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The sustainability of mineral use

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The sustainability of mineral use, like the definition of sustainable consumption patterns, is a function both of the availability of resources and of the environmental impacts of resource use. The environmental impacts are a major factor in modifying consumption patterns and therefore in moderating demand.

In spite of a number of factors tending to moderate demand, global demand is likely to continue to increase for the foreseeable future, mainly as a result of the continuing increase in global population which is unlikely to be stabilised before the end of the 21st century.

Discussion of the relationship between population, resource use and the environment, using the concepts of the support square and per capita resource use, illustrates the unsustainability of present demand trends and of the consumption patterns that cause them. It is therefore important that strategies to maintain supply be linked to effective strategies to move to sustainable consumption patterns.

The capacity to meet the demand for minerals is also being reduced, as the global population increases, by concerns about environmental impacts and by competing land uses. It is therefore important that minerals issues should be part of the integrated approach to land management promoted in Agenda 21.

Sustainability is a long-term concept involving inter-generational equity, and the time scales are beyond those of the reasonably foreseeable future. It is not possible to see beyond a definable 'horizon of sustainability' and the 'precautionary principle' is therefore important for global management strategies. The paper identifies a number of steps at the global level which can assist in the management of resources and of environmental impacts during the period of transition to more sustainable consumption patterns. These relate to improvements in knowledge (1) for assessing the impacts of mineral use in the industrial system as an essential basis for improving efficiency and determining optimum consumption patterns; (2) for monitoring the chemical health of the global land surface; and (3) for assessing resource potential in ways that can be integrated with other land use information, and that can be used to push back the horizon of sustainability.

Introduction

The spectacular technological and economic development and consequent population growth of the last two centuries has been made possible by the expansion of the use of all kinds of natural resources, and, most fundamentally, by the use of petroleum and mineral resources. These resources are the foundation of our energy, manufacturing, communication and construction industries (Fig. 1), and of modern agricultural industry with its dependence on mechanisation, fertilisers and pesticides. Consumption of these resources continues to increase.

There has been concern about the depletion and possible exhaustion of these resources since the beginning of this century, a concern which reached its most forceful expression in the 'Limits to Growth' report for the Club of Rome (Meadows et al. 1972). While its estimates of impending scarcity were wide of the mark, the report was a landmark in the debate on sustainability.

However, in recent decades, concern that the availability of resources would set limits to national or global economic growth has been largely displaced by the more immediate concern that limits are being set by the environmental impacts of the increasing human population and its increasing consumption of resources. Land degradation and pollution of air and water are perhaps the most pressing problems but the issue which has captured the greatest attention from governments (and economists) has been that of global warming arising from greenhouse gases, and from CO_2 emissions in particular. The pressure to move away from fossil fuels towards renewable (or nuclear) energy sources is largely due to the evidence of environmental impacts rather than to recognition either of the clearly finite limits of petroleum supply, or of the desirability of conserving this valuable chemical or material commodity for purposes other than its calorific value.

These environmental issues are therefore having increasing impact on consumption patterns and on the likely future demand for resources. Moreover, the increasing concerns about the environmental impacts of mineral exploitation, extraction and use are also leading to economic or socio-political constraints on the capacity to meet demand. That capacity is also being reduced more generally by competing land uses as the global population increases.

Thus there is a close nexus between minerals and the environment, and minerals issues should be central to the planning for sustainable development, and specifically for the assessment of sustainable consumption patterns.

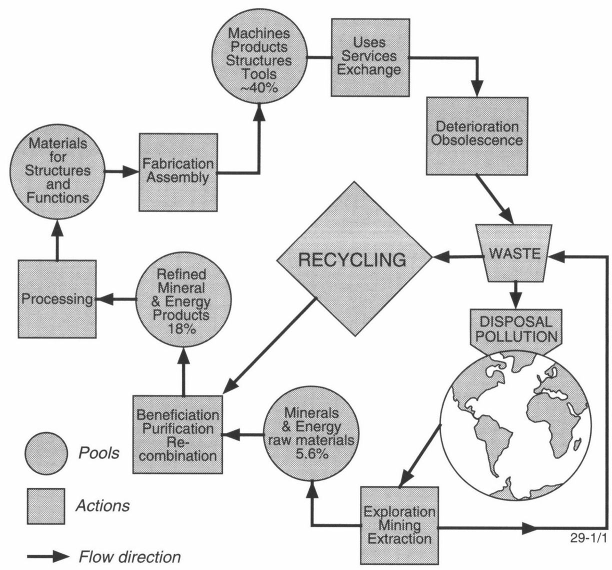

Figure 1. Flow of materials and energy in an industrial society (percentages given are of 1975 GNP for the USA) (After Cloud 1977). Note that while mineral and energy raw materials represented less than 6% of GNP, this increased to 18% and eventually to about 40% in the transition to machines, products, structures and tools.

Sustainability

> The growth of world population and production, combined with unsustainable consumption patterns, places increasingly severe stress on the life-supporting capacities of our planet.
>
> Agenda 21, Chap. 5, Demographic dynamics and sustainability. Report of the United Nations Conference on Environment and Development, Rio de Janiero, 3–14 June 1992. Vol. 1, Resolutions adopted by the Conference. (United Nations Publication Sales no. E.93.I.8 and corrigenda), resolution 1, annex II.

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The concept of a sustainable society was encapsulated in the Brundtland Report *Our common future* (World Commission on Environment and Development [WCED] 1987) as one that 'meets the needs of the present without compromising the ability of future generations to meet their own needs'.

The report recognises that 'the concept of sustainable development does imply limits — not absolute limits but limits imposed by the present state of technology and social organisation on environmental resources, and by the ability of the biosphere to absorb the effects of human activities'. On the depletion of non-living resources, the report suggests that 'the rate of depletion should take into account the criticality of that resource, the availability of technologies for minimising depletion and the likelihood of substitutes being available. Thus land should not be degraded beyond reasonable recovery. With minerals and fossil fuels, the rate of depletion and the emphasis on recycling and economy of use should be calibrated to ensure that the resource does not run out before acceptable substitutes are available. Sustainable development requires that the rate of depletion of non-renewable resources should foreclose as few future options as possible' *(underlining added)*.

Arising from the 1992 United Nations Conference on Environment and Development (UNCED), Agenda 21 was developed to address the pressing problems of today and to prepare the world for the challenges of the next century. The Commission on Sustainable Development (CSD) was established to promote the implementation of Agenda 21.

Agenda 21 (Chapter 4, para. 10 (e)) also called for identification of 'balanced patterns of consumption worldwide which the earth can support in the long term'. The concept of **sustainable consumption patterns** carries with it the concept of sustainable production patterns, and is usually considered in terms of the environmental impacts which provide the short-term constraint. It is recognised in Chapter 4, for example, that 'the major cause of the deterioration of the global environment is the unsustainable pattern of consumption and production, particularly in industrialised countries'.

The concept of sustainable consumption patterns must embrace the varying **levels** of resource use in different countries and the overall global level of resource use. A definition of sustainable development must therefore take into account both of the key minerals issues — the capacity of the environment to absorb the effects of resource use and the sustainability of supply of essentially non-renewable resources. It is necessary that the supply be sustainable for as long as required, and in the longer term, this may become the critical constraint on consumption patterns.

These key minerals issues are linked by the overriding issue of global population growth. Some aspects of the relationship between population, resource use and the environment are discussed below, before further discussion of environmental impacts and the availability of resources.

Population growth and increasing demand

Global population will almost certainly reach 8 billion over the next 30 to 40 years and is unlikely to stabilise much below 12 billion before the end of the 21st century (see, for example, Arizpe et al. 1992). This will place enormous additional burdens on the natural environment. In addition to the goal of an environmentally stable future, embodied in the principles noted above, the United Nations has the parallel goal of improving the living standards in less developed countries. To achieve this, the demand for materials and energy would increase, both from the rapidly increasing population and from the aspirations for improved living standards.

The Brundtland Report (WCED 1987), considered that global economic expansion by a factor of five to ten would be required in order to meet the demand for improved living standards for an increasing population. For this WCED apparently believed that such growth could be achieved largely by more efficient use of materials and energy and by improved technology to reduce environmental impacts (Arizpe et al. 1992 p. 69).

In this connection, there has been an attempt to distinguish between **economic growth**, which involves increased inputs of energy and materials, and **economic development**, which can take place through increased efficiency, without increased consumption of material capital, (e.g. Daly & Cobb 1989). Arizpe et al. (1992 p. 69), take the view that 'WCED is too optimistic — that a factor of 5–10 increase cannot come from development alone and if it comes mainly from growth it will be devastatingly unsustainable'.

There has been significant decoupling of economic expansion from **metallic minerals** consumption in developed countries in recent decades. The intensity of use (kg/million $GNP) of aluminium, for example, has declined since 1975 (Fig. 2A; Wellmer & Kürsten 1992 fig. 12). The substitution by non-metallic materials, combined with efficiencies in the use of the metals, partly accounts for the lower intensity of use of metals in industrialised countries. A further factor is the great increase in value-adding in finished products. But although the relative importance of metals has declined in industrial economies, there has not been significant decline in the total quantities of metals used (Fig. 2B), i.e. there has **not** been an overall dematerialisation).

Globally, consumption continues to increase. While demand

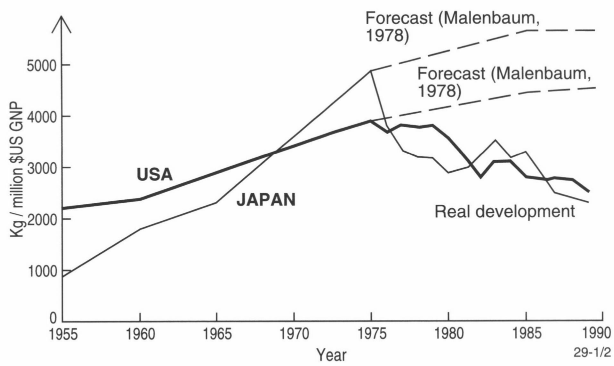

Figure 2A. Comparison of intensity of use of aluminium in Japan and USA, showing a change in trend in the mid-1970s.

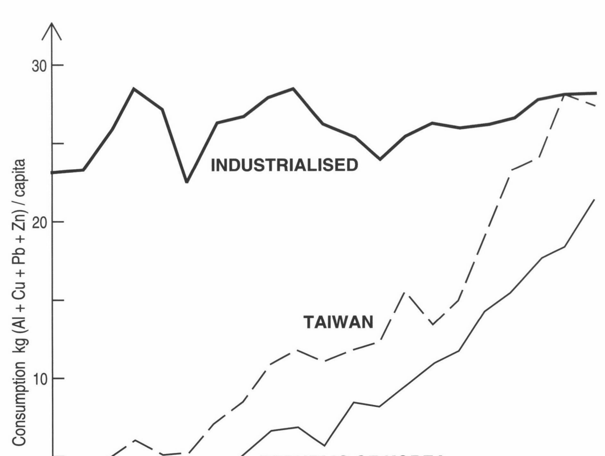

Figure 2B. Aggregated base metal consumption showing how consumption in Taiwan and Korea has grown to match the relatively constant level in industrialised countries.

for some minerals has stabilised, and is even declining in some developed countries, this will be more than offset by increasing demand in the developing countries and particularly those of South East Asia, where population is also growing rapidly. For example, the per capita consumption in the newly industrialising countries of Korea and Taiwan has grown rapidly over the last thirty years to levels similar to those of industrialised countries (Fig. 2B). Recent analyses also show that between 1950 and 1990 the population in underdeveloped regions grew from 68% to 77% of the global population, while the share of consumption of various metals grew from between 1% and 5% in 1950 to between 12% and 25% in 1990 (Wellmer & Kürsten 1992).

For similar reasons, it seems likely that demand for the **fuel minerals** will continue to increase for several decades (e.g. Bookout 1989, Masters et al. 1991). In this case, however, the demand for energy has continued to increase in the developed as well as the developing countries. Estimates on a 'business as usual' or 'as-is' basis (Ogawa 1991, quoted by Foster 1993), indicate that world primary energy consumption will approximately double between 1975 and 2000 and could double again in each of the following 25 years for an estimated population of 9.8 billion in 2050. Foster (1994) comments that he does not pretend that the forecast will come to pass but adds that uncertainty about the outcome cannot mask the trend.

The increased materials and energy use indicated above will inevitably be accompanied by increased environmental impacts.

Population, resource use and the environment can also be clearly linked through the concepts of per capita use of resources, and per capita use of space. The **total impact** of the human population is the product of population and per capita resource use (Daly 1977) and it can be controlled by controlling either or both of these factors.

The support square

The per capita use of space is given by the total available area divided by the total population and has been called the support square, which has been described as 'the scrap of land that must supply all the resources that an individual uses throughout a life, and that must fulfil the same purpose for others who follow. Somehow that space must also consume most of the solid wastes left over' (Skinner 1989). This human-focused concept actually overstates the area available per capita in so far as the needs to preserve areas of natural environment and biodiversity must also be recognised: the same total area has to support most other land-based species as well as the human population.

Nevertheless, the diminishing size of the support square gives a very graphic illustration of the impact of the increasing human population (Fig. 3). The average global support square towards the end of the next century is likely to be about 100 m square, about the same as the local support square for Europe today. But Europe offers a particularly favourable environment for human habitation. Moreover, Europe, like other developed countries in North America and Asia, is not wholly dependent on the local support square: it obtains a substantial part of its resources from other less densely populated regions. To a considerable extent, therefore, environmental impacts associated with the production of both renewable and non-renewable resources are also borne elsewhere. As the global population increases, with its attendant environmental impacts, pressures on land use will also increase, as will pressures on the natural environment and on biodiversity. It will become increasingly difficult to guarantee external supplies of both renewable and non-renewable resources.

In the case of metallic and fuel resources, the global distribution is very uneven and there are very large trade flows. It will be increasingly necessary to recognise mineral

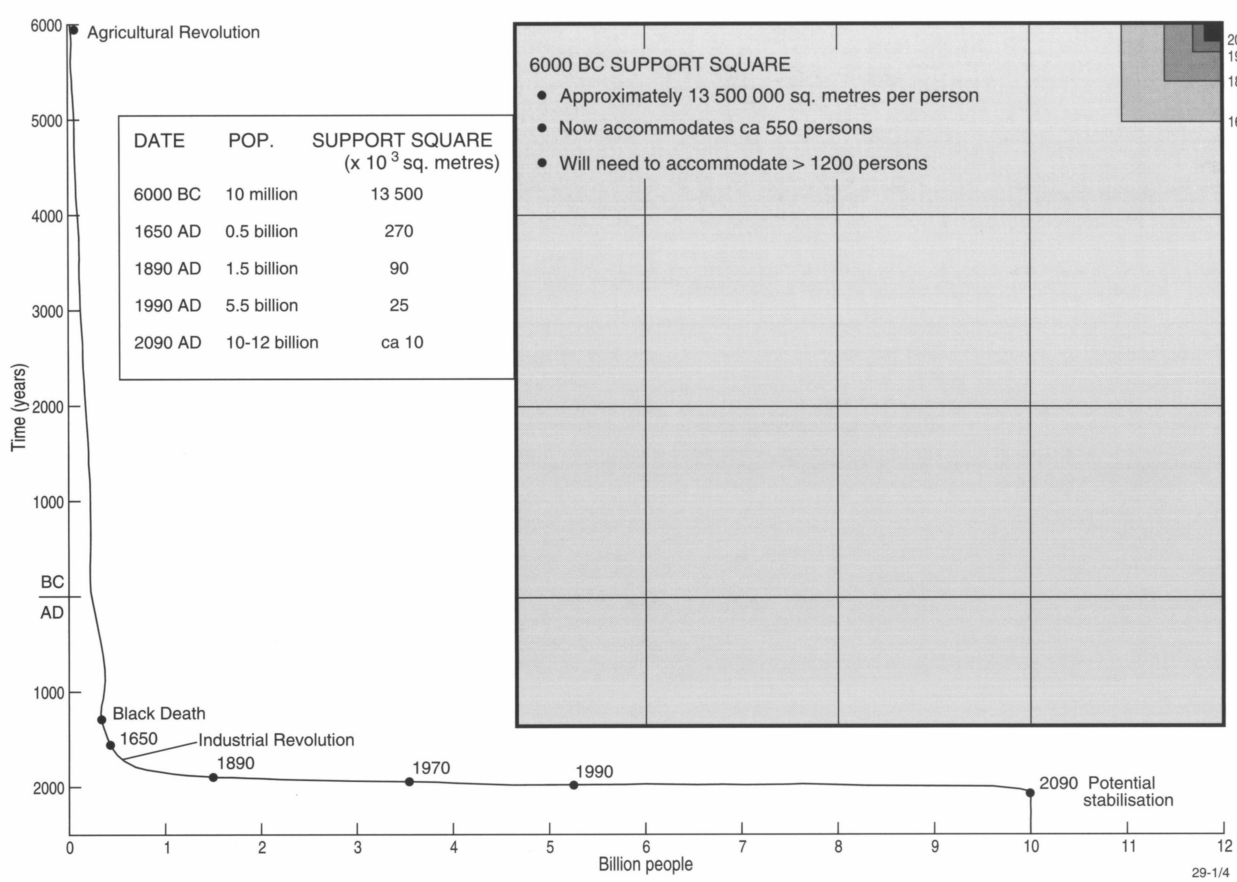

Figure 3. Growth in global population, and resulting shrinkage of the global support square.

supply as a global problem, requiring global cooperation and management. The competition for land use is likely to close additional areas to exploration and development, as it has already done for parts of Europe. It is therefore especially important that issues of mineral supply be considered as part of the proposed **integrated approach to the planning and management of land resources** under Agenda 21, both at the national and international levels (see *Metallic minerals*, below).

Per capita resource use

The average global per capita consumption of all minerals has been estimated at close to 10 tonnes a year (Skinner 1989). The **total impact** for the global population involves the displacement of about 50 billion tonnes of minerals per annum, a figure substantially greater than the amount of material moved by natural processes. A large proportion of this material consists of industrial minerals which are re-located from quarries to the sites of growing cities and to transport networks.

In the major industrial countries, consumption is much higher than the global average. In Germany, for example, it has been estimated that the average individual, in a lifetime of 70 years, consumes about 772 tonnes of construction materials, nearly 54 tonnes of other industrial minerals, about 363 tonnes of fuel minerals and about 43 tonnes of metals (mainly steel) (Fig. 4). Allowing for the quantities of ore and overburden that are involved in producing the final products, it is likely that some 1600 tonnes of rock are consumed by each individual, or well over 20 tonnes a year.

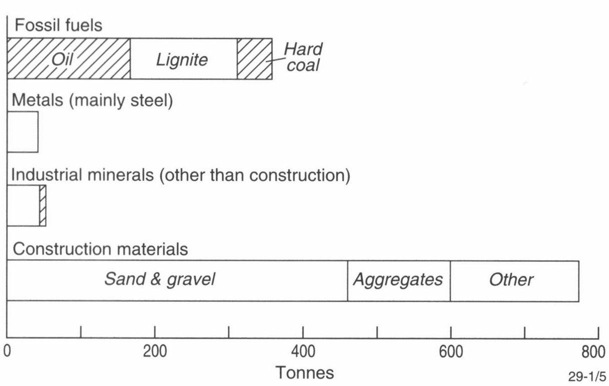

Figure 4. Material consumed in a lifetime of 70 years in Germany. About 17.5% of the total is imported (indicated by shaded areas) — mainly fossil fuels and metallic ores (after Wellmer 1994, personal communication).

The volume of rock involved over the average lifetime is more than 500 cubic metres, which corresponds to an area more than 7 metres square excavated to a depth of 10 metres — approximately 0.5% of the 100 metre support square.

If this kind of consumption were maintained for a population of 10–12 billion, the **total impact** would be more than quadrupled to over 200 billion tonnes, or approaching one hundred cubic kilometres of rock, each year. It is hardly possible to argue that such consumption rates are sustainable, either in terms of environmental impacts or availability of resources.

This discussion serves to illustrate the unsustainability of present demand trends and the consumption patterns that cause them. Clearly, every effort must be made to decouple economic expansion as far as possible from increased use of materials and energy. The fundamental needs of sustainable development are to minimise the primary inputs of materials and energy and to minimise the environmental impacts of these inputs. This will involve acceleration of present trends towards dematerialisation, combined with recycling and substitution. However, as indicated above, the process of adjustment will be counteracted by the increasing global population and the demand for improved living standards. Targets for sustainable consumption patterns will need to be set in the light of the best possible knowledge of the impact of resource use (see **Environmental impacts of minerals use**, below), and of the availability of resources (see **Availability of resources**, below).

Environmental impacts of minerals use

The present relationships between atmosphere, hydrosphere, lithosphere and biosphere are the result of evolution throughout Earth history. The interactions are complex but rates of change resulting from natural processes are relatively slow on human time-scales and the natural environment is in a state of dynamic quasi-equilibrium. Soils, in particular, form part of an oxidised zone resulting from interaction between bed-rock, air, water, plants and animals.

The environmental impacts of minerals extraction and use arise from the disturbance of this natural balance of Earth processes. In the case of phosphate, for example, phosphate which has been sequestered by natural exogenic processes over hundreds of millions of years is being returned to the land surface on a time scale of a few hundreds of years. Similarly, in the case of fuel minerals the current rate of consumption is more than a million times the natural rate of accumulation.

Metallic ore deposits, in contrast, are largely formed by endogenic processes and are unusual concentrations of elements which normally have very low concentrations in soils and water. The ores are largely derived from below the oxidised zone which is broadly in equilibrium with air and ground water. Both natural weathering and mineral processing therefore involve oxidation of these ore minerals and the release of various pollutants, including sulphur dioxide and toxic trace elements.

Fuel minerals

The environmental impacts of the combustion of fuel minerals are well known and have become a global policy issue (see e.g. Steering Committee of the Climate Change Study 1995). The emissions of carbon dioxide and other greenhouse gases continue to increase. If the forecasts of increased consumption of energy given above were realised (Foster 1993), carbon dioxide emissions could increase by a factor of 5.5 between 1975 and 2050. This emphasises what dramatic changes would be required to stabilise the emissions at 1990 levels by the year 2000, as proposed by the Framework Convention on Climate Change.

On the basis of climate models and current knowledge of the carbon cycle, it has been estimated that, depending on the success of the measures taken, carbon dioxide concentrations in the atmosphere will reach between two and three times pre-industrial levels for a population of 11.3 billion by the year 2100 (Inter-Governmental Panel on Climate Change 1994). It has also been estimated that the enhanced greenhouse effect will cause a rise in the average surface temperature of the Earth during the next century of between 1.5° and 4.5°C, and a rise in sea level of between 30 and 110 cm. The latter will add to the effects of coastal subsidence in many areas of very high population density (including mega-cities) in the coastal zone.

The analyses indicate that stabilisation at twice the present level of CO_2 (or less) will require an eventual and sustained reduction of emissions to substantially below present levels, with obvious implications for the substitution of coal and petroleum. However, recent analyses suggest that an **immediate** reduction of emissions is not essential for the achievement of such long-term targets. With orderly planning, they might be achieved by more cost-effective mitigation strategies, which allow adherence to the 'business-as-usual' scenario for up to three decades — but temperature and sea-level rise would initially be more rapid (Wigley et al. 1996).

In any case, it will be necessary to adapt to the consequences of significant climate change. Fortunately, not all these consequences will be negative (e.g. Petit-Maire 1995, for the Sahara) and, in the context of population growth, it might be argued that climate change is of lesser importance than land degradation, water quality and availability, other forms of pollution, and the preservation of biodiversity.

Clearly, although there are many uncertainties in the scientific assessment of climate change, much information is available for decisions in this area, and the precautionary principle requires that steps be taken to mitigate the environmental impacts. Agenda 21 (Chapter 4, para. 24) noted that (in general) significant changes in consumption and production patterns seem unlikely to occur in the near future 'without the stimulus of prices and market signals that make clear to producers and consumers the environmental costs of the consumption of energy, materials and natural resources, and the generation of wastes'. With respect to energy, a panel of the US Academy of Sciences in 1991 concluded (Tickell 1994) that 'on the basis of the principle that the polluter should pay, pricing of energy production and use should reflect the full cost of the associated environmental problems.' For the longer term the panel envisaged 'that a mix of renewable energy resources, together with nuclear power, would gradually assume a larger role in the new price structure. The transition to them raises more political and economic than technical problems'. The timing and nature of the changes in the energy mix will have major implications for the mineral industry as a whole.

Metallic minerals

One of the major impacts of the use of the metallic minerals arises from the energy used in their production. Gases released in the production process, notably sulphur dioxide, have also caused environmental problems, such as acid rain. A number of the metals are toxic, and can cause unacceptable pollution (as with lead in petrol).

Thus, the ideal industrial ecosystem (Fig. 5) would have minimal input of primary materials. Inputs can be reduced by more efficient processing throughout the cycle, by reduction of waste and by recycling. For example, in 1994 in the USA, reclaimed metals and mineral materials accounted for about one quarter of the total mineral raw materials used (USBM 1995). For specific metals, such as lead and copper, recycled material already accounts for well over half the total consumption in some industrialised countries.

Environmental impacts can be further reduced by improved treatment of waste and, where necessary and possible, by substitution. For example, there may be the opportunity to use waste materials from the production of high value commodities to substitute for primary raw materials in the production of low value commodities. Fly ash and rea-gypsum and, potentially, sulphur from the production of electricity based on coal can be used as substitutes for primary raw materials for cement production, gypsum and other sources of sulphur.

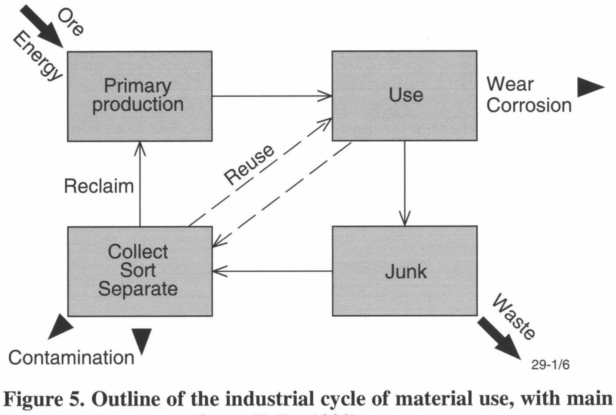

Figure 5. Outline of the industrial cycle of material use, with main inputs and outputs (from Kelly 1990).

New materials and composites are increasingly being used instead of metals (e.g. Kelly 1990). Some of these substitutes, such as ceramic materials, inorganic glasses and optical fibre, are derived from relatively common rock-forming minerals, while others, notably plastics, depend on the supply of fuel minerals. Relatively few are from renewable materials. In general, therefore, substitution involves replacing one non-renewable resource with another. It does not contribute substantially to dematerialisation, although it may reduce environmental impacts.

One reason for substituting other materials for metals for some purposes is that less energy is required, for example in the production of paper and plastic products, than for equivalent metallic products. However, the differences are not large enough to overcome other factors, such as particular properties or the ability to be processed for particular purposes. There have also been great improvements in the energy efficiency of primary production and forming of metals, and further improvements are possible.

Some attempts have been made to assess the environmental impact of extraction and processing involved in the primary production of metals. For example, a pilot study of mass balances (inputs and outputs) in the production of nickel has been undertaken in Germany (Wellmer, BGR Germany, pers. comm. 1994). The study took into account the different flows involved in the processing of laterite ores of various types and of sulphide ores. Information from such studies can be used in assessing total environmental impacts of alternative source materials.

Attempts are also being made to assess the environmental impacts of the production of various goods by focusing on material inputs, and taking into account all phases of product life cycles (Hinterberger et al. 1994). The underlying thesis is that knowledge of the total material inputs involved would allow the assessment of the relative merits of different materials and products and assist in an overall dematerialisation strategy. It is therefore proposed to classify products according to **'material input per service unit'.** Such studies will be valuable in promoting an understanding of environmental impacts. Clearly, general reductions in material inputs would also lead to reductions in energy usage, in waste, and in any toxic chemical flows.

It seems likely, however, that the main approach to environmental impacts related to metallic minerals will continue to be through addressing the problems of particular identified adverse outputs from the industrial ecosystem. Agenda 21, for example, deals specifically with the environmentally sound management of toxic chemicals in Chapter 9, of hazardous wastes in Chapter 20 and of solid wastes and sewage-related issues in Chapter 21. Nevertheless, these strategies will be more effective if it is recognised that these outputs are specifically related to material inputs which may themselves be subject to modification. Remedial measures may therefore be possible at all stages in the mineral cycle.

It is therefore suggested that greater efforts should be made at the international level to coordinate, assess and disseminate technological knowledge of appropriate strategies for improving the efficiency of the industrial ecosystem and reducing environmental impacts. Such efforts could be coordinated by the United Nations with the cooperation of non-government organisations such as the International Council on Metals and the Environment.

The assessment of pollution, at all scales, requires that we monitor the health of the surface of the solid Earth in the same way as is being undertaken for the oceans and atmosphere. The natural concentration of trace elements reflects the variability of the geology and knowledge of the natural variation can be critical in assessing human impacts (e.g. Wyborn et al. 1996).

The International Geochemical Mapping Project of the International Geological Correlation Program (Darnley et al. 1995, p. 15) has addressed the need for a coherent, systematic, worldwide, multi-element geochemical database and has determined the basic requirements and likely costs. It points out that such a database is pertinent to administrative and legal issues and that it 'contains information directly relevant to economic and environmental decisions involving mineral exploration, extraction and processing; manufacturing industries; agriculture; forestry; many aspects of human and animal health; waste disposal; and land use planning'. It has established that available data are substantially incomplete and internally inconsistent. Evidently, the data required could be obtained by enlisting the cooperation of national geological surveys. The necessary central coordination could be carried out by an appropriate United Nations agency.

Industrial minerals

In the context of land-use planning, it is clearly important to take particular note of the demand for **industrial minerals** which, as noted above, form the dominant component of total material usage. Debate concerning the depletion of mineral resources has been mainly concerned with the metallic and fuel minerals, with the implicit assumption that supplies of industrial minerals are inexhaustible. However, because of the enormous quantities involved, and because they are not readily recycled, the supply of industrial minerals raises particular problems of environmental impacts.

It might be supposed that once the main infrastructure of industrialised countries has been established, the needs for **construction materials** (for replacement and maintenance) would be significantly reduced, thus contributing to the process of dematerialisation (Phillips 1987). Apparently, however, this stage has not yet been reached in Europe. Although population there has stabilised, the annual consumption of construction materials continues to increase and there is widespread concern about the environmental impacts of quarrying and transport (Mineral Resources and Sustainable Development 1994). To meet the demand, there has also been an increase in the amount of sand and gravel derived from shallow offshore areas, and coastal superquarries have also been developed. It has been suggested, in this connection, that sustainable development of the coastal zone may require imposition 'of a littoral or "thalassic" tax which, like a carbon tax, takes a global view of the "polluter pays" principle' (Cook 1995).

Thus the rate of consumption of construction materials and the environmental impacts are clearly important issues for the promotion of sustainable construction industry activities (Agenda 21, Chapter 7G).

Amongst industrial minerals, phosphate has a special importance because of its essential contribution to the productivity of the agricultural industry (International Strategic Minerals Inventory 1984). Phosphate production increased roughly sixfold between 1950 and 1980 to around 150 million tonnes a year (roughly 30 kg per capita globally and near 50 kg per capita in some countries). It has fallen recently because of the near-collapse of output from the former USSR, but is likely to continue to rise in the future to meet the needs of the growing global population. Reserves are very large (Northolt et al. 1989, USBM 1995) but clearly finite. However, as with petroleum, the principal concern is with the environmental impacts of phosphate use as a result of the greatly increased levels of phosphate, especially in inland waters. But there is no substitute and it is difficult to control and reduce consumption.

Availability of resources

General outlook

The supply of resources is essentially a response to demand which has largely been regulated by price. Over recent decades, because of the success of the mineral industry in meeting demand, there has been plentiful and low-cost supply, which stimulates consumption and therefore demand. This situation was temporarily changed by the oil price shocks of the 1970s. In general, as discussed above, levels of demand do change through time, not only as a result of changes in cost, but also because of substitution, recycling, technological advances or environmental concerns. At present, the changes in demand are being driven largely by the environmental concerns. It is necessary to consider, however, whether resulting consumption patterns are also sustainable in terms of availability of resources.

The issues involved in assessing the sustainability of mineral supply have been comprehensively addressed in the scientific literature, but they have received little explicit attention in Agenda 21 or in the more general debate on sustainability. There has been a tendency to take too pessimistic a view, using published figures of ore reserves, or too optimistic a view on the basis that mineral resources are essentially infinite and that solutions will be found to the technological problems when scarcities of conventional mineral deposits emerge.

For the very long term it is hardly possible to predict how far technological advances, or specific scarcities, will lead to reduced demand (dematerialisation) or successful substitution, especially of energy, by renewable resources. Eventually, the development of non-polluting energy sources may largely solve the problems of resource supply by allowing extraction of minerals from sources which cannot at present be exploited economically and without unacceptable environmental impacts; but the timescale of any such development is very uncertain.

Because of the potential changes in the level of demand (for the reasons noted above) and potential changes in the nature of the supply (e.g. from lower grade sources as the result of technological change), it is not practicable to assess the overall 'lifetime' of the resources of a particular commodity. It is possible, for example, that the demand for a particular commodity will disappear, in which case it would cease to be a commodity or resource, and its 'lifetime' would be infinite.

Instead it is appropriate to consider a 'horizon of sustainability'. This defines how far we can look ahead to assured supplies of particular commodities making particular assumptions about the nature of demand. This horizon of sustainability can be extended further into the future as appropriate knowledge of resources is developed. On the timescales of sustainable development it is necessary to consider not only those resources which have already been identified but also the scope for discovering new deposits. These 'identified' and 'undiscovered' resources are discussed below.

The horizon of sustainability: identified and undiscovered resources

Identified resources. Most existing national and international assessment programs are limited to the assessment of 'identified resources' and especially of 'demonstrated economic resources' (DER), that part of total resources which has been identified by exploration and drilling, and which can be extracted economically under current conditions (Fig. 9.)

At present, therefore, knowledge of future availability of resources (and of whether production and consumption patterns are sustainable) is based essentially on the assessments of **identified resources,** which are not readily related to prospective mineral provinces or to longer term mineral potential. It is clear, however, from these assessments, that **the supply of mineral and petroleum resources over timescales of a**

few decades is well assured. The trend towards internationalisation of major resource companies, allied with increasingly effective exploration methods, has permitted the ready maintenance of the world's stock of economic identified resources. Technological advances in mining methods and mineral processing (e.g. for gold and copper), and strong competition, have also resulted in stable or declining deflated commodity prices (Fig. 6; see also Wellmer & Kürsten 1992).

The current stock of DER can be related to the changing demand for (and therefore production of) a particular commodity by the resource-production ratio (R/P ratio). This ratio gives the number of years that supply could be maintained from current stocks at the current level of demand. Time series of production, DER and R/P ratio illustrate the availability of mineral resources through time and give an indication of the effects of past changes in demand, and of major social and economic impacts. They also demonstrate that the stock of DER is not a fixed stock, subject only to depletion. It is continually being renewed, either by discovery of new economic resources or transfer from the large pool of known but sub-economic resources, as a result of technological advances or of price rises induced by scarcity.

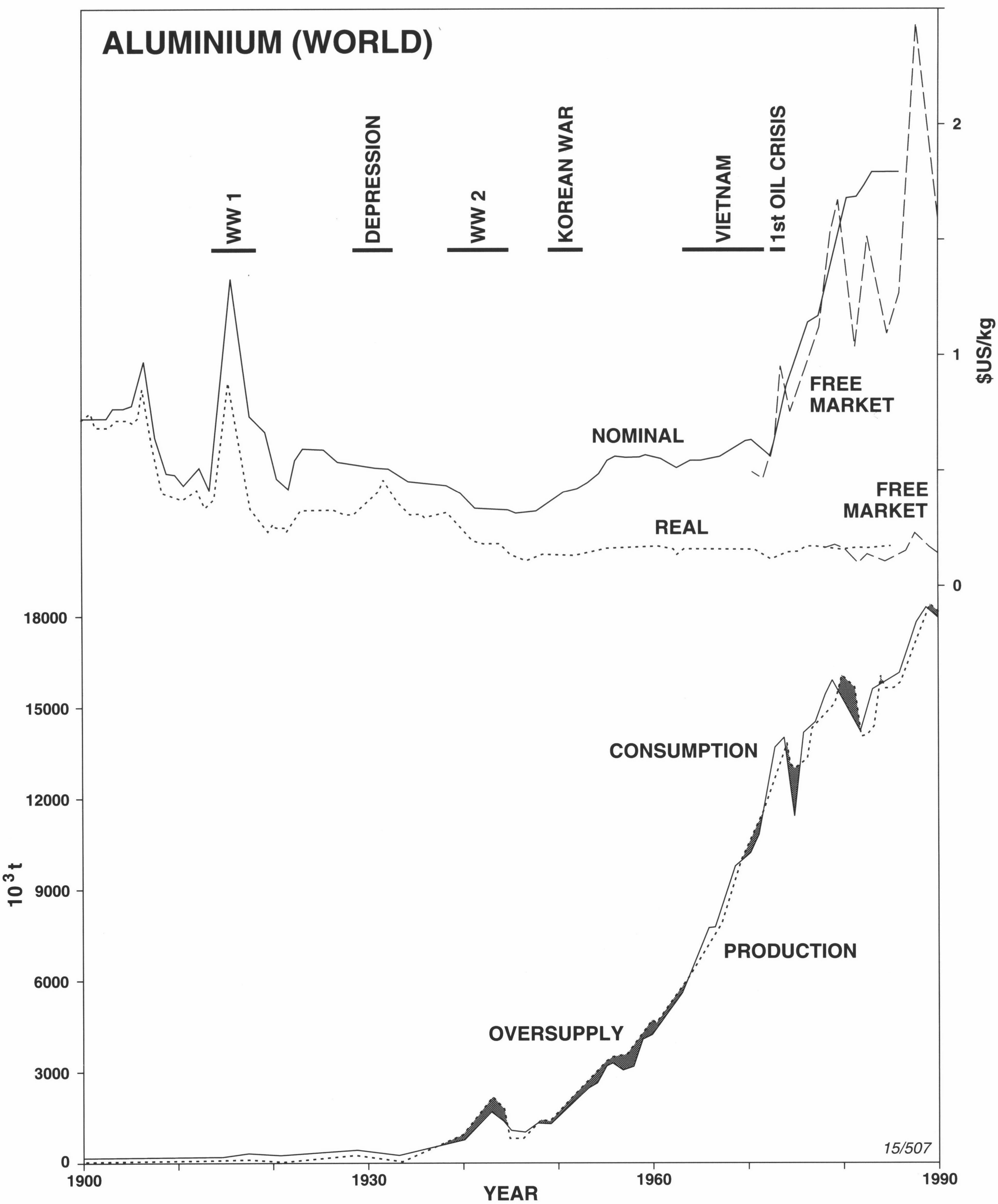

Figure 6. Aluminium as an example of declining real prices while production and consumption have grown rapidly (after Wellmer & Kürsten 1992).

In general, the annual production of mineral commodities has increased greatly and fairly steadily this century, but DER have also grown so that the R/P ratios have been maintained. In the case of bauxite, DER have been maintained but the R/P ratio has declined because of greatly increased annual production.

The large tonnage commodities such as coal, iron ore, bauxite and phosphate have large R/P ratios (hundreds of years). However, these are near-surface deposits and the capacity to continue to renew the stock of DER is in some doubt. Mining of these commodities also has the largest immediate (if transitory) environmental impact.

For most of the metallic minerals, R/P ratios are much smaller (some tens of years), but again it has been possible to maintain these ratios. This reflects the capacity of the minerals industry to take a relatively long-term view of future demand and of the factors likely to affect it, and to make appropriate investment in exploration and development. The time lag between such investment and the establishment of new DER is typically ten years or more. R/P ratios therefore provide a clear horizon of sustainability, usually of around thirty or forty years.

The information on identified resources does not, however, provide an assurance of supply over the longer timescales of sustainable development — to potential stabilisation of the global population at the end of the next century, or to the potential steady state development further in the future.

The evident continuing success in maintaining R/P ratios must be set against the relatively short period since the industrial revolution over which the resources have been exploited, and the exponential growth in demand (Fig. 7). These are essentially non-renewable resources and the economic resources have been severely depleted during the 20th century at an ever increasing rate. On the timescales of long-term sustainability, the situation for metallic ore deposits is not fundamentally different from that for petroleum (e.g. von Engelhardt et al. 1976, Cloud 1977; illustrated in Fig. 8). The trend towards utilisation of lower grade ores is already well established. In the absence of dramatic changes in consumption patterns, there would, at some time in the future, be real scarcity of resources **of the kinds currently mined**. It is clearly desirable to have as much advance warning as possible of potential **mineral shocks**.

As indicated above, technological solutions may well become available, but during the period of increasing global population and increasing demand for mineral resources, prudent management, according to the precautionary principle,

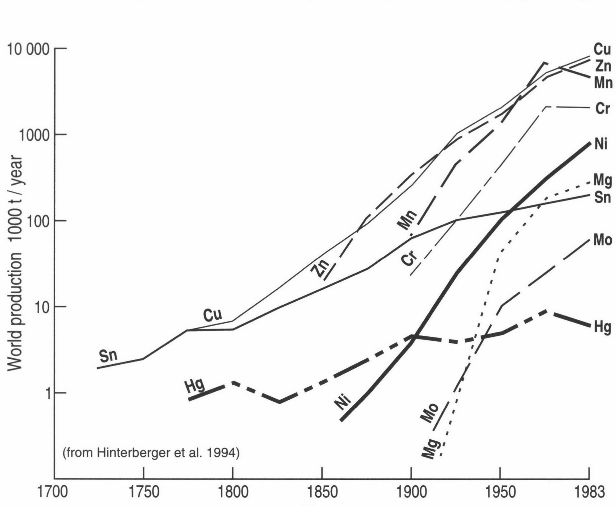

Figure 7. Exponential growth of metals production since the industrial revolution. Note the logarithmic scale for production (after Hinterberger et al. 1994).

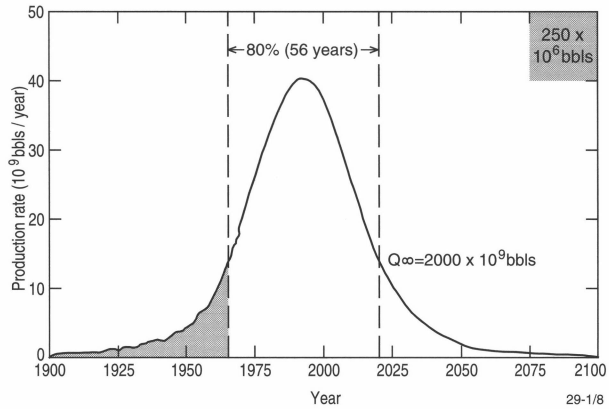

Figure 8A. Complete cycle of crude oil production.

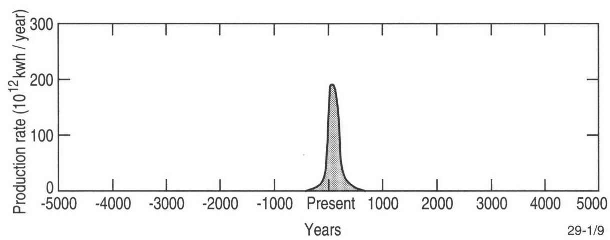

Figure 8B. The epoch of fossil fuel exploitation viewed in the perspective of 10 000 years of human existence, past and future. (Both from Engelhardt et al. 1976, after Hubbert 1974).

clearly requires further knowledge of the sustainability of supply, and of sustainable consumption patterns, beyond the present horizon of sustainability. The concern is not one of 'running out of resources', but of avoiding potential problems, and trying to ensure the optimum and efficient use of available resources with minimum environmental impact.

At present, we have very limited knowledge of the global potential for discovering new deposits, and this deficiency needs to be addressed. There are also increasing pressures on land use, which may make it increasingly difficult to explore for, and develop, the available resources. These issues are discussed in the following sections.

Undiscovered resources. Current information for petroleum (oil and natural gas) is quite comprehensive. As well as reasonably reliable figures for reserves, there are also good estimates of the quantity of undiscovered resources (or potential resources), especially for crude oil. Early estimates of the potential were too low and were soon overtaken by actual production figures. However, as the processes of generation, migration and entrapment of petroleum have become better understood, it has been possible to assess potential within reasonably narrow limits. A recent estimate (Masters et al. 1991) of ultimate resources (cumulative production plus reserves plus mean undiscovered resources) of crude oil gives a figure of 2079 billion barrels (in a range between 1800 and 2480 at the 90% confidence level), which is very similar to various estimates made 20 or 30 years earlier (see also Fuller 1993).

In contrast, there are no reliable global estimates for the undiscovered resources of metallic minerals. There are many different deposit types, the processes of generation of metallic mineral deposits are very complex and less well known than for petroleum, and methods for estimating undiscovered resources are much less reliable. Most methods are of a very general character and do not permit information about undiscovered resources to be linked in integrated systems of land use and management.

This is unfortunate, since it tends to foster the notion that these resources are unlimited, a notion based on the fact that the total amount of most metals and other mineral commodities in the Earth's crust is indeed very high. However, in most rocks, the metallic elements occur in very low concentrations, and not in discrete minerals, so that their extraction is not feasible. Metallic mineral deposits, whether currently economic or sub-economic, result from particular conjunctions of processes in the Earth's crust which have led to the deposition of unusual concentrations of metals as ore minerals in particular locations.

Mineral deposits of the kinds currently regarded as economic or sub-economic might be quite limited by comparison with the resources already identified. Their distribution is highly heterogeneous at various scales both areally and in depth. Different kinds of deposit are characteristic of different geological environments so that their occurrence is limited to particular mineral provinces. Moreover, many deposit types are formed close to the Earth's surface so that the opportunities for discoveries below the uppermost few kilometres are relatively limited.

Many of the more prospective terrains of the world have already been extensively explored by modern methods so that the more readily detected deposits have already been discovered. However, exploration techniques are continually being improved in the search for concealed deposits. Other terrains have only recently been opened to the international exploration industry and there will undoubtedly be major discoveries over the next few decades. It is likely, therefore, that the horizon of sustainability can be pushed back into the second half of the 21st century. Nevertheless, in the present state of knowledge, it is prudent to recognise that there may be real problems of meeting demand over the next century. These problems may be increased by political factors and, more generally, by restrictions on the availability of land for exploration (see below).

Strategic factors

The uneven distribution of mineral deposits worldwide means that the sources of supply of some commodities, such as platinum, chromium, vanadium and manganese, are highly restricted geographically. In recent decades, for example, South Africa and the former Soviet Union have accounted for over 80% of world mine production of platinum group metals. Such commodities will continue to attract high exploration interest in order to establish other sources of supply.

The dependency on supplies of minerals from outside sources has led some countries to the identification of 'strategic minerals', an imprecise term which embraces the concepts of criticality and vulnerability. At the national level, the criticality of a mineral depends on its contribution to the national economy and general physical well-being, and critical minerals may in some cases be vulnerable to interruptions of supply. A report by the Office of Technology Assessment (US Congress 1985) noted that

> Only three nations (South Africa, Zaire and the USSR) account for over half of the world's production of chromium, cobalt, manganese and platinum group metals. These metals are essential in the production of high temperature alloys, steel and stainless steel, industrial and automotive catalysts, electronics and other applications that are critical to the US economy and the national defense.

A fuller knowledge of potential sources of supply is therefore likely to be of increasing interest to many countries.

A number of countries have participated in producing an International Strategic Minerals Inventory (ISMI, recently renamed International Studies of Minerals Issues), and this has produced valuable information on the identified resources of many commodities (mainly metals, but also important non-metallic industrial minerals, such as phosphate and graphite). ISMI has not attempted to make estimates of undiscovered resources (Fig. 9).

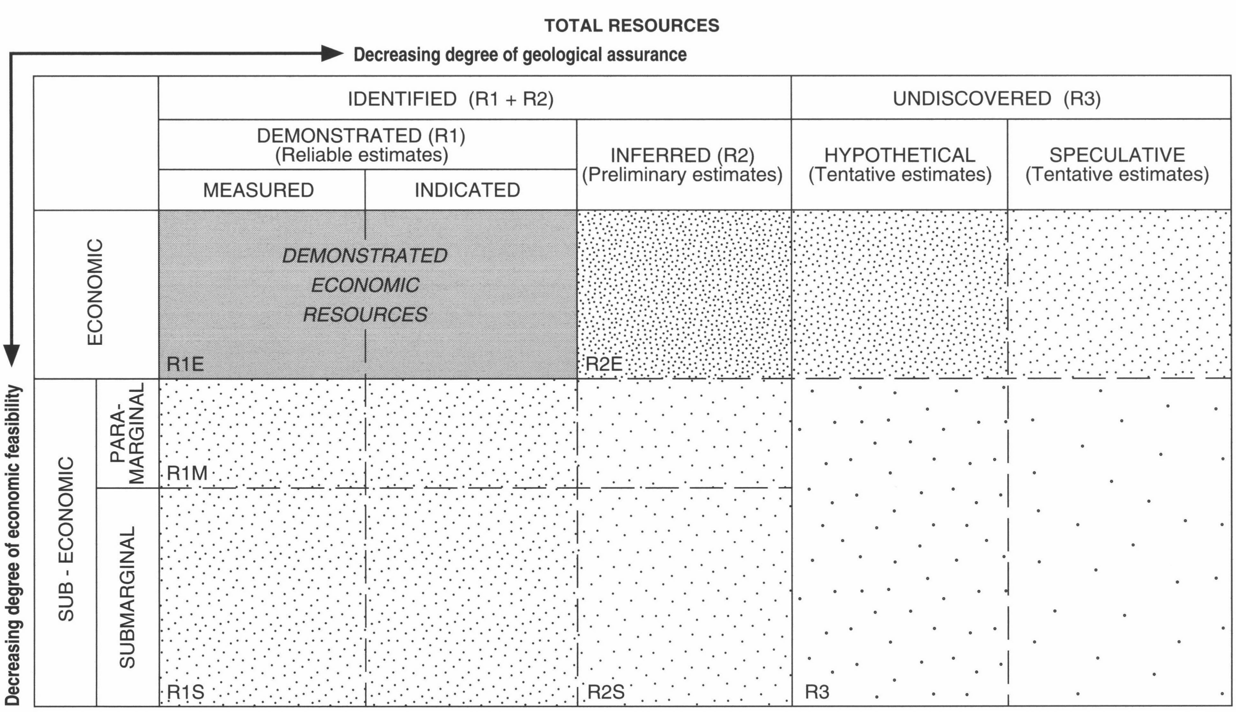

Figure 9. Australian resource classification system (BMR 1984, modified McKelvey system), also showing United Nations resource categories (after Schanz 1980, p. 313). R, in situ resources; R1, known deposits — reliable estimates; R1E, economically exploitable; R1M, marginally economic; R1S, sub-economic; R2, extensions of known and newly-discovered deposits — preliminary estimates; R2E, economically exploitable; R2S, sub-economic; R3, undiscovered deposits — tentative estimates. Note also that the sub-economic categories also represent unusual concentrations of the relevant elements and can be reasonably well defined for particular deposit types.

Availability of land for exploration

Population pressures worldwide and the attendant environmental impacts are causing increasingly severe competition for land use, and there has also been a reaction against mining in some countries. The need to meet the global demand for mineral resources from the most efficient sources worldwide is not readily appreciated either by local communities, whose lifestyles may be affected by major mining projects, or by national conservation movements. This is especially the case if the demand is perceived to be the result of extravagant or wasteful consumption patterns with undesirable environmental impacts. It is therefore important that strategies to maintain supply be linked to effective strategies to move to sustainable consumption patterns.

Population pressure and environmental impacts can militate against the vigorous exploration programs which would need to be pursued in the most prospective areas worldwide if essential mineral supply is to be maintained in the short term. It is important, therefore, for governments to recognise that only a relatively small proportion of the continental areas is highly prospective for each of the various metallic mineral deposit types. These areas need to be identified, and their mineral potential taken into account in determining the needs for mineral exploration, in a global context and using an integrated approach to land use planning. This will not be feasible unless a comprehensive information base is developed on mineral resource potential, which can be integrated with other land use information.

This is recognised in general terms in Agenda 21, Chapter 10 (Integrated approach to planning and management of land resources) viz:

> Integration should take place at two levels, considering, on the one hand, all environmental, social and economic factors (including for example impacts of the various economic and social sectors on the environment and natural resources) and on the other all environmental and resource components together (i.e. air, water, biota, land geological and natural resources).

Assessment of mineral resource potential

Areas which are prospective for particular mineral deposit types have been called **permissive tracts** and their identification is the first step in the assessment of mineral potential and of unidentified resources. Such permissive tracts can be identified on the basis of geoscientific mapping programs carried out by national geological surveys. In Australia, for example, mapping under the National Geoscience Mapping Accord would allow the identification of permissive tracts within the main mineralised provinces (Fig. 10). In conjunction with information on mineral occurrences, such mapping permits **qualitative** estimates of prospectivity and resource potential. It provides the basis for assessment and investment in exploration by mining companies. Mineral maps and/or metallogenic maps can be produced as by-products of geological surveys (e.g. Emberger 1993).

It is also desirable to assess not only the most likely

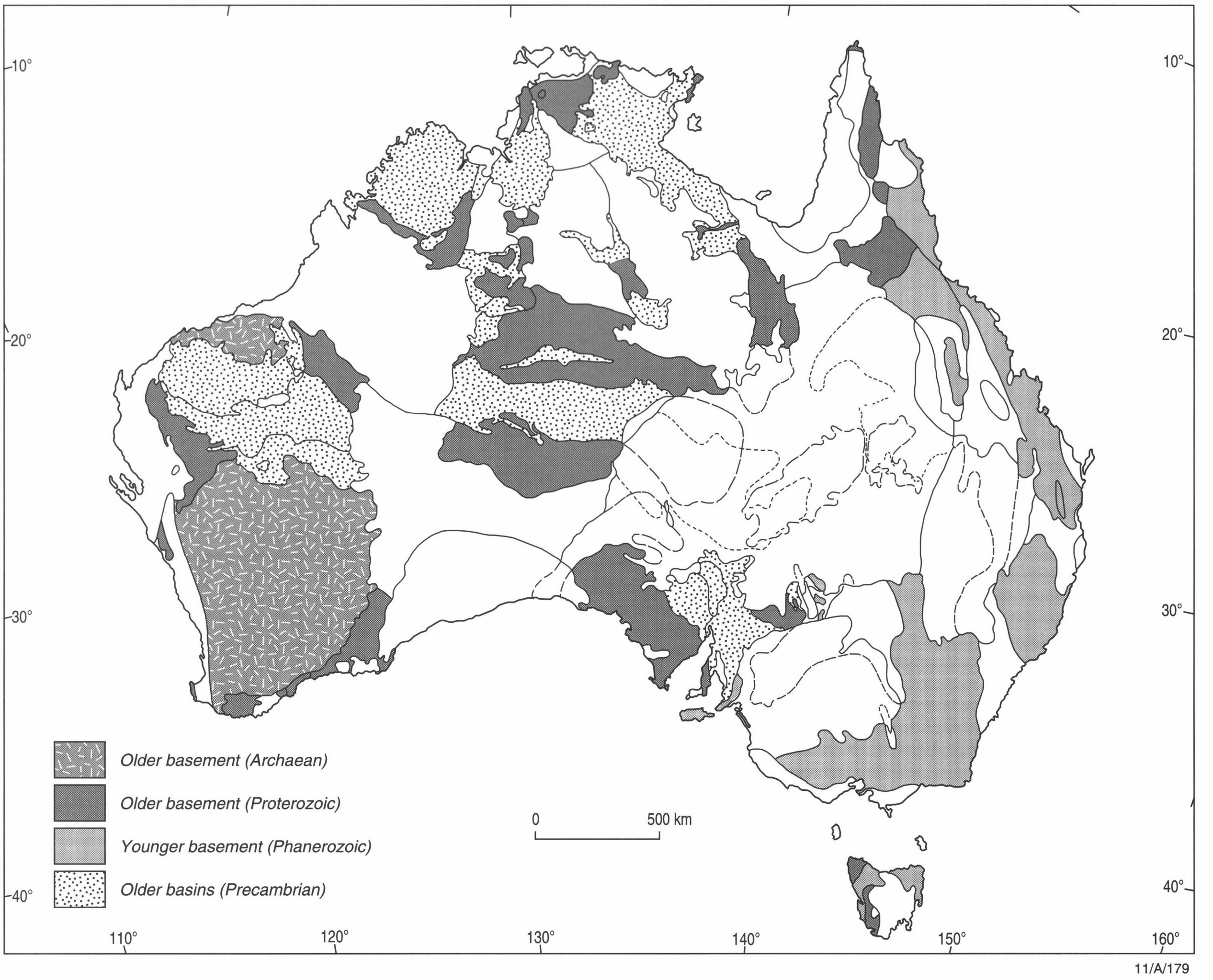

Figure 10. Main basement provinces of Australia and associated Precambrian basins — the principal areas prospective for metallic mineral deposits.

geographic sources, but also the quantities of undiscovered deposits in both the hypothetical and speculative categories (Fig. 9). Hypothetical resources are those 'which may reasonably be expected to exist in a known mining district or mineral province under known geological conditions' while speculative resources are those 'which may occur either in known types of deposits in a favourable geological setting where no discoveries have previously been made, or in yet unknown types of deposits which remain to be recognised' (BMR 1984). Both these categories contain deposits which are likely to be economic or marginally economic under current criteria.

Several approaches have been made to the **quantitative** assessment of undiscovered mineral resources (e.g. Dorian & Zwartendyk 1984). Most notably, a three-part method of quantitative assessment has been applied by the US Geological Survey since 1975. 'Its original purpose was to provide quantitative resource information in a form consistent with an economic analysis so that mineral resource values could be compared with other competing uses of land' (Singer 1993). These assessments are most reliable where the mineral deposit geology is already well-known — usually for relatively small geological provinces.

More recently, there has been a proposal to make a **national** three-part assessment, providing 'a consistent, usable minimum level of current mineral-resource information together with estimates of total undiscovered mineral endowment' for the entire United States (McCammon & Briskey 1992 p. 259). It was suggested that such an assessment 'is essential for ensuring that all domestic mineral resources will be considered in planning the optimum use of the Nation's public lands and for securing long-term mineral supplies from national and international sources'.

As a first step in this program, a two-year preliminary quantitative national assessment based on existing national data was also proposed. This would produce 'maps showing the outlines of tracts that are permissive for the types of deposits concerned' (McCammon & Briskey 1992 p. 61). Such an assessment would be of great value for planners in the United States, and similar assessments would be of even greater value in developing countries with substantial resource potential. Moreover, the value of all such national assessments would be greatly enhanced if they could be examined in the context of global potential and global resource needs. However, whatever the fate of the proposed US program, it is unrealistic at the present time to propose a similar **quantitative** assessment worldwide. In most countries, the level of geological knowledge is inadequate for assessments by this three-part method and there are impediments to the acquisition of such knowledge, both in terms of expertise and financial resources (cf. Harris et al. 1993).

A more realistic goal globally would be to produce maps delineating 'permissive tracts' worldwide using internationally agreed criteria. This would involve only the first steps in the proposed US preliminary assessment, viz

- compile existing data
- apply limited mineral-deposit models
- construct maps of delineated permissive tracts.

Such maps would provide the basis for iterative assessments of undiscovered resources as data became available. Although the assessments of individual tracts would generally be, at best, semi-quantitative, the global picture so provided would allow much more realistic assessments of sustainability beyond the horizon currently provided by identified resources.

More immediately, such maps would help the consideration of minerals issues within an integrated approach to land-use planning. They would allow the needs for mineral exploration and development to be assessed in relation to other land-use needs. Moreover, since perceived mineral resource potential has been identified as the most important single criterion for the international mining industry in assessing the investment environment for exploration, a global program identifying permissive tracts worldwide would aid the efficient and socially harmonious operation of the industry. For example, it would help local and national populations to appreciate the wider global interest in keeping the principal permissive tracts of the world open for exploration and development as far as possible if the global endowment of mineral resources is to be effectively managed and used.

In this context, it is important to distinguish between the scope of mineral exploration and the scope of mineral developments. It must be recognised that, although it is necessary to explore over large areas, this can largely be accomplished by non-intrusive techniques, such as aeromagnetic surveys, and exploration is not generally incompatible with other land uses. Mineral development after successful exploration will continue to affect only relatively small areas. If current best practice in integrating environmental and development concerns is implemented, the short-term environmental impacts of mining can be minimised within acceptable limits, and the long-term impacts can be negligible. It also needs to be emphasised that, under appropriate environmental guidelines, the needs for exploration and development are not incompatible with other forms of land use, including agriculture and national parks.

The Committee on Natural Resources of the United Nations Economic and Social Commission has therefore concluded that the United Nations 'could make a major contribution to the long term management and sustainable development of mineral resources through developing a global knowledge base, at appropriate scales, of the potential for mineral resource exploration and development' (CNR 1994). The committee recognised that the program should be based on GIS technology, which would allow integration with other land management information.

The Committee on Natural Resources was aware that much of the information required is already being collected in many countries, and that a number of existing international organisations (both government and non-government) could help develop such global knowledge (see also Harrison 1993). The World Bank has also recognised the importance of such information for developing countries. It is believed, therefore, that a global knowledge base could be developed at relatively low cost by building on existing efforts of many institutions at the national and regional levels. The UN needs to define the global mission and provide the necessary coordinating mechanisms, including the development of globally consistent approaches to the definition of permissive tracts, and the assessment of resource potential.

Countries with well established geological surveys and mineral industries, and those with existing international minerals programs, can play leading roles in developing such a program at the regional level. Others, such as the countries of the former Soviet Union, need substantial assistance to ensure that information gathered in the past on a confidential basis is not irrevocably lost, but contributes to the global knowledge base.

Such global knowledge is clearly essential if sustainable consumption patterns are to be developed to take into account resource availability as well as environmental impacts.

Conclusion

The non-renewable nature of mineral (including fuel mineral) resources raises special problems in applying concepts of sustainable development.

Present global trends are towards increasing consumption and therefore increasing environmental impacts, in spite of significant efforts in many countries. This is largely because of global population growth and the requirement for improved standards of living in developing countries.

Growth in per capita consumption to levels currently enjoyed by the developed countries for a future global population of 10–12 billion is clearly not sustainable. If the desired global economic expansion by a factor of 5 or 10 is to be achieved in a sustainable way, then it must be decoupled as far as possible from increased input of materials and energy. 'We must devise models for a steady-state society, in which population size is in broad balance with the availability of resources' (Tickell 1991). In these circumstances, it is imperative that minerals issues be given prominence in the implementation of Agenda 21.

As noted above (**Availability of resources**), in the long term, it is hardly possible to predict how far technological advances, or specific scarcities, will lead to reduced demand (dematerialisation) or successful substitution, especially of energy, by renewable resources.

It is therefore impractical to apply the criterion of sustainability proposed by the World Bank economist Herman Daly, i.e. the rate of use of a non-renewable resource should be no greater than the rate at which a renewable resource, used sustainably, can be substituted for it (Daly 1990). Experience suggests that substitution will not occur on a major scale until a clear need has been established, so that changes in consumption patterns will be relatively abrupt.

The issue of sustainable consumption patterns needs to be considered both in terms of the capacity of the environment to absorb the impacts of resource use and the capacity to sustain the supply. The former is more readily assessed and the problems are relatively well-known, but impacts such as those of phosphate use in agriculture and of combustion of fuel minerals have proved difficult to control. In these cases the transition to more sustainable patterns faces severe political and economic problems.

In the case of metallic minerals, it is suggested that the UN could make a significant contribution in coordinating, assessing and disseminating technological knowledge of appropriate strategies for improving the efficiency of the industrial ecosystem and reducing environmental impacts (*The support square*, and *Per capita resource use*, above).

There are also significant gaps in knowledge needed for assessing pollution. A program to monitor the chemical health of the global land surface needs to be implemented. This will allow anthropogenic impacts to be assessed in the context of natural variation and will also assist in the delineation of permissive tracts.

In relation to supply, it is possible to determine the viability of consumption patterns out to a horizon of sustainability. This is only a few decades for demonstrated economic resources, but can be extended by assessment of undiscovered resources. The sustainability of supply can therefore be defined on a rolling basis in relation to this extended horizon of sustainability, which can also take into account changes in demand as a result of improved efficiency of use, recycling and substitution.

Given present trends it seems unlikely that the global consumption of resources can be stabilised, and eventually reduced, for some decades. It is likely, therefore, that there will be increasing difficulty in containing environmental impacts and in meeting the demand for minerals from the finite sources of supply currently regarded as economic or sub-economic. To help manage this situation during the period of transition to more sustainable consumption patterns, it is recommended that:

1. A global knowledge of the potential for mineral exploration and development (especially the identification of 'permissive tracts') should be developed, and integrated with other land information so that land-use planning can properly take into account national and global needs for mineral exploration and development.
2. Based on this knowledge, global estimates of undiscovered resources should be made, so that the horizon of sustainability can be extended as far as possible and maximum warning obtained of potential mineral shocks.

These steps are relatively non-controversial and low cost. Much of the information required is already being collected at national level. It would be appropriate for the United Nations to coordinate the collection of information to provide a global framework for policy formulation at both international and national levels. National geological surveys can make unique contributions both in relation to environmental impacts and in relation to resource availability.

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