Cr_2O_3 in the concentrates, which represent about 75 pct of salable product, is estimated to be very low at 62.5 pct, based on reported results. Specific reasons for this low recovery are not definitely known but most likely are due to the intimate nature of occurrence of chromite with silicate and ferruginous gangue minerals.

The COMISA mill produces on the order of 20,000 to 30,000 tpy of high-iron chromite concentrates, of which about two-thirds is sold to the domestic chemical industry and the remainder to FERBASA for use in the domestic manufacture of ferrochromium. The only apparent difference in the operating method from that of the FERBASA mill is the lack of some hand sorting of lump ore.

Limoeira Operation

In 1972, a joint venture was set up by FERBASA, which owned the mining concessions for the area east of the Limoeira fault, and several Japanese companies. The joint venture company, SERJANA, conducted a major exploration effort from May 1972 to late 1974, spending approximately $2 million. Mine development began in 1975, and the first products were shipped in December of 1976. The operation ran into grade and pit slope problems almost immediately. The overall grade encountered was much lower than expected because selective mining was not possible. The stripping ratio, although initially estimated at 3, was running at 5 only 2 yr after startup. In addition, it is estimated that to mine out all the resource to a 50-m vertical depth, the stripping ratio over the life of the operation will run about 11, or 3,410,000 tpy of waste to 310,000 tpy of crude ore. In 1980, the Japanese members of the joint venture sold their interest to FERBASA.

The mining plan requires drilling and blasting all material other than the colluvial overburden, which ranges from 5 to 15 m thick and can be dozed. Operations are assumed to be conducted on a two-shift-per-day, 300-d/yr basis. Little or no preproduction stripping is required, and clearing is minimal. Mine operating costs per ton of crude ore are composed of 17 pct labor, 9 pct materials and supplies, and 74 pct equipment operation. Mining costs at Limoeiro, primarily as a result of the higher overall stripping ratio, should average 62 pct more than Pedrinhas over the mine life.

The Limoeira mill was constructed in 1975-76. Its estimated capacity of about 1,033 tpd of crude ore throughout is based upon production figures, consideration of the resource position, and the increased stripping ratio encountered in the mine. It is assumed that 17 pct of salable product will be in the form of lump ore and grains and 83 pct will be in the form of concentrates. As the Limoeira mill does not employ magnetic separation, this results in a lower Cr:Fe ratio in the concentrates (~1.5) and the Cr_2O_3 recovery overall is slightly lower than at Pedrinhas. Mill operating costs for the major mills at Limoeira and Pedrinhas are not significantly different. Both costs are composed of approximately 20 pct labor, 43 pct materials and supplies, and 37 pct equipment operation costs.

Underground Mining Potential

There is potential for underground mining at both the Pedrinhas and Limoeira operations in the Campo Formoso District. However, serious planning of underground mining will probably not have to be considered for at least 10 yr at Limoeira and 25 yr at Pedrinhas, since the estimated open pit resources at capacity production will last 12 and 32 yr, respectively. A rough estimate of the operating cost of underground mining at Campo Formoso, based on adopting methods similar to the breast stoping mining method in use in South Africa, would probably be \$35/t to \$40/t of ore (including development costs and excluding mine equipment and mine plant capital costs). However, underground methods such as breast stoping, although labor intensive, do allow for very selective mining and would probably reduce the concentration ratio from the 3.5 experienced in present open pit mining operations, to the 1.5 or less typical of most underground chromite operations around the world. Thus, at an underground mining cost of \$40/t of crude ore, the cost per ton of product would be about \$60/t, which is similar to an open pit operation with a stripping ratio of 9 and a concentration ratio of 3.5. The Jacurici River Valley deposits could also be attractive for underground mining since little or no beneficiation is required and the concentration ratio is low. However, the small size of deposits in the Jacurici Valley may not justify the high initial development costs of a comparatively large underground mine.

CHROMITE AVAILABILITY

The two operations herein evaluated have the potential of producing approximately 4.6 million t of chromite products. Of this total, 82 pct is contained within the Pedrinhas and Cascabulhos trends of the Pedrinhas operation and 18 pct is contained within the Limoeira operation. If operated at full capacity, production would continue for 32 yr at Pedrinhas and 12 yr at Limoeira. Combined output would approximate 190,000 tpy of chromite products with a weighted-average grade of 44 pct Cr_2O_3.

Transportation distances from the major producing area of Campo Formoso in Brazil average approximately 375 km to the ferrochromium smelter at Pojuca and about 450 km to the port of Salvador in Bahia State. The chromite is trucked from the mine site 30 to 40 km to the railhead and transported by rail the remaining distance. Transportation costs for the two operations are essentially equal and average in the intermediate range relative to the other countries studied. Transportation should not pose an economic deterrent to the expansion of chromite exports.

There are significant economic differences, however, between the two operations studied. Because of the higher stripping ratio and lower in situ grade, the mine and mill operating costs per ton of chromite product at the Limoeira operation average 2.1 and 1.4 times greater, respectively, than at the Pedrinhas operation. In addition, the concentration ratio averages around 3.3 at Pedrinhas and 4.4 at Limoeira, again giving an economic advantage to Pedrinhas material. On a country average this works out to be about 3.5 t of material mined per ton of ore and concentrate produced.

The total cost over the life of the demonstrated resources to mine, process, and deliver chromite (FOB) the port of Salvador is estimated to be \$96/t and \$164/t for Pedrinhas and Limoeira, respectively. Thus, for Brazil, the overall costs to mine, process, and transport chromite, on a weighted-average country basis, are \$65.50/t, \$11.50/t, and \$31.50/t, respectively, for a total of \$108.50/t; relative to other world producers herein evaluated, Brazil is the second most expensive. It must be emphasized that these long-run costs were determined based upon extracting all surface minable material to a vertical depth of 50 m over the entire 14-km trend of the Campo Formoso District and take into consideration such factors as increasing stripping ratios and declining average grades. Current production costs are, of course, lower.

HIGH-CARBON FERROCHROMIUM AVAILABILITY

Ferrochromium has been produced in Brazil since 1966. Reported production of high- and low-C ferrochromium and ferrosilicon chromium has increased in line with capacity expansions, rising from approximately 3,000 t in 1966 (*54*, p. 26) to 102,000 t in 1980 (*55*, p. 3). Since 1974, production of high-C ferrochromium as a percentage of total production has averaged 85 pct.

There is one ferrochromium smelter in the country, owned by FERBASA, located at Pojuca, about 75 km north of the Port of Salvador. Rated capacity as of 1980 for the seven furnaces at Pojuca was approximately 90,000 tpy. The products produced are: grade-B, high-C ferrochromium, low-C ferrochromium (68 pct contained Cr), as well as ferrosilicon chromium. If the facility were to operate at this rated capacity, producing only high-C ferrochromium, it would need the entire output of chromite ore and concentrate production from the Pedrinhas and Limoeira operations, as evaluated in this study, as well as the production from the Jacurici River Valley deposits. However, this would leave no chromite available for export.

Present mining and milling capacity is sufficient only for in-country ferrochromium smelting, which is indicated by the fact that the only chromite exported from Brazil during 1975-80 came from the SERJANA-operated Limoeira mine and was sent to Japan. With the sale of the Japanese interest to FERBASA, all production from Limoeira can now be sent to the Pojuca smelter. It is indicated that to further increase the capacity of the Pujuca smelter would require either increasing capacity at the present mines, improving the grade of ore mined by selective mining techniques, or opening up new mines by proving up reserves at the many "other" occurrences throughout the country.

It has been estimated that domestic demand for ferrochromium in Brazil should rise to a total of 110,000 t by 1987 (*54*, p. 31). This 20,000-t increase in smelting capacity would require approximately 50,000 tpy of lump ore and concentrate feed, which in turn would require approximately 175,000 tpy of additional crude ore production if the chromite products from the present operations in the Campo Formoso District were used. Such an increase would not be difficult to attain given the present producers' installed capacity. However, the country would be hard pressed to produce additional chromite for export unless new mines were opened.

It is estimated here that approximately 1.9 million t of grade-B ferrochromium could be produced from the demonstrated resources contained within the two operations studied if the Pojuca smelter were devoted entirely to the production of high-C ferrochromium. The Pedrinhas operation would account for 54 pct of total smelter output and 82 pct of available ferrochromium from the two evaluated operations combined. On an annual basis, production could average 78,000 tpy from the Pedrinhas and Limoeira operations, with the remaining 12,000 tpy being produced from chromite production at the other, smaller mines.

Both Pedrinhas and Limoeira appear, on a relative basis, to be cost competitive with other world producers of grade-B, high-C ferrochromium. The price determinations at the breakeven level on a country basis would average \$0.25/lb ferrochromium or \$0.43/lb contained Cr. To obtain a long-term 15-pct rate of return would require a necessary sales price of \$0.30/lb ferrochromium, or \$0.52/lb contained Cr. Again, the economic differences between the operations are apparent as Limoeira requires a price between 17 and 29 pct higher, depending upon the rate of return sought, than Pedrinhas.

As far as being a potential source of supply of chromite and ferrochromium to the United States, Brazil appears to have, at this point in time, only limited potential. However, it bears repeating that this study analyzed only the demonstrated resources from the Campo Formoso District that are minable by open pit methods. There is a substantial underground resource that may be exploitable in the future and there is also potential for the future proving up of resources elsewhere in the country.

These future developments hinge on two major factors. The first and most important is the cost competitiveness of Brazil in the world market for chromite and ferrochromium, and the second is the developmental objectives and priorities of the Brazilian government. It would appear that Brazil can adequately meet its future domestic demand for ferrochromium but would not have major tonnages available for export. It must be remembered that Brazil's contribution to the world ferrochromium industry is dependent not only upon the state of the world steel industry, but the growth and competitive position of the domestic Brazilian steel industry as well.

SUMMARY

- A total in situ demonstrated resource of 17 million t was cost evaluated.
- This demonstrated resource is estimated to contain a potential 4.6 million t of chromite products with an average grade of 44 pct Cr_2O_3.
- Total grade-B, high-C ferrochromium potentially available from this demonstrated resource is estimated at 1.9 million t.
- Chromite production costs (as defined) are estimated at \$65.50/t for mining, \$11.50/t for milling, and \$31.50/t for transportation, which results in a long-run cost estimate, FOB the port of Salvador, of \$108.50/t of product.
- Ferrochromium production costs (as defined) are estimated at \$0.43/lb of contained Cr for the breakeven level and \$0.52/lb of contained Cr at the 15-pct profitability level.
- Major implications are that Brazil should be able to meet its projected domestic ferrochromium consumption needs and continue to export relatively small quantities of ferrochromium products, but does not hold much promise as a major available source of imported chromite for the United States at this time.

FINLAND

GEOLOGY AND RESOURCES

The Kemi chromite deposits are located at Elijarvi, about 7 km northeast of the town of Kemi on the northern end of the Gulf of Bothnia (fig. 32). The chromite ores are associated with a basic-ultrabasic, sill-like intrusion at the contact between the Pudasjarvi migmatite-granite massif and the Karelian schist area of Perapohja (*56*). The sill-like intrusion reaches a maximum width of 1,500 m with outcrops beginning at the town of Kemi and extending for 15 km to the northeast. In the vicinity of the present mining operations, the chromite horizon occurs 50 to 200 m from the bottom contact of the sill and basically parallels the northeast strike of the contact.

The intrusive host has a dip of 70° to the northeast. The ore bodies are strongly brecciated and thus contain many inclusions of altered wall-rock gangue such as talc, magnesite, dolomite, and serpentinite. The ores can be classified into two types; a soft talcose ore and a hard serpentinite ore, with the former accounting for 85 pct and the latter 15 pct of the total. The grade of the ore is fairly low, averaging about 27 pct C_2O_3 with a Cr:Fe ratio of about 1.5 reflecting dilution with gangue material.

Of the total 15-km length of the intrusive formation, economic ore bodies occur only in a 5-km length located north and northeast of the town of Elijarvi. As of the mid-1970's, eight ore bodies were known to occur over this 5-km length. The ore bodies are named (from southwest to northeast, see figure 32), Matilainen, Surmanoja, Nuottijarvi, Elijarvi, Viiaanranta, Viianlahti, Viianmaa, and Perukka.

The first open pit mining began in 1967 at the Elijarvi ore body and continued through 1977, when a new pit (Viaa) was brought into production to mine the Viiaanranta and Viianlahti ore bodies. At the start of operations in 1967 it was estimated that the Elijarvi ore body contained a total of 14.5 million t of ore, 5.7 million t of which could be mined by open pit methods. It is estimated that prior to closing in 1977 about 5.5 million t of ore had been extracted from the Elijarvi ore body by open pit methods. The relatively new Viaa pit is estimated to contain 6.3 million t of resource amenable to open pit mining to a depth of 110 m at a stripping ratio of 2.7.

Based upon a comparison of ore body dimensions within the Viaa pit to the dimensions of the other available ore bodies, and assuming that there is a correlation between ore body dimensions and available material suitable for open pit mining, then the total demonstrated resource as of 1979 for surface mining of all the ore bodies lies in a range from 25 to 30 million t. This study assumes that the maximum amount of demonstrated resource, less 1979 production, is available (29.2 million t) at an overall stripping ratio of 3 t of waste per ton of ore. There is potential for

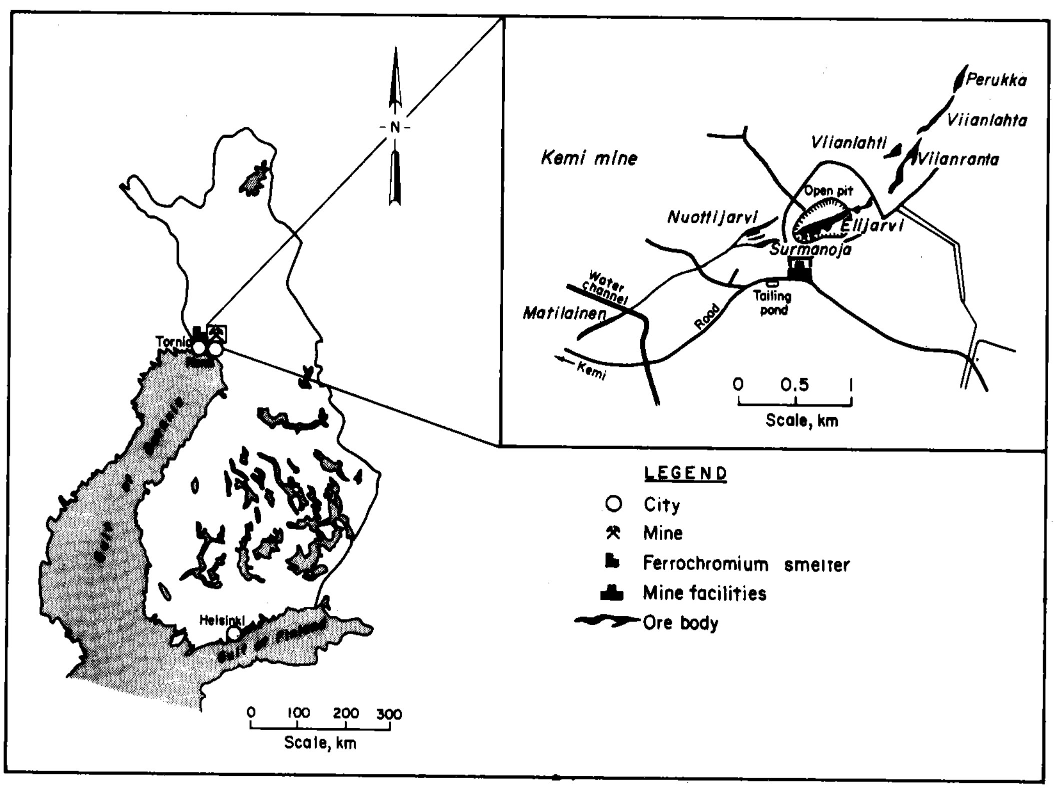


Figure 32. — Location of Kemi chromite mine, transportation network, smelting, and port facilities in Finland.

the future exploitation of underground chromite resources at Kemi, although this is a very long-term issue given that the demonstrated resources available for open pit mining could last up to 40 yr. A preliminary estimate of this resource is that it may be on the order of 30 million t; however, numerous technical issues, such as the weakness of the ore and wall-rock material, must be further studied before any economic evaluation can be made.

MINING AND BENEFICIATION

The Kemi mine employs open pit mining methods for the exploitation of its low-grade ore. The open pit is constructed with low bench heights, which allow for selective mining of the widely varying ore bodies. The mining development plan derived for the engineering cost evaluation of the Kemi mine includes the cost of mining all eight ore bodies sequentially over the mine life with open pit methods. Stripping ratios over all remaining ore bodies are assumed to average around 3. Total mine recovery of all chromite ore should effectively be 100 pct, including dilution. The mine operating cost that was estimated for the mine life includes the necessity to truck ore from the mine site to the mill an average of 3 km over the life of all ore bodies, and also includes all preproduction development costs. Current mine operating costs per ton of ore are relatively low and are not expected to increase significantly in the future as a result of technical or geologic problems.

As the ore is mined, it is separated into lump ore for direct shipping and into feed for the on-site mill. Principal mill phases are crushing, grinding, and wet and dry magnetic separation to produce either a concentrate for feed to the Tornio ferrochromium smelter or direct sale, or a concentrate for use as raw material for further processing to chromite foundry sand. Overall mill recovery for all products averages 85 pct. However, the weighted-average grade of all products is a very low 31 pct Cr_2O_3 reflecting the large amount of production that is sold as direct shipping ore.

CHROMITE AVAILABILITY

The Kemi mine is one of the least expensive major producing chromite operations in the world. This property has a potential of producing approximately 17 million t of 31 pct Cr_2O_3, high-iron chromite over the next 36 yr. Operating at a mine capacity of 800,000 tpy of ore, with a concentration ratio of 1.6, this would represent about 475,000 tpy of chromite products. In addition, approximately 2.5 million t of foundry-grade concentrate is potentially recoverable, which at capacity production would approach 69,000 tpy.

Despite the relatively low grade of the ore and the adverse weather conditions, the government-owned company, Otokumpu Oy, can produce chromite for a combined mining, processing, and transportation cost, FOB the port of Ajos, of only $25/t of product over the life of the mine. There are basically three reasons for this. First, the stripping ratio is relatively low for a surface chromite mine, which reflects the relatively steep dip of the ore bodies. Second, since it is possible to practice selective mining, this allows the concentration ratio to remain relatively low. Third, the deposit is advantageously located with respect to infrastructure and port facilities. The Tornio integrated steel works has the capacity to consume about 30 pct of the chromite ore and concentrate for the domestic manufacture of high-C ferrochromium. The remaining tonnage is available for export, with the Vargon ferroalloy smelter in Sweden being the closest consumer for metallurgical purposes. The Kemi mine enjoys a clear locational advantage for the sale of its high-iron chromite and foundry sands to the markets of northern Europe, Scandanavia, and the COMECON member states of eastern Europe. Finland is not a member of the EEC. The United States, as of the late 1970's, derived between 3 and 4 pct of its chromite imports from Finland.

The mining operation at Kemi faces no major transportation problems of note. Mine output is transported either to the Finnish ferrochromium smelter at Tornio, at a distance by truck of around 50 km, or to the port of Ajos at the town of Kemi, about 20 km away from the mine site, for transshipment to the Vargon smelter in Sweden or for export to other countries. The Tornio steel facility utilizes the outport facilities at Roytta, which from about mid-December to mid-May is generally frozen over. The facilities at these ports pose no major constraints for the exportation of Kemi chromite and ferrochromium products.

HIGH-CARBON FERROCHROMIUM AVAILABILITY

The Tornio integrated steel works is a state-owned enterprise operated by Otokumpu Oy. It includes a ferrochromium smelter, constructed in 1968 and subsequently expanded, with a current rated capacity of 50,000 tpy. The smelting process incorporates pelletizing with a sintered-pellet capacity of 120,000 tpy. Although Otokumpu Oy maintains the stated objective of doubling its steelmaking capacity at Tornio, which would necessitate a concomitant expansion of the ferrochromium plant, this goal is a long-term one with no fixed timetable. For this reason no capacity expansion beyond the current 50,000 tpy was incorporated into this analysis.

At current rated capacity, the Tornio smelter would utilize about 30 pct of the annual chromite production from Kemi given an 800,000 tpy of crude ore mine output. For purposes of establishing the cost and quantity of ferrochromium potentially available from the demonstrated resource at Kemi, the remaining chromite output above the capacity limit at Tornio was transported to the Vargon ferroalloy smelter in Sweden. All smelter operating and transportation costs were put on a weighted-average basis to account for this. The cost determination of $0.31/lb contained Cr that was derived on this basis, therefore, represents the average breakeven long-run cost of high-C ferrochromium, FOB the Vargon and Tornio smelters. Since this very low cost determination still represents a correspondingly higher cost than if 100 pct of Kemi's output was utilized at the Tornio smelter, it further underscores the basic long-run competitiveness of this resource.

The total quantity of grade-C charge ferrochromium that is potentially recoverable from the demonstrated resource at Kemi is approximately 5.4 million t. On an annual-capacity basis, this represents a potential product flow of 800,000 tpy of mine output yielding a high-iron chromite mill output of 475,000 tpy, which in turn yields an average 150,000 tpy of high-C ferrochromium over a total period of 36 yr. Given that internal consumption at capacity operation of the Tornio smelter would utilize roughly one-third of the potential chromite resource at Kemi, Finland should remain an available supplier of chromite and ferrochromium for the remainder of this century.

SUMMARY

- A total in situ demonstrated resource of 29.2 million t was cost evaluated.
- This demonstrated resource is estimated to contain a potential 17.1 million t of high-Fe chromite products at an average grade of 31 pct Cr_2O_3 for further processing to high-C ferrochromium.
- Total grade-C, high-C ferrochromium potentially available from this demonstrated resource is estimated at 5.3 million t.
- Chromite production costs (as defined) are estimated at $9.50/t for mining, $6.50/t for milling, and $9.00/t for transportation, which results in a long-run cost FOB the port of Ajos of $25/t.
- High-C ferrochromium production costs (as defined) are estimated for the breakeven level at $0.31/lb contained Cr.
- Major implications are that Finland should remain a major exporter of both chromite and ferrochromium for the rest of this century.

NEW CALEDONIA

GEOLOGY AND RESOURCES

Late in 1980, INCO Metals Inc. announced plans to bring an 85,000 tpy chromite mining and processing operation into production at Tiebaghi in New Caledonia (*57*, p. 100). The deposit to be mined is reportedly located beneath the former open pit operations which ceased production in the early 1960's after producing around 2 to 2.5 million t of ore since the early 1900's. At these deposits, initial underground mining operations were started in the early 1960's, after closure of the open pits, but ceased in 1962 owing to poor economics. Past literature does not contain much detailed geologic information on the Tiebaghi chromite deposits and INCO has not released geologic details on the "new" deposit. For these reasons, an estimate of available chromite resources at Tiebaghi, as well as deposit characteristics for complete costing purposes, are only approximated at this time.

The Tiebaghi chromite district is located near the northwest tip of New Caledonia, about 7 km north of the village of Pagoumene (fig. 33). The Tiebaghi serpentine dome has a length of about 19 km, extending in a northwesterly direction from the village of Koumac to Nehoue Bay. The dome's width is about 5 km. The old Tiebaghi mining operations were located at the dome's point of maximum elevation of 580 m (*58*, p. 616). The dome consists mainly of peridotite, dunite, pyroxene, and Harzburgite-olivine rocks. The major chromite ore bodies occur in the central portion of the dome at the northeastern edge of a plateau.

Since it is not known with certainty which ore bodies INCO intends to mine in the Tiebaghi area, the exact dimensions and configuration are speculative. Blanchard (*58*), in a description from the early 1940's, describes the mining operations at Tiebaghi as being concentrated on two "pipes"; the Tiebaghi and the Fantoche pipes. He states that the Tiebaghi pipe occupied an area of 30 by 60 m and was proven to a depth of 400 m. No areal extent for the Fantoche pipe was given, but it was mentioned that it had also been proven to approximately the same depth as the Tiebaghi pipe.

As of late 1979, official reserves for Tiebaghi, as reported by the Service des Mines et de la Geologie, were placed at less than 1 million t at an average grade of 55 pct Cr_2O_3 and a Cr:Fe ratio of 3 to 3.6 (*59*). However, standard leasing practice by the government of New Caledonia specifies that a mining lease will not be granted by the government to any operation with less than a 20-yr resource life. Based on this law, it is estimated that the proposed INCO operation must have at least 2.3 million t of in situ resource. This estimate was calculated based on a published (*60*, p. 39) projected run-of-mine ore capacity of 110,000 tpy and assumes a mining recovery of 95 pct. Back-calculation from these published run-of-mine and product capacities indicates that the high-grade ore should average around 44 pct Cr_2O_3 with a Cr:Fe ratio of 3. These data were employed in the engineering and economic analysis.

Comparison with the published dimensions of the pipelike ore bodies mined previously in the Tiebaghi area indicates that this 2.3 million t could be considered as conservative. If the material planned to be mined by INCO is, in actuality, ore remaining in the Tiebaghi and Fantoche pipes, then there certainly is at least 2 million t remaining since open pit mining was terminated at a depth of 240 m in the Tiebaghi pipe and 100 m in the Fantoche pipe, leaving 160 and 300 m of depth extension, respectively, to be exploited.

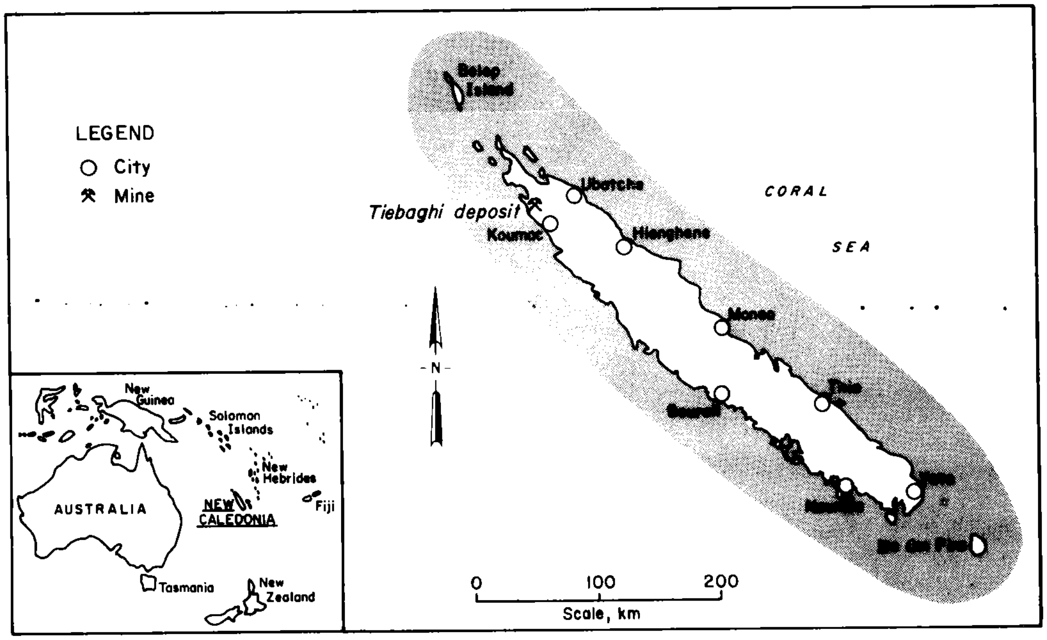


Figure 33. — Location of Tiebaghi chromite mine in New Caledonia.

MINING AND BENEFICIATION

The Tiebaghi mine is evaluated as an underground mining operation, utilizing cut-and-fill stoping, and designed for a 440-tpd production rate with a mine recovery of around 95 pct. Access is via development of new vertical shafts. Mine operating cost per ton of ore is composed of approximately 55 pct labor, 30 pct materials and supplies, and 15 pct equipment operation. Based on announced production plans the mine would operate at full capacity on a 250-d/yr basis.

Beneficiation of this ore is proposed to be by crushing, screening, and gravity separation to produce 340 tpd of concentrate with an overall mill recovery of 90 pct. Mill operating costs are composed of approximately 50 pct labor, 25 pct materials and supplies, and 25 pct equipment operation.

CHROMITE AVAILABILITY

In 1982, chromite production began at the Tiebaghi mine with initial mill product output being sold on the spot market (*61*, p. 49). Full capacity production of 85,000 tpy of salable product is expected to be reached by 1983. This output represents a production life of 20 yr at full capacity operation. At a product grade of 51 pct, it is estimated that 1.7 million t of chromite is potentially available from the 2.3-million-t in situ resource.

On a per-ton-of-product basis, the mine operating cost is estimated at approximately $42.50/t, beneficiation cost at $7/t, and transportation cost (FOB the port of exportation) at $7/t, for a total cost over the mine life of about $56.50/t. The transportation cost is based upon trucking the chromite approximately 10 km to a nearby portage for transshipment via barge to an ocean freighter for final shipment, probably to Japan if long term contracting can be arranged. Transport charges to Japan would depend upon market circumstances and the availability and terms of any contracts made with the Japanese. Relative to the internal cost and difficulties of transport faced by other countries, the delivered cost of chromite to Japan from New Caledonia should be quite competitive.

HIGH-CARBON FERROCHROMIUM AVAILABILITY

There are currently no ferrochromium smelting facilities in New Caledonia, nor are there any current advanced plans for procuring them. In order to ascertain the cost of producing grade-A, high-C ferrochromium from the demonstrated resource of the Tiebaghi operation, the total annual output of chromite was assumed to be transported to Japan for processing. All relevant transportation, handling, and smelting costs were incorporated into the economic analysis. The results indicate that approximately 36,000 tpy, or a total of 726,000 t, of grade-A, high-C ferrochromium could potentially be produced from the Tiebaghi demonstrated resource. The cost determination ranges from $0.25/lb ferrochromium at the breakeven level, to $0.29/lb for a 15-pct rate of return, or $0.38/lb to $0.44/lb contained Cr.

Relative to the cost determinations derived for the same grade ferrochromium product produced in Japan from high-grade Philippine chromite products, the Tiebaghi resource costs $0.08/lb of contained Cr less at a 15-pct profitability level. This indication of relative competitiveness explains the activity underway for the development of New Caledonian chromite resources. It bears mentioning, however, that total ferrochromium availability estimate from the Tiebaghi mine represents only 30 pct of the potential tonnage available from the high-grade resources that have been evaluated in the Philippines, which competes with New Caledonia for the Japanese market.

SUMMARY

- A total in situ demonstrated resource of 2.3 million t was cost evaluated.
- This demonstrated resource is estimated to contain a potential 1.7 million t of chromite products with an average grade of 51 pct Cr_2O_3.
- Total grade A, high-C ferrochromium potentially available from this resource is estimated at 726,000 t.
- Chromite production costs (as defined) are estimated at $42.50/t for mining, $7/t for milling, and $7/t for transportation, which results in a long-run total cost estimate (FOB) of $56.50/t.
- High-C ferrochromium production costs (as defined) are estimated, for the breakeven level, at $0.38/lb of contained Cr on a Japan-market basis.
- The major implication is that all chromite output should most likely go to Japan as raw material feed for the production of high-C ferrochromium.

GREECE

GEOLOGY AND RESOURCES

As shown in figure 34, there are 12 ultramafic rock complexes in Greece that contain chromite deposits-occurrences. Of these 12 complexes, only four are of large proportions, one of which is the Mount Vourinhos Complex in north central Greece. In general, refractory-grade chromite is mainly connected with the ophiolites of central Greece where the chromite ore bodies are closely associated with gabbroic rocks (*62*). Metallurgical-grade chromite is found in the ophiolite complexes of northern Greece, where they are associated with dunitic and peridotitic rocks.

Almost all of Greece's past production of metallurgical-grade chromite has come from either the Xerolivado (Skoumsta) area deposits or the Voidolakkos area deposits, all of which are part of the Mt. Vourin-

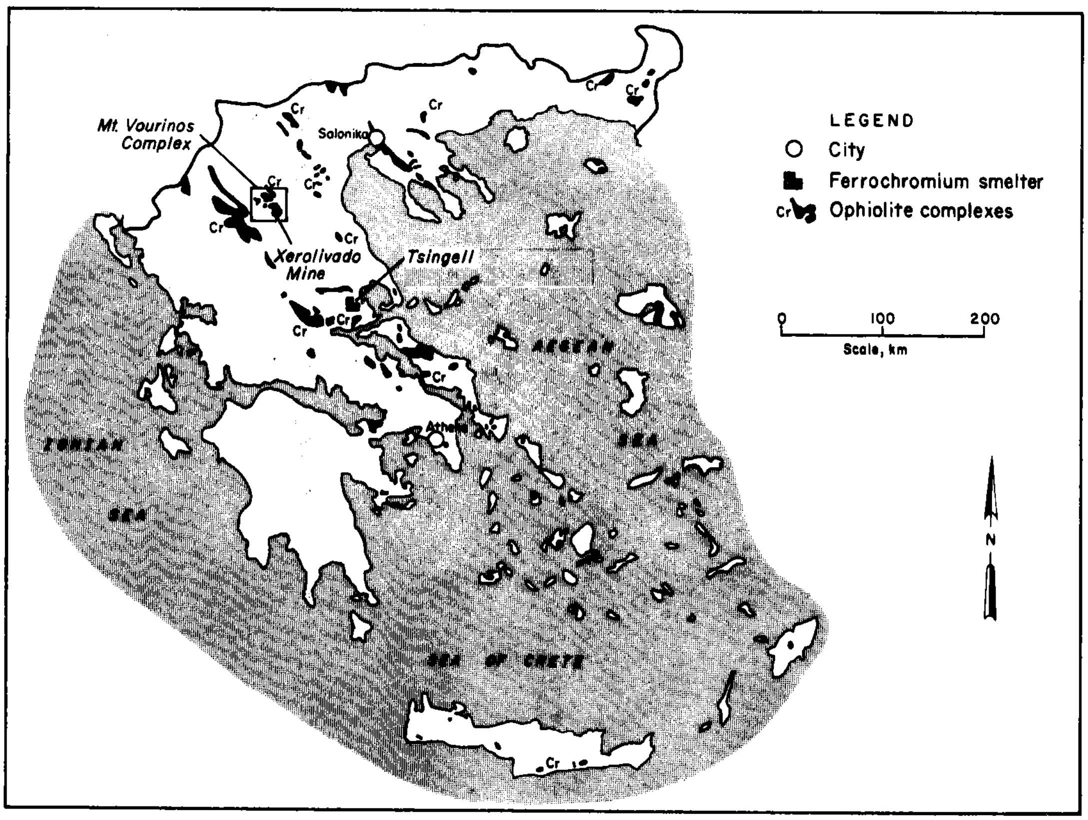


Figure 34. — Location of ophiolite complexes, Xerolivado chromite mine, and ferrochromium smelter in Greece.

has (ophiolite) Complex. Of this past production, the majority has come from the Xerolivado mine (also called the Skoumsta mine) located 2 km west-northwest of the town of Skoumsta.

This study evaluated the cost and availability of high-chromium (metallurgical-grade) chromite from the Xerolivado mine. There are four other areas that could hold future potential. The Voidolakkos area deposits, 15 km northwest of Xerolivado, are or were, high-grade, massive, metallurgical-grade ores. As of the late 1960's, only 20 podiform ore bodies were known in the area, and they were very small in size, ranging from only 1,000 to 10,000 t apiece (*62*). It is possible that the 20 known deposits were mined out as of 1980 although definite knowledge to that effect is not known. An unpublished source[16] states that promising prospects are located at Aetoraches, Koursoumia, and Kerasitsa. Published information (*63*, p. 529) indicates that the deposit at Aetoraches contains 600,000 t. All three of these areas are located in the northern half of the Mt. Vourinhos Complex and have been indicated to play a role in the country's expansion of capacity to feed the proposed ferrochromium smelter. However, not enough is known about these recent discoveries to evaluate them at present.

The Xerolivado deposits are located in the southern portion of the Mt. Vourinhos Complex, 280 km northwest of Athens and 125 km southwest of the port of Salonica. The entire Mt. Vourinhos complex covers an area of 250 sq km and is composed of interlayered peridotites and dunites. Peridotites predominate, occupying an area of 200 sq km in a 25-km long trend following the regional northwest strike. Chromite ore bodies are associated with and confined to the dunite bands (*63*). At Xerolivado, the chromite ore is entirely of the banded type (schlieren). The grade of the ore is low, at around 18 to 20 pct Cr_2O_3, using a cutoff grade of 15 pct. The Xerolivado mining area can be divided into three sections separated by two major fault zones. They are referred to as the northeast, central, and southwest sectors.

Mining was begun in 1952 on the three outcropping ore bodies (lenses) in the northeast sector. This sector is now essentially mined out. Present production is entirely from the central sector where seven separate ore lenses (numbered from 7 to 13) have been outlined by underground workings. At the 910-m level, lenses 13, 12, 11, and 10 have been proven to extend for 300 m along a northeast to southwest trend, while lenses 9, 8, and 7 extend on average for 200 m along this same trend. The ore lenses have thicknesses ranging from 1 to 13 m and extend for depths of around 100 to 150 m. The ore itself consists of coarse to medium grained chromite intermixed with dunite gangue, and the Cr:Fe ratio of concentrates produced from Xerolivado ore is around 3.

The southwest sector has been explored in detail only in the past 2 to 3 yr, during and since development of a 2,200-m exploration-production adit. As of 1980, extensions of four of the seven lenses in the central sector had been intersected in the southwest sector. However, no details of dimensions of the lenses intersected is currently available. Attitudes of the lenses show a progressive decrease from near vertical in the northeast sector to subhorizontal in the lower levels of the southwest. This decrease in attitude has led to the postulation that the deposits in the central and southwest sectors could link up with similar ore bodies 3 km to the south in a broad synclinal structure which would add significantly to the potential of the area (*63*).

Any estimate of chromite resources in the Xerolivado area contains many unknowns. Unpublished estimates[17] as of 1981 were that the central sector contained 500,000 t at a proven level and 200,000 t at a probable-possible level, while the southwestern sector was estimated to contain 100,000 t at a proven level, 400,000 t at a probable level, and 1,100,000 t at a possible level. This gives a total of 2.2 million t of ore at all levels of probability. This is considered to be a conservative estimate because of the possibility of a synclinal extension to the southwest, the relative lack of indications of pinching out of the lenses, and the fact that some of the lenses have proven strike lengths of 1,000 m.

However, for economic analysis, the estimated demonstrated resource at the Xerolivado mine that is costed for this study is the conservative 2.2 million t of in situ ore with an average grade of 18 pct Cr_2O_3. Contained Cr_2O_3 is estimated at 396,000 t.

MINING AND BENEFICIATION

The low-grade chromite at Xerolivado has been mined since 1952, with mining beginning as surface pits in the northeast sector where the ore bodies outcropped. By the late 1950's access to two sectors, the northeast and central, had been developed by sinking two inclined shafts. By 1981, a 2,200-m-long exploration-production adit had been completed to access the southwest sector. The portal is near the site of the new beneficiation plant to be constructed in the near future. Two internal shafts were also raise-bored from the adit to the level 150 m above. It is estimated that about 1 million t of ore has been extracted over the years 1952 through 1979-80 from the Xerolivado operations (northeast and central sectors).

Three different stoping methods, cut and fill, shrinkage, and sublevel, are used underground at Xerolivado, depending upon the geologic characteristics of the lense occurrence. If the thickness of the ore body is less than 5 m and the dip is less than 35°, a type of room-and-pillar method is utilized. As of 1981, only one ore body (No. 7) in the central sector was being mined by the room-and-pillar method. Most of the mining is by shrinkage stoping. In this method ore from the stopes is loaded into rail cars through chutes while in sublevel stoping, drawpoints serve as loading points. Load-haul-dump units load the ore into rail

[16] Confidential source.

[17] Confidential source.

cars which are hauled to the incline shaft by locomotives. When the new beneficiation plant is complete, probably by 1984, ore from the central sector will be delivered to the internal shaft connecting with the adit below, and main rail haulage will be in the adit delivering to the new mill.

Operations are conducted on a 250-d/yr, two-shift-per-day basis. Recent production capacity has been about 50,000 tpy of ore. Announced plans, however, indicate that when the new mill is in operation the Xerolivado production rate will be increased to about 140,000 tpy of ore. This evaluation is based on those production rates. It should be noted, however, that even with the increased capacity at Xerolivado, only 70 pct of the announced design capacity of the new beneficiation plant is accounted for. It is most likely that the remaining 30 pct will be provided from mining of the Anexitika, Koursonmia, Kerasita, and other nearby discoveries which have not been evaluated in this study owing to the lack of geologic and other data.

It is noted that the increasing use of mechanized loading (LHD's) has resulted in increased dilution, causing the mill feed grade to decrease from 20 pct Cr_2O_3 to 18 pct from 1978 to 1980 (*63*). Reference back to the geology and resources section will show that the demonstrated resource tonnage of 2.2 million t at 18 pct Cr_2O_3 evaluated in this study is assumed to include dilution by material of a lower grade than the 15-pct Cr_2O_3 cutoff grade in use in the late 1970's. Mine recovery was reported to be planned at 85 pct for the years prior to the increased use of wheel-loading equipment. This study assumes a somewhat higher mining recovery of 95 pct reflecting the assumption that increased dilution with typical chromite lens deposits would usually be the result of increased mining recoveries.

Operating costs for mining at both capacities evaluated, 200 and 560 tpd of ore, do not vary significantly in terms of total cost. The operating cost for the increased capacity using the new adit is composed of 45 pct labor costs, 40 pct for materials and supplies, and 15 pct for equipment operation. Estimated productivity for the increased capacity is 5 t per worker-shift and is modeled on 75 pct of output coming from shrinkage stoping and 25 pct from sublevel stoping. This productivity is among the highest of underground chromite mines world wide.

It is estimated that for the operation at 140,000 tpy, the total capital cost for mine equipment, including replacement of present equipment, would be nearly $1.5 million while mine plant investments would run about $2 million. Mine development costs are estimated to be $3 million for extraction of the 2.2 million t of demonstrated resource remaining. Total capital requirements for the years 1977 through the process of expansion are estimated to be approximately $10 million and include exploration, development, mine equipment, and mine plant capital costs.

At present, ore from the central sector is crushed and screened to minus 60-mm at the inclined shaft and then trucked about 6 km down a rough, steep haul road to the present mill located near Skoumsta. The new, larger beneficiation plant is, or will be, constructed very near the new adit portal not far from the old mill.

The proposed new mill is designed to handle anywhere from 600 to 720 tpd of ore feed (180,000 to 210,000 tpy). Run-of-mine ore at minus 400 mm to plus 100 mm will go through single stage crushing-grinding to minus 25 mm for feed to heavy media separation and grinding-regrinding. Minus 2.4-mm material from these stages will be fed to a classification-tabling-jigging section to produce four separate concentrates with sizes ranging between 0.3 mm and 2.4 mm. Minus 0.3-mm material will be sent to high-intensity magnetic separation for production of a fifth concentrate. Although it was not evaluated in this study, the company plans at some time to install a "flotation" circuit or plant to treat the 3-pct-Cr_2O_3 "floats" rejects from heavy media separation. Operating with Xerolivado ore as feed, expected overall mill recovery is nearly 82 pct of the contained Cr_2O_3 and concentrate grades of 51 to 52 pct Cr_2O_3 can be attained. The possibility of deliberately altering the flowsheet to produce a lower grade (44 to 45 pct Cr_2O_3) concentrate has been discussed. This is because metallurgical tests have indicated that the proposed ferrochromium smelter to be built at Tsingeli (Almyros) would operate at optimum levels using feed of this lower grade. It is possible that lower grade ore (12 to 15 pct Cr_2O_3) from the Anexitika, Koursoumia, and Kerasitsa deposits would aid in this task.

HIGH-CARBON FERROCHROMIUM AVAILABILITY

Greece has never been a major exporter of chromite. The operation at Xerolivado was evaluated assuming that all output would be trucked approximately 180 km from the mill at Skoumsta to Almyros, the proposed site for Greece's first ferrochromium smelter. The smelter is under the ownership of Hellenic Ferroalloys S.A., a 96-pct owned subsidiary of Hellenic Industrial Mining and Investment Co. of Athens. The discussions and plans for such a smelter have been conducted since the mid-1970's and as of 1982 its construction was underway with the assistance of Outokumpu Oy of Finland. Updated information is that the smelter was commissioned in the late-1982 to early-1983 period and the first shipment was made in May 1983 (*64*, p. 27). The smelter is operating at 30,000-tpy initial capacity with the possibility of later expansion to 45,000 tpy. The final cost of the overall project was $65 million, which included infrastructural investments such as road and harbor improvements, as well as the expansion of the mine and construction of the new concentrator at Skoumsta. The project was completed on time; earlier sources had reported that construction would take 3 yr, with initial startup production scheduled for late 1982 or early 1983 (*65*, p. 85). The process employed at the smelter includes pelletizing to 10- to 20-mm size pellets, sintering, preheating to 1,000° C and smelting in a 20-MVA closed arc furnace.

It is herein estimated that long-run mining, beneficiation, and transportation costs per ton of chromite concentrate from the Xerolivado operation should average approximately $57.50, $18, and $35, respectively, for delivery to the smelter at Almyros (Tsingeli). The transportation distance to Almyros is essentially the same as if the chromite were exported through the next closest major port of Salonica, ranging from 160 to 180 km. The delivered cost of chromite for the production of ferrochromium at the new smelter also represents an FOB export cost. At a long-run total cost of $110.50/t of concentrate, this smelter would be utilizing, over its life, a relatively cost competitive feed material given the geographical availability of high-grade Turkish chromite at a long-run cost of approximately $99.50/t FOB Turkish ports and excluding the cost of transport to Greece. Transportation costs within Greece are high relative to other chromite producers, but the government has entered into a project to modernize and electrify the railway network by 1990 at a cost estimate of $450 million (*66*). Given the potential of the Mount Vourinous area, it is possible that the railway network may be expanded to connect Kozani with the port of Almyros. However, at a distance of 180 km, it may prove less costly to continue to truck the chromite concentrates to the smelter.

Utilizing only the demonstrated resource at Xerolivado (Skoumsta) the new mill would produce around 40,000 tpy of concentrates for 14 yr, or a total of 585,000 t over the life of the demonstrated resource. Assuming a 90-pct recovery in the smelting process, this chromite tonnage would represent approximately a two-thirds smelter capacity utilization rate for the new smelter. Therefore, an additional chromite resource of approximately 1 million t at the other, smaller deposits would be necessary for the smelter to operate over a normal 15-yr life at full capacity from domestic chromite supplies. At this time, it is believed that sufficient local chromite supply is available from the Mount Vourinous area to operate the new Skoumsta mill and Almyros smelter at full design capacity of 30,000 tpy ferrochrome.

An analysis was performed to determine the average total cost of producing grade-A, high-C ferrochromium in Greece at the proposed smelter utilizing feed from the Skoumsta mill. The analyses were performed at both the breakeven and 15-pct profitability levels. The cost estimates range from $0.49/lb Cr at the breakeven level to $0.67/lb Cr in order to obtain a 15-pct rate of return on the invested capital. If the ferrochromium is consumed locally, and the project viewed as a developmental objective, then the marginally economic nature of the project, as reflected in the long-run cost estimates at the 15-pct level, pose no deterrent. It appears from this long-run analysis as though the project is based more upon developmental concerns or EEC trading arrangements than international cost competitiveness. It is worth noting that Greece represents the only member of the EEC (assuming its membership is retained) that possesses economically recoverable chromite resources. In addition, Hellenic Ferroalloys is jointly financing a feasibility study with Larco, S.A. (an 80 pct state-owned nickel and steel company) to investigate the possible construction of a 60,000-tpy stainless steel plant next to the ferrochromium smelter (*65*, p. 85).

SUMMARY

- A total in situ demonstrated resource of 2.2 million t was cost evaluated.
- This demonstrated resource is estimated to contain a potential 585,000 t of chromite products.
- Total grade-A, high-C ferrochromium potentially available from this resource is estimated at 241,000 t.
- Chromite production costs (as defined) are estimated at $57.50/t, $18.00/t, and $35/t for mining, processing, and transportation, respectively, for a total cost FOB the Almyros smelter of $110.50/t.
- High-C ferrochromium production costs (as defined) are estimated at $0.49/lb contained Cr for the breakeven level and $0.67/lb contained Cr at the 15-pct profitability level.
- Major implications are that all chromite production will be processed locally into high-C ferrochromium with smelter output being exported, most likely to the EEC.

MADAGASCAR

GEOLOGY AND RESOURCES

Chromite occurs in three major districts in the northern half of Madagascar (fig. 35): Andriamena, Ranomena, and Befandriana. Of the three, the Andriamena District deposits are by far the most important in terms of resources and production. Table 43 contains the in situ demonstrated chromite resource data for the deposits and deposit groups included in each district as of 1980, along with the associated in situ weighted average grades and amount of contained Cr_2O_3. As this table indicates, nearly 96 pct of the major chromite resource of Madagascar is located in the Andriamena District. In addition, at least 95 pct of Madagascar's chromite production has come from this area. The 1980 demonstrated resource level estimated for the Andriamena District includes 1 million t contained within the Bemanevika deposit, 4.5 million t contained within the Ankazatoalana deposit, and approximately 4.5 million t contained within 25 other fairly large lenses.

The Andriamenha District is located about 180 air km north of the national capital of Tananarive and about 200 air km northwest of the port of Tamatave. The total area of the district covers a rectangular

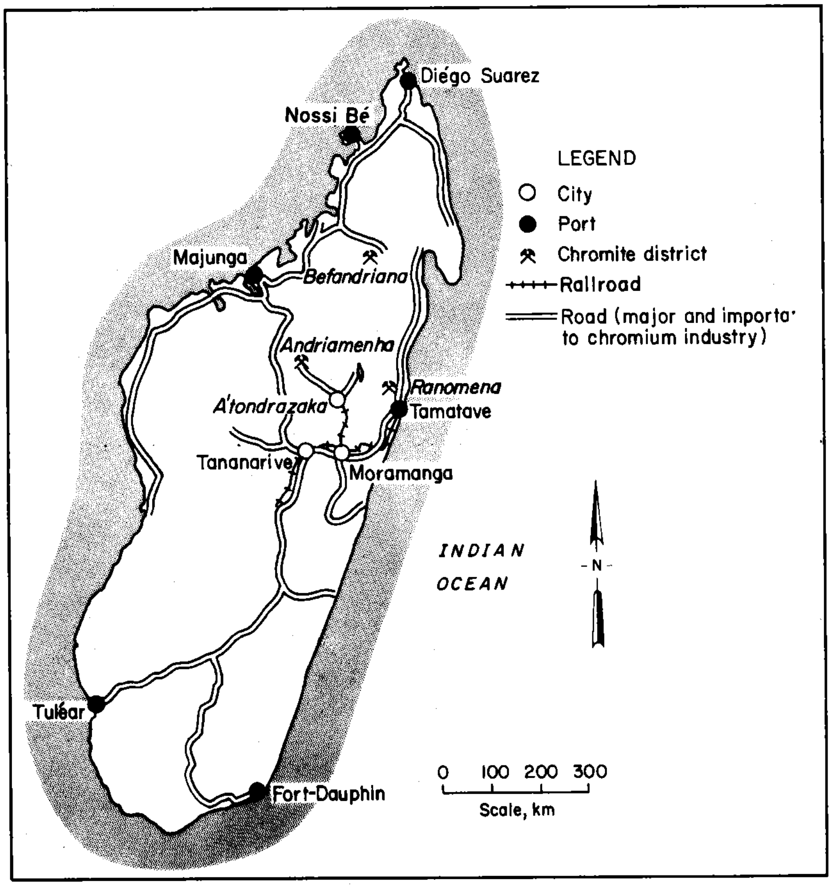


Figure 35. — Location of chromite districts, transportation network, and ports of exportation in Madagascar.

areal extent of about 60 km in a north-south direction and about 40 km in an east-west direction. Within this area, as many as 300 chromite lenses or eluvial deposits of chromite had been located by 1964 (*67*).

The Bemanevika deposit was once the largest known depo ; in this District. The ore was high grade (by Andriamena District standards) at 42 pct Cr_2O_3 with a Cr:Fe ratio of 2.6 to 3.3. This was the first deposit to be mined on a large scale in the District, beginning production in 1964. The Bemanevika operation was shut down in 1974 when the pit face collapsed and dilution by waste rock had become excessive. At the time of shutdown, the deposit was estimated to still contain 900,000 t of ore (*68*). This study has estimated the remaining demonstrated resource at approximately 1 million t.

The Ankazatoalana deposit, a few kilometers from the Bemanevika deposit, was developed in 1974 to replace output from the Bemanevika mining operation. At the time, it was reported that reserves at Ankazatoalana were 5.5 million t (*68*). The remaining resource is estimated at approximately 4.5 million t. The grade of crude ore at Ankazatoalana has proven to be low at 30 to 37 pct Cr_2O_3; however, the Cr:Fe ratio of concentrate products is approximately 2.4 to 2.7. One problem with Ankazatoalana ore has been the rather high phosphorus content, which necessitated addition of a dephosphorizing circuit to the mill in 1977. This reduces the phosphorus content from 125 ppm in the crude ore to 35 to 75 ppm in the concentrates. Dimensions of the ore zones at Ankazatoalana are not known except that plans are for the open pit to operate to a depth of 200 m. It has been assumed that the original 5.5-million-t reserve that was published refers to ore within this 200-m depth. Such an

Table 43. — Estimated in situ chromite resource data for selected deposits and districts in Madagascar, as of 1980

District and deposit	Demonstrated resource[1], 10^3 t	Weighted-average grade, pct Cr_2O_3	Contained Cr_2O_3[2], 10^3 t
Andriamenha:			
Bemanevika, Ankazatoalana, and 25 other lenses	10,000	31.4	3,140
Ranomena:			
Ranomena	250	37.0	92
Befandriana[3]:			
Befandriana and Zafindravoay	100	45.0	45
Total or average	10,350	[4]31.6	3,277

[1] Identified tonnage equals demonstrated plus inferred tonnage; in this case there was insufficient information to support an inferrence beyond the demonstrated level.
[2] Data may not add to totals shown because of averaging and independent rounding.
[3] Befandriana not evaluated for costs because of indicated short life (exhaustion by 1983).
[4] Country grade is the in situ weighted average over all deposits at the demonstrated level.

assumption matches the tonnage-to-depth relationship found at Bemanevika and implies that dimensions of the Ankazatoalana ore bodies are most likely similar to Bemanevika's.

The Ranomena deposit in the district of the same name is the largest individual deposit outside of the Andriamena district. It is located 47 km by road northwest of the port city of Tamatave. Production began in 1960, and 40,000 t of product had been exported by 1964, at which time operations were believed to be terminated. According to Besaire (*69*), the Ranomena deposit, as of 1964, consisted of about 10 lenses of chromite, each <5 m thick, occurring in a 300- by 700-m area. The reserves remaining at Ranomena were placed by Besaire at 100,000 t of "surface" ore and 150,000 t of "depth" ore. The "surface" ore grades 41 pct Cr_2O_3 with a Cr:Fe ratio of 1.5, while the "depth" ore grades much lower at 33 pct Cr_2O_3, with a Cr:Fe ratio of 1.3. The surface ore is also more attractive in terms of the SiO_2 content with a grade of 2.5 pct, while the ore at depth has a relatively high SiO_2 content of 12 pct. The demonstrated resource analyzed for this study is assumed to be these tonnages and grades as reported by Besaire, given the assumption of no significant production since 1964.

The Befandriana District is located about 100 km southeast of the port of Majunga, through which its production is exported. Production at Befandriana began in 1975 and has ranged from 40,000 to 50,000 tpy of run-of-mine ore. Run-of-mine ore has typically been high grade at 46 pct Cr_2O_3 with a Cr:Fe ratio of 2.6. Information on geology of the chromite deposits at the Befandriana operations is scant. All that is presently known is that the mining operation consists of two open pits, one 20 m deep and the other 30 m deep, located about 3 km apart. According to mine officials the remaining reserve at the present Befandriana operations was around 100,000 t in 1981, which would indicate exhaustion of the reserve by 1983 at the present mining capacity. Because of this short life, this operation was not subject to complete cost evaluation in this study. This is not to say that additional resources are not present at other deposits in the Befandriana District. At present, however, not enough is known about the other deposits or their characteristics to economically evaluate their potential.

The total demonstrated resource level, as of 1980, for the three major chromite districts of Madagascar is thus placed at 10,350,000 t, with a weighted-average grade of 31.6 pct, representing a contained resource of approximately 3.3 million t of Cr_2O_3. Of this total, 10.25 million was subjected to a complete cost evaluation.

MINING AND BENEFICIATION

All chromite production in Madagascar has come from surface mining operations. It is also assumed that all of the in situ demonstrated resource tonnage estimated by this study will be extracted entirely by surface mining methods.

All chromite mining operations in Madagascar are owned and operated by a 100-pct state-owned company, Kraomita Malagasy, and have been since nationalization of Pechiney Ugine Kuhlmann's operations in 1976. It is interesting that the country's output of chromite ore and concentrates has fallen nearly 32 pct from 1976 through 1980, from 220,000 t in 1976 to an estimated 150,000 t in 1980 (*70*, p. 629). Proposed development plans for this study's evaluation include the following assumptions for the chromite mining industry of Madagascar: the Befandriana District operations in the north will cease operations by 1983 or 1984 owing to ore reserve exhaustion; the Andriamenha District operations will maintain capacity at about 260,000 tpy of crude ore to produce 100,000 tpy of chromite products; and the Ranomena deposits will be reopened at a capacity to mine 20,000 tpy of crude ore to produce 14,000 tpy of concentrate. Thus, under this scenario, annual production of chromite products from the operations comprising the demonstrated resource of 10.25 million t that was estimated for this study will not exceed 120,000 t from 1985 through the end of the appropriate lives of the operations evaluated.

First production of chromite in Madagascar came from the Ranomena deposit because of its close proximity to Tamatave port and because much of its ore was float ore or outcropping and was easily mined. About 40,000 t of ore (probably run-of-mine ore) was exported during its 3- to 4-yr period of production (*69*). In 1964, the largest single lens deposit known in the Andriamenha Destrict, Bemanevika, began production and a milling plant was constructed. The Bemanevika pit ceased operation in 1974 because of problems with excessive dilution and because the pit face collapsed. A nearby large lens, Ankazatoalana, was quickly brought into production to replace the Bemanevika output and is still the major producer, estimated to account for about 70 pct of Madagascar's present total output of chromite ore and concentrates. Relatively large-scale surface production, believed to have been started in the Befandriana District in 1975, is presently estimated to account for the remainder of the country's output.

As evaluated, the Andriamenha surface mine is estimated to operate 300 d/yr, two shifts per day. At present the stripping ratio is estimated at ~7, moving 866 tpd of ore and 6,000 tpy of waste, or a total of 6,866 tpy of ore plus waste. Mining operations for the proposed reopened Ranomena operation are assumed to be similar in characteristics to the Andriamenha operation, except that the haul distance to the mill is less and crude ore capacity is much smaller.

Mining productivities with surface mining are estimated to be 3.7 t of ore per worker-shift, while overall productivity (including mill and administrative personnel) is estimated to be about 2.8 t of ore per worker-shift. Labor costs comprise only 27 pct of the mining cost, while materials and supplies costs represent only 15 pct. Equipment operation accounts for a very high 58 pct of the total mining cost, reflecting high fuel costs, fairly lengthy haul distances for ore, high waste-ore ratios, and fairly deep pit operations.

On a replacement basis, mine equipment capital cost estimates range from \$22/t to \$32/t of annual crude ore capacity. A rough estimate of exploration and development capital costs is in the range of $1/t to $2/t of ore reserve. Overall, to bring a surface mining operation into production of the description above, would require about $100/t of annual capacity in capital investments, including infrastructure.

The KRAOMA mill in the Andriamenha District began production in 1964 with the installation of shaking tables and a crusher. Design capacity has been constantly increased until it reached the capacity to handle about 450,000 t of crude ore feed in the mid-1970's. A dephosphorizing circuit to decrease the phosphorus content in concentrates was added in 1977 at a cost of about $1.6 million.

Due to conflicting data, the actual mass-balance through this mill is difficult to ascertain, especially in terms of the percent of total production that is lump ore material (plus 4-mm to minus 150-mm) and the grade of this lump material. An unpublished source[18] indicates that the lump product in the Andriamenha District grades a very low 30 to 37 pct Cr_2O_3, not much higher than the overall in situ grade, and that fully 45 pct of crude ore feed is lump material. Assuming that this very low grade product also has the higher phosphorus content of 125 ppm, it is questionable whether the market for this material is large enough to constitute as much as 75 pct of the output from the Andriamenha mill as a mass balance based on "50 pct recovery of concentrates and 70 pct recovery of lump ore" would indicate. In fact, all published references to output from Andriamenha District refer simply to concentrate output and never mention lump-ore production. For marketability reasons, this study chose to determine the availability of chromite from the Andriamenha District mill as if 100 pct of production was in the form of chromite concentrates at an average grade of 49 to 50 pct Cr_2O_3 with an overall recovery of 60 pct in the milling process. This assumes that the percentage of production that is lump ore is a negligible amount.

In the production of concentrates, the process at the KRAOMA mill involves two-stage crushing, screening at 40 mm, classification-grinding to minus 5 mm, followed by gravity separation with some hand sorting of waste from ore prior to feeding the parallel classify-table circuits. Top size from initial tabling is reground in a ball mill and sent to a second stage of tabling. Concentrates from both gravity circuits are dried in a kiln and then sent to a high-intensity magnetic separation for removal of phosphorus. The final concentrate grades 49 to 50 pct Cr_2O_3, 35 to 75 ppm of phosphorus, and has a Cr:Fe ratio of 2.4 to 2.7, and sizes ranging between 30 and 100 mesh.

For the Ranomena operation, it is proposed that both types of ores, high and low grade, be beneficiated from respective feed grades of 41 and 33 pct Cr_2O_3 to concentrate grades of 48 pct Cr_2O_3 in both cases. Processes for the two ores differ slightly in that the higher grade ore would not need a magnetic separation circuit while the low Cr:Fe ratio of the lower grade ore is assumed to require a circuit identical to the present KRAOMA mill described above.

[18] Confidential source.

As a percentage of total mill operating cost, labor accounts for about 45 pct, while equipment operation represents 35 pct, and materials and supplies represent 20 pct.

The estimated replacement cost for a mill similar in size and process to the KRAOMA mill in the Andriamenha District is estimated to be $8/t to $11/t of annual crude ore feed.

CHROMITE AVAILABILITY

The total availability of chromite products from the demonstrated resource level determined for Madagascar is limited to a potential of approximately 3.9 million t of high-Cr chromite, with a weighted-average grade of 49 pct Cr_2O_3, the great majority of which (3.7 million t) is contained within the Andriamenha operation. This operation could produce about 100,000 tpy at full capacity for 37 yr from the demonstrated resource level. Ranomena could provide around 13,000 tpy of chromite products, beginning in 1985 but declining to about 8,000 tpy, at planned capacity, by 1990 due to declining ore grade. The life of this operation is estimated at 13 years given its demonstrated resource level and proposed capacity.

The long-run mine operating cost of chromite products in Madagascar, on a weighted-average basis, is approximately $31/t; long-run beneficiation cost is estimated at $16/t of product, and the transportation cost, on the same basis, is estimated at around $19.50/t. This gives a long-run total cost estimate, FOB the port of Tamatave, of $66.50/t. Although this estimate compares favorably with costs in South Africa and Zimbabwe, the tonnages available both annually and over the resource life are literally dwarfed by the chromium industries of these two nations.

Currently, concentrates from the Andriamenha operation are trucked about 110 km east-southeast to the railhead at A'tondrazakao then railed approximately 400 km to the port of Tamatave for export. Concentrates proposed for production from the Ranomena operation would be trucked 45 to 50 km southeast to the same port for export.

HIGH-CARBON FERROCHROMIUM AVAILABILITY

There has never been a ferrochromium smelter constructed in Madagascar. In the mid-1970's a feasibility study was conducted for the construction of a high-C ferrochromium smelter at Moramanga, a city located on the railroad to Tamatave. The capacity of the smelter studied was 50,000 tpy and included an exploration program to increase reserves in the Andriamenha District. The project was found to be uneconomic, because estimated capital investment, at that time, was $100 million. It is believed that there were several additional problems with the proposed project, including (1) the lack of a cheap fuel source, (2) the requirement to site the smelter 200 to 300 km by rail inland from the port, and (3) the economic competiveness of the product relative to the competition from South African ferrochromium. With a demonstrated resource of 10.25 million t and a production capacity of 100,000 tpy of concentrates, it would be possible to produce about 40,000 to 45,000 tpy of ferrochromium for 38 yr (for a total of about 1.6 million t) according to the criteria of this analysis—an adequate level of reserve to support a smelter. However, on a strict operating cost basis, excluding capital cost recoupment, taxes, etc., the expected cost of ferrochromium production, including the additional transport cost to Tamatave port, would exceed the cost of an average South African operation delivering to the port of Durban, South Africa.

In the past, the chromite products of Madagascar have primarily been exported to Japan and the EEC. For the purpose of this report, the total annual output of chromite products from the operations studied were transported to Japan for the manufacture of grade-A, and grade-C, high-C ferrochromium. The average total costs thus determined range at the breakeven level from \$0.42/lb to \$0.47/lb contained Cr for the grade-A and grade-C products, respectively. This compares with cost of \$0.37/lb and \$0.38/lb contained Cr for grade-A products from Philippine and New Caledonian based chromite resources, also delivered and processed to high-C ferrochromium in Japan. The cost differential is due almost entirely to both greater inland transport distances within Madagascar and greater ocean shipping distances to Japan.

SUMMARY

- A total in situ demonstrated resource estimate of 10.25 million t was cost evaluated.
- This demonstrated resource is estimated to contain a potential 3.9 million t of chromite products with an average grade of 49 pct Cr_2O_3. Of this tonnage, 95 pct is contained within the Andriamenha operation.
- Total high-C ferrochromium potentially available from this demonstrated resource is estimated at 1.535 million t of grade-A ferrochromium and 65,000 t of grade-C ferrochromium.
- Chromite production costs (as defined) are estimated at \$31/t for mining, \$16/t for processing, and \$19.50/t for transportation for a total long-run cost estimate FOB the port of Tamatave of \$66.50/t.
- High-C ferrochromium production costs (as defined) were estimated, for the breakeven level, at \$0.42/lb and \$0.47/lb contained Cr, for grade-A and grade-C ferrochromium, respectively. These costs are on a Japan-market basis.
- Major implications are that no major change in trading patterns is expected and the construction of a domestic ferrochromium smelter remains doubtful.

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