THE NATURAL HISTORY OF A MINE

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This essay might be classed in the realm of *geographic economics* rather than in *economic geography*. Considerations that are eminently geographic, that is, are tied to the peculiar characteristics of particular localities, are examined. However, the models presented are designed primarily to inform economic policy, specifically policies that would exploit local mineral resources to achieve economic development of economically underdeveloped countries or regions.

Gold is where you find it. For thousands of years efforts have been made to develop a theory that would predict the occurrence of concentrations of desired minerals in sufficient intensity to make their extraction economically feasible. Geologic knowledge certainly has increased, and there have been greater improvements in prospecting techniques which can be applied intensively in geologically promising zones. The discovery of a great mine, however, continues to be a largely fortuitous event, although once a major mineralized district has been identified, exploring it to its limits can be a more ordered investigation with more generally predictable returns. It would seem that the processes of mineral implantation and secondary enrichment, occuring sporadically over vast periods of geologic time, that occasionally lead to singularly intense concentrations of one or more rare and valuable elements or minerals will long remain mysterious. The isolated prospector with his burro, pick, and pan, and the elaborately equipped geophysical and chemical prospecting team perform the same economic function in essentially the same manner. They hope to bump into something good, more or less by accident. Their professional skill consists of a capacity to recognize what they have encountered.

*This paper was written during a sabbatical year spent in Chile, a country whose economy has been and remains closely dependent on the exploitation of its mineral resources. For this reason most of the mines referred to by way of examples are Chilean. It is my belief that equally cogent examples would be found in Canada, Australia, Peru, or any other country in which mineral production for export constitutes a significant part of the economy. I wish to acknowledge indebtedness for both intellectual stimulus and informational support to Pedersen's notable monograph, *The Mining Industry of the Norte Chico, Chile* [5].

General Characteristics of Mineral Deposits

Once a mine has been discovered its development and exploitation, leading to eventual depletion and abandonment, seem to follow an inevitable course, though the size and richness of the deposit will determine the duration of its several stages. The determination of this course is significantly conditioned by a number of physical characteristics that apply to essentially all economic mineral deposits.

a) The economically workable mineral concentration is finite. Its establishment frequently took place in the distant past under geologic conditions no longer present, or in the cases where mineral implantation is continuing, it almost always occurs at a rate so slow that it must be measured on a geologic time scale. Exploitation is destruction, and at a foreseeable point in time the mine will be exhausted. Mining engineers speak of exploiting a wasting resource though they have developed a remarkable capacity to avoid thinking too much about the bleak ultimate end of the operation in which they are at any time engaged.

b) Mining itself consists of highgrading a mineral deposit. The richest veins or deposits that can be identified will be worked first, and subsequent operations will inevitably deal with poorer ores, continuing as long as those that remain still can be worked profitably. The relatively small size of the mining claims that traditionally have been allowed by states as diverse as Britain, the Spanish Empire, the United States, and the modern Latin American nations has tended to reinforce this pattern of highgrading. Heavily capitalized mass mining procedures capable of exploiting vast bodies of low grade ores, notably copper, tend to weaken it. But it may be suggested that the highgrading tendency is based on a fundamental desire to economize on the effort invested in achieving the identifiable end, the production of a valuable mineral.

c) A mine starts at a point on the surface. As material is removed the pit, shaft, or tunnel deepens and the extraction process becomes progressively more expensive. Transport and lifting costs always increase; in underground workings the protection of shafts and tunnels from cave-ins and increasingly complex ventilation and drainage problems multiply costs.

d) The most superficial part of any mineral deposit is likely to be the richest for two reasons. 1) This is where the mine was found. A portion of the earth's crust was sectioned by erosional forces, and at one or more points of exposure the special mineral concentrations could be located. It is statistically probable that a deeper probe at those points will enter materials more closely resembling the surrounding country rock. There have been famous exceptions. Great pockets of extraordinarily rich silver and copper ores were encountered underground at Chañarcillo, Tamayo, Carrizal Alto and elsewhere in the Chilean Norte Chico, often associated with the intersection of veins of differing orientation or with veins that cut through different sorts of rocks [5, pp. 182–7]. 2) Further, the natural processes of ore enrichment seem almost invariably to be most effectively beneficial near the surface. In silver and copper ores, for example, those near the surface may be oxides while the deeper ores are sulfides. The former are commonly of higher tenor and are always easier to process from a technical standpoint. Similarly the mechanical processes that concentrate gold in placer deposits occur only at the surface, although sometimes such deposits have been buried through subsequent geologic activity. Thus, even in the largest and richest of ore bodies or mineralized districts there is almost a certainty that in its later stages a mine will be working progressively poorer ores.

General Characteristics of Mining Operations

In the mining operation itself and in the processing of ores technology has not been static. Especially during the past century there has been an enormous increase in the capacity to handle lower grade ores, and with few exceptions, notably aluminum, the chemical character of the native mineral in which a desired element is enfixed has ceased to be a barrier to its exploitation except in a limited, cost sense. The trends in technological development have held a consistent direction, all leading to a notably heavier capital investment in each operating mining unit.

The mining operation itself falls into two parts: an extractive or rock-breaking one accomplished with explosives, bars, or in soft ore simply with shovels; and transporting the loosened material to the pithead, concentrator, smelter, or market. The latter phase is in general the more costly. With increasing mechanization and growth in the size of machinery used, it has become possible to handle material at notably lower costs per ton. In the United States, for example, it is economically feasible to extract copper ores with as little as one-half percent

copper content, and the Gran Minería, or great mines in Chile, are utilizing copper ores with a tenor of less than one percent. Mass mining of this sort is feasible only in huge ore bodies from which the enormous capital investment can be amortized. It is also capable of using up such ore bodies in relatively short time spans. Relatively speaking, narrow, rich veins are no longer essential, and vast rock masses with widely and thinly disseminated values can for the first time constitute a mine. In some instances, although the rich veins have been exhausted, the surrounding rock holds enough value to make it exploitable in mass.

Progress in massive chemical treatment of ores, again involving heavy capital investment reinforced by the declining tenors of the ores being worked, has resulted in a tendency to carry on an increasing amount of concentrating, smelting, and refining as close as possible to the point where the ore is extracted. Again the size of the capital investment demands an enormous ore reserve for its justification. In some instances, notably in the Chilean Norte Chico, it has been possible to afford certain economies of scale by placing a large refinery or concentrating plant in a convenient location amidst a number of small mines.

With the exception of coal mines with great reserves, which have for nearly two centuries demonstrated their ability to attract permanent industrial developments to the immediate vicinity of their pitheads, most major modern mining activities are carried on in otherwise little-settled and relatively isolated districts. An element, of course, is that the ore bodies closer to population centers, such as the famous silver mines of Lavrion in Attica, have long ago been depleted if not worked out. The three major copper mines of Chile are quite typical: one, El Teniente, is in the Andes and the others, Chuquicamata and Potrerillos (El Salvador), are far in the desert north. In such cases major additional investments in living quarters and services for the labor force (in dry regions an exotic water supply often must be obtained) and transport facilities capable of bearing heavy loads must be introduced, often with the sole justification of supporting the mining operation. In some degree these investments too must be amortized by the product of the ore body before it is depleted.

Mineral Values and Prices

It is the price at which a given metal or other mineral can be sold that ultimately determines whether a deposit containing it is a mineable ore or just so much rock. Forces acting in opposing directions over the past few centuries have created the modern unstable tableau of mineral prices. Increasing industrial demands for minerals and the rising costs of extraction associated with depletion of mines, lower grade ores, and increasing inaccessibility of unworked deposits exert an upward pressure on prices. Improved mass mining techniques along with modern chemical and physical means of treating ores have tended to reduce them as have important new discoveries. A growing technical capability to substitute a number of materials for a particular use is one of the few forces that would tend to stabilize prices.

An examination of the resultant in real prices of the action of these conflicting forces on each of the significant minerals of commerce is beyond the scope of this study, but a few generalizations seem possible. Trends in mineral prices have been highly variable over time with the most heavily used substances, iron and the mineral fuels, showing a degree of price stability as do the precious metals used for monetary rather than industrial purposes. Price instability seems to reach its greatest intensity in those minerals of just less than the maximum intensity of use, and peaks perhaps in copper.[1] As a given mineral, often a metal, increases its industrial importance it is likely to move into an era of increasing price instability, not simply one of rising prices. The development of uranium mining in the past 25 years affords an excellent example. It would seem fairly safe to predict that the same pattern of price instability, at least in many minerals, will continue into the future, occasionally yielding a bonanza, but more characteristically plaguing the mine operator as he tries to plan the exploitation of a deposit. In particular, capital investments will be amortized as fast as possible, reinforcing all other tendencies toward highgrading the deposit.

[1] Compare E. Zimmermann [*1*, pp. 698–705] and D. W. Fryer [3, pp. 400–2].

Graphic Expression of a Mine's History

Despite their almost infinite diversity in terms of kind of material produced, size and richness of the deposit exploited, and accessibility, individual mines go through an established series of stages, and each stage presents a specific set of problems and opportunities to the operator, to the labor force, and to the society at large. In their simplest form these stages are illustrated in Figure 1. The scales on this model for both money and time are, of course, highly variable, and the variation is not always parallel in the two elements. A major fraction of the mines of history have passed through the first three stages and entered the fourth; often the abandonment of the mine completes this stage within a single decade. In the past 150 years very few mines have persisted as long as fifty years without passing well into the fourth stage, although in earlier times when man had less inanimate energy at his disposal, the depletion of an ore body could proceed less rapidly and the third stage might endure for centuries. The history of modern mines of greater durability would have to be described by more complex models as in Figures 2 and 3.

For small deposits of a high value, easily processed mineral such as rich pockets of placer gold, curves of different slope might better describe the first two stages. In such cases the amount of capital investment would be relatively less in relation to labor investment, and really profitable returns might be generated from large gold nuggets almost from the instant of discovery. Conversely, when mass mining of low grade ores is involved, as in modern large copper mines, there may be no returns at all until after substantial investments of both labor and capital have been made, i.e., well into Stage II.

Some characteristics of each of the stages may be noted.

Stage I. Until recently the prospector's wearying efforts were sustained largely by hopes of vast rewards that were seldom realized. His grubstake was painfully amassed through work in other enterprises, or might be supplied in modest form as the most risky of investments by an individual or corporate backer who would receive most of the value of any discovery that might be made. The moderately high labor input shown in the model represents the innumerable prospectors who found nothing, ore samples scratched from the ground that never paid their assay charges, and incipient mines that were never developed beyond this stage. Modern prospecting teams, usually salaried and with corporate backing, with substantial geophysical and geochemical equipment would show a considerably higher level of capital investment. Sample core drilling or comparable activities to determine the extent and quality of the now located deposit are properly placed in the latter part of Stage I, and are represented by increasing capital investment.

Stage II. At the beginning of this stage someone has decided that the discovery represents a mine with profitable prospects. It may be the discoverer, his backers, or an investor who has bought the rights. Once the decision is made, capital investment and the importation

of a labor force is likely to proceed as rapidly as is technically feasible. Not only mine workings such as shafts and tunnels are involved. Rock-crushing, concentrating, and smelting and refining plants are often installed. Except in those ever rare instances in which a new mine is developed in an already settled district, there must also be a substantial investment in an infrastructure not directly related to mining itself. The major elements in this infrastructure are a transportation system, a factor that clearly enhances the mine's productivity, and living quarters and social services for the labor force. The latter may be financed directly by the mine or indirectly through relatively high wages, but in

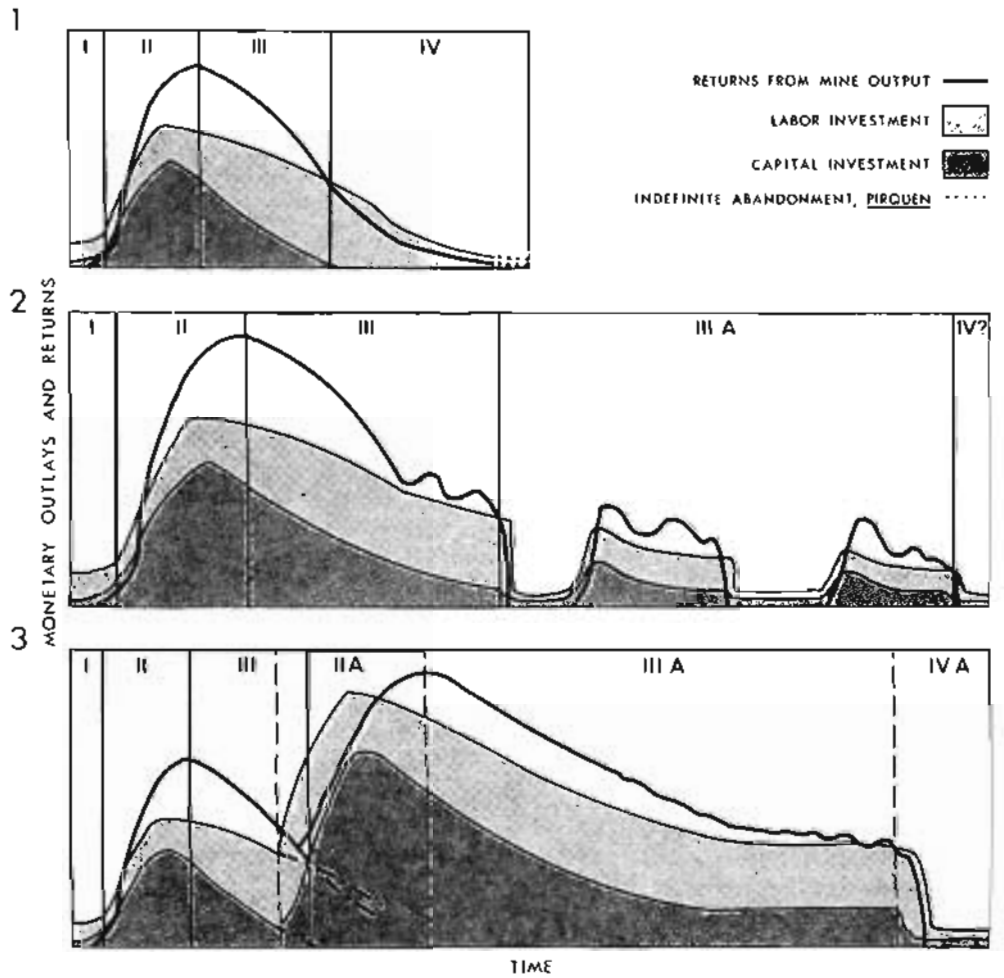

Fig. 1. Stages in Mine Development. I: Prospecting and Exploration. II: Investment and Development. III: Stable Operation. IV: Decline.

FIG. 2. Mine Development Influenced by Prices. (IIIA: Intermittent Operation Governed by Prices).

Fig. 3. Mine Development with Renewed Investment. (IIA: Renewed Investment. IIIA: Secondary Operational. IVA: Cessation of Operation or abandonment. In stages III and IIA the dashed lines represent prospective developments if new investment had not occurred.)

any case they are a proper charge against the mine's output. Commonly this investment comes relatively late, and continues well into Stage III in the mine's history.

With a heavy input of capital and labor, mineral output increases rapidly, and if judgements as to the extent of the deposit are accurate, quickly rises to highly profitable levels.[2] Stage II terminates at the point where the mine reaches its highest level of profitability. Although gross output may remain high, and even rise, factors come into play which cut down on net to the mine's owner or operator.

Stage III. Where a major deposit is being worked this stage of stable operation may endure for some time, but three factors tend to reduce its profitability. Inexorably the mine deepens or extends, increasing the cost of bringing out the mineral, and with only rare interruptions the tenor of the ore tends to decline. The state or society begins to extract a growing toll, either through taxes or in requirements that the mine construct and maintain social service facilities for its labor force and often for the region as a whole. Finally, this is the period when the labor force is in its best position to claim an ever larger share of the return from a mine's output. In antiquity when miners were truly slaves this factor presumably did not operate, nor did it under the *encomienda* system in Spain's New World empire. The inability of this labor to improve its returns permitted long-continued production of the gold from basically poor placers in Chile, the West Indies, and elsewhere in America during the sixteenth and early seventeenth centuries; the Indian's only defense was to die.

Even before laws favoring labor organizations were enacted during the last few decades, the stage of the stable operation of a mine was the one in which the worker could most effectively express his demands to the mine owner or operator. A fixed investment was in a place that could seldom be moved or oriented to any other productive activity, and using it in the mine was still profitable. Originally of diverse origins and sentiments, the workers had come to feel an identity of condition and purpose that could sustain a struggle for economic power. The history of repression on the part of management and destructive violence on the part of labor is well known. It is suggested here that as long as the individual mine continues to be profitable, i.e., remains within Stage III of its development, the labor force will be able to increase its share of the return. Even a policy of repression of workers has the effect of increasing labor costs through the employment of more guards and related personnel. It is when the individual mines approach the end of Stage III that the struggle reaches its bitterest point. Examples are numerous and come from many places. Coal mines in Harlan County or Lota, or the Chilean nitrate fields in the 1920s show similar patterns. And inexorably the mine becomes more costly to work both because of its depletion and physical extension, and the heavier labor charges.

Stage IV. At some point the mine ceases to be profitable, though commonly it does not immediately cease production. Significant new investment, however, does cease. The later operation of a mine may be financed in part by the destruction of works that were necessary for its continuing operation. In underground mines, pillars of ore that protected the tunnels might be extracted along with shoring for use elsewhere underground; thus extensive areas are

[2] Data concerning the profitability of famous mines during their early history are singularly hard to procure. An unusual record from the isolated Caracoles district east of Antofagasta was assembled by Pedro Lucia Cuadra in 1875. In the preceding three years seventeen mines had been opened, but eight of them showed no production or were operating at a loss. Total expenses for the nine better mines amounted to 4,114,000 pesos. Their silver production was valued at about 16,000,000 pesos [4, pp. 399–401].

made inaccessible because of danger of roof collapse. Machinery of all types is simply worn out rather than maintained and replaced. These activities represent the salvaging of a small fraction of fixed investment that otherwise would only be abandoned. Occasionally a heavily financed corporation with other profitable operations will close a mine suddenly without running it down, hoping to reopen it in good condition at some future time when price conditions are more favorable or a technological development reduces costs. Clearly only a major, long-lived corporate enterprise can justify such actions; ghost company towns such as Jerome, Arizona or many abandoned nitrate *oficinas* in Northern Chile have had a long quiet period of slow decay and rather poor future prospects. Such ghost towns are singularly characteristic of desert areas. Elsewhere, flooding and the more rapid decay of fixed investments under humid conditions soon erase them from the landscape.

Reaching Stage IV represents a particularly grim development for the labor force. Normally it occurs at just the point when labor organizations have gained their maximum power and effectiveness, and have thereby made the declining mine unprofitable because of a granted wage increase. Suddenly the inevitable decline in productivity of the mine makes them unable to achieve gains for their members or even to sustain their present incomes. At this point agitation for nationalization and continued operation at a loss, or government subvention such as tax rebates and maintenance at government expense of part of the infrastructure that once was the responsibility of the mine, becomes intense. Because the labor force has political power some of these concessions often are granted, but when this occurs the mine ceases to be a contributor to national wealth. Rather it is an economic burden that improverishes the economy. To a more than comfortable degree the coal mines of Chile, along with those in many other parts of the world, have for some years been in this situation.

Where a good deal of the infrastructure, particularly in the area of housing, is in the private possession of the labor force, that force is vulnerable to pressure to accept lower wages, a singularly unpleasant option which keeps the mine operational for an extended period. Even less attractive is the possible acceptance of deteriorating safety and health provisions as a means of reducing operating costs. The break in the labor investment (Figure 1) well into Stage IV represents these developments.

In Northern Chile, in mines that exploit minerals of such value that they can be transported by primitive means, an institution has developed that permits a nearly exhausted mine to continue to operate sporadically over long periods of time. This is the *pirquén* [5, pp. 118–21, 228], and it was being described and complained about by royal mining inspectors during the eighteenth century; it still exists. A mine no longer profitable to work in an organized fashion could be abandoned and just taken over by one or more *pirquineros,* or it might be leased to them formally for a nominal sum. The *pirquinero* worked on his own account, almost without capital investment, picking over old dumps, taking ore from support pillars, and following tiny veins by hand and pick. A mine given over to *pirquén* soon became dangerous even to enter, though this might not deter a later generation from following the same practice. The *pirquinero's* rewards for his labor are singularly meager. Often in the Norte Chico they must be supplemented by goathearding for a bare survival. His economically miserable situation is sustained by hopes, generally vain, of making a new discovery. Thus the *pirquén* supports, from its extremely marginal returns, some prospecting costs—Stage I perhaps of another mine.

Figure 2 introduces into the model the effects of cyclical price fluctuations on the history of a large mine. It is probably applicable only to mines that command extensive low-grade deposits and which are controlled by powerful corporate entities, either private or national. Such entities must be carrying on important economic activities in addition to operating the mine in question. Finally, for a mine to show such a history, the organization and power of its labor force could never have gained for it a dominant position.

Most critically, the pattern of price changes that might produce such a history is fairly sharply defined. There must be strong cyclical fluctuation on a base of sustained demand and a long-term stable or rising price structure. Such conditions are fulfilled by metals of fundamental industrial importance which are of sufficient value in relation to bulk that they can be shipped all over the world, and thus have their prices determined by an unstable world market. Copper is the classic example, but other non-ferrous metals and the ferro-alloys tend to satisfy these conditions. An interesting development of the last fifty years is that the increasing technical and industrial importance of silver has taken it out of the precious metal class with fairly stable prices, and placed it in the much more volatile industrial material category.

Even fairly violent price changes have little effect on the operation of a mine in Stages I, II, and the early part of III. The richest and most accessible deposits may be and normally are worked at a profit. As ores of lower tenor from deeper shafts that are more expensive to exploit come to be worked, fluctuation in price may make the difference between profit and loss. To the extent that they can control the management of the mine, both the labor force and society through the state are likely to urge continued production and stockpiling though seldom will they accept wage cuts to return to profitable operation. Even a state-managed mine if it is of major dimensions, however, cannot long be operated at a loss or without continuing income without serious damage to the structure of the economy.

Some major corporations, and possibly some socialist states, can make a costly decision on the basis of confidence that despite short-time fluctuations the long-term price trend is stable and rising. The choices are either to abandon the mine completely, work it at lower costs by not maintaining and renewing the capital investment thus making it hard ever to reactivate, or maintain at their expense the capital investment both in the mine workings and the supporting infrastructure. The latter alternative is illustrated in Figure 2. It will be noted in Stage IIIA that while income from the mine ceases completely during the inactive periods, considerable expenses connected with the orderly shutdown of operations and maintenance and protection of works continue. There are also start-up expenses before profitable operation can be renewed.

Because of the unpredictability of price fluctuations the decision described is highly risky. Most disastrous would be a technological innovation or discovery of substitute material that permanently affected the price structure of the product. Synthetic nitrates provide Chile with a painful example. Rarely would any operator invest to keep a mine ready for reactivation for more than a decade if a favorable price structure did not develop. Even that duration would only exist in a developed country with abundant capital and low interest rates. In Chile five years is probably an absolute maximum. On the other hand, the capacity to adjust production to take advantage of the best prices results in great efficiencies in the exploitation of a given mineral deposit toward the end of human welfare. As a comparison of Figures 1 and 2 shows, the total output of the mine is increased and the period of its effective exploitation lengthened. By investing modestly to preserve the extant capital investment, an enormous waste of resources in reactivating the mine is avoided so only a moderate price appre-

ciation is needed to reactivate it. Finally, when the mine is operating it is operating profitably and severe downward pressure on wages is avoided.

The most intractable element in the productive forces that might make it impossible for a mine to sustain itself in Stage IIIA, that of intermittent operation, is the labor force. Laying it off is unpleasant at best and is likely to produce social disturbance. Once that force is laid off and has found other employment, reassembling it may be costly though such costs provoke an upward pressure on wages that may be considered socially desirable. Chilean labor law has for decades endeavored to make layoffs and the intermittent operation of an enterprise difficult if not impossible, perhaps to the considerable detriment of the entire economy. An optimal situation would be found if the mine were located in a settled region with an economy rich and diversified enough to absorb the mine workers without forcing them to emigrate and lose their personal investment in living quarters and community facilities. Then, to reattract them the mine would have to offer perceptible advantages in wages and working conditions. The above statements may seem to say merely that it is nice to be rich for both the individuals and societies. One may still observe that union rules, particularly in respect to seniority, that deter an individual from changing occupations freely introduce a rigidity that is economically detrimental to the entire community.

In the mining region of Chile, notably in the Norte Grande, the economic barrenness of entire regions has long posed a severe physical limitation. Once a mine closed down, be it a producer of nitrates, copper, or precious metals, it was improbable that any other economic activity in the vicinity could be found. In the Norte Chico, however, the limitation has been less severe. The capacity of Illapel to survive as a mining community for centuries, sustaining the residential investment of the mine workers' families after scores of individual mines were worked out and temporarily or permanently abandoned is worthy of intensive investigation.

It must be admitted that a pattern, intermediate between those illustrated in Figures 1 and 2 and a notably less efficient use of all resources than the latter, has been much more common both in Chile and elsewhere. In this case the mine is just abandoned. When price improvement or new technological processes, often ones that permit reworking the old tailings, occur a new enterprise takes up and reactivates the claim. Such developments are singularly costly in capital investment because deterioration of both the investment in infrastructure and the mine workings themselves has intervened. A specially frequent deterrent to reactivation is flooding of shafts and tunnels. Such reactivations may be so degenerate that they are scarcely distinguishable from the *pirquén*, with minimal wages, dangerous working conditions, and other attributes of social distress. In vacant and extremely arid regions such as the Norte Grande, however, deterioration of the capital investment through both natural decay and human scavenging is minimized, and mine abandonment and reactivation are economically less irrational.

While the pattern of exploitation illustrated in Figure 2 may greatly prolong the useful life of a mine and more than double its output the end is still inevitable. Eventually the deposit will be exhausted.

Of the myriad of mines discovered, worked, and depleted only a few ever experience the rejuvenation illustrated in Figure 3. Because the sort of rejuvenation indicated is only possible in large-scale operations, however, many once individually operated mines in a district may have to be combined into a single operation to permit the rejuvenation to take place. Its main feature is capital investment on a greatly increased scale. Since the goal of the investment is to reduce costs per ton of material extracted

and shipped, if the enterprise is to be successful there cannot be a proportionate increase in labor costs. Mechanization to reduce the amount of labor needed to extract, process, or ship the minerals is an invariable feature.

Rejuvenation seldom occurs during the first bonanza period of a mine's operation when rich ores are close to the surface. Rather, it is introduced late in Stage III as returns are falling off and costs are rising. It may even take place in the decadent stage or after abandonment. It will be noted in Figure 3 that the curves for Stages I, II and III are replicas of those in Figure 1. The identification of a huge body of ore is a requisite. It may be of too low a grade to be worked profitably under the initial system or be inaccessible because of depth or flooding without heavy new investment. Multiple holdings along a vein or other deposit serve to deter attempts at rejuvenation. Mining claim laws, whether derived from English or Spanish traditions, have long favored the fragmentation of holdings and operations in any major mineral deposit. Only after such operations have ceased to be significantly profitable is it feasible to obtain control of enough reserves to justify a major investment.

A mine may be rejuvenated by increasing the efficiency of any or several of the activities that come between the mineral in the ground and its delivery to a consumer. These activities may be grouped in three sections. The first involves extraction of the material and its transport from within the mine to the pithead or, in Chilean terms, *cancha*. Concentrating, smelting, or other processing is a second element, one which may occur close to the pithead or at some fairly distant point en route to market, often a seaport. Finally, improving transport facilities to get ore out and supplies in may bring about reductions in costs. In addition to results achieved by constructing roads or railroads, a mine can be rejuvenated by improving port facilities hundreds of miles away. In the case of the last two sets of activities, the investment that rejuvenates a mine or group of mines may be made by other than the mine operator himself. Custom smelters in or near mining districts and privately financed and operated railroads have more than a century's history in Chile, and more recently road construction and public smelters at Las Ventanas and Paipote as well as beneficiation plants at Illapel, Domeyko, and elsewhere have been built with public funds with the express intent of rejuvenating as many as possible of the declining small and middle-sized mines in the several regions.

The introduction of new and advanced technology can but need not be a part of the rejuvenation process; often only the investment needed to apply long-known techniques in isolated areas is involved. In Chile's mining history the area of concentrating and processing ores is the one in which technological developments have been able to exert their strongest impact, but even here progress has not been uniform. Rich ores are often given little or no treatment at the mine and only as their tenor declines will the investment needed to concentrate them and reduce shipping costs be considered. Any new mine, of course, takes advantage of the state of the mining art at the time of its inception, particularly in those activities where the new technique requires only moderate capital outlay. Fire and water to break up hard rock gave way to black powder blasting and then essentially everywhere to dynamite, but *apires* still hauled bags of rich ore up ladders until mines were abandoned because the investment in tunnels through sterile rock and rails could not or did not need to be financed.

A few features of the model shown in Figure 3 may be noted. There is a considerable time gap between the initiation of the investment that rejuvenates a mine and the return to profitable operation. Because of the heavy investment and the lower grade ore treated, even

though total production may greatly exceed that in the original bonanza period, the level of profits is likely to be lower. If the investment was judicious, however, the mine's life will be extended enough to provide full amortization. The operating phase, Stage IIIA, is again one in which labor costs tend to rise, characteristically through union-demanded wage increases. In considerable measure to counteract such costs there is likely to be a continuing capital investment in labor-saving mechanization as long as the mine is profitable. Finally, in the later stages of the mine's operation, because of high fixed costs, the degree of profitability is likely to be strongly affected by even relatively slight price fluctuations.

At some point, however, ore of a tenor that makes operation profitable will be gone. A second or even a third rejuvenation by new investments that make it possible to handle still lower grade ores is possible but infrequent. The end of a rejuvenated, and by definition a heavily capitalized mine, tends to be definite, and the long declining phase, Stage IV in Figure 1, seldom develops. Intermittent operations related to price fluctuations, as illustrated in Figure 2, are somewhat more probable.

THE MINE AND THE MINING DISTRICT

The natural conditions that give rise to mineral concentrations in the earth's crust are likely to affect fairly extensive areas, frequently with special concentrations along large veins or at nodal points, with lower grade ores or thinner veins in the intermediate region. In the first rush after discovery of a mineralized district the entire area is likely to be staked out in claims which often extend into the completely sterile periphery. Many claims never pass Stage I to become mines, but in major mining districts such as Chañarcillo or Andacollo there were more than a hundred mines each.[3] Each of the individual mines of the district would show a history like that illustrated in Figure 1, though progress to the stage of decadence for some might take only three or four years while others might still be operating profitably after thirty. Thus Figure 1, with both the monetary and temporal scales expanded, might represent the history of a district as well as a single mine.

In a large mining district the investment in infrastructure and the benefits derived therefrom could be shared among a number of mines. Elements of importance in this infrastructure are the transportation facilities to outside markets and sources of supply, concentrating or smelting plants, and a settlement offering greater social services and facilities than the camp at the mine to which miners could repair on weekends and in which their families might reside. This fixed investment might prolong the life of individual mines letting them work at a small profit lower grade deposits that would not in themselves pay for the needed infrastructure. In the same way, abandoned mines in the district or places bypassed in the first rush because of relatively poor ores might become workable once the infrastructure was created. In the Norte Chico of Chile still a further level of support was provided by valley oases with urban centers that were central to and served a number of *minerales*. Copiapó, Vallenar, and La Serena-Coquimbo are major examples[4] as Denver would be for the silver mines of the Central Rockies or Sacramento for the northern part of the Mother Lode of California.

THE PURPOSE OF A MINE

It is not proposed that the historical models offered in this paper will be of particular use to a mine operator in planning the exploitation of his own property. The particular characteristics of its deposits will remain his overwhelming concern. The fundamental

[3] Segerstrom comes to the conclusion that almost all the production of the Chañarcillo district came from 15 or 20 mines [6, pp. 1427–61].

[4] See maps in Pedersen [5, p. 83, 181].

universality of mines' histories, however, does have relevance to national policy, particularly for a country such as Chile in which the exploitation of mineral deposits plays such a critical role in the national economy, and where regional disequilibria constitute a chronic problem. Some general notions about the ultimate social purposes served by mining may be reviewed first.

Until the time of Agricola (mid-sixteenth century) there was serious question as to whether it was morally appropriate for men to engage professionally in extracting from the earth minerals that they had not put there and could not replace [1]. The question still holds philosophical interest, but on the practical level modern industrial society has committed itself; a continuing and increasing flow of a wide variety of minerals into the world's industrial centers is absolutely essential for our very survival. The laws and tradition that govern society's relation to mining operations, however, especially in regions that once were part of the Spanish Empire, stem from a less idealistic source. Mines were easy to tax. The king retained title to mineral deposits and claimed a fifth of the gross output of any mine within his realm. The more mining activity that was carried on the greater his revenue was. All classes were allowed to prospect for and claim mines, even on privately owned lands, and the size of any claim was restricted so that as many mines as possible could go into production. A claim could not be held unless it was worked. Should a conflict over water for agricultural or mining use develop, the mine was likely to be favored [2]. Placing an export tax on certain minerals, notably nitrates, in the late nineteenth and early twentieth centuries, the Chilean government sought to succeed to the king's former position in regard to mineral wealth.

Another view is that the wealth a mine yields during its bonanza phase is deserved by either the prospector who discovered it or the entrepreneur who risked his capital to put the mine into production. This premise also tends to bring about maximum development of mineral resources and a supply of minerals at minimal prices to the world's industrial markets. The premise is distinctly English in origin and has been carried over into the United States as well as into the British Dominions.

A more recent viewpoint stands in sharp contrast, especially in regard to its effects on the productive process. It is that the largest possible fraction of the returns from a mining operation should reward the labor force that invariably performs exhausting, often dangerous work under conditions of isolation and social privation. A modern student gives this viewpoint immediate sympathy, perhaps more intense if he is aware of mining history and knows how long mines just used up slave or forced labor, or has read the poignant descriptions of working conditions in coal mines, be they of British mines of the nineteenth century, Baldomero Lillo's stories of the Chilean mines at Lota at the turn of the century, or accounts of the mines at Vorkuta in the 1940s. During the past few decades labor organizations in mining enterprises, exploiting the general sympathy noted above to gain enabling legislation, have made enormous progress in capturing a greater fraction of any successful mine's returns for its miners.

At the same time, the very nature of mines as described above and the technological developments to which they are subject combine to make a strictly labor-oriented division of returns dangerous and destructive. Except in the initial bonanza period, and then only in certain deposits, the individual workman, though skilled and industrious, can produce little from a mineral deposit. It is the capital invested in applying inanimate energy and engineering a plan for mass extraction, concentration, and shipment of the mineral that makes the mine worker's daily output so substantial. Almost by definition the worker does not control his capital. It must come from

capitalist entrepreneurs or from a society that includes many elements other than mine workers. Either investor will want returns on his capital and have alternate places in which to invest it.

Perhaps a more critical feature is shown in the models presented here. Any mine's maximum yield and profitability occurs very early in its cycle of exploitation. Later, costs will rise as the less accessible and commonly lower grade portions of a deposit must be worked. A major new infusion of capital may lower costs and rejuvenate the mine, but the cycle of decline soon reasserts itself. After a few years of operation at a given level of investment in mechanization any mine will have a smaller net return to share with its workers, regardless of the management's willingness to do so. Conversely there is no prospect so abhorrent to the labor force, either as individuals or organized in a union, as that of a continuing decline in real wages.

These considerations seem to lead to an inescapable conclusion that early in a good mine's history it will yield profits that rationally cannot be distributed to the labor force. There is no implication here that wages should not be high; they should be at least enough to induce free labor to move to the mine and live under difficult conditions. But the society will not benefit if wages are fixed at a level that cannot be sustained through the operational life of the mine, or which will substantially shorten that life. It does not seem significant whether the financing and management of the mine come from domestic or foreign private capitalists, or from the national society as a whole (through an agency such as CORFO—the Chilean Corporación de Fomento de la Producción). Advantages and disadvantages can be identified for each source. It is assumed that the society as a whole (at this stage in the world's development, the nation-state in which the mine is physically located) will exercise some direction over how the wealth the mine generates will be distributed. A set of considerations that recognizes the inherent prognosis of any mine's development may be presented.

Capital amortization. There must be provision to return from the mine's profits before the deposit is exhausted the capital that was invested to develop it, plus a reasonable interest that compensates for the risk that the mine might be a failure. At the political extremes this applies equally to a mine financed by foreign capital and to one financed by the government of the country within which it is located. Should this provision be ignored in the former case the foreign capital and management and technical skills will not be available in the future. In the latter case other sectors of the society will be financing mining activity at the cost of their own living standards. Above all it is essential to maintain a body of capital available to activate new mines, rejuvenate old ones by further investment in mechanization and newer, more efficient technology, or to invest in other productive enterprises.

Recapture of Excessive Gains. Several mechanisms have been employed historically to bring to the society as a whole as much as possible of the enormous return that an especially rich mineral deposit may yield in the early phases of its exploitation. Property taxes and export or *ad valorem* taxes on the mineral output fall into one group. They are direct and potentially equitable, but must be applied to mining enterprises with a temporal sensitivity that governments find hard to exhibit. At just the time that a mine proves to be profitable it has its greatest capacity to bear a tax burden. As the mine is depleted or becomes more expensive to operate this capacity declines. Sustaining the tax load, something that governments ever in need of revenue find hard to avoid will force the mine into decline or abandonment before its time, Stage IV in Figure 1. Then intense local unemployment and the premature abandonment of capital investment can only make the society poorer. The disastrous condition

of the Chilean nitrate fields in the 1920s was at least exacerbated by sustaining an export tax on that mineral for too long a period. Should taxes of this sort be retained it is essential that they be applied in a manner which takes account of each mine's position in its own course of development. It is suggested that progressive individual and corporate income taxes may be a more effective means of making each mine's early wealth yield social returns without paralyzing its operation in the later, leaner period.

Regional Infrastructure. As an essential part of its earliest development a mine or the grouped enterprises of a mining district must create or have created for them a set of facilities that can serve not only the mines but the entire region. It happens with great frequency that the exploitation of mineral resources constitutes the first effective settlement of an extensive region. Even when the mine itself is located high in the mountains or in an area barren for other reasons so that the immediate locality is unlikely to support other economic activity, a transportation facility that can handle heavy cargos must be built either to connect it with an existing settlement or with a newly constructed seaport. Thus the intervening terrain will be made more advantageous for settlement. It does not seem unreasonable for the society to request that this transportation facility be routed in such a way as to support regional economic development in other directions, if such routing carries only a modestly greater cost than the cheapest one to serve the mine's immediate needs. Such encouragement of settlement will later redound to the mine's benefit in providing supplies, a labor market, and a reduction in isolation, and thus a more attractive ambience for the mine's labor force. These features will be important in keeping down mining costs during a later period when the richest ores are gone and profit margins are low.

In desert regions a mine may need to provide its own water supply, or its own drainage operations may incidentally create one. Unfortunately, processing the ore may also contaminate part of the limited extant water supply, as it did for example, at Chañaral. In any case, it is in society's interest that an effort be made to integrate the mine's water requirements and provision with present and potential future agriculture and urban developments in the basin, maximizing opportunities for multiple use of the same water, and minimizing damage from contamination either by purification or segregation. The mine is inherently transient, but it may have the option of promoting future development or creating a permanent desert.

In both transportation and water manipulation the mine is most capable of contributing to a regionally supportive infrastructure during its early life, Stage II, that of investment and development, or even more probably Stage IIA in Figure 3 when a massive new investment is being undertaken. At this time the margin between its returns and costs is the widest. Demands that a mine rectify earlier errors in creating its own infrastructure after it has passed well into Stage III may raise its costs insufferably and hasten the end of its operations. Conversely, as mines move toward the end of Stage III and the prospect of the end of profitable operations becomes imminent, both their management and their labor forces are often able to unite to put all the political pressure they can on society at large to create for themselves at public expense an improved infrastructure that would reduce costs and prolong the period of profitable operation.[5] It would be well for public authorities to note carefully the place where the mine to be supported falls in its own cycle of development. Unless

[5] An example of how uninhibited these late demands can be is provided by the discussions and resolutions of the recent seminar on problems of the coal industry in Chile: El Carbón, sus Problemas y Posibles Soluciones, Seminario efectuado los días 26, 27 y 28 de Abril, Santiago, 1967.

there are committed funds for a rejuvenation of the mine itself, even a heavy public investment in the infrastructure may keep the mine operating profitably very few years longer, and the worth of the public investment would be little in an area in the process of abandonment.

Another sector of the infrastructure is the community in which the mine's labor force lives. Typically housing during the period of development is either makeshift shacks in the case of small mines or company barracks in the case of larger, better financed ones. Often an open city of the makeshift sort grows up independently, as close to the mine as it can get, to provide dubious recreation to the mine workers and to be financed indirectly by their salaries. Later in the mine's history, during the period of labor gains, the creation of a real community for the miners and their families merits continuing investment. Chile affords a variety of examples of such communities, and indeed there is some trend toward progress from the grim massed tenements in the company town of Lota Alto. It is suggested that a free town that can serve as a regional center for the area is a better solution if there is any physical prospect for it, even if it means transporting the help to their places of work. Providing credit for housing and higher salaries rather than subsidized low rents appears to be the wiser use of a given part of the total cost of labor. A wise infrastructural investment for both the society and the mining enterprise, however, is in the urban amenities such as theaters, well-equipped schools, and parks that will tend to make the place where the miners live a regional economic and cultural center, thus broadening its economic base. As a negative example one might ask whether anyone in the neighboring province of Arauco ever goes to Lota to shop despite the fact that it is the nearest city and far larger than any within the province. Investment in the residential community, if in part supported by individual decisions, can and should continue as long as the mine retains its labor force. It can also support the rejuvenation of the mine or the development of others within the district, as Illapel seems to have done. And except in the most desolate locales, as in the Norte Grande, may be the basis for economic activities of a permanent nature when the mine comes to its inevitable end.

Maintaining the Mine for a Maximum Useful Life. The minerals extracted from a given deposit serve several functions. They provide raw material for national or world industry, or for consumption, and in the latter case afford foreign exchange to the country in which the deposits are located. Further, the mine affords employment and a market which stimulates the regional economy. These benefits are maximized as the deposit can be most completely utilized and the level of exploitation sustained at a fairly uniform rate over the period of operation. The models presented in this essay show two inescapable limits. Any deposit is finite and ultimately will be mined out, and most of the capital investment will have to be abandoned. The labor force will have to move or find other economic activities. A somewhat less absolute limit arises from the condition that only early in its history of exploitation, or shortly after a cycle of reinvestment, is the mine highly profitable. Later there is a period in which only leaner ores, thinner seams in the case of coal, or deposits less accessible because of depth will remain, and it is barely economic to work the mine. It is neither politically feasible nor morally attractive to sustain operations at the cost of the labor force by reducing wages, but there have been abundant instances when a mine was prematurely abandoned because the labor force at the height of its growing organizational strength gained wage increases that immediately or shortly forced the mine into Stage IV, that of unprofitability.

Wise public policy will encourage in addition to a satisfactory wage level, the heavy investment of capital in features that will improve living conditions (social services such as schools and hospitals) and working conditions early in the mine's profitable history so that this capital charge will serve for the life of the mine and not come as a burden later when the mine is less able to bear it. As the mine nears its end, however, particularly if the state has come to play a major part in its operation, as it did for example in the coal mines of Arauco, there is strong pressure to develop an elaborate infrastructure with public funds. It may be justified as reducing costs and thus prolonging the mine's life, but is likely to be a means of relieving unemployment. The models presented here would indicate that such late construction is a bad investment and that the money might better be spent in relocating the population or developing other industries for their employment. After a mine enters Stage IV in its history, its continued operation can only be sustained by a continuing waste of funds or by cutting rewards to the labor force below acceptable standards. Only massive investment in the mine itself, new technology, or a substantial change in price structure on the world market, such as silver has experienced in the past two years, can revive a mine when it has reached this point.

The Mine as a Market. A mine consumes goods and services as well as producing a product. Its first impact is specially focused on the labor market. Rarely is a new mine developed in a region sufficiently densely settled to supply its labor force locally, and recruiting labor has a national and often an international impact. A consistently positive effect is that of providing work for miners in near or distant mines that have reached the stage of decline, a group welcomed for its skill but sometimes shunned because of its affinity for strong labor organizations. In nineteenth century Chile there were continuing complaints that withdrawal of labor for the mines was impeding the agricultural development of central Chile. This paper will not attempt to assess the question of whether the mining industry proved beneficial in improving the status of agricultural labor, or unfortunately provided a minimally effective safety value that deferred too long any effective steps toward agrarian reform and more efficient and productive use of agricultural labor. At the other end of its cycle the mine turns this force back into the labor market, often in a region with few other economic resources, as in the case of the Norte Chico of Chile, or even with no other resources as in much of the Norte Grande. Ideally all would leave to work in other mines. Unfortunately many do not, and in intolerable poverty in the Norte Chico ex-miners scratch a living from a combination of *pirquén*, the scavenging and often destroying of abandoned mines, and overgrazing the landscape with their flocks of goats.

Mines have traditionally served as a basis for national development, attracting foreign capital that may develop a generally useful infrastructure in addition to developing the mine, by providing foreign exchange, and attracting immigrants. Sometimes, as in Chile's case, they temporarily support most government activities through export taxes, provoking serious malaise when they reach a stage in which they cannot bear this burden.

The goods a mine consumes can be put in four categories: 1) supplies for the labor force, 2) capital investment goods from pit props to heavy machinery, 3) combustibles for processing the mineral and transporting it, 4) and water. Clearly, obtaining these goods as close as possible to the mine will be advantageous, but, as needed, a profitable mine can seek its supplies successively in national and international markets. In supporting its labor force a mine constitutes a powerful stimulus to local agriculture, particularly in regard to perishable, hard-to-ship commodities. In dry areas this market may finance

irrigation works of permanent value and productivity. Certainly the Elqui and Huasco valleys would not have reached their present level of agricultural development without this stimulus. In the past, but probably not again, the need for transport also stimulated agriculture to supply mules and fodder for them, leaving a sensible gap in the agricultural economies of all the valleys of the Norte Chico when technological change eliminated most of the need for draft animals. The market for capital goods will at least be national and can serve as support for the broader industrialization of a country. A singularly delicate timing of legal pressures is required if using the mining market as a basis for industrialization is to be healthy. In its early, most profitable phase a mine can pay heavily for the capital goods it needs, either through import duties or by buying from new and still inefficient industries that a developing country might be trying to establish. At a later stage, however, being forced to do so will raise costs and hasten the shutdown of the mine. A protected, assured market in a profitable mining industry may allow suppliers, protected by tariff barriers, to avoid increasing their efficiency and seeking broader markets. Forcing mines to serve as a basis for developing the national industries is clearly a legitimate means of recapturing for society some of the wealth a mine may produce during its early stages. But this laudable social effort must be sharply limited temporally or there will be a risk of forcing a premature end to mining activity and leaving the country with inefficient industries that have no other market.

In the areas of combustibles and water, especially in arid or semiarid regions, the market provided by the mine may have effects that are beneficial for the regional and national economy or are disastrous to the region's long-term welfare. The stripping of the Norte Chico of its woody vegetation to sustain widely scattered smelters in the early and middle nineteenth century is still perceptible in the landscape. Fragile ecologic communities were destroyed that will not regenerate for many centuries, if ever. It is fortunate that remnants of an extraordinary, fog-sustained forest survived at Fray Jorge and Tongoy, if only for scientific study. Stripped hillsides have increased soil erosion and made stream flow more erratic and unmanageable. Great forests of the hardwood *guayacán* were burnt in the great smelter that bore the same name and elsewhere, and now little is left to supply a potential craft industry. Across the Bolivian border the process continues, using the slow-growing *llareta* in industrial quantities to process sulfur from the volcanos of the Altiplano.

The Chilean coal industry and, to some degree as secondary effects the glass, firebrick, and steel industries, have as a major part of their origins the market offered by mining smelters and the railroads that serve the mines. It is historically unfortunate that Chilean coal reached the Norte Chico so late, after many mining districts were so depleted that they could not afford to create transport facilities to bring in coal and continued instead to destroy the natural vegetation until both it and the ore that could be worked under those conditions were gone. Again the time in a mine's history in which the more desirable provisioning of its market was afforded proved to be critical.

Major mines must develop a water supply, and in their early, profitable phases they can bear heavy costs and construct long pipelines to do so. They can also take more accesible water that is being or might be used for irrigated agriculture and degrade or pollute it so that it is useless or even harmful to the land over which it flows. Public policy concerning a mine's access to limited water supplies will do well to note both that the mine's life is finite though the damage it can do to the landscape may be permanent, and that early, and only early, in its history a mine has the economic capacity to develop new water supplies or to take costly engineering steps to minimize the damage done by its pollution.[6]

[6] It is believed that the models presented in this paper are basically valid for all but one set of the minerals, metallic or non-metallic, of commerce. The exception is petroleum and natural gas. In their case the higher costs of exploration and initial development are distinctly disproportionate to the minimal cost of exploitation, though the end of the field's life is similarly determinate. A distinctive and simpler model for the history of an oil field that suggests a specific public policy in relation to its exploitation is called for, but that subject is not treated here.

LITERATURE CITED

1. Agricola, G. *Georgius Agricola: De Re Metallica.* Translated by H. C. and L. H. Hoover. London, 1912.
2. Bourgeois, J. R. *Derecho de Minería: Apuntes de Clases.* Santiago, 1932.
3. Fryer, D. W. *World Economic Development.* New York: McGraw-Hill, 1965.
4. Vicuña Mackenna, B. *El Libro de Plata.* Santiago, 1882.
5. Pedersen, L. R. *The Mining Industry of the Norte Chico, Chile.* Evanston: Northwestern University Studies in Geography, No. 11, 1966.
6. Segerstrom, K. "Regional Geology of the Chanarcillo Silver Mining District and Adjacent Areas, Chile," *Economic Geology,* 57 (1962), pp. 1247–61.
7. Zimmermann, E. W. *World Resources and Industries.* New York: Harper, 1951.