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Availability of Bauxite Reserves

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Based upon a large database, this paper analyzes the record of bauxite mine production, exploration success, and resource depletion and evaluates the availability of bauxite reserves in the near future. The record clearly shows that for the past 50 years world bauxite production rose by an annual increase of over 5% while per capita consumption rose during the same period by about 4%. Time trends of the world bauxite reserve life index (RLI); that is, known world reserves of a given year divided by world production of the same year, are episodic and seem to follow bauxite price cycles. The present-day RLI indicates adequate bauxite supply for about 180 years and is the same as it was in 1950. However, if an annual growth rate of 5% is considered, the currently known reserves will be exhausted within the next 20 years and the reserve base will be adequate for not more than 25 years. This scenario is based, of course, on the unrealistic assumption that future exploration efforts fail to discover additional reserves. Evaluation of the quality, in terms of bauxite signatures, and quantity of presently known bauxite prospects that may be mined in future suggests that there is sufficient potential for adequate bauxite supply for the next 20 to 25 years at least. Bauxite signatures cover a wide range of values that allows selection of the most favorable bauxite prospects for future mining, both in economic as well as environmental terms. Although, there is the general believe that the world abundance of bauxite resources will ensure sufficient supply to meet future demands significant additional reserves have to be discovered if exponential growth rates continue. As the question of future bauxite supply is subject to economic and geologic principles one has to take into consideration that increasing exploration maturity in many mineral provinces will make it difficult to locate additional bauxite reserves and that decreasing real commodity prices will influence the level of investment in bauxite exploration.

KEY WORDS: Bauxite mines, bauxite quality, world bauxite production, sustainable development, reactive silica, in-situ alumina reserves.

INTRODUCTION

Bauxite is the principal ore for the production of aluminium metal via a two-stage process that involves, firstly the refining of bauxite to alumina by a wet chemical caustic leach process (the Bayer process) and, secondly the electrolytic reduction of alumina to aluminium metal (the Hall-Heroult process). Approximately 85% of all the bauxite mined is converted to alumina for the production of aluminium metal, 10% is utilized for nonmetal products, and the remaining 5% is nonmetallurgical applications such as production of refractory and abrasive materials (Plunkert, 2001).

From a geologic point of view, bauxite is a residual rock that formed intermittently throughout much of the geologic record during periods of intense continental subaerial weathering. As such, bauxite formation is the result of distinct climatic and tectonic conditions favorable for sustaining prolonged weathering processes. Bauxite deposits usually are classified in three genetic types according to mineralogy, chemistry, and host-rock lithology (Bárdossy and Aleva, 1990). Of all known bauxite deposits, about 88% belong to the laterite-type, 11.5% are of the

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karst-type, and the remaining 0.5% are of the Tikhvin-type (Bárdossy 1982; Bárdossy and Aleva, 1990). Laterite bauxites are derived from a variety of parent rock types and formed in a variety of paleogeographic settings during specific epochs of the Earth's history (Bárdossy, 1995). They are developed preferentially on flat-topped plateaus and occur on large continental-scale planation surfaces exposed to a tropical monsoon climate, whereby optimal hydraulic conditions are controlled by the balance between precipitation and evaporation (Bárdossy and Aleva, 1990).

The ore minerals in bauxite comprise gibbsite [$Al(OH)_3$], boehnite [γ-AlO(OH)], and diaspore [α-AlO(OH)]. Gangue minerals include hematite [Fe_2O_3], goethite [FeO(OH)], quartz [SiO_2], rutile/anatase [TiO_2], and kaolinite [$Al_2Si_2O_5(OH)_4$]. The mineralogy of bauxite deposits controls the efficacy of the Bayer process. Gibbsite is more soluble the in caustic soda solution than boehmite and diaspore. Therefore, gibbsitic bauxite has lower energy requirements than boehmitic ore at the refining stage whereas diasporic bauxite requires the highest energy. Some of the gangue components such as clays, fine-grained quartz, and Ti-oxides are deleterious as they react with the leaching solution which causes caustic soda losses in the Bayer process.

There is a large number of papers and books that describe genetic aspects of bauxite formation and provide geologic and economic geology information on bauxite deposits. Other references are concerned with economic aspects and case histories that detail individual bauxite discoveries, commencements of mines, and mining methods (for example Bárdossy, 1982; Bárdossy and Bourke, 1993; Bárdossy and Aleva, 1990; Carvalho and others, 1997; Gow and Lozey, 1993; Metallgesellschaft, 1997; Mosier, 1986a, 1986b; Meyer and others, 2002; Patterson and others, 1986; Roullier, 1996; Valeton, 1972). However, there is no one reference in the literature where all this information has been compiled. Because of that, the Collaborative Research Center 525 built its own database (Hausberg, 2000). The CRC 525 database records the details of more than 70 bauxite mines and about 100 bauxite exploration projects.

The Collaborative Research Center 525 "Resource-oriented Analysis of Metallic Raw Materials Flow" was established in 1997 by the Deutsche Forschungsgemeinschaft (DFG) at the University of Technology (RWTH) Aachen. It aims at developing an integrated resources management system that analyzes and quantifies the flow of minerals, metals, and energy through the production cycle from ore to metal.

Based upon the CRC 525 database, this paper takes a long-term view, and examines firstly aspects of past world bauxite production and its effect on the depletion of bauxite reserves. Secondly, it defines and evaluates geologic signatures of bauxite deposits, with the focus on the adequacy of future bauxite supply.

BAUXITE PRODUCTION

The world-wide geographic distribution of bauxite deposits (Fig. 1) suggests accumulation of laterite-type bauxite in a number of large provinces such as Australia, the Caribbean, the Guyana and Brazilian shields in South America, as well as the Guinea Shield and Cameroon in West Africa. Karst-type deposits are known to occur preferentially in Europe and Jamaica.

In 2001, bauxite was mined in 22 countries but the 12 largest producing countries accounted for about 97% of the world production (Plunkert, 2001). Australia currently is the largest producer with about 53.3 million metric dry tons (Mt) of bauxite mined in 2001, followed by Guinea (15.7 Mt), Brazil (13.9 Mt), Jamaica (12.4 Mt), China (9.5 Mt), and India (8.39 M). Bauxite production in Russia, Suriname, Venezuela amounted to more than 4 Mt whereas Guyana reported an output of close to 2 Mt.

Bardossy and Bourke (1993) note that bauxite deposits are known from 50 different countries, with at least 211 deposits containing 1 Mt of reserves. Figure 2 presents the historic trends of bauxite mine commencements for which the CRC 525 database records detailed information. Bauxite mine commencements rose throughout the 1950s and peaked mainly in the 1960s and early 1970s, with new start-ups continued to the mid 1980s and early 1990s. During these periods new mine developments took place mainly in India, Jamaica, Australia, Brazil, and Venezuela.

Figure 3 plots orebodies for the two bauxite deposit types; that is, karst and laterite bauxite, by ore grade versus reserves. Contours indicate the in-ground tonnage of alumina (Al_2O_3). The grade is presented here as weight percent available Al_2O_3 which accounts only for the amount of alumina which is extractable in solution by the Bayer process. Most of the data scatter between 40 and 55% av.Al_2O_3 with bauxite reserves ranging from 10 to 1000 million tons. The graph also reveals that all deposits with in-situ

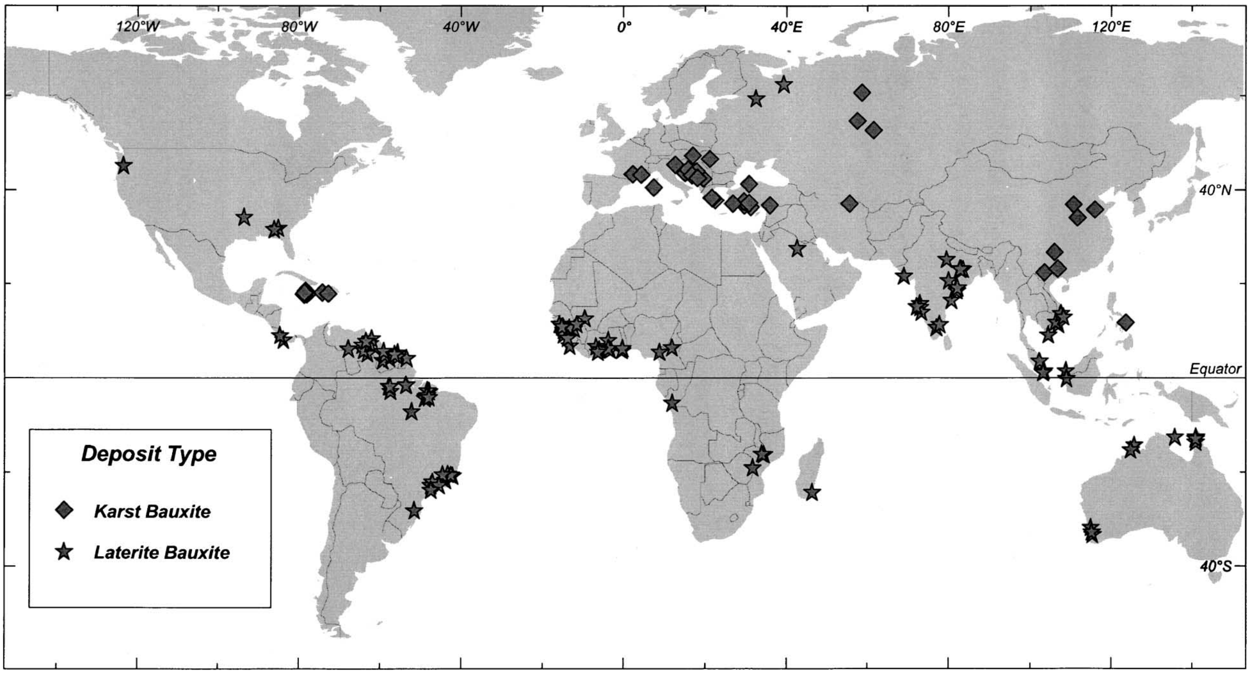

Figure 1. World distribution of karst and laterite bauxite deposits.

reserves in excess of 5 Mt av.Al_2O_3 contain an in-ground alumina value of more than 1 billion US$, based on the 1999 unit value of 203 US$/t alumina (Kelly and others, 2003).

The relationship, on a per capita basis, between the potential value of national bauxite reserves and the gross domestic product (GDP) of bauxite producing countries is examined in Figure 4. The bauxite

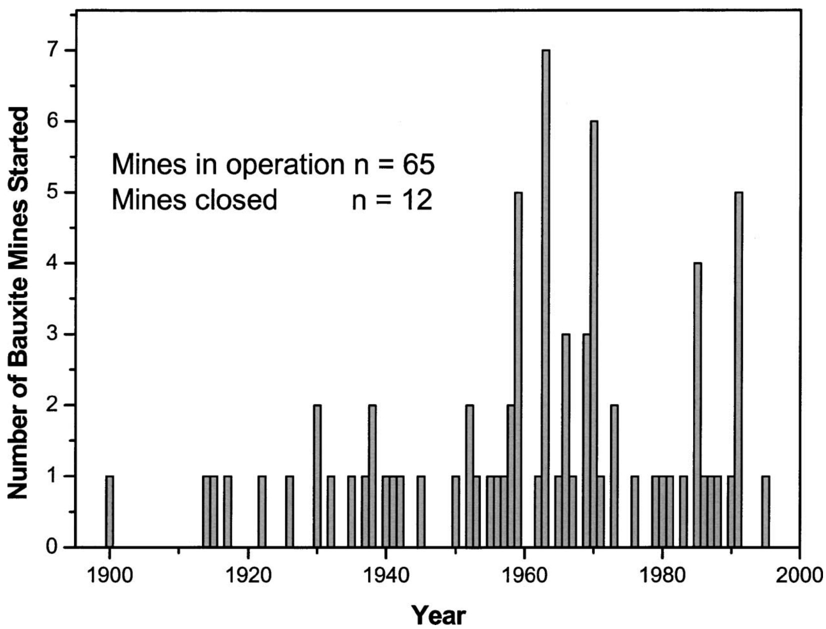

Figure 2. Time trends in bauxite mine commencement each year for period 1900 to 2000. Data from CRC 525 database.

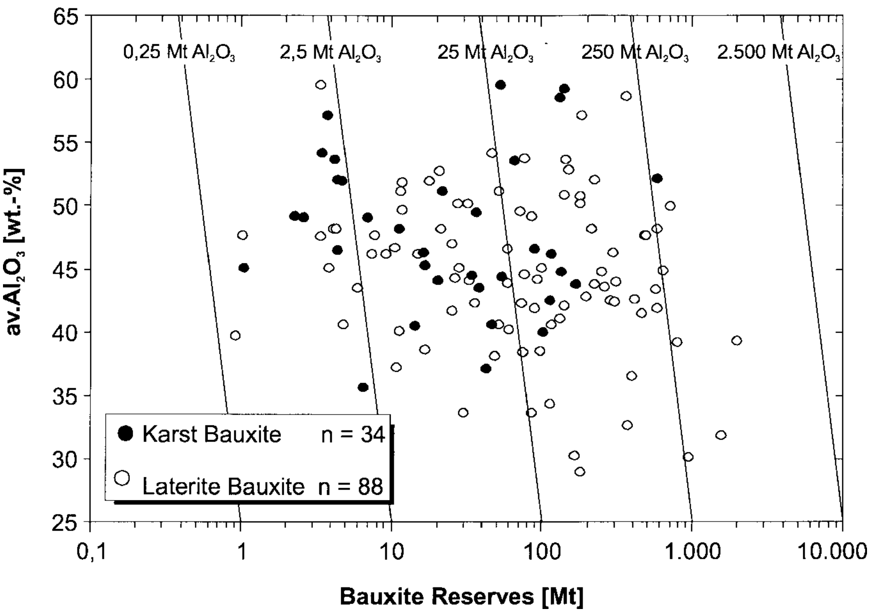

Figure 3. Grade versus reserves plot for karst and laterite type bauxite deposits. Data from CRC 525 database.

value was calculated from the countries bauxite reserves and the 2000 unit value for bauxite and indicates the in-ground value. The graph demonstrates that for a number of countries such as Jamaica, Guyana, Guinea, and Suriname the potential bauxite value may constitute more than 10% of the GDP,

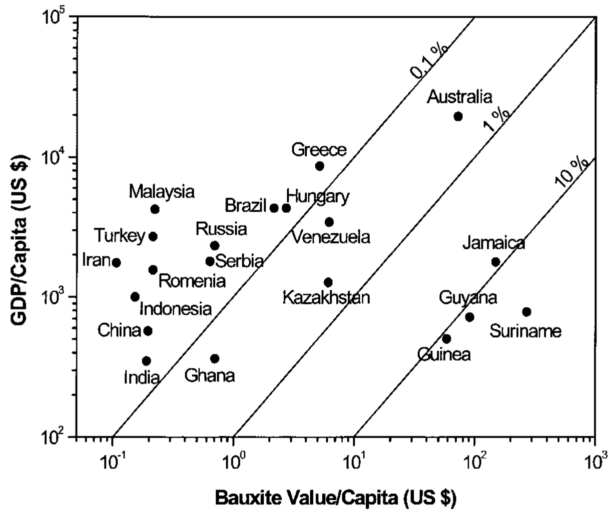

Figure 4. Plot of gross domestic product (GDP) per capita versus potential bauxite value per capita in 2000 US dollars. Data source: CRC database; EIA, 2003; Kelly and others, 2003.

and future bauxite extraction could contribute substantially to the countries economies.

Driven by increasing demand, world bauxite production has risen during the past five decades from less then 9 million metric tons per annum to c. 141 Mt in 2001 (Plunkert, 2003). The enormous growth in world bauxite production from 1900 to 2001, with an average annual increase of 5.7%, is shown in Figure 2. The cumulative amount of bauxite produced during that period amounts to 3.827 Mt. A similar quantity (i.e. 3.882 Mt) will be mined during the next 25 years, if a more moderate growth of world bauxite production is assumed of 1.7% a year (Fig. 5).

Figure 6 shows, by decade, the growth in the per capita consumption of bauxite for a 100-year period, beginning from 1900. Per capita consumption is defined here as world bauxite mine production, for a given year, divided by world population (United Nations Population Division, 1999), for the same year. For the period 1950 to 2001, a steady rise in bauxite use from 3.2 to 22.1 kg per person occurred, with an average annual increase of about 4%. Up to now, bauxite production has kept pace with the growing demand, driven by the combination of increasing population and increasing per capita consumption of bauxite. If we consider an annual increase in future bauxite production of 5%,

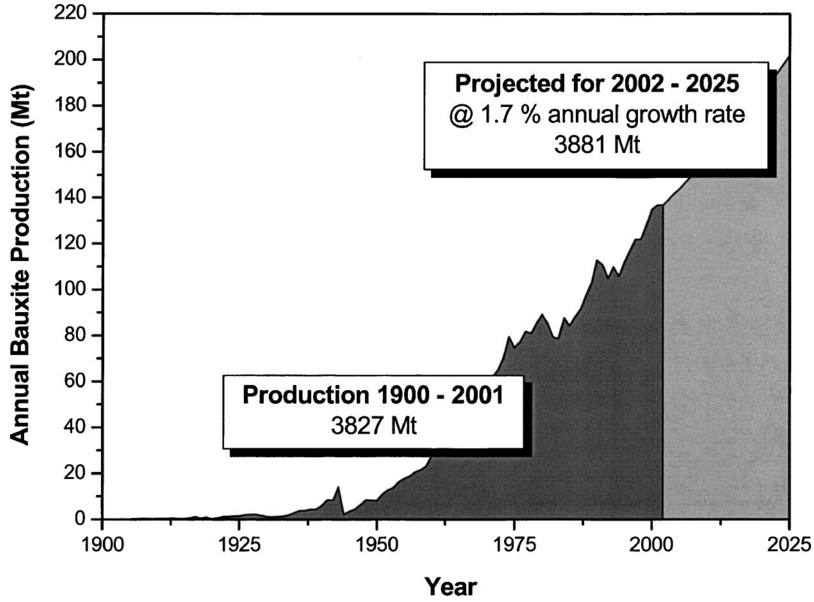

Figure 5. Time trends in bauxite production from 1900 to 2001 and projected for period 2002 to 2025 assuming an annual increase of 1.7% for future bauxite production. Data source: CRC 525 database; USGS Minerals Yearbook, 2001; Kelly and others, 2003.

the adequacy of world bauxite reserves (currently known reserves are 22 billion metric tons) will be less than 20 years. This is only true, of course, if future exploration efforts fail to discover new additional reserves.

BAUXITE RESERVES

In 2002, world bauxite reserves; that is, that part of the reserve base which could be extracted economically at the time of discovery, were estimated

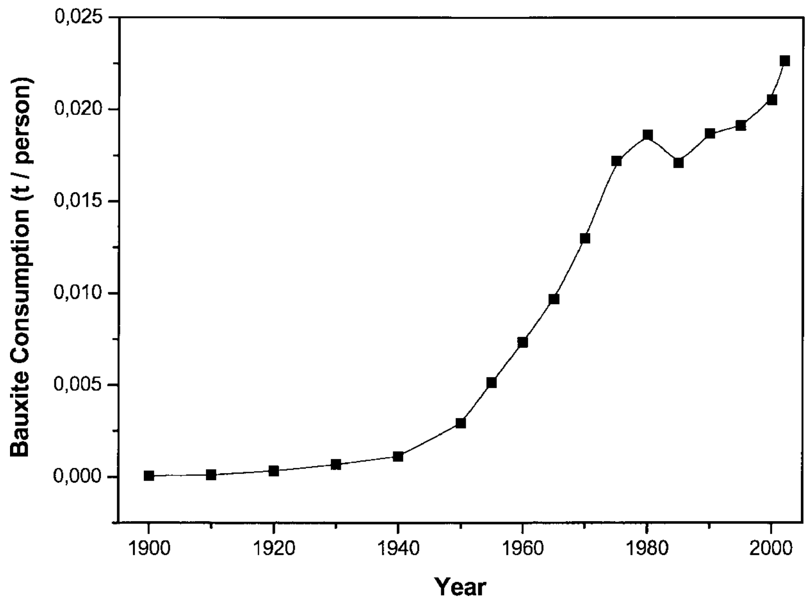

Figure 6. World bauxite per capita consumption, 1990 to 2001. Data source: Kelly and others, 2003; United Nations Population Division, 1999.

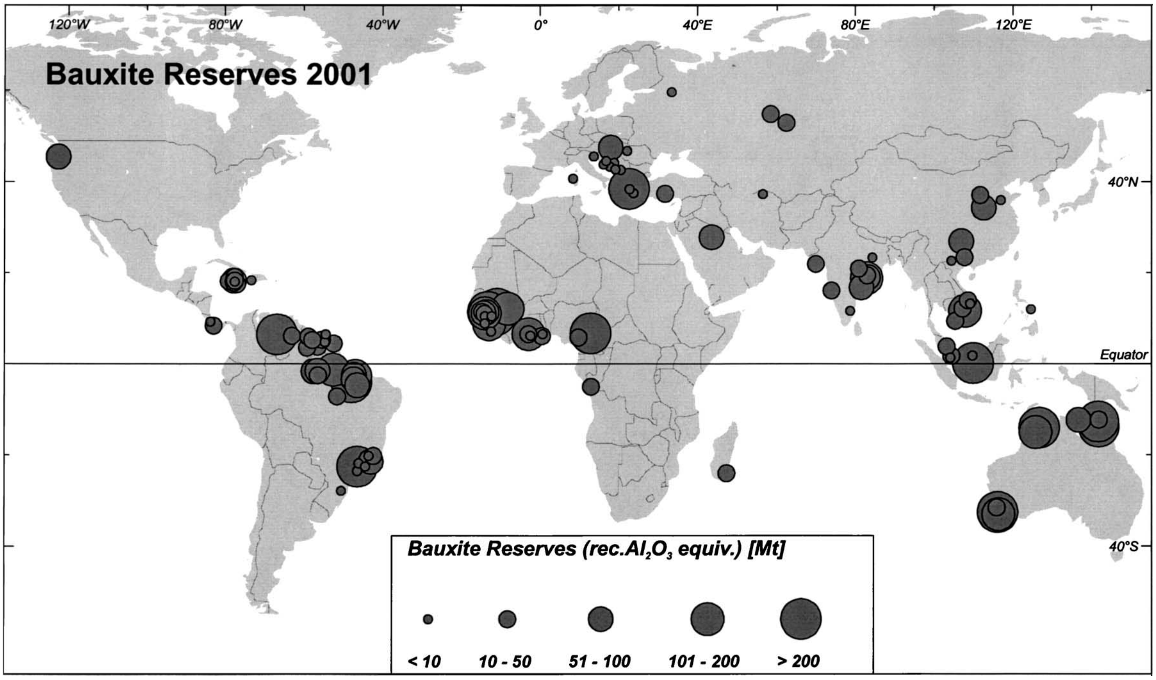

Figure 7. World distribution of bauxite reserves according to tonnages of recoverable alumina (rec.Al_2O_3). Further explanation is given in text. Data from CRC 525 database.

to amount to 22000 Mt (Plunkert, 2003). Bauxite reserves are unevenly distributed throughout the world, with the largest reserves being located in Guinea (33.6%), Australia (20.1%), Jamaica (9.1%), and Brazil (8.18%) (Plunkert, 2003).

The world distribution of bauxite reserves as was known in 2001 is shown in Figure 7. In order to portray bauxite quality rather than quantity, the reserve figures are presented as the tonnage of recoverable Al_2O_3. Rec.Al_2O_3 is defined here as the amount of alumina contained in the bauxite reserves that can be extracted in solution by the Bayer process. Also taken into account is the efficacy of the process which is controlled by the relative abundance of the alumina minerals gibbsite, boehmite, and diaspore and the presence of deleterious minerals such as kaolinite. Numerically, rec.Al_2O_3 is equal to av.Al_2O_3 multiplied by the percentage recovery of alumina in the Bayer process. For example, alumina recovery from gibbsitic ore with low (<3%) boehmite content is 98%, whereas the yield from boehmite-rich bauxite is reduced to 90%. As can be seen from Figure 7, the distribution of reserves mirrors that of the current bauxite mines (Fig. 1). Major reserves in excess of 200 Mt rec.Al_2O_3 are located in Australia, Indonesia, West Africa and South America. Smaller provinces include that of China, Jamaica, and southern Europe.

Figure 8 presents the annual discovery rate of bauxite reserves for the period 1900 to 2000. The patterns of discovery are not continuous, the periods 1950–1970 represent the most prolific with distinct peaks in 1958, 1969, and 1970. Since 1976 the discovery rate fell and has not risen since above 4 discoveries per year.

It is widely believed that, at least for the foreseeable future, there is an abundance of bauxite resources globally to ensure a readily accessible supply for the future (cf. Plunkert, 2001). World bauxite supply estimates, derived from ratios of known world reserves and world production for a given year (i.e. bauxite reserve life index) indicate adequate bauxite supply for almost 200 years. Inspection of historic trends of the bauxite reserve life index (RLI) for the years 1950 to 2000 (Fig. 9) suggests that the pattern is cyclic, with a period of low RLIs followed by a period of high values. A dramatic low of 60 years was recorded in 1969 and a high of almost 400 years in 1980. Comparison with discovery rates given in Figure 8 leads to the conclusion that the high exploration success in the 1960s and 1970s resulted in the addition of new reserves that have outweighed

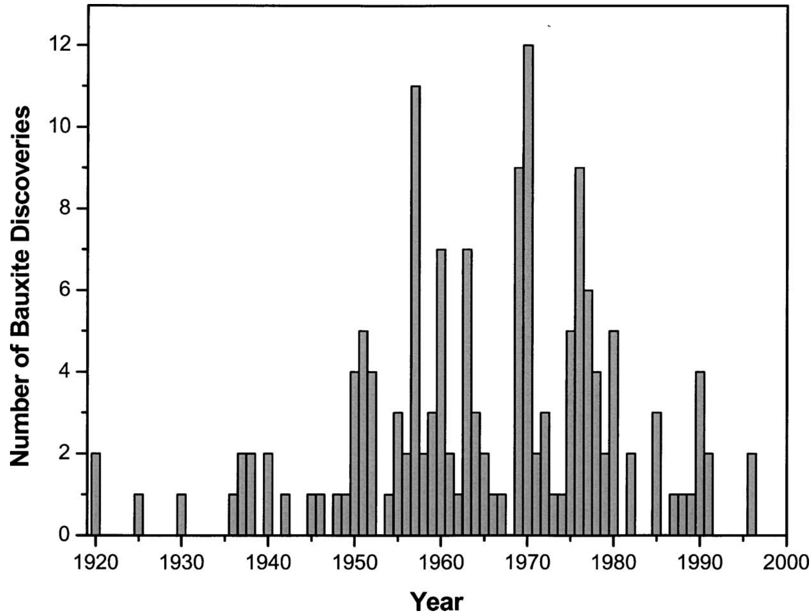

Figure 8. Time trends in bauxite reserve discoveries each year for period 1900 to 2000. Data from CRC 525 database.

resource depletion even with increase in bauxite production rates of 5% (Fig. 5). Interestingly, the present-day RLI of c. 180 years is at the same level as it was in 1950.

The superimposed trends in bauxite unit value, given in 1998 US dollars (Kelly and others, 2003), serve to review the relationships between historic RLI changes and bauxite prices. At first inspection it

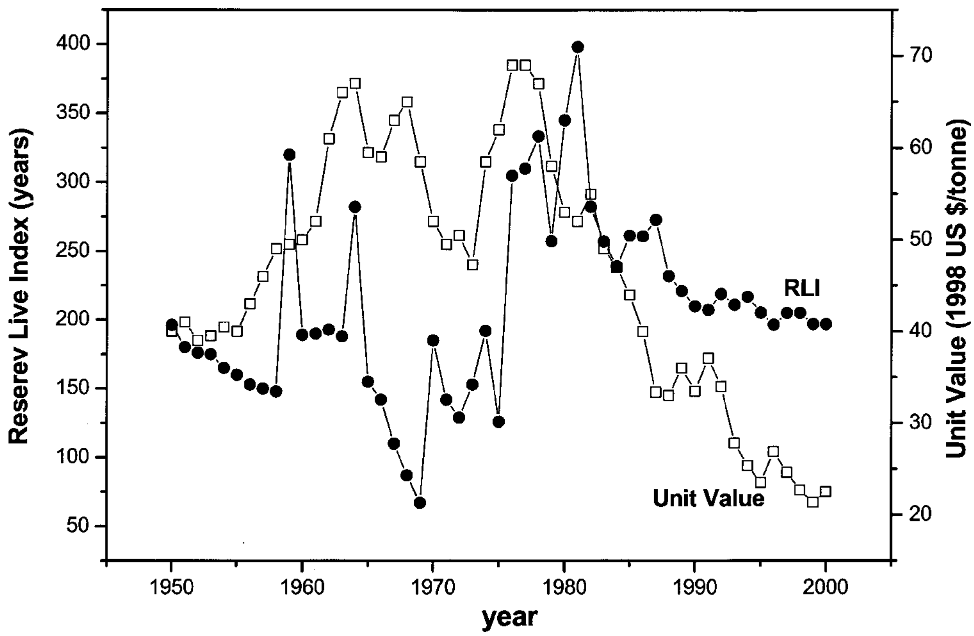

Figure 9. Time trends in bauxite reserve life index (RLI = world reserves divided by world production at given year) for period 1950–2001 and trends in bauxite prices. Data from CRC 525 database and Kelly and others, 2003.

appears that RLI and bauxite prices follow similar patterns. The period 1965–1975 shows a decline for both figures. The 1974 peak of 83.11 US$ per ton of bauxite is followed by a sharp rise in RLI from 125 years to 300 years in 1976. Since then, both bauxite unit value and RLI have declined steadily to the present level. This might suggest that the RLI may be inadequate for long-term prediction of bauxite supply. Firstly, RLI does not take growth rates into consideration, and secondly, the definition of the terms reserve and production have an economic basis and do not consider geologic principles.

The consensus among forecasters of the long term trends in the aluminium market seems to be that consumption will continue to grow at its historical growth rate of 3% at least (IIED, 2002). It has been shown, that for the period 1950–2000 the growth rate for bauxite consumption per capita was 4%, and that bauxite production growth rate for the same period was 5.6%. If we consider an annual bauxite production growth rate of 5% the currently known reserves of 22 billion metric tons will be exhausted within the next 20 years. The world bauxite reserve base; that is, that part of identified resources that include currently economic, marginally economic, and some subeconomic occurrences is estimated to amount to 33 billion metric tons of bauxite (Plunkert, 2003). If we take this figure and apply again an annual growth in bauxite production of 5%, then the reserve base will be adequate for 25 years. This implies, however, that during this period some of the currently marginally economic and subeconomic resource can be converted into reserves (i.e. economic resources).

FUTURE TRENDS

The question of future bauxite supply is certainly subject to economic and geologic principles. One other issue that pertains to this question is the problem with resource depletion and environmental degradation. As the concept of sustainable development need not require conservation of nonrenewable mineral resources, depletion of mineral resources, such as bauxite, is consistent with sustainability. Sustainability requires, however, that the impact is minimized ore extraction, beneficiation, and processing has on the environment.

To investigate further possible future trends in bauxite supply geologic signatures of bauxite were defined that control the economic as well as environmental performance of bauxite deposits. In that sense bauxite signatures also are a measure of bauxite quality. The CRC 525 database records detailed information on 70 bauxite deposits currently in operation and information on feasibility studies and exploration results of c. 100 bauxite discoveries. This enables comparison of geologic signatures between currently operating mines and prospects that may be mined in future. The comparison is based on the following signatures.

Recoverable Al_2O_3: This signature relates to the mineralogical composition of bauxite, in particular to the abundance and type of alumina-bearing minerals and deleterious minerals. These parameters controls the energy and caustic soda consumption of the Bayer process and the alumina yield.

Reactive silica and (R.SiO_2) and TiO_2-content: The presence of SiO_2 in aluminosilicates and TiO_2 has a negative effect on the Bayer process, because their concentration in the ore have a negative effect on the amount of energy and flocculants used in the process.

Bauxite/Al_2O_3-ratio and Red mud/Al_2O_3-ratio: The bauxite/Al_2O_3-ratio as well as the bauxite/rec.Al_2O_3-ratio provide information on how much bauxite has to be extracted from the orebody to produce 1 t of alumina. The red mud/Al_2O_3-ratio as well as the red mud/rec.Al_2O_3-ratio specifies the amount of red mud that results from the production of 1 t of alumina.

Bauxite reserves: This term refers to the economic characteristics of ore deposits and is determined by the geologically proven and economically recoverable amount of ore.

Annual bauxite production: This relates to annual production figures of individual mines or the accumulated bauxite production world-wide.

Moisture content and waste/ore-ratio: The moisture content refers to the amount of nonmineral-bound water in the ore. A high moisture content has a negative effect on mining and processing and transportation of the ore. The waste/ore-ratio provides a figure for the amount of country rock that has to be moved to produce a given amount of ore. This value also influences the mining method.

Land use/t rec.Al_2O_3: This ratio considers surface disruption in terms of land area (m^2) required for bauxite mining per ton of recoverable alumina extracted. The figure differs with the geometry and thickness of the orebody as well as with the alumina content and in-situ density of the ore.

The next series of figures plot the distribution of selected bauxite signatures in currently active mines and prospects that may be mined in future (Figs. 10,

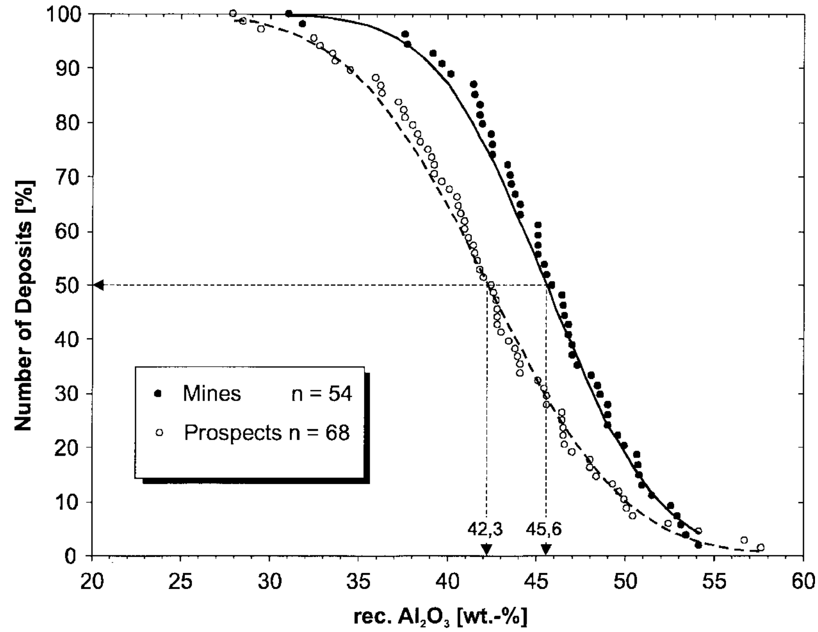

Figure 10. Distribution of rec. Al_2O_3 in current mines and prospects. Data from CRC 525 database.

11, 12, and 13). A comparison of mean values indicates that the signatures *rec.Al_2O_3*, *Bauxite/rec.Al_2O_3 Ratio*, and *Land Use* may become less favorable in future. However, future mines may have larger mean *Bauxite Reserves*. The two curves follow parallel trends with only one intersection in Figure 11 at low values. Therefore, the range of values in both populations is similar with a proportion of the prospects have more

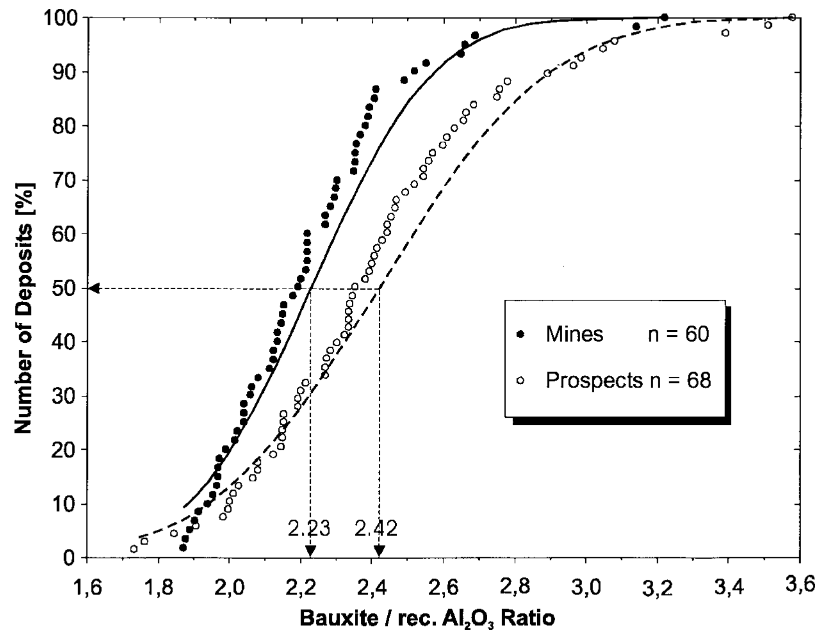

Figure 11. Distribution of bauxite/rec. Al_2O_3-ratios in current mines and prospects. Data from CRC 525 database.

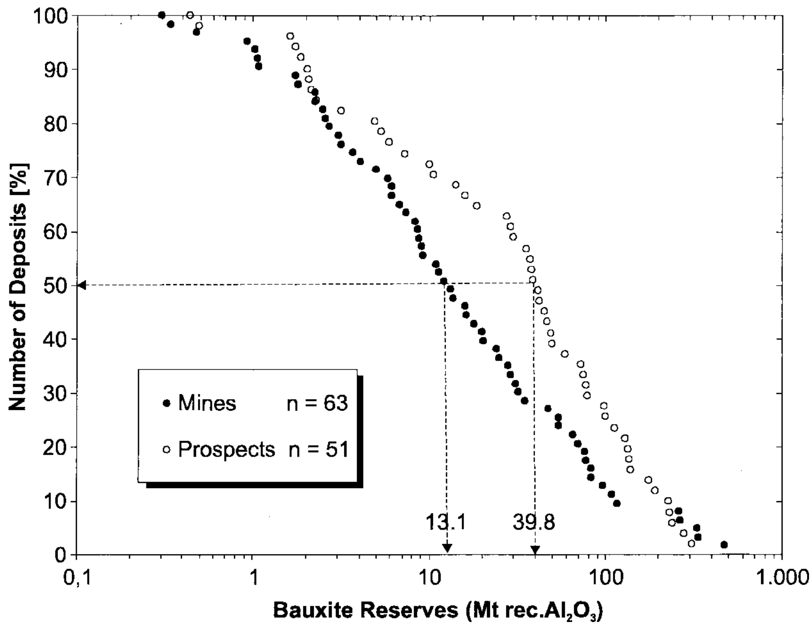

Figure 12. Distribution of bauxite reserve in current mines and prospects. Data from CRC 525 database.

favorable bauxite signatures than the current mines and vice versa.

It is more instructive to look at the summary plot in Figure 14. This graph plots results of a substitution model. The model design allows the successive replacement of current mines by prospects (that have the potential for future exploitation) with more favorable bauxite signature whereby the amount of

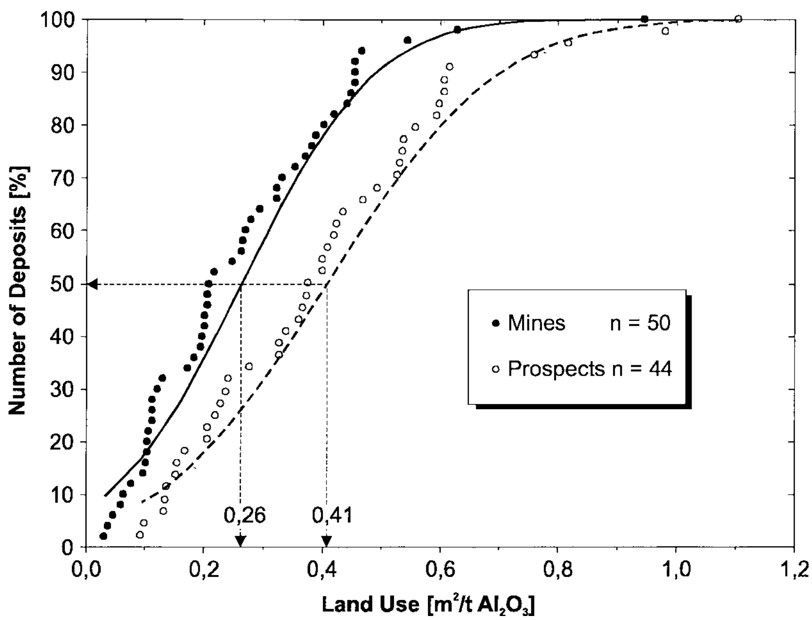

Figure 13. Land use (m^2/t rec.Al_2O_3) by current mines and prospects. Data from CRC 525 database.

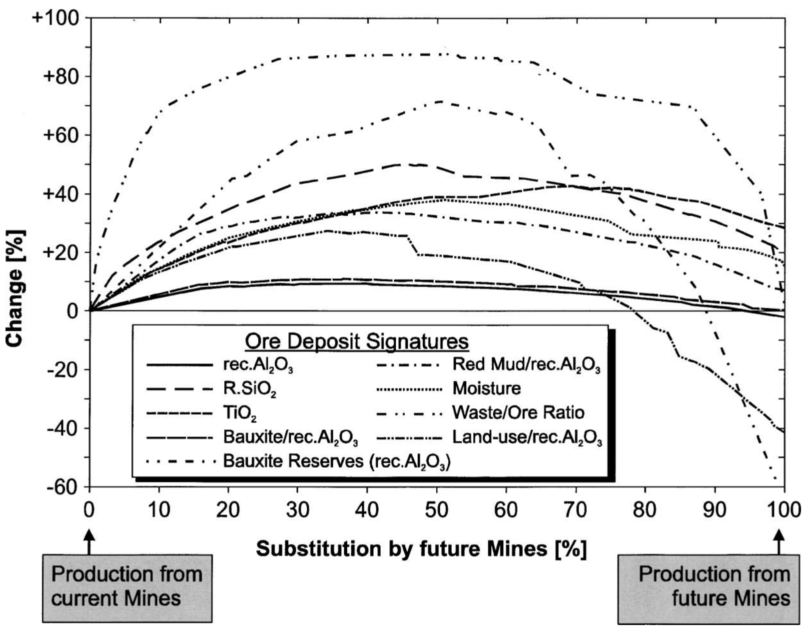

Figure 14. Substitution model showing percentage changes in bauxite signature for successive replacement of current mines by prospects (future mines) that have potential for exploitation in future. Data from CRC 525 database.

bauxite production is maintained. In other words, currently mined bauxite deposits with the least favorable signatures were successively replaced by prospects having the most favorable signatures. This also indicate an enhancement of bauxite quality, both in economic as well as environmental terms. Figure 14 depicts percentage changes of the nine bauxite signatures that were explained previously in relation to percentage substitutions of current mines by future mines (i.e. prospects). All curves have a convex shape indicating initial positive changes in bauxite signatures und thus ore quality. At low substitution rates, the most significant positive changes are recorded for the *Waste/Ore Ratio*, *Bauxite Reserves*, and the reactive silica content (R.SiO_2). Substitution has a smaller affect on ore grade in terms of rec.Al_2O_3 and the Bauxite/rec.Al_2O_3 Ratio. Close to 100% substitution, the curves for most signatures approach the base line or show even negative changes as is the case for *Land Use* and *Bauxite Reserves* at 75 and 90% substitution, respectively.

The substitution model shows that, in general, the currently known bauxite prospects have the potential to meet future bauxite demands. The bauxite signatures discussed here encompass a wide range of values that allows selection of the most favorable bauxite prospects for future mining, both in economic as well as environmental terms.

CONCLUSIONS

World cumulative bauxite production through the period 1900–2001 was 3.827 Mt with an average production growth rate of more than 5%. World bauxite consumption per capita rose during this time from 0.05 to 22.1 kg. The growing demand for bauxite was met by the industry with the commencement of up to seven mines per year, in particular, during the 1960s and early 1970s.

The majority of currently operating bauxite mines contain reserves in the range from 10 to 1000 Mt dry bauxite whereby ore grades vary between 40 and 55 wt.% available Al_2O_3. Accordingly, in-situ alumina reserves range from 2.5 to 250 Mt with most deposits having an in-ground alumina value of more than 1 billion US$. For some bauxite producing countries such as Jamaica, Guyana, Guinea, and Suriname the potential bauxite value contributes to 10% and more to the countries gross domestic product.

Current world bauxite reserves amount to 22 billion tons and the reserve base is estimated to be in the order of 33 billions tons of dry bauxite. The discovery rate for new bauxite reserves rose throughout the 1950s, 1960s, and 1970s, and evidently fell during the 1980s and 1990s. The world bauxite life index; that is, the ratio of present world reserves to present world production, indicates adequate bauxite supply for about 180 years. However, both bauxite production and per capita consumption curves display exponential growth with an average increase of about 5% a year. If we consider this growth rate then the currently known reserves will be exhausted within the next 20 years and the reserve base will be adequate for not more than 25 years. Although, there is the general believe that the world abundance of bauxite resources will ensure a readily accessible supply for the future additional reserves have to be discovered if exponential growth rates continue.

Evaluation and comparison of bauxite signatures of presently mined bauxite deposits and prospects that may be mined in future suggests that there is sufficient potential to maintain at least the current level of bauxite quality as well as quantity for the next 20 to 25 years.

It has to be considered, however, that mineral deposits have a place value in that their geographic location is determined by the geologic environment and they may occur in regions with unfavorable economic or political conditions. Increasing exploration maturity in many mineral provinces will make it more difficult to locate additional bauxite reserves in areas where profitable alumina plants are already established. If bauxite prices will continue to fall, this will affect the profitability of the industry and will influence levels of mine capacity and exploration efforts.

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