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SUMMARY

Approximately 556 000 tonnes of tin-in-concentrates were produced in Australia in the period 1872 - 1973, more than 60 percent of which was production before World War I. Peak production of 12 000 tonnes in 1881 was not achieved again until 1972.

Tin occurs in Australia chiefly as the oxide, cassiterite. Although stannite, a complex sulphide of copper, tin, and iron, occurs along with cassiterite, copper pyrites, blende or galena in the Zechan district of Tasmania, stannite has never been an important commercial source of tin in Australia.

The main commercial tin deposits in Australia are

(a) large alluvial deposits worked by floating dredges and dry-mining methods using scraper loaders;

(b) small alluvial deposits worked by monitors, and by front-end loaders in dryer areas where high-grade pockets are available;

(c) quartz vein lode deposits worked by expensive, labour-intensive underground mining methods; and

(d) disseminated tin deposits worked by conventional open-pit methods or underground where there is a tendency towards trackless mining via declines in place of conventional shaft and level development.

Aggregated statistics indicate that published domestic reserves of tin have increased from 84 000 tonnes in 1965 to 326 000 tonnes in 1973, rather because of extensions of known deposits than because of discoveries in new fields. Estimates of the tin content of many lodes and alluvial deposits in Australia are probably conservative. Improved assaying techniques employing nuclear methods, and improved recovery of fine tin from tailing dumps and complex and refractory ores by the use of flotation and gravity methods, would substantially expand known domestic reserves of recoverable tin over without the discovery of new deposits.

INTRODUCTION

In recent years the problems of conservation have attracted considerable interest and attention has focused on the relationships between human societies and the environments that sustain them. It is immediately obvious from the statistics that the demands of the more developed countries on world resources are growing very rapidly and concern has been expressed that if growth continues reserves of many commodities and particularly minerals will be exhausted in a relatively short space of time. However, such views are over-simplistic; it is very desirable that the optimum utilization of the world's resources should be carefully considered, but it is a mistake to underestimate the effectiveness of the complex controls and feed-backs that have, up to now, kept human societies in equilibrium with their environment.

In order to establish some of the facts about Australia's resource position the Australian Bureau of Mineral Resources is undertaking an assessment of the resources of a number of metals and minerals (Noakes, 1972), of which the tin project reported on here is an example. At first sight such an inventory seems a very simple matter of collecting data on ore reserves published or released by the mining companies and adding them to establish total reserves. Several studies have, in fact, proceeded in this way and a number of paradoxical conclusions have directly followed. For example, Forrester (1971) has taken natural resources as a system level and the only rate flow is the outgoing usage rate. No positive loop is provided through which capital might be applied to exploration for the discovery of additional reserves. At the present rate of resource usage he assumed that the world's presently existing natural resources would last for 250 years. A model must radically simplify the relationships that it represents, but it cannot neglect an essential characteristic of an important sector. It is inadequate to regard the level of natural resources as a variable that can only decline with time. This procedure ignores a number of factors that bear on the environment in which mining companies carry out their operations and sell their product. These are summarized below:

(a) Searching for new deposits and proving ore reserves is an expensive and time-consuming activity. The money spent cannot be recovered until the ore is mined and sold and in the meantime is attracting actual or imputed interest. All industrial enterprises try to keep their inventories of raw materials to a minimum compatible with their production plans. It follows that established reserve figures are systematically lower than total resources; moreover, published reserve figures are normally much less than the reserves which mining organizations have established.

(b) The concept of a reserve has an economic basis, since to call mineralized rock 'reserves' implies that it will be possible to mine the material at a profit Profits in turn depend on the difference between revenue and costs, both of which are affected by the prices ruling in the remainder of the economy. Mineralized rock can be converted into ore reserves without any physical change whatsoever by remote events such as a new invention, cheaper transportation, or new demand, which are themselves reflected in the prices of a mine's inputs and products.

(c) The material classified as reserves forms a part of a continuum of mineralized rock that stretches from high grade ore through marginal and submarginal material to rock which contains only a few parts per million of metal above the background mineralization. In the case of base metals such as tin the greatest tonnage of metal is contained in rocks at the lower end of the spectrum. This fact could be described statistically by saying that the distribution of the values is skewed to the right. The effect of a rise in the price of metal after removing any inflationary element is to bring lower grade categories of rock into the class of reserves. Though we are frequently reminded that the Earth is finite it is also very large and the ultimate resources of metals are limited not so much by their scarcity as by the capital and energy necessary to mine and process the minerals. A limit may also be set by the amount of pollution generated by mining and processing activities. Generally speaking the power required to produce a unit of metal rises as the grade of ore falls.

The problem of assessing ore reserves from a national rather than a company point of view is not new, and the classification recommended for this purpose by Blondel & Lasky (1956) in their report to the Society of Economic Geologists has been adopted for this project. So far as possible the various classifications used by the mining companies have been translated into Blondel & Lasky's categories.

The quality of the data provided by mining companies has varied very greatly. The information provided by the major established mining companies and based on systematic exploration and development has been accepted and classified as either reserves or marginal resources. No attempt has been made to recalculate the ore reserves from the original drilling records. On the other hand, some of the smaller mining and exploration companies have little firm information about their reserve position and their records are incomplete or non-existent. Where it is possible to arrive at a rough figure the material has been classified as inferred reserves or marginal/sub-marginal resources. In such cases a subjective judgement of the credibility of the data in the light of the geological environment has been made. Situations also exist in which ambitious exploration programs have been undertaken and the size and grade are known with some precision but the deposit cannot be worked under prevailing market conditions. This type of material has been regarded as a marginal resource.

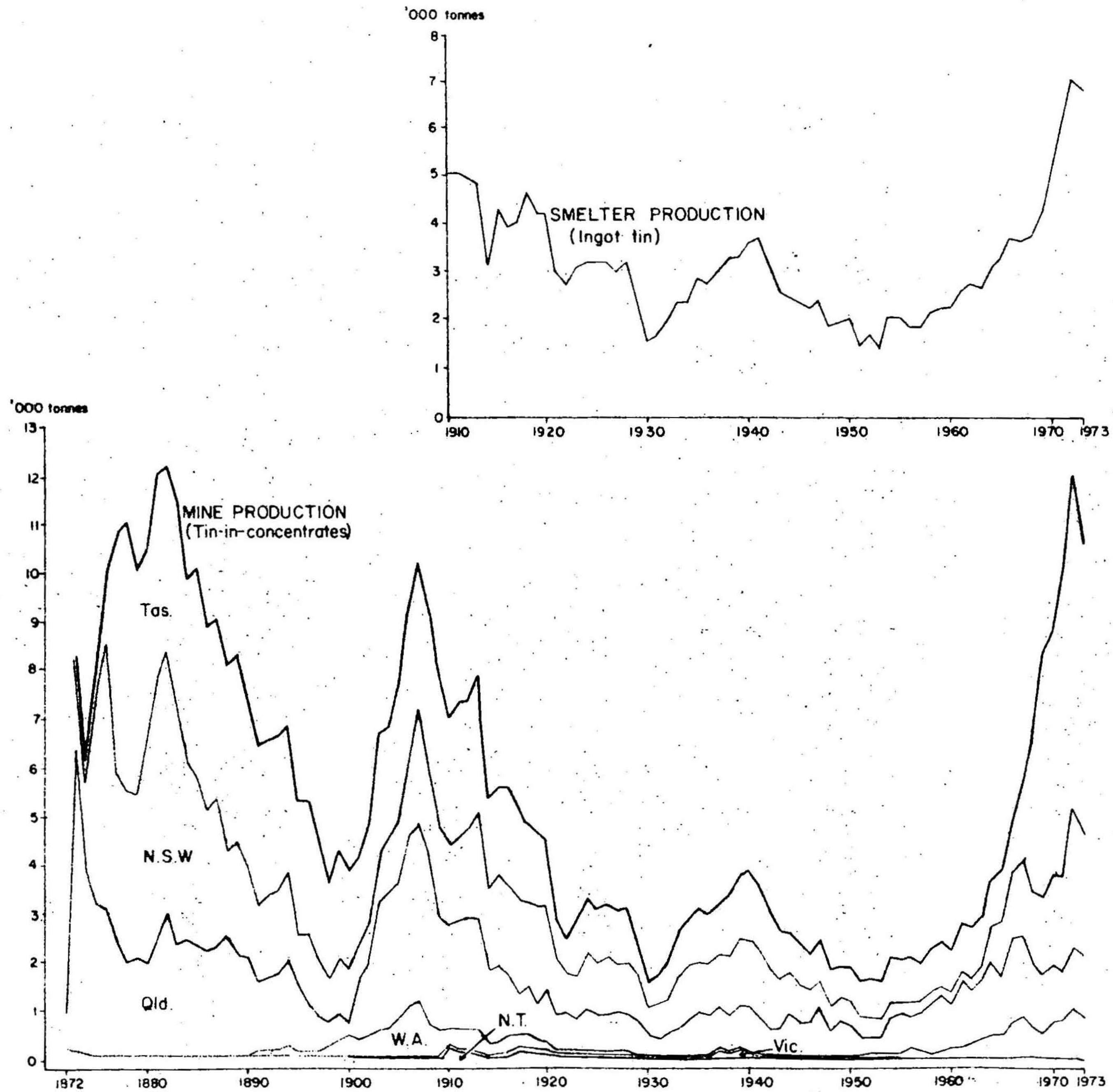

Fig. I. AUSTRALIAN PRODUCTION OF TIN, 1872-1973

To accompany Record 1974/74

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These categories do not exhaust the possibilities. It is certain that further reserves have yet to be discovered and that large resources exist which have not been evaluated because the grade is too low to warrant the expenditure on exploration. This category would include the griesen tin deposits and the low-grade alluvial material in northeast Tasmania. In such cases it may be possible to estimate the order of magnitude of a resource by statistical methods which depend on assumptions about the distribution function of the values. Phillips (1973) has suggested a statistical procedure for the estimation of mineral resources and derived a relationship between resources and grade in a tin province. Similar statistical methods might be applicable to other metals and minerals.

Since some of the data were collected on a confidential basis the results have had to be published in an aggregated form by State and type of deposit. It will be noted that tin resources exist in all the States except South Australia, where the only known deposit is below economic size.

Historical Background to Tin Mining in Australia.

Australia is a tin producer of long standing, production dating back to the early 1870s (Figure 1). Between 1872 and 1973 approximately 556 100 tonnes of tin-in-concentrates was produced, more than 60 percent of it before the First World War. Although records of production from several States were incomplete before 1900 it is believed that peak output was achieved in 1881, with the production of more than 12 000 tonnes of tin-in-concentrates. In the years 1873-83, Australia was the world's leading producer of tin, except for two years, averaging about 11 700 tonnes per annum or approximately one-quarter of the world total.

Australia's pre-eminence as a tin producer in this period was mainly due to Mount Bischoff in Tasmania, which, having attained an output of more than 2 000 tonnes of concentrates (approximately 67% Sn) by the late 1870s, maintained this level until 1898, with a maximum of 2 790 tonnes in 1885. However, production from smaller mines in Queensland and New South Wales was markedly sensitive to price movements during the period and in fact the level of production in these two States almost paralleled the variations in the London price, with a general downward trend to a nadir in 1898-1900. Thereafter, improved prices caused a revival, but from 1907 onwards domestic output again declined, this time as much because of the exhaustion of higher-grade reserves as because of another general fall in world prices.

By 1930, domestic production of tin-in-concentrates had fallen to 1500 tonnes. The downward trend was halted with the advent of the depression; labour thrown out of employment was attracted to tin gouging and lifted production, and by 1939 domestic output of tin-in-concentrates had recovered to a level of more than 3700 tonnes per annum.

Production was affected adversely during the Second World War by a shortage of materials and manpower, and after the war by poor prices and the further exhaustion of better-grade ground. By 1953 domestic production had receded to 1580 tonnes.

During the 1960s Australian-based mining companies and overseas interests, aided by government instrumentalities, stepped up prospecting and development programs, and such was the intensity and success of this activity that by the early 1970s domestic tin production had been restored to the record levels of the 1880s.

Two points should be noted in connexion with tin mining activities in Australia during the last ten years. Firstly, although admirable results have been achieved in expanding reserves and levels of output, the increases represent extensions of known or hitherto depleted deposits rather than discoveries in fresh fields. Between 1962 and 1972, the proportion of lode tin in total domestic output more than doubled to approximately 70 percent, mainly because of the revival and extension of operations on the long - known

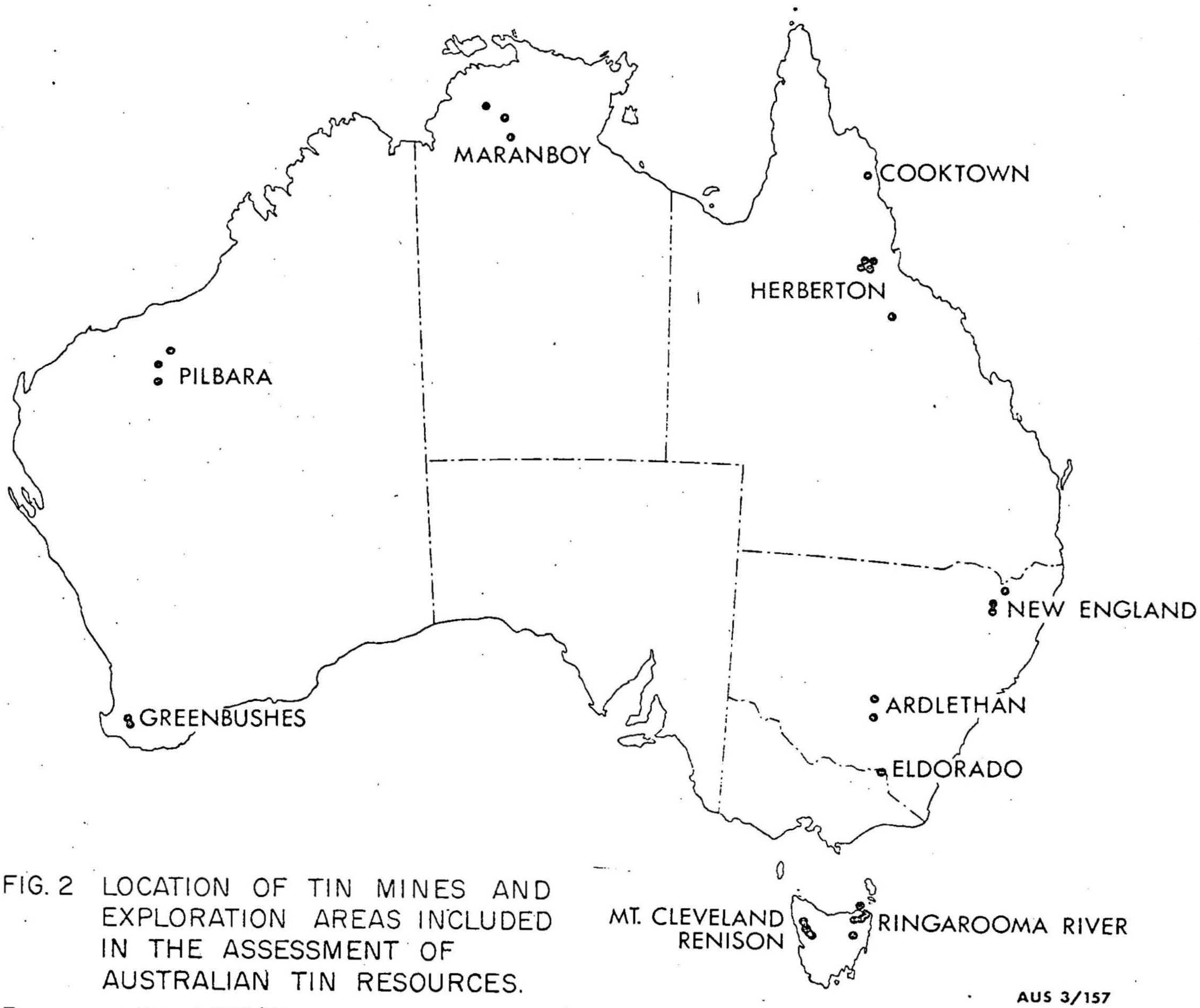

FIG. 2 LOCATION OF TIN MINES AND EXPLORATION AREAS INCLUDED IN THE ASSESSMENT OF AUSTRALIAN TIN RESOURCES.

To accompany Record 1974/74

sulphide deposits of northwestern Tasmania. Secondly, although improved tin prices have stimulated long-term investment in tin-mining, this by no means fully explains the resurgence of the tin mining industry in Australia. Advances in prospecting, mining, and metallurgical practices have been responsible in their turn for bringing to the point of economic exploitation deposits of tin previously regarded as marginal in grade. Delineation of reserves has been facilitated by improved geophysical and geochemical techniques, combined with the use of more advanced drilling equipment. Development of new earth-moving equipment and water supply schemes has helped to contain production costs within reasonable limits and improvements in metallurgical and ore-dressing techniques have improved the recovery of tin concentrates of a saleable grade.

Occurrence of tin minerals

Tin is chiefly found in Australia in the form of the oxide, cassiterite or tinstone, the main source of the metal; tin also occurs as stannite, a complex sulphide of copper, tin, and iron.

Cassiterite is obtained commercially from both lode and alluvial deposits. In the former it may be associated with copper and iron sulphides (e.g. Mount Cleveland) or wolfram (e.g. Aberfoyle). In alluvial deposits it is commonly associated with ilmenite or titaniferous iron ore, monazite, zircon topaz, and tourmaline (e.g. Mount Garnet). The proportion of tin in alluvial deposits is usually expressed in ounces of 'seventy percent tin' per cubic yard, that is cassiterite containing about 70 percent of the metal. The alluvial material is concentrated to as near 70 percent of metallic tin as is practicable by jigs and shaking tables; when the tin is associated with ilmenite, wolfram, or other magnetic minerals, electromagnetic separators are employed. Antimony and tantalum can be removed by electrostatic methods. Sulphides of copper and iron associated with cassiterite are removed first by flotation. Several companies have recently experimented with the direct flotation of cassiterite in an attempt to recover finely divided material down to 5 microns in diameter.

The primary mode of occurrence of cassiterite is in pneumatolytic veins associated with granitic rocks such as the Elizabeth Creek Granite near Irvinebank, Qld, and the Ben Lomond granite at Rossarden, Tas. The chief veinstone is quartz, associated with such boron and fluorine-bearing minerals as fluorspar, topaz, tourmaline, axinite, and apatite. The alluvial deposits of Mount Garnet, northeast Tasmania, New England, and Greenbushes result from the degradation of such primary tin veins. In addition to the lode and alluvial tin deposits, which are of the greater economic importance, cassiterite occurs as an original constituent of granite, as on the Blue Tier tinfield, where a process of differential crystallization and segregation appears to have taken place. In recent years two important underground mines in Tasmania (Mount Cleveland and Renison) have developed contact metamorphic deposits in dolomite beds adjacent to granite contact. Under these conditions the cassiterite occurs disseminated in small grains within massive iron and copper sulphides.

Stannite occurs associated with cassiterite, copper pyrites, blende, or galena in the Zeehan district. The deposits occupy irregular fissures in the country rock and the mineralization is associated with a granite instrusive. The ore types are arranged in zones with stanniferous ores closest to the granite and lead farthest away. Stannite has never been an important commercial source of tin in Australia.

Mining of tin minerals

Tin is found in Australia in several different types of deposit, which call for a veriety of different mining methods. An interesting point that emerges from this study is the extent to which civil engineering techniques have encroached on traditional mining methods. This is connected with the increasing size and sophistication of self-propelled earth- and rock-moving equipment. The same machinery can be used for constructing or mining and it is common to find rock breaking and haulage in the hands of a contractor with no previous mining experience. Underground machinery is also becoming more like its surface counterparts, the main differences being in the greater manoeuverability, lower profile, and cleaner exhaust of the underground version.

(i) Large Alluvial Deposits

Large alluvial deposits have been traditionally mined by floating dredges; two still operate in Australia. They require a good supply of water and are most efficient on unconsolidated alluvium lying on smooth bedrock. They suffer from the disadvantage that selective mining is difficult and high-grade pockets in the bedrock cannot be recovered. The small area of a dredge imposes a limit on the sophistication of the tin-saving plant and therefore the recovery may not be optimal, particularly of the fine sizes. There is some evidence of a trend towards dry-mining methods using scraper loaders which can carry the wash to an efficient land-based separation plant. Bucket-wheel excavators are also being considered for this application.

(ii) Small Alluvial Deposits

Where adequate water is available monitors are used to loosen the wash, which is then conveyed to jigs by gravel pumps. The use of nickel alloy liners for these pumps has greatly reduced maintenance costs. In the dryer areas high-grade pockets are worked by front-end loaders and the was is transported by trucks. The Ledger cone is falling out of favour and jigs are being used despite their higher water consumption. In compensation more attention is being paid to water storage and recycling.

(iii) Quartz Vein Lode Deposits

Though the lode deposits is one of the traditional sources of tin its importance is declining in Australia. The narrow irregular veins require expensive labour-intensive mining methods. Because mineralization is erratic it is difficult to establish the grade of reserves with confidence and it is therefore impossible to satisfy financial institutions that capital investment is justified. In compensation a high recovery of tin can be achieved in a relatively simple mill.

(iv) Disseminated Tin Deposits

Lode tin occurs in mineralized granitic breccias and as replacement deposits associated with sulphides. Deposits close to the surface are mined by conventional open-pit methods. Underground there has been a tendency towards trackless mining via declines rather than conventional shaft and level development. Rubber-tyred diesel equipment is used to apply such methods as mechanized sub-level overhead stoping (MOSB), which are very capital-intensive and are applicable only to large consistent orebodies with strong walls and back. Diesel equipment requires good ventilation to remove exhaust fumes and the excavation of ventilation shafts by raise borers has been introduced with some success. Low unit costs can be obtained by these methods but maintenance costs of the expensive and complex equipment can be high.

Recovery and Assay of tin minerals

Estimates of the tin content of many tin orebodies and alluvial deposits in Australia are probably conservative. In day-to-day mine management operators are mainly interested in the amount of recoverable tin that the ore contains. The assay methods are therefore attempts to estimate this quantity rather than the absolute weight of metallic tin in the sample. In a wider context this procedure is unsatisfactory because operators tend to lose sight of the tin lost to tailings and imagine that their rates of recovery are better than they really are. There are several reasons for this state of affairs. Cassiterite is a very brittle mineral and tends to break up quickly once it has been liberated from the host rocks by erosion. Fine particles of cassiterite are impossible to recover in the traditional jigs and tables that are usually found on dredges, partly because the available space on a dredge severely limits the type and sophistication of the equipment that can be used. With these facts in mind operators approach the evaluation of an alluvial prospect with little regard for the refinements of assaying and sampling techniques. Samples are taken by costeaning or drilling and a heavy mineral concentrate is made, in the field, by panning a fixed volume of alluvium. In the assay office the magnetic minerals may be removed with a magnet and the residue is then weighed to give an estimate of the grade. All the tin less than (say) 100 mesh is lost in the panning operations and all the minerals in the heavy mineral concentrate are not cassiterite The assumption usually made is that this concentrate contains 70 percent metallic tin as compared with the theoretical value of 78.8 percent metallic tin in tin dioxide. Some of the larger mines use heavy liquids and 'zincing' of the cassiterite grains to obtain a better estimate.

It would be desirable to calibrate the field procedures by more accurate laboratory methods. Unfortunately, tin estimates by volumetric and fire assay methods are slow, expensive, and unreliable. The introduction of nuclear methods for assaying tin must therefore be regarded as an important innovation. These methods are based on the behaviour of tin atoms when exposed to radiation. The sample is exposed to radiation from an X-ray tube or a neutron source (e.g. radioactive cobalt) which is absorbed and re-emitted by the tin atoms, at a characteristic frequency. The secondary radiation is measured with a photo-multiplier tube to give a measure of the tin content. Filters can be used to suppress radiation from minerals other than tin. The apparatus is calibrated against similar samples of known tin content. With better data about the total tin content of alluvial deposits it may be hoped that operators will set themselves higher standards of recovery.

Some analogous problems occur in the underground mining of tin. Most tin mines have adequate methods for the complete assay of tin ores and therefore the recovery rates give a more realistic estimate of the loss of tin in tailings. Recovery rates are particularly low in those mines which are treating ores in which cassiterite is disseminated in fine grains in a pyrite/chalcopyrite matrix. The process requires that the sulphides should first be removed by flotation and then a cassiterite concentrate made by gravity methods. Liberation of the cassiterite requires fine grinding, which decreases the efficiency of both the flotation and gravity stages. Interest has recently been aroused by techniques of recovering fine tin by flotation that have been developed in Japan. These methods involve the handling of minerals down to a few microns in diameter. Conditions are more exacting than in traditional milling, and specially designed flotation cells, high speed centrifuges, and flash driers have been introduced. By the end of 1973 it appeared that most of the technical problems had been overcome. The fact that smelters have been reluctant to accept consignments of fine tin or mixed tin-copper concentrates presents an additional obstacle.

The figures presented in this paper are in terms of recoverable tin metal. In other words the raw ore reserves have been decreased by a factor depending on the type of orebody and expected recovery rate. From the foregoing discussion it will be apparent that an improvement in the technology of tin recovery would have an immediate effect on the resources of tin. All mining operations take place within an economic framework and no operator can afford to spend more on producing concentrate than it will realize at market prices. On the other hand, high tailings losses represent an inefficient use of a national asset. A technological advance in this area would make a genuine contribution to the conservation of Australian tin resources.

Australian Tin Resources

The quantitative results of the project are summarized in the table in Appendix A. In accordance with the usual procedure in these cases the figures are presented in a highly aggregated form to preserve the confidential nature of the information. The resources are divided into five categories as recommended by Blondel & Lasky. It is important to exphasize that the primary difference between measured, indicated, and inferred reserves is that of certainty about the grade and tonnage. There is an implicit assumption that all three categories of reserves could be mined at a profit. On the other hand the main distinction between reserves, marginal resources, and submarginal resources is one of grade. We are, in fact, dealing with a two-dimensional table in which some of the cells are empty. This is because no exploration company could justify the expense of proving marginal or submarginal material (Zwartendyk, 1972).

One of the objectives of this project was to collect data on tin mining costs; however, the subject is too complex to survey in this context. The mines differ very widely in location, type of deposit, metallurgy of ore, and mining method. For our purpose it was necessary to arrive at a simple rule of thumb to divide tin reserves from resources. Bearing in mind that ore reserves are defined as mineralized rock that can be worked at a profit we chose the cut-off grade as the criterion. Cut-off grade varies with costs and the following figures were used as a guide:

	Type of deposit		Cut-off grade
Lode:	(i)	narrow veins	.7% Sn
	(ii)	wide orebody	.5% Sn
	(iii)	open-cut	.2% Sn
Alluvial:	(i)	Scraper-loaders (excluding North-west)	8 oz SnO_2/yd^3 (297g SnO_2/m^3)
	(ii)	dredges and monitors	4 oz $SnO_2 yd^3$ (148g SnO_2/m^3)

The grades represent the break-even point; to justify mining, the average grade of the reserves would have to exceed these figures to allow for depreciation and a profit margin.

It is interesting to compare the results shown in Appendix A with the figures published in 1965 by the International Tin Council, which are given in Appendix B. From these it is apparent that published reserves have increased from 84 000 tonnes in 1965 to 326 000 tonnes of tin in 1973. This four-fold increase is in part the results of more rigorous compilation of reserves previously known and in part reflects an increase in exploration activity by the mining companies with higher rates of production and a change in the status of Australia from an importer to an exporter of tin. The assessment also indicates that there are 65 000 tonnes of tin in the categories marginal and sub-marginal resources which have not previously been surveyed.

These figures suggest that any substained price increase for tin would create considerable new reserves. Since such an increase would possibly tend to cause a decline in tin consumption we would expect the life of these reserves to be extended. This type of behaviour can be observed wherever finite resources are produced and consumed and is one of the means whereby supply and demand are brought into equilibrium with one another. We can expect that this mechanism will continue to allocate supplies of tin metal to those areas where it has the greatest value. It seems unlikely that the usage pattern of tin will remain any more constant in the future than it has in the past. On average there are only 4g / tonne of tin in the Earth's crust, rising to a maximum of 44g / tonne in the tin granites. In the long run we may have to abandon the use of tin as a tonnage commodity in favour of metals like aluminium, iron, calcium, and magnesium which are major constituents of the rock-forming minerals. Tin will then be devoted to those uses in which its unique physical and chemical properties have no substitutes.

Conclusions

Total tin production in Australia is currently running at a level of about 12 000 tonnes per annum and domestic consumption is about 4100 tonnes per annum. It follows that if production continues at current rates and no further reserves are proved the reserves will be exhausted in 32 years. If all these reserves were diverted to domestic consumption they would last for 80 years.

If we make the alternative assumption that Australian production will grow at the same rate as world consumption (i.e. 1.5 percent per annum) it appears that domestic reserves would come to an end in about 27 years, assuming no new discoveries.

Noakes (1972) has suggested that an apparent life expectancy of presently known reserves of about 30 years could be regarded as the threshold of concern in the field of mineral conservation and the point at which at least a critical review of the situation is desirable.

The Australian tin industry would appear to be in such a situation, even though there may not be a call for immediate action. However, it does not seem too early to suggest appropriate lines of research and development, which might be summarized as follows:

(i) Improvement of tin recovery rates from alluvial deposits and sulphide ores;

(ii) Analysis of tin samples by nuclear methods;

(iii) Recovery of tin from tailings dumps and complex ores;

(iv) Geochemical and geophysical survey methods for tin;

(v) Offshore mining methods;

(vi) Recycling tin from tinplate.

With progress along these lines to add to our theoretical knowledge and improve our techniques of recovery, discovery and re-cycling there seems little doubt that we can secure adequate supplies of tin for the forseable future.

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APPENDIX A

Australian Tin Resources - 1973

In terms of tonnes of recoverable tin metal

State	Type	Measured	Reserves Indicated	Inferred	Resources Marginal	Resources Submarginal
New South Wales	Lode	3192	3950	7214		
	Alluvial	794	1549	39	366	
Northern Territory	Lode		2613	2195	2378	
	Alluvial	156		700		
Queensland	Lode	6701	1301		1016	
	Alluvial	3538	2421	512	10316	12701
Tasmania	Lode	92763	29994	159574	15709	
	Alluvial	821	759	535	3841	12485
Victoria	Lode				741	
	Alluvial			324	707	
Western Australia	Lode					
	Alluvial	395	2198	1611	4478	
Total	Lode	102657	37858	168982	19843	
	Alluvial	5704	6927	3722	19707	25186
GRAND TOTAL		108361	44785	172704	39551	25186

APPENDIX B

Estimated Total Reserves of Tin-in-Concentrates, (tonnes) 1965

(After Robinson (1965) Table X)

	1960	1965 at £700*	1965 at £900*	1965 at £1100*	1970 at £700*	1970 at £900*	1970 at £1100*
Measured	6000						
Indicated	22000						
Inferred	19000						
TOTAL	47000	3000	69000	84000	2000	68000	82000

* hypothetical cash prices for tin on the London Metal Exchange in £stg/long ton and the assumption that there would be no general world inflation or deflation.